

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Higher Normal School of Technological Education of Skikda



Department of : Physics and Chemistry

THESIS

Submitted in fulfillment of the requirements for the degree of

Doctorate

Domain: Materials Sciences

Field of study : Physics

Speciality: Materials Physics

Presented by :

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Title:

**Development and Characterization of Porous Silicon Layers for
Photovoltaic Applications.**

Publicly defended on: 05/2026

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Academic Year : 2025/2026

République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche
Scientifique

École Normale Supérieure de l'Enseignement Technologique de
Skikda



Département de : Physique et chimie

THÈSE

Présentée en vue de l'obtention du diplôme de

Doctorat

Domaine : Sciences de la matière
Filière : Physique
Spécialité : Physique des matériaux

Présentée par

M^{me} : Nasri Nihal

Thème :

Élaboration et caractérisation des couches de silicium poreux
pour applications photovoltaïques.

Soutenue publiquement le : 05/2026

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Année Universitaire : 2025/2026

Dedication

To my self

To my parents Khaled & Dalila

To my sisters Nour & Manar

Little Layan

*To my best friends Sbrina, Salsabil, Asma, Basma,
Imen, Raja, Boutaina, Hana.*

To my classmates Khalida, Selma & Sonia

To all who lead me to being here today

Especially professor Rahmouni Salah

Acknowledgements

First and foremost, I would like to express my deepest gratitude to God Almighty, who has blessed me, guided me, and granted me the strength and patience to reach a level greater than I once aspired to. Without His grace and mercy, this achievement would not have been possible.

I would like to extend my sincere and heartfelt thanks to Professor **Salah Rahmouni**, who was not merely a supervisor, but a true mentor, a supportive father figure, and a constant source of guidance throughout this journey. He stood by me at every step, offering invaluable advice, encouragement, and unwavering support. His dedication, generosity with his time and knowledge, and belief in my abilities played a fundamental role in the completion of this work. I am deeply grateful for everything he has done for me.

I would also like to express my sincere appreciation to **Dr Boukhenoufa Nouredine**, my co-supervisor, for his valuable assistance, constructive guidance, and continuous support. His contributions and encouragement greatly enriched this work, and I will always remain grateful for his help and kindness.

I would also like to express my sincere gratitude to the members of the examination committee for honoring me with their presence and for their valuable time and effort in evaluating this work.

My special thanks go to the President of the jury, **Dr. Chebli Abdelhak (HNSTE of Skikda)**, for chairing the committee.

I am equally grateful to the examiners:

Professor Djefel Faycel (University of Batna 2),

Dr. Boubekri Hani (HNSTE of Skikda), and

Dr. Tifouti Issam (HNSTE of Skikda),

for their insightful remarks, constructive feedback, and valuable contributions to the improvement of this thesis.

I would also like to express my sincere thanks to my dear friends, **Salsabil** and **Asmae**, who have encouraged and supported me since the very beginning of this journey. Their motivation and belief in me meant more than words can express.

My special and deepest gratitude goes to my soulmate and closest friend, **Sabrina**, who has been my constant support during my most difficult days. Her presence, understanding, and unwavering encouragement gave me strength whenever I felt overwhelmed.

I would like to express my special thanks to my dear and close friend, **Imen** who has always been there for me, comforting me in difficult moments and filling my days with positivity. Her constant support, kindness, and uplifting spirit gave me the strength to keep going, and I am truly grateful to have her in my life.

I would also like to express my heartfelt thanks to my sisters, **Manar** and **Nour**, who have always been my support and encouragement, helping me reach the goal of obtaining my PhD. To my beloved parents, **Khaled** and **Dalila**, your love, sacrifices, and faith in me have been the foundation of my achievements.

Finally, I extend my sincere appreciation to all my friends and to everyone who supported, encouraged, and believed in me throughout this journey. Your kindness and support will always be remembered.

Abstract

One of the most promising renewable energy sources is solar power. Using photovoltaic cells, sunlight is directly converted into electrical power to create photovoltaic electricity. We employed porous layers on the front surface to lower reflection in order to enhance solar cell performance without requiring intricate technological procedures.

In our work, porous silicon films were prepared on N-type and P-type silicon substrates with different crystal orientations. Our study allowed us to determine the effect of different oxidation treatments and the properties of the silicon substrates used on the nature of the resulting porous silicon, specifically the shape, porosity, and thickness of the layers

We were able to get diverse outcomes by using different experimental circumstances. Porous silicon layers may have their shape and structure changed by magnetic fields, which enhances their functionality and opens up new technological possibilities. This can involve altering the distribution, size, or form of the pores, which enhances the material's mechanical, optical, or electrical qualities. Additionally, it is crucial to create novel synthesis techniques in order to create sophisticated magnetic nanostructures inside silicon matrices.

Also, Rare earth ion deposition can raise silicon-based solar cells' photo conversion efficiency. And in order to Understanding how emission spectra intensities change in relation to porosity, thickness, and refractive index factors is the goal of additional research.

In order to clarify Photoluminescence (PL) properties of porous silicon films investigated as a function of temperature we first investigated how the material's photoluminescence characteristics vary with temperature.

Key Words: Porous silicon, renewable energy, Photoluminescence, temperature effect and magnetic fields

ملخص

واحدة من أكثر مصادر الطاقة المتجددة الواعدة هي الطاقة الشمسية باستخدام الخلايا الكهروضوئية، يتم تحويل ضوء الشمس مباشرة إلى طاقة كهربائية لإنشاء الكهرباء الكهروضوئية. استخدمنا طبقات مسامية على السطح الأمامي لتقليل الانعكاس بهدف تحسين أداء خلايا الشمسية دون الحاجة إلى إجراءات تكنولوجية معقدة. في عملنا، تم تحضير السيليكون المسامي على ركائز السيليكون من النوع N والنوع P بتوجيهات بلورية مختلفة. سمحت لنا دراستنا بتحديد تأثير العلاجات المؤكسدة المختلفة وخصائص ركائز السيليكون المستخدمة على طبيعة السيليكون المسامي الناتج، وبشكل خاص الشكل، المسامية، وسمك الطبقات.

تمكنا من الحصول على نتائج متنوعة من خلال استخدام ظروف تجريبية مختلفة. يمكن أن تتغير أشكال وهياكل طبقات السيليكون المسامي بفعل المجالات المغناطيسية، مما يعزز وظيفتها ويفتح آفاقاً تكنولوجية جديدة. يمكن أن يتضمن ذلك تغيير توزيع أو حجم أو شكل المسام، مما يعزز الخصائص الميكانيكية أو البصرية أو الكهربائية للمادة. بالإضافة إلى ذلك، من الضروري ابتكار تقنيات تخليق جديدة من أجل إنشاء هياكل نانوية مغناطيسية متطورة داخل مصفوفات السيليكون.

أيضا يمكن أن يؤدي ترسيب أيونات الأرض النادرة إلى زيادة كفاءة تحويل الضوء في خلايا الطاقة الشمسية القائمة على السيليكون، ومن أجل توضيح الخصائص المعتمدة على درجة الحرارة للضوء المحفز (PL) لأفلام السيليكون المسامي، قمنا أولاً بالتحقيق في كيفية تغير خصائص الضوء المحفز للمادة مع درجة الحرارة. إضافة إلى ذلك دراسة كيفية تغير شدة أطيف الانبعاث فيما يتعلق بعوامل المسامية والسماكة ومعامل الانكسار هو هدف البحث الإضافي.

الكلمات المفتاحية: السليسيوم المسامي، الحقل المغناطيسي، الطاقات المتجددة، تأثير درجة الحرارة والفوتوضوئية

Résumé

Parmi les différentes sources d'énergie renouvelable, l'énergie solaire se distingue comme l'une des plus prometteuses, en raison de sa capacité à être convertie efficacement en énergie électrique à l'aide de cellules photovoltaïques, la lumière du soleil est directement convertie en énergie électrique pour créer de l'électricité photovoltaïque. Nous avons utilisé des couches poreuses sur la surface avant pour réduire la réflexion afin d'améliorer les performances des cellules solaires sans nécessiter de procédures technologiques complexes. Dans notre travail, des films de silicium poreux ont été préparés sur des substrats de silicium de type N et de type P avec différentes orientations cristallines. Notre étude nous a permis de déterminer l'effet de différents traitements d'oxydation et des propriétés des substrats de silicium utilisés sur la nature du silicium poreux résultant, en particulier la forme, la porosité et l'épaisseur des couches.

Nous avons pu obtenir des résultats divers en utilisant différentes circonstances expérimentales. Les couches de silicium poreux peuvent voir leur forme et leur structure modifiées par des champs magnétiques, ce qui améliore leur fonctionnalité et ouvre de nouvelles possibilités technologiques. Cela peut impliquer de modifier la distribution, la taille ou la forme des pores, ce qui améliore les qualités mécaniques, optiques ou électriques du matériau. De plus, il est crucial de créer de nouvelles techniques de synthèse afin de créer des nanostructures magnétiques sophistiquées à l'intérieur des matrices de silicium.

La déposition d'ions de terres rares peut augmenter l'efficacité de conversion photoélectrique des cellules solaires à base de silicium. Comprendre comment les intensités des spectres d'émission changent en relation avec la porosité, l'épaisseur et les facteurs d'indice de réfraction est l'objectif de recherches supplémentaires afin de clarifier les caractéristiques de photoluminescence (PL) dépendantes de la température des films de silicium poreux, nous avons d'abord étudié comment les caractéristiques de photoluminescence du matériau varient avec la température.

Mots Clés: Silicium poreux, énergie renouvelable, Photoluminescence, Effet de la température et champs magnétiques.

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General Introduction

General Introduction

General Introduction

The world's energy consumption has increased significantly in recent decades owing to the expansion of industry, transportation, communications, and many other areas. Electrical energy is usually produced by burning non-renewable resources (coal, oil, gas, etc.), which have run out in the last few decades [1].

A significant contribution to sustainable development is made by the electrical energy produced by solar cells. In fact, the photovoltaic industry has a lot of promise and might eventually rank among the primary energy sources. Since the sun is a limitless supply of energy, it transfers 5,000 times as much energy to the Earth as was used [2].

Without the need for an intermediary, photovoltaic technology (PV) aims to transform sunlight directly into electrical power. This device is easy to use and has a straightforward design [3]. The fundamental building block of a photovoltaic system is the PV solar cell, which is made up of two thin layers of various semiconductor materials, the only ones that can absorb photon energy from sunshine. There are two types of semiconductors: the positive (P-type) and the negative (N-type) [4]. PV solar cells are most frequently made of silicon due to their adaptability and effectiveness. There are three types of silicon: monocrystalline, polycrystalline, and microcrystalline. However, additional semiconductor design materials, such cadmium-telluride and Copper-indium-diselenide, can be utilized in PV systems in addition to silicon. Numerous considerations determine which material will be used [5].

Silicon is a semiconductor characterized by an indirect bandgap, which fundamentally limits its optical emission efficiency. In silicon, radiative band-to-band recombination of electron-hole pairs requires the participation of a phonon to conserve momentum, making this process intrinsically slow. Consequently, radiative recombination must compete with no radiative recombination pathways, which are generally far more efficient. These no radiative processes occur through deep-level states associated with impurity atoms, intrinsic crystal defects, or surface states. As a result, crystalline bulk silicon is inherently unsuitable for efficient light-emitting devices based on electron-hole recombination. Nevertheless, since silicon remains the cornerstone material of modern microelectronics, the development of light-emitting silicon would be highly desirable,

General Introduction

particularly for applications such as optical interconnects and monolithically integrated display technologies.

The observation by Canham [6] when crystalline silicon is properly anodically etched in hydrofluoric acid, it forms a porous silicon structure (also known as "porous silicon") in 1990.

That demonstrates effective room-temperature photoluminescence led to a massive research effort in this and similar materials. The investigation was spurred not only by the possibility of technological uses but also by the assertion that the production of porous silicon [7] and photoluminescence [6],

There are numerous uses for porous silicon in the photovoltaic industry as well. Porous silicon nanostructures preserve the substrate's original crystallographic orientation, making them suitable for use as a seed for epitaxial silicon growth in the solar sector. Additionally, porous silicon has intriguing qualities as an antireflection layer that raises the efficiency of photovoltaic energy conversion [8-12]. Through electrochemical dissolution in an electrolyte based on hydrofluoric acid (HF), porous silicon nanostructures are created. There is ongoing discussion over the mechanism of silicon dissolution in HF. Although many models have been put forth, the Lyman and Gossel model from 1991 is the one that is most frequently cited [7].

Our objective is to create porous silicon while taking into account the following factors: how magnetic fields affect the shape of porous silicon layers; how trivalent erbium ions (Er^{3+}) penetrate silicon holes using electrochemical techniques; how altering etching current densities affect the optical characteristics of porous silicon films; and how temperature affects the photoluminescence (PL) characteristics of porous silicon (PSi).

After this study, analyses using scanning electron microscopy (SEM) were conducted. Evaluation via XRD Morphological Research and PL Measurements

This thesis is presented in four chapters:

- Chapter one: In this chapter, silicon and porous silicon are defined, their various manufacturing circumstances and techniques are examined, and their optical and physical properties are examined.

General Introduction

- Chapter two: We will discuss the various forms, generations, and uses of photovoltaic solar energy systems, as well as photovoltaic cells.
- Chapter three: Several characterization methods are presented in Chapter 3, including PL spectroscopy, The samples were characterized using Fourier transform infrared spectroscopy, scanning electron microscopy, and X-ray diffraction.
- Chapter four: This chapter will cover the preparation of porous silicon samples under various conditions, including the presence of erbium ions, a magnetic field, and varying the current intensity. It will also cover sample characterisation and outcomes.

General Introduction

References

- [1] S. Rahmouni, *Fabrication of antireflection coatings for improving photovoltaic conversion* (Doctoral dissertation). Faculty of Technology, Department of Electrical Engineering, University of 20 August 1955–Skikda 2017.
- [2] RAPC., Ombre passagère sur le photovoltaïque, le Journal du Photovoltaïque n°1. PP: 12-17. 2009
- [3] P. P. Barker and J. M. Bing, “Advances in solar photovoltaic technology: An applications perspective,” in Proc. IEEE Power Engineering Society Summer Meeting, 2005.
- [4] K. A. Khan, S. Paul, and A. Zobayer, “A study on solar photovoltaic conversion,” *International Journal of Scientific and Engineering Research*, vol. 4, pp. 1–5, 2013.
- [5] T. Razykov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, et al., “Solar photovoltaic electricity: Current status and future prospects,” *Solar Energy*, vol. 85, pp. 1580–1608, 2011.
- [6] L.T. Canham, Appl. Phys. Lett., 57 (1990) 1046.
- [7] V. Lehmann and U. Gösele, "Porous silicon formation: A quantum wire effect," Appl. Phys. Lett., vol. 58, no. 8, pp. 856–858, 1991.
- [8] P Menna. G. DI Francia. V.LA. Ferrara. Porous silicon in solar cells, a review and a description of its applications, as an AR coating. Solar Energy Material & solar Cells. Vol : 37, pp :13-24. 1995
- [9] M .LEE, K. Y Wang. H C.H .CHU. Characterization of silicon photovoltaic devices through rapid thermal oxidation, rapid thermal annealing and HF dipping processes, solar Energy Mat and Cells. Vol: 59, pp: 59-64. 1999 5
- [10] C.Levy Clement. S. Strehlke, S. Bastide. Optimization of porous Silicon, Reflectance of Silicon Photovoltaic, Cells Solar Energy Material & Solar Cells. Vol (58) . pp: 399 409. 1999.

General Introduction

- [11] S. Strehlke., Sarti D., Krotkus A, et AL. The Porous Silicon concept Applied to multicrystalline, Silicon Solar Cells. Thin Solid Film.Vol 297; pp: 291-295. 1997
- [12] R. B. Bergmenn, T.J Rinke, T. A Wagner et AL. Thin Film Solar Cells on glass based on the transfer of monocrystalline, silicon films, Solar Energy Materials & Solar Cells. Vol 65, pp :355-361. 2001

Chapter I: Porous Silicon

I-1 Introduction

Silicon consumption has rapidly increased because of the growing demand for semiconductor devices brought about by developments in digitalization and information and communication technology. Because of its many mechanical, chemical, and electrical characteristics, silicon, a metalloid, is the most utilized raw material in the semiconductor industry. Owing to its excellent electrical, thermal, and mechanical properties, silicon has long been considered the material of choice for a broad range of technological applications [1–3]. Regardless of its crystalline or nanostructured form, the identification of remarkably potent photoluminescence within the visible spectrum of porous silicon by Canham [4] in 1990 and Lehmann [5] in 1991 instilled significant optimism in the scientific community for the advancement of optoelectronic devices.

I-2 Silicon

I-2-1 Silicon structure

Silicon is a group IV-A semiconductor in the periodic table, characterized by an atomic number of 14, an atomic weight of 28.086, and a density of 2.33 Mg/m³. It exhibits a melting point of approximately 1410 °C. The electronic configuration of a silicon atom is (Ne) 3s²3p², and its atomic radius is about 0.132 nm. Crystallographically, silicon adopts a diamond cubic structure with a lattice constant of 0.543 nm, while the nearest-neighbor atomic spacing is 0.235 nm [6]. This diamond cubic structure can be described as a face-centered cubic (fcc) lattice with a two-atom basis, as illustrated in Figure I-1.

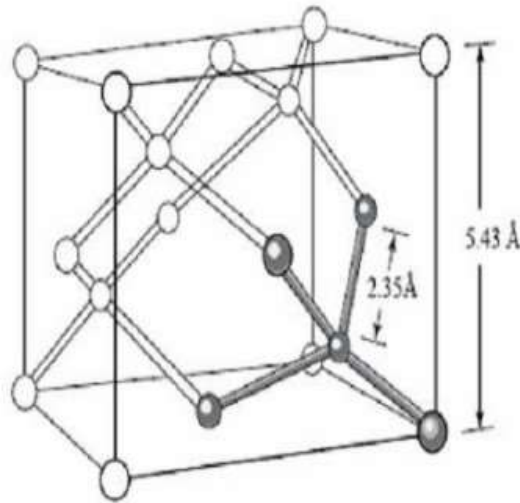


Figure I.1. Crystalline structure of silicon [7].

I-2-2 Energy bands

As a semiconductor, silicon has more free electrons than an insulator but less than a conductor. There are two kinds of energy bands: valence and conduction. The valence band in a solid is made up of a sequence of energy levels with valence electrons. At 0°K, electrons fill the energy levels of the Valence band, which holds the maximum energy when occupied by electrons.

A photon and a phonon must both be involved in a momentum change transition from the valence band top to the conduction band bottom. The conduction band is the band with the lowest energy level and the highest energy level. The electrons, which are referred to as free electrons because they can move anywhere in a material, partially occupy the conduction band and control the flow of current [8]. Figure I-2 illustrates the energy band structure of silicon.

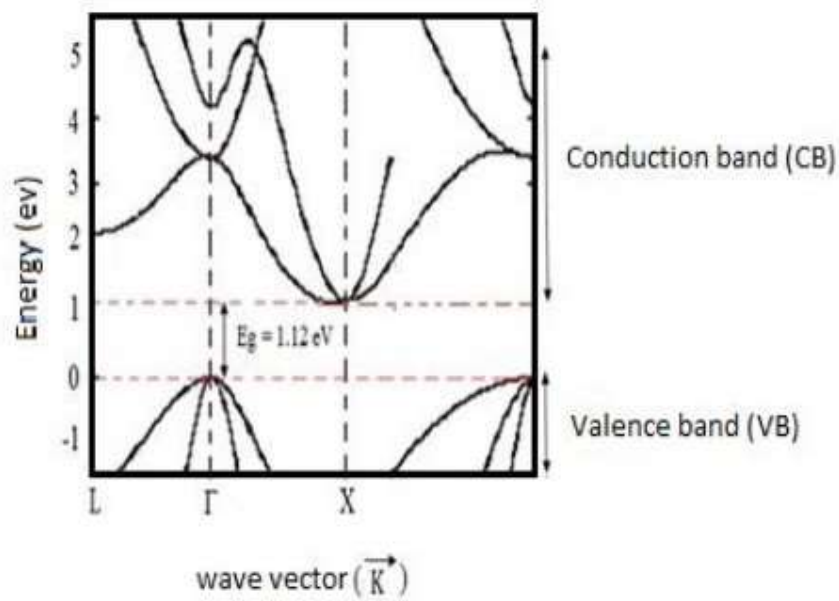


Figure I.2. Diagram for the conduction and valence bands of silicon [9].

I-3 Porous silicon

I-3-1 History

The discovery of porous silicon dates back to 1956, when Arthur Uhlir Jr. and Ingeborg Uhlir at Bell Laboratories in the United States accidentally observed its formation. While developing techniques for polishing and shaping silicon and germanium surfaces through electrochemical processing, they noticed the appearance of a thick film, typically black, red, or brown, forming on the material surface under certain conditions. At that time, this unexpected product was not thoroughly investigated and was only briefly documented in Bell Laboratories' technical reports [10]. Despite this early observation, porous silicon attracted little scientific attention until the late 1980s. Interest was renewed when Leigh Canham, working at the Defense Research Agency in the United Kingdom, proposed that porous silicon could exhibit quantum confinement effects [11]. Guided by this hypothesis, he conducted experiments that led to a breakthrough in 1990, demonstrating that chemically and electrochemically etched silicon wafers could emit visible light. This discovery marked a significant milestone and stimulated extensive research into the optical properties and potential applications of porous silicon.

The scientific community was interested in the published result because of its non-linear optical and electrical properties. The growing interest was mirrored in the number of publications published on the properties and potential uses of porous silicon. A 2000 study found that between 1991 and 1995, the number of published works rose significantly [12].

I-3-2 Porous silicon fabrication

I-3-2-1 Dry Elaboration

Two approaches are employed in this manner:

Plasma erosion, also known as spark processing, is the process of ionizing the gas molecules in the cage by driving the silicon's electrons towards the anode through a high voltage discharge between the anode and the silicon (cathode). The ions are then driven towards the silicon cathode, where their collision produces enough heat to cause the silicon to evaporate [13].

PECVD deposition of silicon nanocrystals: in this process, the deposition is accomplished by silane SiH_4 discharge in an RF field. Deposition rates of several nanometers per minute can be achieved [14].

I-3-2-2 Humid Elaboration

Porous silicon can be made by stain etching with hydrofluoric acid, nitric acid, and water. A 1957 paper states that stain films can be made in concentrated hydrofluoric acid in diluted nitric acid solutions. The production of porous silicon through stain etching is particularly appealing (HF) due to its ease of use and the availability of readily available corrosive chemicals, such as hydrogen fluoride and nitric acid (HNO_3). Additionally, stain etching is beneficial if very thin porous Si films are needed [15]. R. J. Archer published a paper in 1960 that showed that stain etching with HF- HNO_3 solution can result in stain coatings as thin as 25 microns [16].

Since the early experiments of Uhlir [17] and Turner [18], and more recently Cahnam [4], porous silicon has primarily been produced by electrochemically dissolving silicon wafers in hydrofluoric acid (HF)-based solutions [19]. Electrochemical anodization involves altering an electrical parameter within a silicon electrolyte solution, and it can operate at constant voltage and variable current or constant current and variable voltage.

I-3-2-3 Electrochemical anodization of porous silicon

If some key parameters are set suitably, pore development via silicon dissolving occurs after applying a voltage (in the right direction) between the wafer backside contact and an electrode in the HF solution.

I-4 Characterization I (V)

The typical i-V curves for n- and p-type silicon in aqueous HF are shown in Figure I-3. The i-V curves reveal some basic parallels to the behaviour of a conventional Schottky diode at a semiconductor/electrolyte interface, such as photo generated currents at reverse bias. However, there are some discrepancies [20-22]: first, the chemical processes at the interface do not change depending on whether the majority carriers are n-type or p-type. Secondly, reverse-bias dark currents in Schottky diodes have been reported to be at least three orders of magnitude larger than those expected.

In the presence of cathodic polarization, n- and p-type silicon are both stable. The only notable cathodic reaction is the reduction of water at the silicon/HF interface, which produces gaseous hydrogen and only takes place at high cathodic over potentials, or reverse biased breakdown as it is known in Schottky-diode terminology.

At high anodic over potentials, the silicon surface is electro polished, while at low anodic over potentials, the surface morphology is dominated by a dense grid of channels that reach deep into the silicon bulk. Only anodic polarization causes silicon to dissolve [10].

For a potential value below the potential of the first sharp peak, pore formation occurs only during the first rising portion of the i-V curve. The current that peaks at this location (JPS) is the source of the electro polishing current's moniker. The grey area of the i-V curve in Figure I-3 is where pore formation takes place.

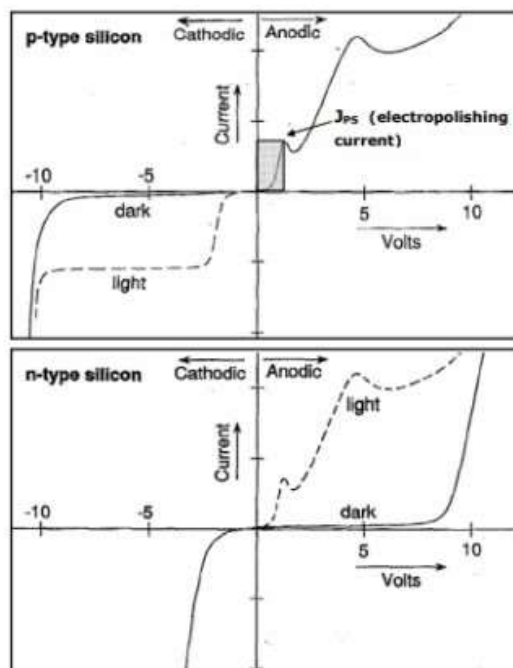


Figure I.3. Characteristic i-V curves for n- and p-type doped silicon in aqueous HF [19].

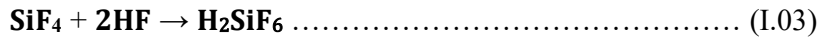
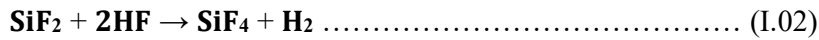
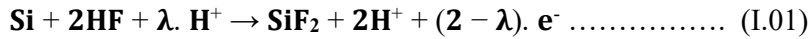
I-5 Porous silicon formation chemistry

In an acidic environment, silicon dissolves electrochemically by an oxidation reaction. The system consists of an electrolyte with a negative potential and silicon, which serves as the anode (positive pole). Most of the ions in solution are composed of the ions H^+ and F^- .

The hydrides $Si-H$ are formed when the surface atoms of silicon mix in acidic liquids. This means that hydrogen controls the surface, and the presence of H^+ ions is necessary to break these $Si-H$ bonds. These ions are supplied by silicon via current.

The kind and degree of silicon doping are therefore very important. We often operate with a changing current and continuous voltage.

The following dissolving process was postulated by Turner [23], Memming, and Schwandt [24].



Lehmann and Gosele [5] proposed the following model in 1991:

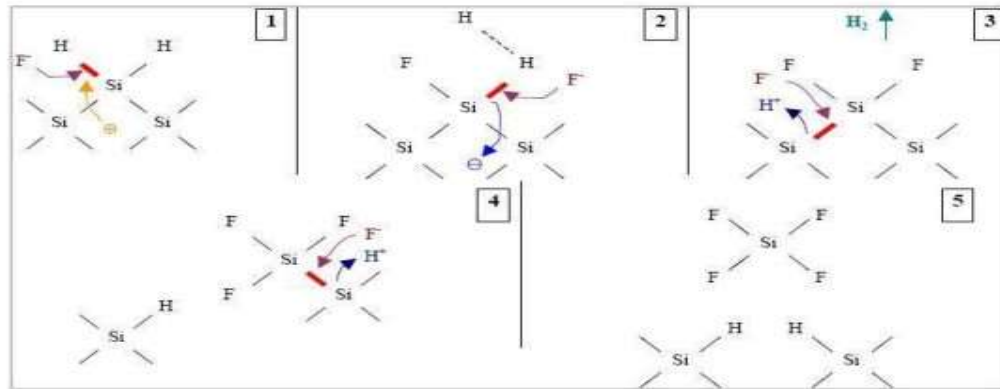


Figure I.4. : Dissolution mechanism of Silicon [5].

The liberation of silicon atoms at the surface is made possible by the ions F-weakening the Si-Si bonds when the hydrogen layer is removed.

The procedure is then repeated, with either Fluor atoms or hydrogen atoms reclaiming the silicon surface.

Tetravalent dissolution occurs when a cell's current flow is large, requiring four holes for every silicon atom.

Under these circumstances, no porous silicon is produced; however, a surface oxide is formed as a result of the reaction and silicon polishing. Therefore, the movement of carriers at the silicon/solution electrolytic interface must be the phenomenon limiting the total charge transport mechanism in order to form porous silicon. This phenomenon can be regulated by employing low current densities.

Immersion in the electrolyte solution also causes chemical damage to the sample's porous layer. This is because hydrofluoric acid dissolves the oxide that forms when it

comes into contact with water, and the pH of the solution controls the rate of the reaction, which rises as the concentration of OH-ions increases.

Controlling the production process of porous silicon is challenging because of the simultaneous electrochemical attack and chemical dissolution. The quality of chemically dissolved porous silicon improves over time in the acid and saturates for a duration that is determined by the electrolyte concentration.

Consequently, attempts are made to minimize the effects of chemical dissolution by using acid concentrations higher than 10% and the shortest attack times [25].

The initial step, when pores randomly form on the silicon surface, is shown in figure I-5. In the center, the self-regulatory mechanism is shown. Instead of growing isotropically, the pore grows highly directly when the depletion zones surrounding each pore converge.

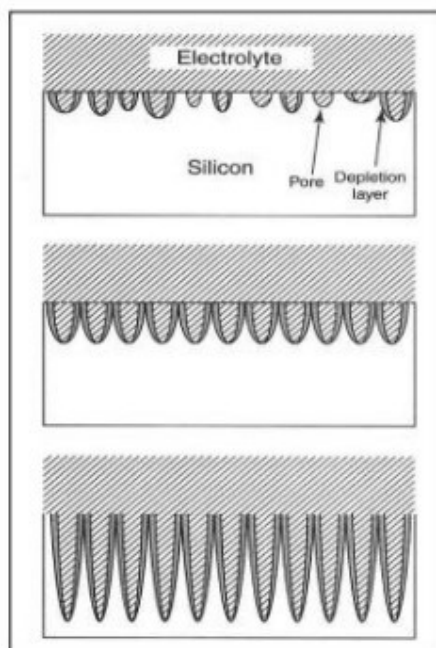


Figure I.5. Pore formation in porous silicon [26].

A photonic crystal operating in two dimensions. Photos shows the cross section (a) and the same sample in top view (b). In an n-type doped silicon substrate, it was realized using ordered microporous porous silicon.

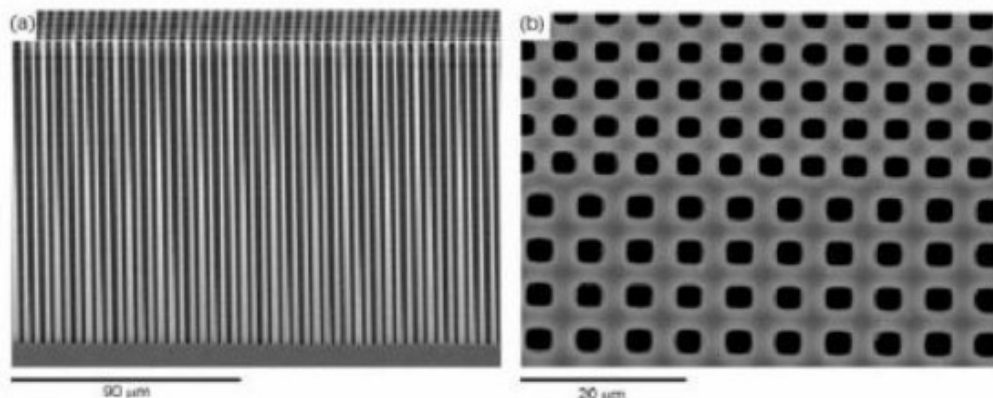


Figure I.6. Example of a two-dimensional photonic crystal [27].

I-6 Porous silicon properties

I-6-1 Physical properties

The International Union of Pure and Applied Chemistry (IUPAC) has defined micro pores, miso pores, and macro pores based on the current terminology, with typical pore sizes of 2 nm, 2-50 nm, and > 50 nm, respectively [28].

This classification relies exclusively on pore diameter and therefore provides limited insight into pore morphology. Pore morphology encompasses features such as pore shape (e.g., smooth, branched, or faceted), orientation, and the degree of interconnection between pores. Among these characteristics, pore shape is the least quantitative parameter. A systematic and comprehensive characterization of porous silicon morphology is particularly challenging due to the exceptionally rich variety of pore sizes, shapes, and spatial distributions that can occur. From a morphological standpoint, microporous and miso porous silicon typically exhibit a sponge-like structure, characterized by densely packed, randomly branched pores with no well-defined orientation. As the pore diameter decreases, the tendency for pore branching increases. In contrast, macro porous silicon often contains well-defined pores with smooth walls, as well as short or dendritic branches.

These pores preferentially propagate along the $\langle 100 \rangle$ crystallographic direction and toward the source of positive charge carriers (holes) involved in the electrochemical dissolution process.

Dendritic pores are oriented in the 100 direction, whereas smooth-walled pores are aligned to the source of holes. Although pore size and shape are not taken into account because their existence and variation determine the refractive index of the porous silicon layer (As shown in Figure I-7).

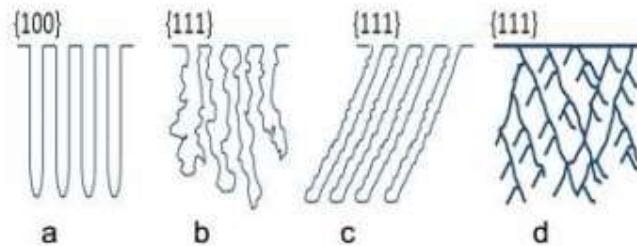


Figure I.7. Main crystallographic orientations of the pores [29].

Porous silicon is formed selectively in relation to the doping of the substrate. For many types of beginning silicon substrates, some broad tendencies in layer morphology can be deduced. Four cross-sectional TEM pictures of porous silicon samples with various starting substrates are shown in Figure I-8 [30].

The morphological contrast is obvious. Both size and interpore spacing are quite tiny in p-type doped silicon Figure I-8 a typically between 1 and 5 nm, and the pore network seems relatively uniform and linked. Pore diameters and interpore spacing rise as dopant concentration increases, while specific surface area decreases. In strongly p-type doped silicon (p^+), the structure becomes anisotropic, with lengthy gaps running perpendicular to the surface, as shown in Figure I-8 c .

The situation is more difficult in n-type doped silicon. Pore size and interpore spacing decrease with increasing dopant concentrations in n-type doped silicon, and pore size and interpore spacing drop with increasing dopant concentrations in p-type doped silicon.

Low porosity (1-10%) is found in lightly doped n-type substrates anodized in the dark, with pores in the micrometre range. Higher porosity values can be attained under illumination, and mesopores can form alongside macropores. Anodization conditions, particularly light intensity and current density, have a significant impact on the final structure. While heavily n and p-type doped silicon have comparable topologies (see Figure I-8 c and d), the pores in n-type doped silicon tend to develop a randomly directed

filamentary structure and pipe, producing enormous straight channels as the electro polishing regime approaches (see Figure I-8,b).

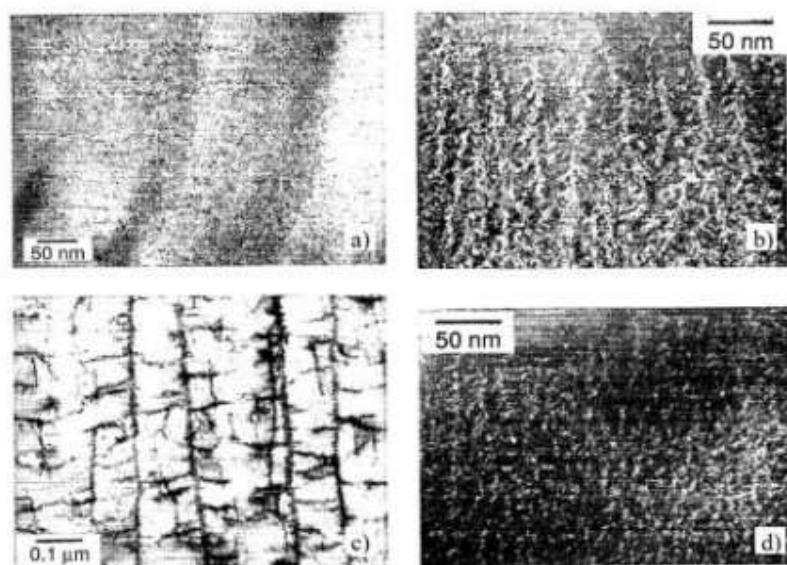


Figure I.8. Cross-sectional TEM images demonstrating the basic morphological distinctions between different types of materials. (a) P type silicon; (b) N type silicon; (c) P + type silicon; (d) N + type silicon [19].

II-6-2 Optical properties

The 1990 discovery of pronounced visible luminescence from anodically etched p-doped silicon by Canham garnered significant interest within the scientific world, as porous silicon emerged as a favoured material in electronics and optoelectronics [31, 32].

Porous silicon is of great technological interest because it may make it possible to incorporate optical components easily into silicon integrated circuits. The possibility of commercial applications is significantly increased when a microelectronic circuit incorporates a stable and effective luminous porous silicon element.

It has been discovered that porous silicon-based structures glow efficiently in all wavelength ranges, from visible and near UV to near infrared (1.5 m). As shown in Table I-1, a few distinct luminescence bands of different origins are responsible for emission throughout such a broad spectral range.

Table I.1. Porous silicon luminescence bands [33].

Spectral range	Peak wavelength (nm)	Luminescence band label	PL	EL
UV	~350	UV band	YES	NO
Blue-green	~470	F band	YES	NO
Blue-red	400-800	S band	YES	YES
Near IR	1100-1500	IR band	YES	NO

A recent review was conducted on the general properties of each luminescence band and the situations under which they are observed [34].

Since it can be effectively electrically stimulated, the "S-band" luminescence has received the most attention to date [35,36] and has the most technological significance. Over the visible spectrum, this band has been adjusted from deep red to blue [37]. It is worthwhile to quickly address the most likely source of the other luminescence bands, though. The blue-green photoluminescence (PL) emission, known as the "F-band" because of its quick millisecond decay period, was initially observed by Harvey et al [38].

Following Kovalev et al.'s [39] showing of a very considerable PL output of this type from oxidized porous silicon generated via RTO treatment, the F-band has been the focus of several recent studies [34,40,41]. It is only observed in oxidized structures, though, and is most likely the result of defective silicon oxide [40] or contaminated silicon [42].

Infrared emission at room temperature for materials annealed at ultrahigh vacuum (UHV) was first produced by Fauchet et al [43]. Although a clear association has not yet been shown, the cause of this radiation may be related to dangling bonds [44], as stated in [45].

Jiang et al. [46] were the first to report ultraviolet emission from oxidized material under 1993 mild x-ray excitation. Stronger output at normal temperature was thereafter observed [47, 48]. The defective oxide phase is probably the cause of the UV bands, such as the blue-green F-band, which are only visible in oxidized layers [49].

As shown in Figure I-9, the detected large band, which spans 550 nm to 780 nm, reduces in time with a peak of 668 nm and a decreased full width at half maximum (FWHM) of 226 to 112. Additionally, the PL intensity increases from 0,07 to 21,06.

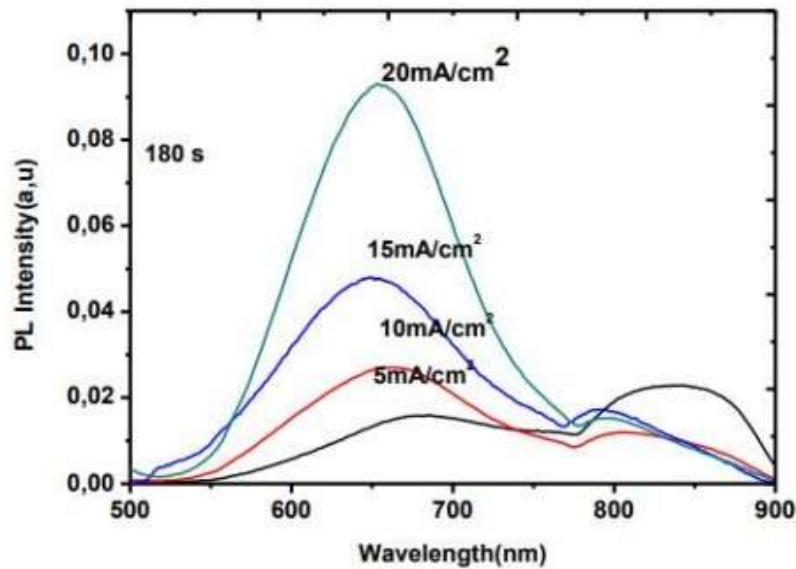


Figure I.9. The photoluminescence spectra of P-type porous films produced at various etching current densities [50].

I-7 Conclusion:

There are numerous potential uses for porous silicon. The investigation and design of porous silicon multilayers for photovoltaic applications has been the main emphasis of this work. Because the refractive index and layer thickness may be chosen by adjusting the formation parameters during the fabrication process, porous silicon is a good material for creating multilayers.

References

- [1] V. Haapamäki, Silicon lifecycle and recycling in the semiconductor industry, Bachelor's thesis, Aalto University, Finland, 2025.
- [2] Yuting Wan, Jian Sha, Bo Chen, Yanjun Fang, Zongli Wang, and Yewu Wang, Nanodevices Based on Silicon Nanowires, Recent Patents on Nanotechnology. Vol 3, pp:1-9, 2009
- [3] Yao Hea, Chunhai Fanc, Shuit-Tong Lee, Silicon nanostructures for bio applications, Nano Today. Vol 5, pp:282-295, 2010
- [4] L T. Canham, Silicon quantum wire array fabrication by electrochemical dissolution of wafers Appl, phys, letters. Vol 57 n° 10, pp :1046-1048, 1990
- [5] V. Lehmann, U. Gosele, Porous silicon formation: a quantum wire effect. Appl .Phys. Lett. Vol 58 n° 8 pp : 856-859, 1990.
- [6] “Silicon,” Princeton University, [Online]. Available: <https://princeton.edu/~maelabs/mae324/glos324/silicon.htm>. [Accessed: Jan. 27, 2026].
- [7] Josh Schaefferkoetter, « Dilute magnetic semiconductors February »27, (2007).
- [8] Z. Beddiaf and S. Belghit, “Introductory Chapter: Silicon,” in *Silicon Materials*, B. Zaidi & S. Belghit, Eds., IntechOpen, 2019, doi:10.5772/intechopen.85802.
- [9] Henry Mathieu. Physique des semi-conducteurs et des composants électronique, 4ème édition. Masson, pp: 5, (1997).
- [10] L. T. Canham, “Title of the article if available,” New Scientist, 10 April 1993. [Online]. Available: (original source if online). Accessed: Feb. 25, 2013.
- [11] Sailor Research Group, “Introduction to Porous Si,” Sailor Research Group, Department of Chemistry, University of California, UCSD, 17 Feb. 2003. [Online]. Available: http://www.sailorgroup.ucsd.edu/intro_porous_si.html.

- [12] V. Parkhutik, "Analysis of publications on porous silicon: From photoluminescence to biology," *Journal of Porous Materials*, vol. 7, pp. 363–366, 2000.
- [13] M. H. Ludwig, A. Augustin, R. E. Hummel, and T. Gross, "On the formation process of luminescing centers and spark-processed silicon," *Journal of Applied Physics*, vol. 80, n°. 9, pp. 5318–5324, 1996.
- [14] E. Edelberg , S. Bergh, luminescence from plasma deposited silicon film J, appl, phys, , Vol. 81, n°. 5, pp. 2410-2417, 1997
- [15] J. L. Coffey, "Porous silicon formation by stain etching," in *Properties of Porous Silicon*, L. T. Canham, Ed., Institution of Engineering and Technology, London, 1997, pp. 23–28, ISBN: 0-85296-932-5.
- [16] R. Archer, "Stain films on silicon," *Journal of Physics and Chemistry of Solids*, vol. 14, pp. 104–110, 1960.
- [17] A. Uhler, Bell System Technology Journal, 35, p.333 (1956).
- [18] D.R. Tuner, J. Electrochem. Soc., 138, 807 (1991).
- [19] R.L. Smith, and S.D. Collins, J. Appl. Phys. 71, R1 (1992)
- [20] A. J. Bard, Encyclopedia of Electrochemistry of the Elements, Dekker, New York (1986).
- [21] P. J. Holmes, The Electrochemistry of Semiconductors, Academic, London, (1962).
- [22] H. Foll, Appl. Phys. A, 53, 8 (1991).
- [23] Turner D. R. Electro polishing silicon in hydrofluoric acid solutions. J. Electro chem. Soc. Vol. 105, n° 7, pp: 402-408, 1958
- [24] R. Memming, G. Schwandt, anodic dissolution of silicon in hydrofluoric acid solutions. Surf.sci. Vol 4 n° : 2 pp : 109-124, 1966
- [25] Susanna Setzu, Réalisation et étude de structure a modulation d'indice optique en silicium poreux. Thèse de doctorat de l'université de joseph fourrier, Grenoble I,(1999).
- [26] L. Pavesi, J. Appl. Phys., 80, 216 (1996).

- [27] T. Trifonov, A. Rodriguez, F. Servera, L.F. Marsal, J. Pallarès, R. Alcubilla, *phys. stat. sol. (a)*, 202, 1634 (2005) .
- [28] P. Müller, IUPAC Manual of Symbols and Technology, *Pure Appl. Chem.*, 31, 578 (1972).
- [29] V. Lehmann, H. Foll, Formation Mechanism and Properties of Electrochemically Etched Trenches in n-Type Silicon J, *Electrochem soc*, Vol 137, pp : 653-659, 1990.
- [30] W. Theiss, “Chapter I: Porous Silicon,” *Surface Science Reports*, vol. 29, pp. 91, 1997.
- [31] J.C. Li, W.L. Chen, W.C. Tsai, *Optics Express*, 14, 9764 (2006).
- [32] Y. Zhou, P.A. Snow, and P.St.J. Russell, *Appl. Phys. Lett.*, 77, 2440 (2000).
- [33] A.G. Cullis, L.T. Canham, and P.D.J. Calcott. *J. Appl. Phys.*, 82, 909 (1997).
- [34] L. T. Canham, *phys. stat. sol. (b)*, 190, 9 (1995).
- [35] A. Richter, P. Steiner, F. Kozlowski, and W. Lang, *IEEE Electron Device Lett.*, 12, 691 (1991).
- [36] H. Mimura, T. Matsumoto, T. Futagi, and Y. Kanemitsu, *J. Phys. Soc. Jpn.*, 63, 203 (1994).
- [37] H. Mizuno, H. Koyama, and N. Koshida, *Appl. Phys. Lett.*, 69, 3779 (1996).
- [38] J.F. Harvey, M. Shen, R.A. Lux, M. Dutta, J. Pamulapati, and R. Tsu, *Mater. Res. Soc. Symp. Proc.*, 256, 175 (1992).
- [39] D.I. Kovalev, I.D. Yarostietzkii, T. Muschik, V. Petrova-Koch, and F. Koch, *Appl. Phys. Lett.*, 64, 214 (1994).
- [40] L. Tsybeskov, Y.V. Vandyshev, and P.M. Fauchet, *Phys. Rev. B*, 49, 7821 (1994).
- [41] A. Kux, D. Kovalev, and F. Koch, *Thin Solid Films*, 255, 143 (1995).
- [42] L.T. Canham, A. Loni, P.D.J. Calcott, A.J. Simons, C. Reeves, M.R. Houlton, J.P. Newey, K.J. Nash, and T.I. Cox, *Thin Solid Films*, 276, 112 (1996).

- [43] P.M. Fauchet, E. Etteedgui, A. Raisanen, L.J. Brillson, F. Seiferth, S.K. Kurinec, Y. Gao, C. Peng, and L. Tsybeskov, *Mater. Res. Soc. Symp. Proc.*, 298, 271 (1993).
- [44] G. Mauckner, J. Hamann, W. Rebitzer, T. Baier, K. Thonke, and R. Sauer, *Mater. Res. Soc. Symp. Proc.*, 358, 489 (1995)
- [45] F. Koch, *Mater. Res. Soc. Symp. Proc.*, 298, 319 (1993).
- [46] D. T. Jiang, I. Coulthard, T. K. Sham, J. W. Lorimer, S. P. Frigo, X. H. Feng, K. H. Tan, R. A. Rosenberg, and D. C. Houghton, "Observations on the surface and bulk luminescence of porous silicon," *Journal of Applied Physics*, vol. 74, no. 10, pp. 6335–6338, 1993..
- [47] J. Zuk, R. Kuduk, M. Kulik, J. Liskiewicz, D. Maczka, P.V. Zhukovski, V.F. Stelmakh, V.I. Bondarenko, and A.M. Dorofeev, *J. Lumin*, 57, 57 (1993).
- [48] Q. Chen, G. Zhou, J. Zhu, C. Fan, X.G. Li, and Y. Zhang, *Phys. Lett. A*, 224, 133 (1996).
- [49] J. Lin, G.Q. Yao, J.Q. Duan, and G.G. Qin, Ultraviolet light emission from oxidized porous silicon *Solid State Communications*, 97, 221 (1996).
- [50] S. Rahmouni, L. Zighed, S. Chaguetmi, M. Daoudi, M. Khelifa, M. Karyaoui, and R. Chtourou, "Correlation between photoluminescence and ellipsometric measurements of porous silicon layers," *Optoelectronics and Advanced Materials*, vol. 12, no. 9–10, pp. 553–558.

Chapter II: Photovoltaic Applications

II-1 Introduction:

The environmental effect of electricity generated by photovoltaic (PV) systems are significantly lower than that of conventional electricity generation methods [1]. Energy systems have advanced significantly in the twenty-first century [2]. Rapid population and economic growth since the industrial revolution led to a rise in energy consumption and a populations reliance on fuels for a variety of purposes, which forces the world's non renewable resources to be depleted. A significant portion of electricity (77.9%) is produced mainly by nuclear power and fossil fuels. These energy sources emit harmful gases that contribute to the greenhouse effect, these energy sources are costly and are significant environmental pollutants [3].

The extensive use and exploitation of fossil fuels cause severe disturbances to the natural equilibrium, leading to the degradation of ecosystems. These activities contribute significantly to global climate change and adverse environmental impacts, including polar ice melting and the consequent rise in sea levels worldwide [4]. Consequently, intensified efforts are required to promote and expand the global adoption of renewable energy sources [5].

Providing the required volumes of clean and sustainable energy on a global scale is a major challenge today. Energy technology of the future will rely on renewable energy sources, such as solar, wind, and biomass [2].

Since solar energy is abundant in nature and is a free energy source, numerous studies have demonstrated that it can be used to meet the world's energy needs [6].

Solar energy represents an almost inexhaustible resource, and the deployment of photovoltaic (PV) systems is not fundamentally limited by land availability or material scarcity. Since the early 1970s, the cost of PV technologies has decreased by more than an order of magnitude, with reductions exceeding a factor of twenty. Ongoing research across a wide range of PV technologies continues to focus on further cost reductions to enable large-scale and widespread adoption [7].

"Energy obtained from the continuous or repetitive currents on energy recurring in the natural environment" or "energy flows which are replenished at the same rate as they are used" are two definitions of renewable energy sources. Nearly all renewable energy sources on Earth originate from solar radiation, which can be harnessed either directly or

indirectly using various energy conversion technologies. This radiation spans a wide range of wavelengths, extending from the ultraviolet to the short-wave infrared region, and is commonly referred to as white light. Solar energy plays a crucial role in electricity generation, as it can be directly converted into electrical power through photovoltaic (PV) cells or indirectly transformed into thermal energy to produce high temperatures that drive mechanical engines connected to electrical generators. Among these technologies, the photovoltaic effect represents one of the simplest and most straightforward approaches for converting solar energy into electricity. Although photovoltaic systems remain relatively costly compared with some other renewable energy technologies, they offer significant advantages, including low maintenance requirements, environmental friendliness, and the absence of pollutant emissions, making them a sustainable and attractive energy solution [8].

The history of PV began in 1839 when Alexandre-Edmond Becquerel observed that "electrical currents arose from certain light-induced chemical reactions." A few decades later, other scientists noticed comparable results in a solid material (selenium). However, the first silicon solar cell with 6% efficiency was not developed until the late 1940s when the first solid state devices were constructed. As it served as a PV system's power conversion unit and had real-world applications, the creation of the first silicon solar cell was essential for the advancement of solar technologies. These silicon cells are assembled into modules rather than being used individually. Many kinds of solar cells are currently commercially available. However, efforts to expand and improve this energy collector are still being made through research and development [8].

II-2 Photovoltaic Systems:

Since 1839, when the French physicist Edmond Becquerel first demonstrated the generation of electricity by illuminating a metal electrode immersed in a weak electrolyte solution, the photovoltaic phenomenon has been recognized and scientifically understood.

In 1876, Adam and Day initially investigated the photovoltaic effect in solids and created a solar cell with a 1%–2% efficiency using selenium. In 1904, Albert Einstein used his photon theory to describe the photovoltaic phenomenon. In 1916, Polish scientist Jan Czochralski developed a method for producing pure crystalline silicon, which was a major advancement in modern electronics. First-generation silicon cells had an efficiency of

approximately 6%, which is significantly lower than that of modern solar cells, which have an efficiency of roughly 14–20%. Early efforts to make photovoltaic cells a viable method of electricity generation attempts at terrestrial applications were unsuccessful primarily due to the high cost of the devices. However, the energy crises of the 1970s triggered a renewed wave of initiatives and intensified research efforts in several areas [9].

II-3 PV Technologies

The main purpose of a solar cell is to use the photovoltaic effect to directly convert light energy into electrical energy. Solar cells are used as building blocks of solar modules, as photodetectors for automatic streetlight switching and other light-sensitive devices (like infrared detectors), and as light sensors for scientific research. Their electrical properties, such as current, voltage, or resistance, change when exposed to light from any source, whether natural or artificial [10].

II-4 Wafer-Based Solar Technology (First generation)

Solar cells can be single-junction, which uses a single layer of light-absorbing material, or multi-junction, which uses multiple physical configurations to apply various Mechanisms of charge separation and absorption [11]. Crystalline silicon, such as polysilicon and monocrystalline silicon, constitutes the first generation of wafer-based cells. To allow unrestricted light absorption, a thin layer of p-type material is incorporated into the cell's upper surface (Figure II-1). The p-type and n-type materials are surrounded by metal rings, which serve as the positive and negative output terminals, respectively. The PV cell consists of a single semiconductor unit [12].

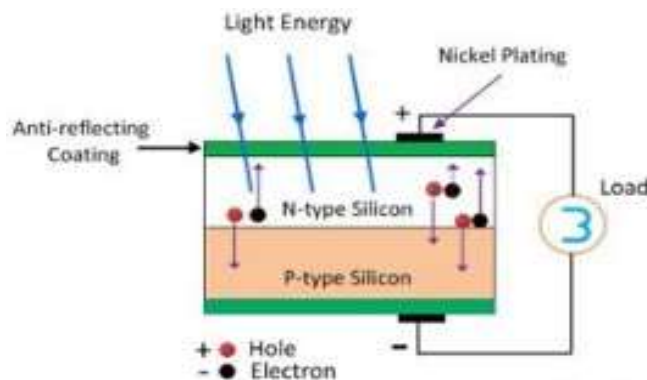


Figure II.1 Wafer-based Solar Technology [13].

II-4-1 Monocrystalline Solar Cell

The Czochralski technique uses a single silicon (Si) Crystal to create monocrystalline solar cells (Figure II-2) [14]. Si crystals are typically produced with high precision from large ingots. Monocrystalline cells have been found to have an efficiency of 16% [14]. However, improved multicrystalline silicon solar cells have demonstrated efficiencies of up to 19.8%, while monocrystalline cells have reached efficiencies of 24.4% [13].



Figure II.2 Monocrystalline Solar Panel [15]

Improvements in multicrystalline cells have been achieved through isotropic etching, which creating a hexagonally symmetric "honeycomb" surface pattern, and coating multicrystalline surfaces with thermally produced oxides to reduce harmful electronic processes Dobrzanski and al. [16] demonstrated a conventional technological process using the screen-printing method to creating monocrystalline silicon solar cells. Zener and Schottky diodes protected the devices while the cells were connected to PV modules to generate power [17].

II-4-2 Polycrystalline Silicon Solar Cell (Poly-Si or Mc-Si)

A unit cell is formed by joining multiple crystals to construct polycrystalline PV modules (Figure II-3) [18]. A graphite mold made of molten silicon is cooled during an economical forming process. As it solidifies, it produces crystal formations of varying sizes with boundary defects. These defects reduce the efficiency, with manufacturing ranging from 14% to 17% and laboratory efficiency between 18% and 23% [19]. The most prevalent type of solar cells are polycrystalline Si ones, which accounted for 48% of global production in 2008 [20].



Figure II.3 Polycrystalline Solar Panel [21].

Zsiboracs and al. [22] discussed the use of water vaporisation to cool monocrystalline and polycrystalline solar modules in light considering the effect of temperature on performance and its economic implications. The findings indicated a temperature-related efficiency decrease of approximately 0.5% per 1°C for both monocrystalline and polycrystalline solar modules. « Systems with solar module cooling were 10–15% more expensive to implement effectively than non-cooled systems. Khalis and associates [23] stated that while the maximum output power was found to be negative, « the maximum power and efficiency of polycrystalline cells decreased with increasing cell temperature and the temperature coefficient of efficiency.

II-5 Thin-Film Technology

These include amorphous silicon, copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) cells, which constitute the second generation of solar cells. Due to their superior performance under cloudy conditions, they are widely used in utility-scale solar power plants and are commercially available [24].

II-5-1 Solar Cell Made of Amorphous Silicon (A-Si)

This was Amorphous silicon (a-Si) is one of the most well-known thin-film solar cells, having been commercially available for decades [25]. It has been widely used in desktop and pocket calculators, and more recently, in solar panels that generate electricity for residential and utility applications. Amorphous-Si: A thin layer of silicon vapour, about 1 μm thick, is applied to a substrate material, such as metal or glass, to create modules. As seen in figure II-4, a transparent conducting oxide (TCO) is used in the setup to help lower the series resistance by offering a lateral conducting channel for current [26]. The resistivity of the doped ZnO must be low because carriers in the doped ZnO must travel a relatively significant lateral distance in order to provide a large enough surface to receive

sunlight. The series resistance would cause a large quantity of current to be lost in the event that there was no TCO and only metal fingers, leading to a major loss in efficiency. The efficiency of amorphous solar cells remains around 8.1%, significantly lower than the approximately 18% efficiency of crystalline silicon [27]. The Staebler-Wronski effect, which happens in the initial hours after the panels start getting sunlight, is the cause of this low efficiency. The main advantage of amorphous silicon solar cells over others is their significantly lower manufacturing costs.

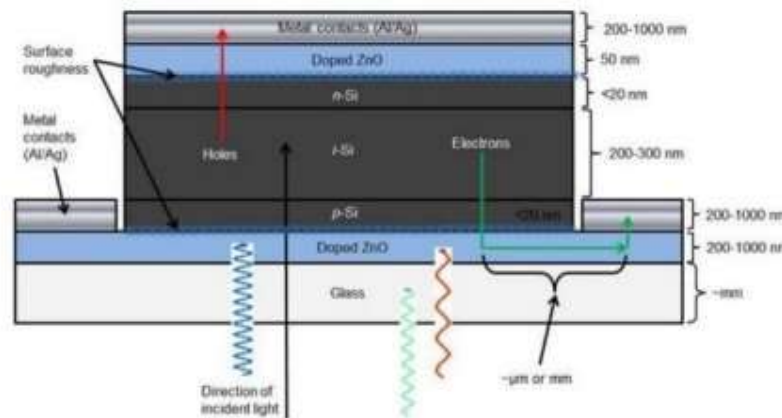


Figure II.4 Amorphous Silicon Solar Cell Composition [26].

The slow development of microcrystalline ($\mu\text{-Si:H}$) and amorphous silicon (a-Si) silicon-based cells was covered by Kabir et al. [28]. The effectiveness of hydrogenated Thin film solar cells made on amorphous silicon (a-Si:H) increased from 2.4% to 15.2% (constantly 13.0%). The multijunction device function, bandgap allocation, ease of manufacture, scalability, and large optical absorption coefficient of a-Si:H solar cells were also observed.

II-5-2 Thin Film Solar Cell using Cadmium Telluride (CdTe)

Cadmium telluride, a thin semiconductor layer created to construct photovoltaics, is used to create CdTe. to absorb sunlight and turn it into electrical power [29] (figure II-5) . The only thin-film technique that is less expensive than conventional multi-kilowatt solar cells made of crystalline silicon is cadmium telluride photovoltaics [30]. According to Basol and McCandless [31], the greatest notable increase in CdTe efficiency happened between 2013 and 2014 when A champion module efficiency of 17% was achieved, while small-area cell conversion efficiency increased to around 20% range [32]. This technology

also has a smaller carbon footprint, shorter energy payback periods, and fewer life-cycle greenhouse gas and heavy metal emissions.

To ascertain the energy payback time (EPT) and life-cycle CO₂ emissions of a CdTe photovoltaic module, Kato et al. [33] conducted a lifecycle analysis. PV system on a residential rooftop. At an annual production scale of 100 MW, it was observed that the primary energy required for the manufacturing of one m² of the CdS/CdTe PV module was nearly the same as that of the a-Si PV module. EPT was assessed at 1.7 years, which is comparable to the lifespan of a-Si PV modules but significantly less than the PV system's lifetime. According to calculations, the life-cycle CO₂ emissions from the findings were between 14 and 9 g-C/kWh, which is less than the amount of electricity produced by utilities.

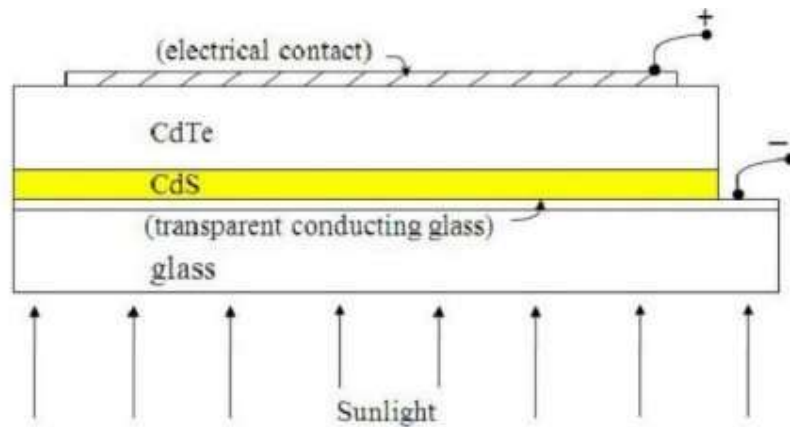


Figure II.5 CdTe Thin Film Solar Cell Layers [34].

II-5-3 Solar Cells using Copper Indium Gallium Di-Selenide (CIGS)

CIGS is a quaternary compound with a direct band gap. semiconductor made up of selenium, gallium, indium, and copper (figure II-6) [35]. Figure II-5 displays a transverse section of an actual device seen through a scanning electron microscope. Compared to CdTe, CIGS has a higher efficiency. (on average between 10% and 12%), with some reaching an efficiency of 22.8%, making them competitive with solar cells based on crystalline silicon (c-Si) wafers [36].

Devi et al. [37] used the Solar Cell Capacitance Simulator in One Dimension (SCAPS-1D) simulation program to design and analyse the Cu (In, Ga) Se₂ (CIGS) solar cell. They proposed a simpler model than the conventional one to achieve a straightforward construction with lower cost and material usage. With OVC as the ordered vacancy

compound, this CIGS model therefore became ITO/CIGS/OVC/CdS/Metal contact. Even in low light, the outcomes of this altered structure outperformed those of the more intricate one.

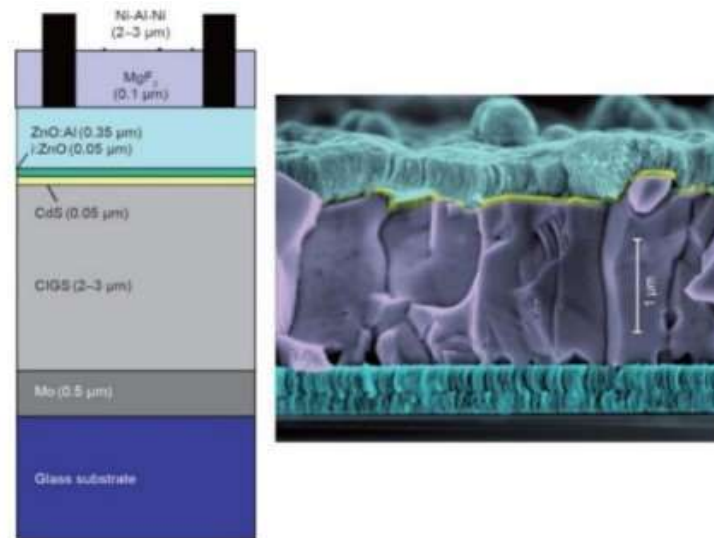


Figure II.6 CIGS Solar Cell Composition [35].

II-6 Solar Technologies of the Third Generation

Third-generation solar technologies include the recently emerging thin-film technology. Most of them are not yet commercially available but still in the R&D stage

II-6-1 Solar Cells Based on Nano Crystals

Quantum dots (QD) solar cells are a common name for solar cells based on nanocrystals [38].

Among them are semiconductors, which are commonly found in transition metal groups and range in size from nanocrystals made of semiconducting materials, and can attain 16.6% efficiency levels. In order to increase efficiency by lowering the contact forces between the exciton and the nanoparticle surface, layers of various chemicals are typically placed on top of a core in QDs. Gur [39] discussed efforts to improve stability and incorporation in nanocrystal-based solar cells through advancements in device construction and materials engineering. The creation of three-dimensional nanocrystals demonstrated how to improve flow and mobility in hybrid solar cells and made it possible to use innovative production techniques for the best possible introduction in these systems. The results demonstrated that controlled carrier diffusion and donor-acceptor charge

transfer may be used in a configuration devoid of organic components, and that nanocrystals could serve as the basis for more effective, dependable, and affordable thin film solar cells.



Figure II.7 Nano Crystal Based Solar Cells [40].

II-6-2 Solar Cells Made of Polymers (PSC)

Thin functional layers that are serially connected and arranged on top of polymer foil form a PSC. In essence, it functions as a combination of an acceptor and a donor (polymer). Various materials, including organic components like a conjugate/conducting polymer, are used to capture solar energy [41]. Figure II-8 depicts a typical organic bulk heterojunction device made up of layers of several materials, including an indium-tin oxide (ITO) transparent bottom electrode, The donor polymer/acceptor molecule functions as both the active layer and the top electrode layer (often metallic), much like the hole transport layer (HTL).

For the next generation of effective and affordable solar cells, polymeric nanocomposites with graphitic nanostructures were thoroughly studied in a study by Abdurazzaq et al. [42]. The nanoparticles displayed outstanding mechanical and electrical qualities, outstanding carrier transport capacities, and an effective route to the dissociated charge carriers.

A evaluation of the most recent PV cell materials used in production and their effects on manufacturing efficiency and total cost was conducted by Luceno-Sanchez et al [43]. It was anticipated that future fourth generation (4GEN) PSCs that incorporate carbon-based nanomaterials would offer higher performance levels to rival those of conventional silicon-based cells. With an efficiency of 6.5%, polymer solar cells find use in a variety of

applications because of its flexibility and low weight, including solar curtains and windows.

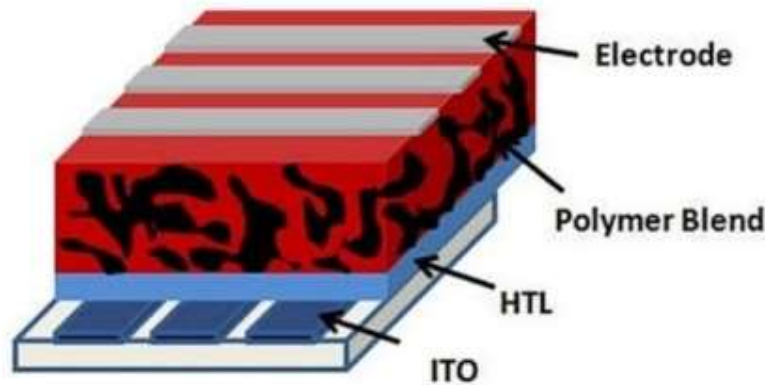


Figure II.8 Polymer Solar Cells Layers [42].

II-6-3 Solar Cells Sensitised to Dye (DSSC)

The different electrodes in DSSC-based solar cells (Figure II-9) are divided by dye molecules [44]. DSSCs consist of four components: a dye sensitizer, a redox mediator, a semiconductor electrode (n-type TiO_2 and p-type NiO), and a counter electrode. Typically, they are referred to as organic solar cells when organic dyes are utilised. The DSSCs are appealing due to their low production costs, flexibility, and ease of use [45]. They are chosen for use in energy-efficient architectural applications like as solar windows and glass walls of buildings because they may be utilised to construct solar panels in a variety of eye-catching hues.

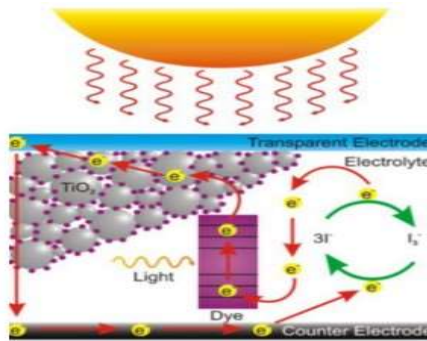


Figure II.9 Dye Sensitized Solar Panel Composition [46].

The photosensitisation of visible optically active dyes and Nano grained TiO_2 coatings gives rise to the novelty of DSSC solar cells, increasing their efficiency to as much as 10% [47]. A porous layer of titanium dioxide nanoparticles encased in a molecular dye that absorbs sunlight makes up more recent DSSCs. A platinum-based catalyst is positioned on top of titanium dioxide, which is positioned beneath an electrolyte solution. An anode (titanium dioxide) and a cathode (platinum) are placed on opposite side of a liquid conductor (the electrolyte), much like in conventional alkaline batteries. Sunlight excites the electrons in the dye layer by penetrating the transparent electrode, which then moves into the titanium dioxide. Utilising this electron flux, load power is produced. They are reincorporated into the cell through a metal electrode on the back, entering the electrolyte, once the movement in the external circuit is finished. The electrons are then returned to the dye molecules by the electrolyte [48].

II-6-4-PSCs, or perovskite solar cells

Because of their distinctive optical, thermal, and electromagnetic characteristics as well as their cubic lattice-nested octahedral layered structures, perovskite materials have gained popularity [49]. They are a combination of inorganic and organic metal halides with a perovskite structure that are used in solar cells. Because of their high extinction coefficient, enormous charge mobility, long carrier lifetime, and wide carrier diffusion distance, perovskite materials can also function as an electron/hole transport layer in addition to being a light-absorbing layer. They are expected to replace traditional Si solar cells in the upcoming years due to their increased photoelectric power conversion efficiency, which increased from 3.8% in 2009 to 20.9% in 2019. PSCs are constructed using two common architectures that are specific to perovskite crystals: mesoporous and planar. Figure II-10 and II-11 illustrates both kinds. The former has a metal oxide layer of the mesoporous type (TiO_2 or Al_2O_3) that is encased in perovskite sensitizer. The latter is made up of layers that carry electrons and holes around a perovskite film [48].

By using yttrium-doped TiO_2 as the electron transport material and upgrading the ITO to reduce the effort required to insert the electrons from TiO_2 into the ITO electrode, Zhou et al. [50] were able to achieve more electron mobility. With the PCE rising to 19.3%, the device's open circuit voltage and short-circuit current significantly improved.

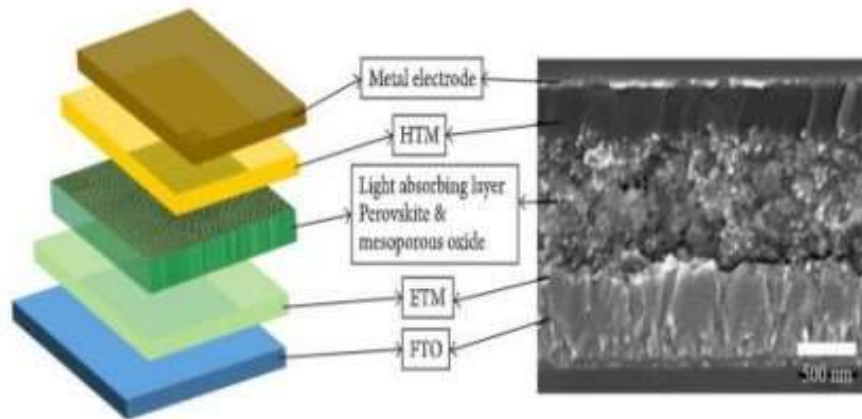


Figure II.10 Mesoporous Structure PSCs [50].

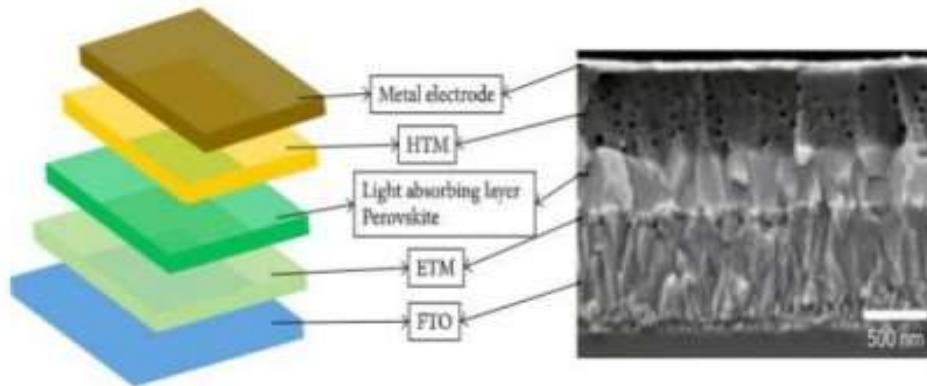


Figure II.11 Planar Heterojunction Structure PSCs [50].

II-7 Mathematical Solar Photovoltaic Model

The current-voltage (I-V) characteristics of a solar cell exhibit an exponential relationship [51]. A current source positioned parallel to a diode makes up the ideal equivalent circuit of a solar cell (Figure II-12). There are two internal resistances (series and shunt) in the realistic equivalent model of a solar cell.

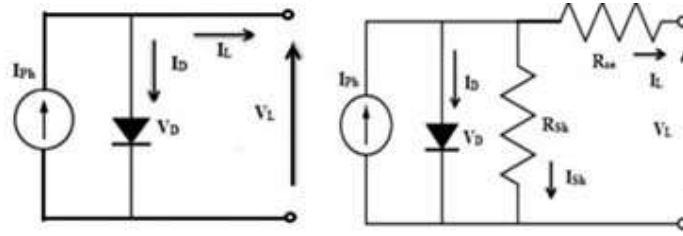


Figure II.12 Ideal Circuit (left) and Equivalent Circuit (right) of a Solar Cell [48].

The series resistance R_{se} arises from the resistance to electron flow in the semiconductor material, metal contacts, and interconnections. Electrons and holes combine to generate the shunt resistance or R_{sh} . Charge carrier recombination, particularly before they contribute to the load current, is represented by the shunt resistance R_{sh} . I_L is the load current, while V_L is the voltage across the external load. The electrons in the "n" side area are activated whenever sunlight strikes the top of the solar cell. The photocurrent I_{ph} is created when electrons move from the "n" area to the "p" region. Kirchhoff's Current Law yields the following current equation for solar cells.

$$I_L = I_{ph} - I_D - I_{sh} \dots \dots \dots (II.1)$$

The following defines diode current (I_D) and voltage V_D :

$$I_D = I_0 (e^{\frac{qV_D}{nKT}} - 1) \dots \dots \dots (II.2)$$

$$V_D = V_L + I_L R_{se} \dots \dots \dots (II.3)$$

where T is the temperature in $^{\circ}K$, k is the Boltzmann constant, and q is the electron's charge.

The load current I_L is 0 for the open circuit voltage V_{OC} . As a result, it is provided as:

$$V_{OC} = \frac{nKT}{q} \ln\left(\frac{I_{ph}}{I_0} + 1\right) \dots \dots \dots (II.4)$$

The short circuit current is also obtained by taking V_L to be zero. The current is thus:

$$I_{SC} \approx I_{ph} \dots \dots \dots (II.5)$$

This is primarily due to the extremely low series resistance R_{se} value.

II-8-Solar Photovoltaic (PV) System Application

Photovoltaic systems have gained popularity due to their high efficiency, low cost, and low pollution, allowing for diverse applications.

II-8-1 Desalination Plant.

In 2008, the electricity price at which solar energy can be regarded economically viable for reverse osmosis (RO) desalination was debated, regardless of RO plant size. An equation was proposed to estimate unit production costs for RO desalination plants, which may also be used to compute unit production costs for desalinated water utilising solar photovoltaic (PV) energy based on existing and projected PV unit costs. A simple 5.8 m³ per day mono-effect solar still plant for treating reject brine PV-powered RO desalination plant that can be set up as a 100% solar-powered desalination system for any location and brackish water quality was discovered. It was discovered that small-scale mono-effect solar stills are more practical to use in remote areas where land value is minimal because solar stills are simple to install and maintain and can be made using locally available materials [52]. Lastly, the process of designing, building, and running a standalone desalination plant using wind and solar photovoltaic electricity was demonstrated [53].

II-8-2 Constructing integrated solar power systems

A building plan was put forth that would allow solar energy to enter the structure during the heating season to offer daylight while permitting the photovoltaic modules to shade the structure in the summer to lessen cooling demands. The efficiency and energy production of the system were assessed, and its performance was examined [54]. A computerised renewable energy technology evaluation tool is used to analyse the technical and economic aspects of a grid-connected BIPV system, including its installation, technical features, operation, and economic assessment [55]. An Active Building Envelope (ABE) system, representing an advanced building enclosure technology that dynamically controls temperature through solar interaction by coupling photovoltaic (PV) and thermoelectric (TE) modules, was designed, implemented, and its performance was experimentally assessed [56]. The effectiveness of natural airflow cooling was also statistically evaluated using two cooling solutions with an air gap between the PV panels and the outer facade: (a) an open air gap with mixed convection, and (b) a solar chimney with vertical buoyant flow.

The researchers discovered that efficient cooling of PV panels increases solar cell electricity production [57]. A lightweight, semi-transparent PV roofing material with a radiant transmission rate of 50% has been proposed for residential usage, with the potential to reduce heating and cooling energy consumption by up to 5.3% when compared to a typical building-integrated photovoltaic (BIPV) roof [58]. In Taiwan, researchers

developed an experimental method to assess the annual solar radiation of inclined planes with 0-90° inclination and 0-90° azimuth angles on building envelopes for BIPV applications [59]. The behaviour of building-integrated, grid-connected solar PV energy conversion in an urban area of a Brazilian state capital was also investigated in order to maximise the benefits of PV power generation's distributed nature [60].

II-8-3 Space

A novel concept for an Earth-orbiting solar power satellite (SPS) named the European Sailing Tower (SPS) has been created. It has a gigantic, ultra-light, tower-like orbital system capable of supplying Europe with massive amounts of photovoltaic-generated electricity, which is subsequently delivered to Earth via microwaves [52]. Furthermore, the ability to generate photovoltaic energy at night on planetary bodies such as the Moon utilising light energy flux reflected from adjacent planetary bodies was investigated using the most recent low-intensity, low-illuminance (LILT) solar cell technologies [61].

II-8-4 Solar Home Systems.

Timor-Leste is now conducting many experiments and demonstrations using solar photovoltaic (PV) technology, including the implementation of solar household systems (SHS) [62]. Commercially available SHSs are also being proposed, providing a low-cost alternative to kerosene and dry cell batteries while reducing greenhouse gas emissions and thereby greatly contributing to climate protection [63].

II-8-5 Pumps

A solar photovoltaic (PV)-powered pump-driven drip irrigation system for orchards in arid regions was designed and developed, taking into account a variety of design parameters such as pump size, water requirements, daily variations in pump pressure due to irradiance changes, and dripper pressure compensation [64]. Some policies were considered to make the solar photovoltaic water pumping system (SPVWP) a viable technology for the relevant application region, given that its technical, economic, and environmental benefits have been demonstrated in industrialised countries [65]. Some concerns with solar-powered water pumping projects were investigated, their possible good and negative social repercussions were explained, and a completely new form of pump was presented, taking into account the steps that may be taken to ensure long-term sustainability [66]. A complicated time-dependent solar water pumping system comprised

of four main modules was investigated: a photovoltaic cell array, a battery, a DC motor, and a centrifugal pump [67].

II-8-6 Photovoltaic and thermal (PV/T) collector technology

An experimental investigation of a centralised photovoltaic power generation and water heating system is presented. It can be used as a water preheating system, with collectors installed on vertical facades that prioritise natural water circulation over forced circulation. At low zero temperatures, the thermal efficiency was 38.9%, with an electricity conversion efficiency of 8.56 [68]. A hybrid photovoltaic (PV/T) collector technology with water as a coolant is offered as a method for enhancing energy performance [69]. The study examines a photovoltaic thermal system for home heating and cooling, and it is shown that the system can meet a sizable amount of the needs for these purposes [70]. The energy performance of a domestic photovoltaic thermal collector with rectangular flow channels was presented and analysed [71]. Compared to other power production methods, photovoltaic technology has the advantages of being noiseless, comparatively ecologically benign, proven, having a long lifespan (crystalline silicon modules have a 20–30 year lifespan), and requiring little maintenance. Nevertheless, a number of issues restrict the solar module's efficiency, such as crystalline Si's 20% or less and amorphous Si's 12% or less. Specifically, PV cells only use a portion of the solar spectrum (less than 1.11 μm for c-Si) to generate energy, and their efficiency declines with increasing temperature. -> Due to silicon's bandgap of 1.12 eV, even the portion of the solar spectrum with energy greater than 1.12 eV (wavelengths below approximately 1.11 μm) is not fully converted into electricity [72]. Since 1970, the potential of PV/T collectors has been acknowledged, and throughout the last 10 years, their significance has grown. The production of heat and electricity from the same collector surface is frequently seen as more cost-effective, needs less area, and exhibits much reduced balance-of-system costs as compared to employing separate solar technologies for these purposes [73].

II-8-7 Cooking

The newest products on the market are solar cookers. Commercially available, solar cookers are simple to use and maintain. At Tahiti, next to Mount Abu, which is 1219 meters above sea level in Rajasthan, India, the largest solar kitchen in the world has been installed. It has 84 parabolic dish concentrators with shell-type receivers and a six-module solar steam cooking system [74].

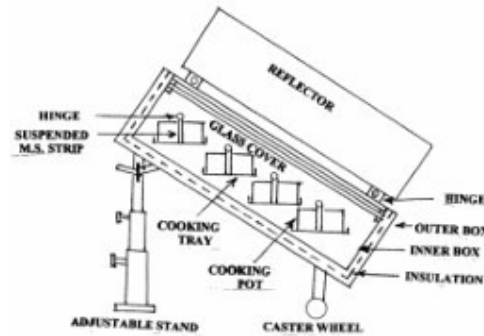


Figure II.13 Schematic Representation of Solar Cooker [74].

II-8-8 Heating:

Even before PV cells were invented, solar air and water warmers were widely used for decades. By alone, solar water heaters significantly lower energy use. These systems retain hot water in insulated storage tanks by trapping solar thermal energy [75].

II-8-9 Solar Lighting:

Also referred to as day lighting, these lights run on solar energy. During the day, these lights store the sun's natural energy, which they subsequently transform into electricity to illuminate at night. By using this technology, the burden on nearby power plants is decreased [76].

II-9 Porous Silicon Solar Cells

Porous silicon (PS) solar cells represent a significant advancement in silicon-based photovoltaic technology due to their unique structural and optical properties. PS consists of a network of nanoscale pores within a crystalline silicon matrix, which increases the surface-to-volume ratio and reduces surface light reflection across the solar spectrum, thereby enhancing light absorption and photo generated carrier collection. PS layers can be fabricated using various techniques such as chemical or electrochemical etching in HF-based solutions, where process parameters (e.g., current density and etching time) control pore size, morphology, and layer thickness, directly affecting the optical and photoelectrical properties. PS layers are commonly used as anti-reflection coatings (ARC) to improve short-circuit current and overall power conversion efficiency in crystalline silicon solar cells. Recent studies also explore the use of PS as an active absorption layer or in combination with intermediate layers like graphene to further enhance efficiency, with reported efficiencies up to 13 % under optimized conditions. These developments demonstrate the potential of PS to improve solar cell performance while reducing fabrication costs compared to conventional silicon technologies [77].

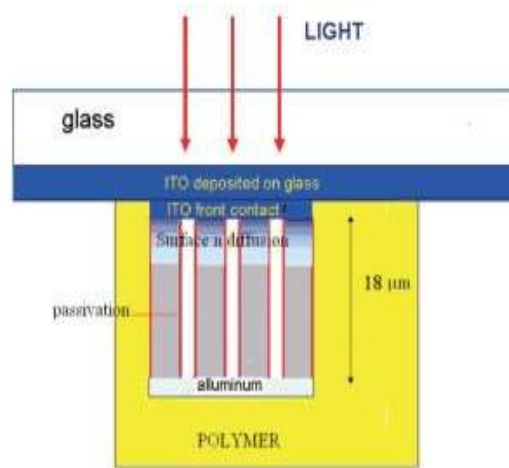


Figure.II.14 The configuration of the solar cell fabricated using porous silicon [77].

II-10 Conclusion

Compared to traditional power generation methods, the environmental effect of electricity generated by photovoltaic (PV) systems is substantially reduced. PV cells require no fuel, emit no pollutants into the air or water, and need no cooling water for operation. PV systems do not contribute to acid rain or global warming, in contrast to power plants that use fossil fuels (coal, oil, and natural gas). Since the sun is a nearly limitless source of energy, the usage of PV systems is not constrained by a lack of land or materials. Since the early 1970s, the cost of PV systems has more than doubled, and research into a wide range of technologies keeps bringing costs down to levels that are suitable for broad use.

In some applications, such as remote power generation, current PV cells are reliable and cost-effective, and standalone PV facilities are being constructed in places that are not serviced by utility networks. Additionally, it has become more appealing to integrate photovoltaic (PV) systems into residential structures. In these cases, the PV system is connected to the electrical grid to provide an alternate power source for loads. Even though PV solutions are now more expensive than other energy sources, the use of integrated building solutions and the incentives offered by national laws and installation initiatives should lower the cost of PV system purchases. The adoption of PV systems in the future will be mostly dependent on cost-cutting research and public awareness of the detrimental environmental effects of other power generation methods.

This can be summed up in the following points:

- Regardless of the application, solar photovoltaic systems are distinguished by their favourable production, as demonstrated by the few examples covered above.
- Each stage of their development and implementation leads to lower costs and higher efficiency.
- Using solar photovoltaic technology helps safeguard the environment and enhances energy security, in addition to reducing reliance on fossil fuels.
- All carbon and nitrogen oxides, greenhouse gases, and emissions will be decreased by using these renewable energy sources.
- Additionally, they will have a wide range of applications in the future since renewable energy will displace non-renewable energy sources across the board.

References

- [1] K. Zweibel, *Harnessing Solar Power: The Photovoltaics Challenge*. New York: Plenum Publishing, 1990.
- [2] R. Foster, M. Ghassemi, and A. Cota, *Solar Energy: Renewable Energy and the Environment*, 1st ed., Taylor & Francis eBooks, CRC Press, 2009.
- [3] *Renewables Global Status Report*, Secretariat Renewable Energy Policy Network for the 21st Century (REN21), Paris, 2014.
- [4] B. Schlamadinger, M. Apps, F. Bohlin, L. Gustavsson, G. Jungmeier, et al., “Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems,” *Biomass Bioenerg.*, vol. 13, pp. 359–375, 1997.
- [5] L. D. Roper, *Future World Energy*, 2012.
- [6] N. S. Lewis, “Toward cost-effective solar energy use,” *Science*, vol. 315, pp. 798–801, 2007.
- [7] F. Sick and T. Erge, *Photovoltaics in Buildings: A Design Handbook*, International Energy Agency, 1996.
- [8] L. E. Chaar, L. A. Iamont, and N. E. Zein, “Review of photovoltaic technologies,” *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 2165–2175, 2011.
- [9] R. Kumar and M. A. Rosen, “A critical review of photovoltaic–thermal solar collectors for air heating,” *Applied Energy*, vol. 88, pp. 3603–3614, 2011.
- [10] S. Sharma, K. K. Jain, and A. Sharma, “Solar Cells: In Research and Applications—A Review,” *Materials Sciences and Applications*, vol. 6, pp. 1145–1155, 2015. doi: 10.4236/msa.2015.612113
- [11] N. Rathore, N. L. Panwar, F. Yettou, and A. Gama, “A Comprehensive Review on Different Types of Solar Photovoltaic Cells and Their Applications,” *International Journal of Ambient Energy*, 2019. doi: 10.1080/01430750.2019.1592774

- [12] J. Zhao, A. Wang, and M. A. Green, “19.8% Efficient ‘Honeycomb’ Textured Multicrystalline and 24.4% Monocrystalline Silicon Solar Cells,” *Applied Physics Letters*, vol. 73, no. 14, 1998. doi: 10.1063/1.122345
- [13] Photovoltaic or Solar Cell, Circuit Globe. [Online]. Available: <https://circuitglobe.com/photovoltaic-or-solar-cell.html>. [Accessed: Apr. 27, 2020]
- [14] T. Zimmer, Photovoltaic Cell Types. [Online]. Available: https://www.labri.fr/perso/billaud/Helios2/resources/en06/Chapter_6_UB_zimmer.pdf. [Accessed: Oct. 15, 2019]
- [15] A. Sendy, “Pros and Cons of Monocrystalline vs Polycrystalline Solar Panels,” *Solar Reviews*, 2017. [Online]. Available: <https://www.solarreviews.com/blog/pros-and-cons-of-monocrystalline-vs-polycrystalline-solar-panels>. [Accessed: Oct. 31, 2019]
- [16] L. A. Dobrzanski, A. Drygala, M. Giedroc, and M. Macek, “Monocrystalline Silicon Solar Cells Applied in Photovoltaic System,” *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 53, no. 1, pp. 1–12, 2012. [Online]. Available: https://www.researchgate.net/publication/289642017_Monocrystalline_silicon_solar_cells_applied_in_photovoltaic_system. [Accessed: Oct. 29, 2019]
- [17] A. Tascioglu, O. Taskin, and A. Vardar, “A Power Case Study for Monocrystalline and Polycrystalline Solar Panels in Bursa City, Turkey,” 2016. [Online]. Available: https://www.researchgate.net/publication/298432080_A_Power_Case_Study_for_Monocrystalline_and_Polycrystalline_Solar_Panels_in_Bursa_City_Turkey. [Accessed: Oct. 29, 2019]
- [18] T. Kato, J. Wu, Y. Hirai, H. Sugimoto, and V. Bermudez, “Record Efficiency for Thin-Film Polycrystalline Solar Cells Up to 22.9% Achieved by Cs-Treated Cu(In,Ga)(Se,S)₂,” *IEEE Journal of Photovoltaics*, vol. 9, no. 1, pp. 325–330, 2019. doi: 10.1109/JPHOTOV.2018.2882206
- [19] Dena German Energy Agency, Information about German renewable energy, industries, companies and product (Federal Ministry of Economics and Technology), pp. 41, 2013–2014.

- [20] T. Saga, “Advances in crystalline silicon solar cell technology for industrial mass production,” *NPG Asia Materials*, vol. 2, pp. 96–102, 2010. doi: 10.1038/asiamat.2010.82
- [21] Tata 250 Watt Polycrystalline Solar Panel, Indiamart. [Online]. Available: <https://www.indiamart.com/proddetail/250-watt-polycrystalline-solar-panel-16449465433.html>. [Accessed: Nov. 1, 2019]
- [22] H. Zsiboracs et al., “Technical-Economic Study of Cooled Crystalline Solar Modules,” *Solar Energy*, vol. 140, pp. 227–235, 2016. doi: 10.1016/j.solener.2016.11.009
- [23] M. Khalis et al., “Effects of Temperature and Concentration Mono and Polycrystalline Silicon Solar Cells: Extraction Parameters,” *Journal of Physics: Conference Series*, 2016.
- [24] M. Powalla et al., “Advances in Cost Efficient Thin-Film Photovoltaics Based on Cu(In,Ga)Se₂,” *Clean Energy—Review*, vol. 3, no. 4, pp. 445–451, 2017. doi: 10.1016/J.ENG.2017.04.015
- [25] M. Imamzai, M. Aghaei, Y. Hanum Md Thayoob, and M. Forouzanfar, “A Review on Comparison between Traditional Silicon Solar Cells and Thin-Film CdTe Solar Cells,” *Proc. National Graduate Conference (NatGrad 2012)*, Tenaga Nasional Universiti, Putrajaya, 8–10 Nov. 2012, pp. 1–5.
- [26] T. C. Yang, *Transparent Conducting Aluminium Doped Zinc Oxide for Silicon Quantum Dot Solar Cell Devices in Third Generation Photovoltaics*, Doctoral Thesis, 2016. doi: 10.13140/RG.2.2.13188.22407
- [27] Best Thin Film Solar Panels – Amorphous, Cadmium Telluride or CIGS?, *Energy Informative*. [Online]. Available: <https://energyinformative.org/best-thin-film-solar-panels-amorphous-cadmium-telluride-cigs/>. [Accessed: Nov. 1, 2019]
- [28] M. I. Kabir, Z. Ibarahim, K. Bin Sopian, and N. Amin, “A Review on Progress of Amorphous and Microcrystalline Silicon Thin-Film Solar Cells,” *Recent Patents on Electrical Engineering*, vol. 4, pp. 50–62, 2011. doi: 10.2174/1874476111104010050

- [29] P. M. Kaminski, F. Lisco, and J. M. Walls, “Multilayer broadband antireflective coatings for more efficient thin film CdTe solar cells,” *IEEE Journal of Photovoltaics*, vol. 4, no. 1, pp. 452–456, 2014. doi: 10.1109/JPHOTOV.2013.2284064
- [30] B. E. McCandless and J. R. Sites, “Cadmium telluride solar cells,” in *Handbook of Photovoltaic Science and Engineering*, A. Luque and S. Hegedus, Eds., John Wiley & Sons Ltd., West Sussex, England, pp. 617–662, 2003.
- [31] B. M. Basol and B. E. McCandless, “Brief review of cadmium telluride-based photovoltaic technologies,” *Journal of Photonics for Energy*, vol. 4, no. 1, pp. 1–8, 2014. doi: 10.1117/1.JPE.4.040996
- [32] E. Wild, “First Solar sets thin film module efficiency world record of 17.0 percent,” *Solar Power World Online*, 2014. [Online]. Available: <https://www.solarpowerworldonline.com/2014/03/first-solar-sets-cdte-thin-film-module-efficiency-world-record-17/>. [Accessed: Oct. 25, 2019]
- [33] K. Kato, T. Hibino, and K. Komoto, “Life-cycle analysis on thin-film CdS/CdTe PV modules,” *Solar Energy Materials and Solar Cells*, vol. 67, pp. 279–287, 2001. doi: 10.1016/S0927-0248(00)00293-2
- [34] I. M. Dharmada et al., “Fabrication of CdS/CdTe-Based Thin Film Solar Cells Using an Electrochemical Technique,” *Coatings*, vol. 4, pp. 380–415, 2014. doi: 10.3390/coatings4030380
- [35] K. Ong et al., “Review on Substrate and Molybdenum Back Contact in CIGS Thin Film Solar Cell,” *International Journal of Photoenergy*, vol. 2018, Article ID 9106269, 2018. doi: 10.1155/2018/9106269
- [36] J. Ramanujam and U. P. Singh, “Copper Indium Gallium Selenide Based Solar Cells – Review,” *Energy & Environmental Science*, vol. 9, pp. 1306–1319, 2017. doi: 10.1039/C7EE00826K
- [37] N. Devi, A. Aziz, and S. Datta, “Numerical modelling of CIGS/CdS solar cell,” *AIP Conference Proceedings*, vol. 1953, 100031, 2018. doi: 10.1063/1.5032967

- [38] S. Sagadevan, “Recent Trends on Nanostructures Based Solar Energy Applications: A Review,” *Rev. Advance Material Sci.*, vol. 34, pp. 44–61, 2013. [Online]. Available: http://www.ipme.ru/ejournals/RAMS/no_13413/06_13413_suresh.pdf. [Accessed: Oct. 27, 2019]
- [39] I. Gur, *Nanocrystal Solar Cells*, PhD Dissertation, University of California, Berkeley, 2006. [Online]. Available: <https://www.osti.gov/servlets/purl/922721>. [Accessed: Oct. 27, 2019]
- [40] S. Anthony, “Cheap, Ink-Based Printable Nanocrystal Solar Cells Become a Reality,” 2011. [Online]. Available: <https://www.extremetech.com/extreme/103477-cheap-ink-based-printable-nanocrystal-solar-cells-become-a-reality>. [Accessed: Oct. 29, 2019]
- [41] A. Gusain, R. M. Faria, and P. B. Miranda, “Polymer Solar Cells—Interfacial Processes Related to Performance Issues,” *Frontiers in Chemistry*, 2019. doi: 10.3389/fchem.2019.00061
- [42] O. A. Abdulrazzaq, V. Saini, S. Bourdo, E. Dervishi, and A. S. Biris, “Organic Solar Cells: A Review of Materials, Limitations, and Possibilities for Improvement,” 2013. https://www.researchgate.net/publication/263732376_Organic_Solar_Cells_A_Review_of_Materials_Limitations_and_Possibilities_for_Improvement. [Accessed: Oct. 18, 2019]
- [43] J. A. Luceno-Sanchez, A. M. Diez-Pascual, and R. P. Capilla, “Materials for Photovoltaics: State of Art and Recent Developments,” *International Journal of Molecular Sciences*, vol. 20, no. 976, 2019. doi: 10.3390/ijms20040976
- [44] N. Papageorgiou, “Dye-sensitized solar cells rival conventional CE,” *EPFL News*, 2013. [Online]. Available: <https://actu.epfl.ch/news/dye-sensitized-solar-cells-rival-conventional-ce-2/>. [Accessed: Nov. 3, 2019]
- [45] A. Hossam-Eldin, M. Refaey, and A. Farghly, “A Review on Photovoltaic Solar Energy Technology and its Efficiency,” *17th International Middle-East Power System Conference (MEPCON'15)*, pp. 1–8, 2015. [Online]. Available: https://www.researchgate.net/publication/287792329_A_Review_on_Photovoltaic_Solar_Energy_Technology_and_its_Efficiency. [Accessed: Nov. 3, 2019]

- [46] Dye-sensitized solar cell, Wikipedia, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Dye-sensitized_solar_cell. [Accessed: Apr. 8, 2020]
- [47] J. Gong, J. Liang, and K. Sumathy, “Review on dye-sensitized solar cells (DSSCs): Fundamental concepts and novel materials,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 5848–5860, 2012. doi: 10.1016/j.rser.2012.04.044
- [48] K. E. Sarah, R. Uhumwangho, and E. N. C. Okafor, “A Review of Solar Photovoltaic Technologies,” *International Research Journal of Engineering and Technology (IRJET)*, vol. 4, no. 8, Aug. 2017.
- [49] D. Zhou, T. Zhou, Y. Tian, X. Zhu, and Y. Tu, “Perovskite-Based Solar Cells: Materials, Methods, and Future Perspectives,” *Journal of Nanomaterials*, 2018, pp. 1–15. [Online]. Available: <https://www.hindawi.com/journals/jnm/2018/8148072/>. [Accessed: Apr. 30, 2020]
- [50] H. Zhou, Q. Chen, and G. Li, “Interface Engineering of Highly Efficient Perovskite Solar Cells,” *Science*, vol. 345, no. 6196, pp. 542–546, 2014. doi: 10.1126/science.1254050
- [51] E. M. Rodrigues, R. Meelicio, V. F. Mendes, and J. P. Catalao, “Simulation of a Solar Cell Considering Single-Diode Equivalent Circuit Model,” *RE&PQJ*, vol. 1, no. 9, pp. 369–373, 2011. [Online]. Available: <http://icrepq.com/icrepq%2711/339-rodrigues.pdf>. [Accessed: Nov. 11, 2019]
- [52] B. Parida, S. Iniyan, and R. Goic, “A review of solar photovoltaic technologies,” *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 1625–1636, 2011.
- [53] D. Weiner, D. Fisher, E. J. Moses, B. Katz, and G. Meron, “Operation experience of a solar- and wind-powered desalination demonstration plant,” *Desalination*, vol. 137, pp. 7–13, 2001.
- [54] S. H. Yoo and E. T. Lee, “Efficiency characteristic of building integrated photovoltaics as a shading device,” *Building and Environment*, vol. 37, pp. 615–623, 2002.

- [55] G. C. Bakos, M. Soursos, and N. F. Tsagas, "Technoeconomic assessment of a building integrated PV system for electrical energy saving in residential sector," *Energy and Buildings*, vol. 35, pp. 757–762, 2003.
- [56] X. Xu and S. Dessel, "Evaluation of an active building envelope window-system," *Energy and Buildings*, vol. 40, pp. 168–174, 2008.
- [57] T. T. Chow, J. W. Hand, and P. A. Strachan, "Building-integrated photovoltaic and thermal applications in a subtropical hotel building," *Applied Thermal Engineering*, vol. 23, pp. 2035–2049, 2003.
- [58] P. W. Wong, Y. Shimoda, M. Nonaka, M. Inoue, and M. Mizuno, "Semi-transparent PV: Thermal performance, power generation, daylight modelling and energy saving potential in a residential application," *Renewable Energy*, vol. 33, pp. 1024–1036, 2008.
- [59] C. L. Cheng, C. Y. Chan, and C. L. Chen, "Empirical approach to BIPV evaluation of solar irradiation for building applications," *Renewable Energy*, vol. 30, pp. 1055–1074, 2005.
- [60] S. C. Jardim, R. Ruther, I. T. Salamoni, S. T. Viana, S. H. Rebechi, and P. J. Knob, "The strategic sitting and the roofing area requirements of building-integrated photovoltaic solar energy generators in urban areas in Brazil," *Energy and Buildings*, vol. 40, pp. 365–370, 2008.
- [61] T. E. Girish, "Nighttime operation of photovoltaic systems in planetary bodies," *Solar Energy Materials & Solar Cells*, vol. 90, pp. 825–831, 2006.
- [62] M. Bond, R. J. Fuller, and L. Aye, "A policy proposal for the introduction of solar home systems in East Timor," *Energy Policy*, vol. 35, pp. 6535–6545, 2007.
- [63] R. Posorski, M. Bussmann, and C. Menke, "Does the use of Solar Home Systems (SHS) contribute to climate protection?" *Renewable Energy*, vol. 28, no. 10, pp. 61–80, 2003.
- [64] P. C. Pande, A. K. Singh, S. Ansari, S. K. Vyas, and B. K. Dave, "Design development and testing of a solar PV pump based drip system for orchards," *Renewable Energy*, vol. 28, pp. 385–396, 2003.

- [65] K. Meah, S. Ula, and S. Barrett, “Solar photovoltaic water pumping opportunities and challenges,” *Renewable and Sustainable Energy Reviews*, vol. 12, pp. 1162–1175, 2008.
- [66] T. D. Short and P. Thompson, “Breaking the mould: solar water pumping—the challenges and the reality,” *Solar Energy*, vol. 75, pp. 1–9, 2003.
- [67] V. Badescu, “Time dependent model of a complex PV water pumping system,” *Renewable Energy*, vol. 28, pp. 543–560, 2003.
- [68] T. T. Chow, W. He, and J. Ji, “An experimental study of facade-integrated photovoltaic/water-heating system,” *Applied Thermal Engineering*, vol. 27, pp. 37–45, 2007.
- [69] W. He, T. T. Chow, J. Ji, J. Lu, G. Pei, and L. S. Chan, “Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water,” *Applied Energy*, vol. 83, pp. 199–210, 2006.
- [70] G. Vokas, N. Christandonis, and F. Skittides, “Hybrid photovoltaic–thermal systems for domestic heating and cooling—A theoretical approach,” *Solar Energy*, vol. 80, pp. 607–615, 2006.
- [71] T. T. Chow, W. He, and J. Ji, “Hybrid photovoltaic-thermosyphon water heating system for residential application,” *Solar Energy*, vol. 80, pp. 298–306, 2006.
- [72] W. G. J. Helden, R. J. C. Zolingen, and H. A. Zondag, “PV thermal systems: PV panels supplying renewable electricity and heat,” *Progress in Photovoltaics: Research and Applications*, vol. 12, pp. 415–426, 2004.
- [73] H. A. Zondag, D. W. Vries, W. G. J. Helden, R. J. C. Zolingen, and A. A. Steenhoven, “The yield of different combined PV-thermal collector designs,” *Solar Energy*, vol. 74, pp. 253–269, 2003.
- [74] “World's Largest 38,500-meal Solar Kitchen in India,” *Inhabitat*. [Online]. Available: <https://inhabitat.com/worlds-largest-38500-meal-solar-kitchen-in-india/>. [Accessed: Jun. 4, 2014]

- [75] N. Shankarappa, M. Ahmed, N. Shashikiran, and H. Naganagouda, “Solar Photovoltaic Systems – Applications & Configurations,” *International Research Journal of Engineering and Technology (IRJET)*, vol. 4, no. 8, Aug. 2017.
- [76] M. N. Arshin, Z. Ullah, M. A. Khan, M. Z. Uddin, M. F. Uddin, and M. A. Rahman, “Smart lightning solutions for smart city with solar energy,” *International Research Journal on Advanced Engineering Hub (IRJAEH)*, vol. 3, no. 5, pp. 2141–2147, 2025, doi: 10.47392/IRJAEH.2025.0314.
- [77] R. Kumar and S. Singh, “Porous silicon solar cells,” *Academia.edu*, 2023. [Online]. Available: https://www.academia.edu/96934010/Porous_silicon_solar_cells. [Accessed: Mar. 30, 2026]

***Chapter III: Techniques for
characterizing the physical
properties of porous silicon
layers***

Chapter III: Techniques for characterizing the physical properties of porous silicon layers

III-1 Introduction

In materials science, the term "characterization" refers to the broad range of techniques used to investigate a material's structure and properties. This fundamental process is the basis for the scientific understanding of materials. It encompasses techniques used to examine a material's microstructure and properties, including procedures for density calculation, mechanical testing, and thermal analysis. Traditional characterization techniques are continually being supplemented by newer, more sophisticated methods. Characterization enables us to assess the effectiveness of any technique and aids in determining the structure and composition of materials. While some methods are quantitative, others are qualitative [1].

III-2 Scanning Electron Microscopy (SEM)

One method that makes utilizes electron-matter interactions is scanning electron microscopy.

In electron microscopy, a sample is exposed to a focused electron beam. The interaction between the electrons and the sample produces various signals, including Auger electrons, secondary electrons, backscattered electrons, and X-ray photons. Numerous secondary phenomena, including electron and photon re-emission, electron absorption, induced currents, electrical potentials, and lattice vibrations, are produced when incident electrons lose energy through repeated collisions with the material's atoms. As these signals are generated simultaneously, specific features of the sample can be observed and analysed [2].

III-2-1 Working Principle

The scanning electron microscope (SEM) consists of three main components: the optical column, the sample chamber, and the imaging system [3]. The optical column houses the electron gun, which serves as the source of the electron beam. This section includes condenser lenses to control and concentrate the beam, an objective lens to achieve precise focusing on the specimen surface, and an anode plate subjected to a high voltage to accelerate the electrons toward the sample. In addition, apertures of different sizes are used to regulate the beam diameter and electron density, thereby optimizing image resolution and signal quality. The electron beam from the electron gun is thinned and focused on the sample surface by magnetic lenses and deflectors situated here. The electrons and radiations produced when the sample interferes with the incoming electron beam are collected by detectors in the imaging system. Electrons or signals that are reflected or

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interfered with by the surface are amplified by these detectors. These detectors amplify the signals, which are then converted into digital signals and displayed on a monitor [4].

III-2-2 SEM's Components and Operating System

The main components of an SEM are as follows:

a-As seen in Figure III-1, an electron gun is a source that produces high-energy electrons.

b- As seen in Figure III-2, column down allows electrons to pass through two or more electromagnetic lenses.

c-Scan coils make up the deflection system.

d- Electron detector for secondary and backscattered electrons, as shown in Figure III-3.

e- A sample chamber, as shown in Figure III-4.

As shown in Figure III-4, a computer system consists of a keyboard to operate the electron beam and a viewing screen to display the scanned images.



Figure III.1 Electron gun [5].



Figure III.2 Electromagnetic lenses [5].

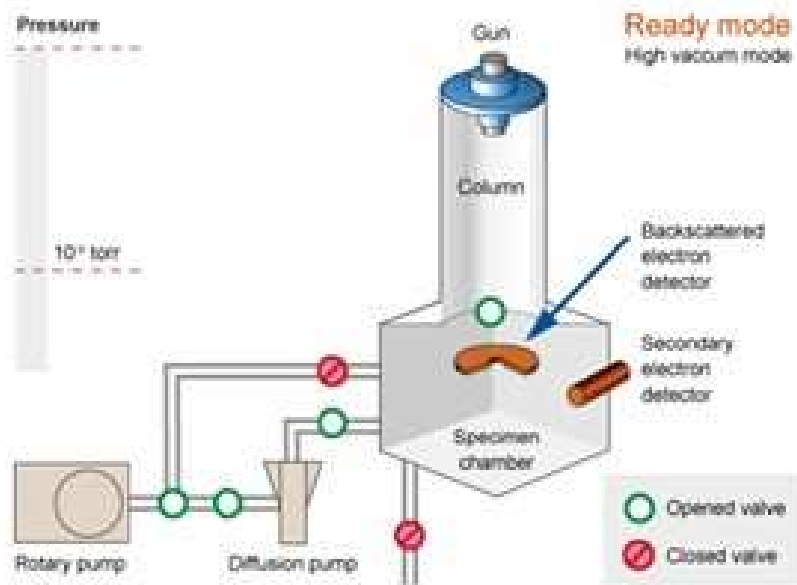


Figure III.3 Electron detectors in the SEM system [5].

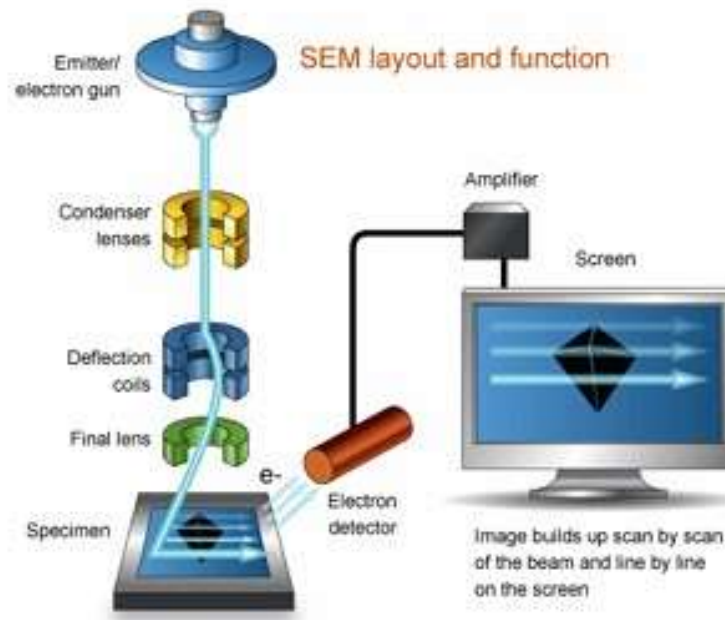


Figure III.4 All SEM components [5].

III-2-3 Advantages and Disadvantages of S E M

The primary advantages of SEM include its high resolution (ranging from sub-nanometre to around 10 nm), capability for in-depth morphological analysis, elemental composition determination, and surface topography investigation. Modern SEMs also enable the simultaneous imaging of many surface viewpoints, which makes this characterization method appropriate for a wide range of sectors, including material science, nanotechnology, biotechnology, and biomedicine [6-8].

Conversely, the high energy of the electron beam can damage sensitive surfaces, such as hydrogels, biological specimens, and soft polymers. [7, 8]. Moreover, this technique's high resolution is limited by the electron beam broadening effect [8]. Several operational factors can affect image quality, including: low resolution when imaging large areas at high speed [9]; projection distortion (foreshortening) when the sample is tilted; poor contrast resulting from a small beam size combined with low beam current; and electron scattering due to inadequate vacuum conditions. Although resolution deterioration may be a drawback, using a high beam current enhances the visibility of objects with flux contrast.

Additionally, a more thorough sampling depth of field can be obtained by lowering the beam divergence angle, which will increase the image's sharpness [6].

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Modern SEMs are computer-controlled, making them relatively easy to operate with minimal training. They can generate large quantities of images for analysis and support multi-user environments. Nevertheless, the computer system is insufficient to record and categorize the vast volume of created data. Consequently, neural network techniques are increasingly being employed for automated labelling, classification, and feature recognition in SEM data [10].

III-2-4 Applications of S E M

SEM is a primary tool for assessing the topography (e.g., texture, roughness) and morphology (e.g., size, shape) of diverse samples. High-resolution pictures with a spatial resolution of 1 nm can be created thanks to signals generated by the electron beam's elastic and inelastic interactions with the sample surface. Image quality is primarily determined by the incident electron beam energy, the angle of incidence, and the composition of the sample. When analysing biological samples, where organisms, organs, tissues, macromolecules, and cells must be hydrated to preserve their natural condition, drying techniques are crucial because the SEM is incompatible with wet samples. SEM can be used to examine structural defects and characterize a sample's thickness, shape, and lateral dimensions. Because it is a non-destructive instrument that produces sharp, high-quality images, the SEM is frequently employed in nanoscience.

For example, the size of nanomaterials, a critical parameter in photocatalytic and electrocatalytic applications, can be verified using SEM [11, 12].

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III-2-5 Jsm 6460 SEM;

The model used in this work for some samples is the JSM 6460 SEM, as it is presented in figure III-5

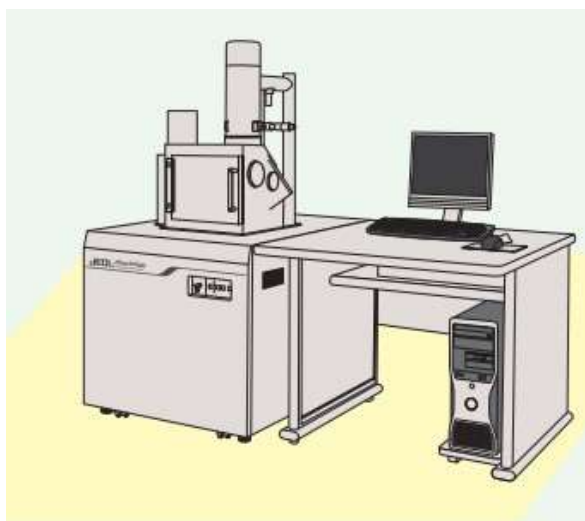


Figure III.5 picture of Jsm 6460 SEM [13].

This high-performance, wide-area analytical scanning electron microscope (SEM) features a JEOL EDS (electron scattering system) integrated into the JSM-6460. Designed with seamless integration of observation and analysis, it includes an analysis station for highly efficient observation and analysis of elements over large areas. This wide-area analytical scanning electron microscope, designed for low-vacuum operation, incorporates the low-vacuum scanning electron microscope function found in the JSM-6460LV, enabling the observation and analysis of non-conductive samples [14].

III-3 Fourier transform infrared spectroscopy

Infrared spectroscopy is an efficient, reliable, sensitive, rapid, and cost-effective technique for studying polymers. [15]. The intensity and wavelength of a sample's infrared absorption are measured using Fourier-transform infrared spectroscopy (FTIR). FTIR has been employed more extensively in the present period to track the functional groups and chemical structure of lignocellulose substances [15-17]. For instance, the mid-infrared region ($4000\text{--}400\text{ cm}^{-1}$), where absorption bands correspond to transitions between the vibrational and rotational energy levels of molecules, is widely used in a variety of applications in the biological, biochemical, and food industries [15].

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III-3-1 Working principle

A precise method for determining a substance's functional groups and molecular bonds is Fourier Transform Infrared (FTIR) spectroscopy. Similar to how an FTIR instrument produces its infrared (IR) spectrum, spectrophotometers are used in spectroscopic procedures to determine a compound's absorption spectrum. The spectral encoding process is started by an infrared beam that enters an interferometer from a blazing blackbody source within an FTIR device. The interferometer generates an interferogram showing the constructive and destructive interference resulting from the recombination of beams of different wavelengths. The beam is then redirected to the sample chamber to interact with it, where the sample absorbs specific energy frequencies taken from the sample's interferogram. Lastly, the detector simultaneously records the background signal and receives the interference signal for all frequencies. A Fourier transform software is used to acquire the desired spectrum after the interferometer subtracts the background spectrum from the sample spectrum [18].

III-3-2 Fourier Transform Infrared Spectroscopy Benefits and Drawbacks

Infrared (IR) spectra are used in Fourier Transform Infrared (FTIR) spectroscopy to provide detailed information about samples. Accordingly, the peak positions in a sample's spectrum show the molecular structure, peak intensities show the molecular concentration, and peak widths show pH and hydrogen bonding [19]. Since many compounds have strong absorbance in the mid-infrared radiation band where FTIR operates, -> this technique can analyse nearly any material [19,20].

Other general features that set FTIR apart from other spectroscopic methods include its ease of use [19–21], affordability [19], good repeatability, and precise measurements [21]. Additionally, conventional FTIR is quite sensitive, detecting micrograms (10^{-6} g) of analyte in a sample. The sensitivity of the employed detectors, the high optical throughput that generates low noise levels, and the quick scanning speed that enables random measurement noise to be reduced to any predicted level are responsible for this benefit [19, 21].

Additionally, because FTIR uses self-calibrating equipment that applies an internal wavelength calibration standard using a helium-neon (He-Ne) laser, it does not require calibration. Since all frequencies are measured simultaneously, the FTIR mechanism is advantageous in and of itself since it provides a quick response time. However, because

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these chemical species do not vibrate, which is necessary for FTIR operation, this technique cannot detect noble gases, monatomic ions, or homonuclear diatomic molecules. Furthermore, associating specific peaks with particular molecules becomes more challenging with complex sample spectra, which limits the ability to evaluate sample spectral peaks to distinguish components in a mixture [19, 20].

Another significant disadvantage that needs to be considered is water interference. Water produces broad, intense peaks that can interfere with the sample spectrum, potentially dissociating chemicals used in sample preparation and masking solute signals [19]. One drawback of FTIR technology is that it only has one beam, in contrast to other dual-beam dispersive devices [21].

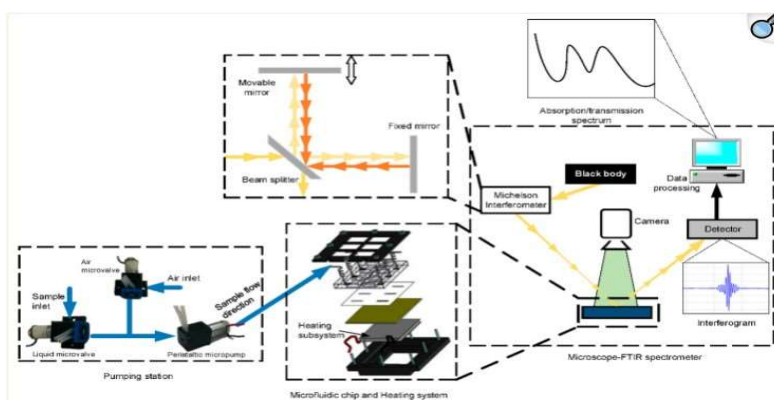


Figure III.6 Schematic representation of the operating principle of a pseudo-continuous FTIR flow system integrated into a microfluidic platform for sugar detection and characterization.” [22].

III-3-3 Applications of Fourier Transform Infrared Spectroscopy

A straightforward, precise, and efficient method for identifying polymeric, inorganic, and organic species in materials with known or unknown chemical compositions is Fourier Transform Infrared (FTIR) spectroscopy. Because of its benefits, this analytical tool is frequently employed in both scientific and industrial circles. For instance, FTIR only needs a very small amount of sample (1.5 μL) for analysis and requires little to no sample preparation. Since the sample is not harmed by the infrared radiation, the process is non-destructive. Fourier transform infrared (FTIR) is a crucial technology in many domains, including environmental science, because of these appealing characteristics [23,24]. Plastics development [25, 26], environmental quality monitoring [27, 28], polymer science

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[29, 30], food quality control [31, 32], forensics [33, 34], pharmaceuticals [34, 35], sensing and bio sensing [35, 36], and polymer science [29, 30].

III-4 PL spectroscopy

Photoluminescence (PL) spectroscopy, also known as emission spectroscopy, measures the light emitted by a substance when electrons transition from a higher to a lower energy state [37].

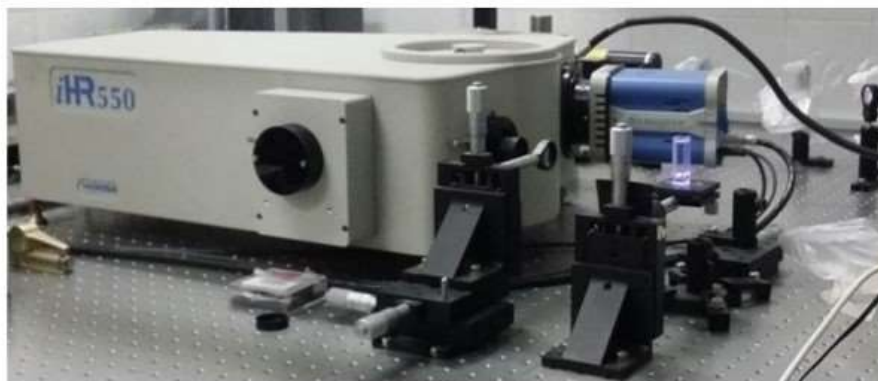


Figure III.7 Photoluminescence spectrometer setup [38].

III-4-1 Photoluminescence (PL)

Since photoluminescence (PL) is triggered by photoexcitation, it is the emission of light from any material following photon absorption. At a specific energy, photoluminescence is seen to be a sign that the excitation population is in an excited state connected to its transition energy. Additional layers of complexity are imposed by the photoluminescence characteristics' great sensitivity to the internal electric fields and the dielectric environment. Numerous intriguing inherent effects in quantum wells are revealed by photoluminescence research, including the carrier–carrier interaction, the homogenous broadening of the excitation recombination line, and the rise in excitation binding energy brought on by charge carrier localization. Analysing a nanostructure's radiative recombination spectrum can aid in its characterization by revealing details about the materials' quality and interface morphology [39].

III-4-2 Working principle

Photons are absorbed and electronic excitations are produced when a substance is exposed to light with enough energy. These excitations eventually subside, allowing the electrons to revert to their ground state. The light that is released when radiative relaxation

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takes place is referred to as PL. A plethora of knowledge regarding the photo excited substance can be obtained by gathering and examining this light. Electronic energy levels can be ascertained using the transition energies provided by the PL spectrum. The relative rates of radiative and no radiative recombination are measured by the PL intensity. The underlying electronic states and bands can be further characterized by varying the PL intensity with external factors like temperature and applied voltage. The excitation energy controls the incident light's penetration depth and chooses the initial photo excited state.

The density of photo excited electrons frequently determines the PL signal, and this parameter can be controlled by varying the input beam's intensity. The PL signal will alter with the excitation position when the kind or calibre of the material being studied varies spatially [40].

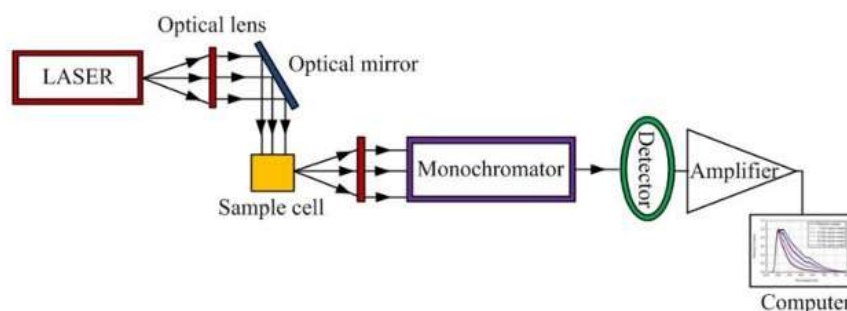


Figure III.8 Configuration of photoluminescence spectrometer [38].

III-4-3 Applications of PL

III-4-3-1 Bandgap Determination

The bandgap is the energy differential between the conduction and valence bands. The electronic bandgap is non-destructively determined by the distribution of the photoluminescence spectrum. This makes it possible to identify a semiconductor compound's elemental composition, which is crucial for single-cell device efficiency [39].

III-4-3-2 Impurity and Defect Level Detection

Localized defect levels in semiconductors are a part of radiative transitions. The photoluminescence energy linked to these levels can be used to identify particular faults. Spectral peaks linked to contaminants in the host material are frequently visible using low-temperature photoluminescence spectroscopy. The detection of extremely low quantities of purposeful and inadvertent impurities, which can significantly affect material quality and

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device performance, is made possible using Fourier transform photoluminescence microscopy [39].

III-4-3-3 Determination of Surface Structure and Excited State

The most widely used techniques, including Raman spectroscopy, XRD, and IR spectroscopy, are insensitive to supporting oxide catalysts with modest concentrations of metal oxide. However, particles are used as a probe for electron-hole surface processes because photoluminescence is highly sensitive to adsorbed species from semiconductor surface effects [39].

III-4-3-4 Recombination Mechanism

"Recombination," which includes both radiative and non-radiative processes, is the process of regaining equilibrium. The relative magnitude of the radiative and non-radiative recombination rates determines how much photoluminescence a material emits. Impurities affect the non-radiative rates, whereas the predominant recombination determines the amount of photoluminescence and how it relates to temperature and photoexcitation level [39].

III-5 X-ray diffraction techniques

X-ray radiography is an imaging method that uses films or detectors to register the intensity of light travelling through an object, enabling the interior structure that is apparent because of the absorption's local fluctuation. X-ray computer tomography is one of the most significant advancements in this industry during the past few decades. The foundation of XRD techniques is crystals' distinctive ability to diffract X-rays, which enables an accurate analysis of the crystalline phases' structure. Multiple micro- and macrostructural characteristics of a sample are additively contributed to recorded diffraction patterns. With the space group, chemical composition, peak position, and lattice parameters. This technique enables the investigation of material composition, macroscopic stresses, and qualitative phase identification. Peak intensities can be analyzed to determine crystallographic texture, perform quantitative phase analysis, and extract detailed crystal structure information, including atomic positions, occupancy, and temperature factors. Furthermore, the analysis of peak shapes provides insight into sample-induced broadening effects, such as macrostrain and crystallite size contributions [41]

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III-5-1 X-ray Diffraction Principle

The X-rays are scattered by the electrons orbiting around the atoms' nucleus when they strike solid objects. These dispersed waves interfere with one another since they are released in various directions. Depending on the nature of the wave interaction and propagation direction, interference may be either constructive or destructive [42]. Diffraction corresponds to the constructive interference of scattered X-rays by the atomic planes of a material. This phenomenon arises from the periodic and well-ordered arrangement of atoms within crystalline solids. Consequently, the X-ray diffraction (XRD) patterns of crystalline materials exhibit distinct and sharp peaks, making them relatively straightforward to interpret. Periodicity and diffraction are closely related: shorter interplanar spacing lead to larger diffraction angles, whereas larger spacing result in smaller angles, in accordance with Bragg's law [42]. Figures 3a and b, respectively, depict the XRD graphs of crystalline and amorphous materials as demonstrated by Lamas et al. [43].

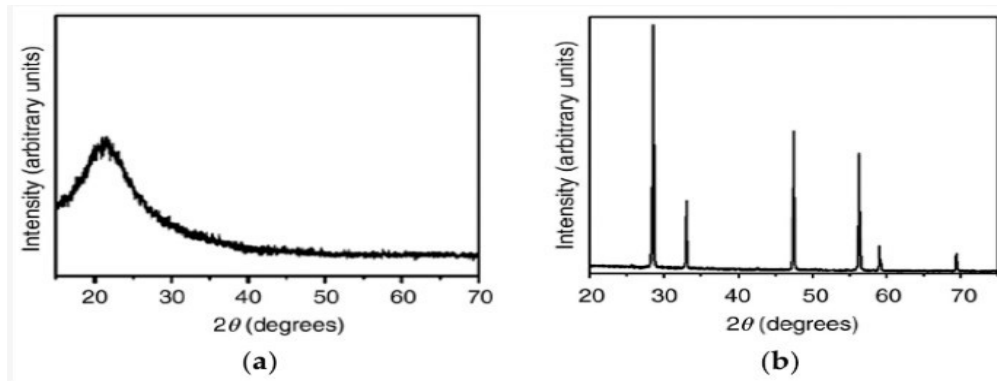


Figure III.9 Qualitative X-ray diffraction (XRD) patterns of (a) an amorphous material and (b) a crystalline material [43].

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III-5-2 XRD Applications

X-ray diffraction (XRD) has become a vital analytical tool across various scientific fields, including materials science, pharmaceuticals, geology, and planetary research. For instance, the CheMin XRD instrument on NASA's Mars Science Laboratory successfully detected clay minerals and amorphous phases on the Martian surface, highlighting the technique's reliability in extra-terrestrial environments [44]. In pharmaceutical research, XRD is essential for characterizing polymorphic forms of drug molecules, which directly affect their stability and therapeutic performance [45]. In industrial settings, fully automated XRD systems enhance process efficiency in sectors such as mining, cement production, and superconductor manufacturing by enabling rapid and accurate phase identification [46]. Moreover, high-resolution synchrotron-based XRD enables highly sensitive detection of strain states in advanced composite conductors, providing critical insights into material performance [47].

The increasing focus on nanomaterials and hybrid polymers has further broadened XRD applications. Studies have shown that temperature-dependent XRD measurements can track variations in nanoparticle size and morphology [48-51], while combined XRD and SEM analyses offer detailed understanding of structural changes in graphene oxide-based composites, thereby clarifying their electrical and mechanical properties.



Figure III.10 The XRD-based analytical equipment [52].

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III-6 Conclusion

In order to improve materials for particular applications in domains like nanotechnology, electronics, and materials science, these technologies work in tandem to provide a greater understanding of a material's chemical composition, surface morphology, and optical properties.

The importance of Characterization Techniques: FTIR, SEM, and PL Fourier Transform Infrared Spectroscopy (FTIR):

- Determines a material's chemical bonds and functional groups.
- vital for identifying contaminants and confirming chemical composition.
- aids in the molecular understanding of material changes and reaction mechanisms.

Scanning electron microscopy, or SEM,

- produces high-resolution pictures of the microstructure and surface morphology.
- crucial for analyzing surface flaws, porosity, particle size, and shape.
- essential for characterization of nanomaterials, failure analysis, and quality control.

Photoluminescence spectroscopy, or PL,

- examines optical and electrical characteristics such defect levels and band gaps.
- helpful in determining the crystallinity and purity of semiconductors and nanomaterials.
- crucial to the creation of optoelectronic devices such as solar cells and LEDs.

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References

- [1] D. Titus, E. J. J. Samuel, and S. M. Roopan, "Nanoparticle characterization techniques," in *Green Synthesis, Characterization and Applications of Nanoparticles*, Elsevier, 2019, pp. 303–319, doi:10.1016/B978-0-08-102579-6.00012-5.
- [2] S. Rahmouni, *Study, design, and fabrication of antireflection coatings for improving photovoltaic conversion*, Ph.D. dissertation, University of 20 August 1955–Skikda, 2017.
- [3] FEI Company, *Tools for Nanotech*, [Online]. Available: <http://www.fei.com>, Jan. 18, 2013.
- [4] R. B. C. et al., *Encyclopedia of materials characterization: Surfaces, interfaces, thin films*, Gulf Professional Publishing, 1992, pp. 65–87.
- [5] Australian Microscopy & Microanalysis Research Facility, *My Scope: Scanning electron microscopy*, 2018. [Online]. Available: <http://www.ammrf.org.au/myscope/sem/background>, May 3, 2018.
- [6] J. Goldstein, D. E. Newbury, J. R. Michael, N. W. Ritchie, J. H. J. Scott, and D. C. Joy, "Scanning Electron Microscopy and X-ray Microanalysis," 4th ed., Springer, New York, 2018. doi: 10.1007/978-1-4939-6676-9.
- [7] L. Prokai, D. J. Aaserud, and W. J. Simonsick, "Microcolumn size-exclusion chromatography coupled with electrospray ionization mass spectrometry," *J. Chromatogr. A*, vol. 835, no. 1–2, pp. 121–126, 1999.
- [8] C. Gottschalk, J. Barthel, U. Aulwum, G. Engelhardt, J. Bauer, and K. Meyer, "Application of a GPC-LC-MS/MS method for the determination of 31 mycotoxins in edible oils," *LCGC North Am.*, vol. 1, Feb. 2009, p. 38.
- [9] S. Sato, T. Takanohashi, and R. Tanaka, "Molecular weight calibration of asphaltenes using gel permeation chromatography/mass spectrometry," *Energy Fuels*, vol. 19, no. 5, pp. 1991–1994, 2005.
- [10] M. Chikri et al., "Discrimination of chemical compounds of the oil of *Mentha suaveolens* (L.) of Eastern Morocco by GPC-MS and chemometric methods," *J. Mater. Environ. Sci.*, vol. 9, no. 3, pp. 909–917, 2018.
- [11] E. Buyukpamukcu, D.M. Goodall, C.E. Hansen, B.J. Keely, S. Kochhar, H. Wille, "Characterization of peptides formed during fermentation of cocoa bean. *J. Agric. Food Chem.* 49(12), 5822–5827 (2001).

Chapter III: Techniques for characterizing the physical properties of porous silicon layers

- [12] B. Zhu et al., Simultaneous determination of 13 pesticides in tea by on-line GPC-GC-MS/MS using graphitized multi-walled carbon nanotubes as dispersive solid phase extraction sorbent. *Food Chem.* 276, 202–208 (2019)
- [13] PubCompare.ai. (n.d.). AI-powered research and experimental protocol database. Retrieved January 27, 2026, from <https://www.pubcompare.ai/>
- [14] JEOL Ltd. (n.d.). JSM-6460A / JSM-6460LA scanning electron microscope. Retrieved from https://www.jeol.co.jp/products/scientific/sem/JSM-6460A_6460LA.html
- [15] M. Kačuráková, R. Wilson, Developments in mid-infrared FT-IR spectroscopy of selected carbohydrates, *Carbohydr. Polym.* 44 (4) (2001) 291–303.
- [16] D. Trache, A. Donnot, K. Khimeche, R. Benelmir, N. Brosse, Physico-chemical properties and thermal stability of microcrystalline cellulose isolated from Alfa fibres, *Carbohydr. Polym.* 104 (2014) 223–230.
- [17] S.F. Sim, M. Mohamed, N.A.L.M.I. Lu, N.S.P. Sarman, S.N.S. Samsudin, Computer-assisted analysis of fourier transform infrared spectra for characterization of various treated and untreated agriculture biomass, *BioResources* 7 (4) (2012) 5367–5380.
- [18] D.J. Harvey, Gas chromatography|Gas chromatography/mass spectrometry, in *Encyclopedia of Analytical Science* (2019), pp. 169–179.
- [19] B. Smith, Introduction to infrared spectroscopy, in *Fundamentals of Fourier Transform Infrared Spectroscopy*, 2nd edn. (CRC Press, 2011), pp. 1–17
- [20] S.F. Sim, M.X.L. Chai, A.L. Jeffrey Kimura, Prediction of lard in palm olein oil using simple linear regression (SLR), multiple linear regression (MLR), and partial least squares regression (PLSR) based on Fourier-transform infrared (FTIR). *J. Chem.* 2018, 1–8, (2018). <https://doi.org/10.1155/2018/7182801>
- [21] A. Dutta, Fourier transform infrared spectroscopy, in *Spectroscopic Methods for Nanomaterials Characterization*, vol. 2 (Elsevier, 2017), pp. 73–93
- [22] H. Landari, M. Roudjane, Y. Messaddeq, and A. Miled, “Pseudo-Continuous Flow FTIR System for Glucose, Fructose and Sucrose Identification in Mid-IR Range,” *Micromachines*, vol. 9, p. 517, 2018, doi: 10.3390/mi9100517.

Chapter III: Techniques for characterizing the physical properties of porous silicon layers

- [23] M. Mecozzi, L.Nisini, The differentiation of biodegradable and non-biodegradable polyethylene terephthalate (PET) samples by FTIR spectroscopy: a potential support for the structural differentiation of PET in environmental analysis. *Infrared Phys. Technol.* 101, 119–126 (2019). <https://doi.org/10.1016/j.infrared.2019.06.008>
- [24] H. Barndök, N. Merayo, L. Blanco, D. Hermosilla, Á. Blanco, Application of on-line FTIR methodology to study the mechanisms of heterogeneous advanced oxidation processes. *Appl. Catal. B Environ.* 185, 344–352 (2016). <https://doi.org/10.1016/j.apcatb.2015.12.036>
- [25] M. Mecozzi, M. Pietroletti, Y.B. Monakhova, FTIR spectroscopy supported by statistical techniques for the structural characterization of plastic debris in the marine environment: application to monitoring studies. *Mar. Pollut. Bull.* 106(1–2), 155–161 (2016). <https://doi.org/10.1016/j.marpolbul.2016.03.012>
- [26] A.P.M. Michel, A.E. Morrison, V.L. Preston, C.T. Marx, B.C. Colson, H.K. White, Rapid identification of marine plastic debris via spectroscopic techniques and machine learning classifiers. *Environ. Sci. Technol.* 54(17), 10630–10637 (2020). <https://doi.org/10.1021/acs.est.0c02099>
- [27] O. Anjos, A.J.A. Santos, L.M. Estevinho, I. Caldeira, FTIR-ATR spectroscopy applied to quality control of grape-derived spirits. *Food Chem.* 205, 28–35 (2016). <https://doi.org/10.1016/j.foodchem.2016.02.128>
- [28] J. Bell, P. Nel, and B. Stuart, “Non-invasive identification of polymers in cultural heritage collections: evaluation, optimisation and application of portable FTIR (ATR and external reflectance) spectroscopy to three-dimensional polymer-based objects,” *Heritage Science*, vol. 7, no. 1, p. 95, 2019, doi: 10.1186/s40494-019-0336-0.
- [29] R.Kumar, S. Sharma, D. Pathak, N. Dhiman, N. Arora, Ionic conductivity, FTIR and thermal studies of nano-composite plasticized proton conducting polymer electrolytes. *Solid State Ionics* 305, 57–62 (2017). <https://doi.org/10.1016/j.ssi.2017.04.020>
- [30] A. Pawlicka et al., Dielectric behaviour and FTIR studies of xanthan gum-based solid polymer electrolytes. *Electrochim. Acta* 305, 232–239 (2019). <https://doi.org/10.1016/j.electacta.2019.03.055>

Chapter III: Techniques for characterizing the physical properties of porous silicon layers

- [31] C. Agudelo-Cuartas, D. Granda-estrepo, P. J. A. Sobral, W. Castro, Determination of mechanical properties whey protein films during accelerated aging :application of FTIR profiles and chemometric tools. *J. Food Process. Eng.* 44(5) (2021). <https://doi.org/10.1111/jfpe.13477>
- [32] O.F. Vázquez-Vuelvas, F.A. Chávez-Camacho, J.A. Meza-Velázquez, E. Mendez-Merino, M.M. Ríos-Licea, J.C. Contreras-Esquivel, A comparative FTIR study for supplemented agavin as functional food. *Food Hydrocoll.* 103, 105642 (2020). <https://doi.org/10.1016/j.foodhyd.2020.105642>
- [33] J. Ziłeba-Palus, B. Trzcińska, A. Weselucha-Birczyńska, P. Moskal, J. Sacharz, The sequence of changes observed during degradation process of paper by the use of UV/VIS and FTIR spectrometry with application of the PCA and 2D correlation method for forensic purposes.
- [34] H. Lin, Y. Zhang, Q. Wang, B. Li, P. Huang, Z. Wang, Estimation of the age of human bloodstains under the simulated indoor and outdoor crime scene conditions by ATR-FTIR spectroscopy. *Sci. Rep.* 7(1), 13254 (2017). <https://doi.org/10.1038/s41598-017-13725-1>
- [35] T. Rymasz, E. A. Ribeiro, L. F. das Chagas e Silva de Carvalho, T. Bhattacharjee, R. de Azevedo Canevari, Human papillomavirus detection using PCR and ATR-FTIR for cervical cancer screening. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* 196, 238–246 (2018). <https://doi.org/10.1016/j.saa.2018.02.004>
- [36] K. Chrabaszcz et al., Label-free FTIR spectroscopy detects and visualizes the early stage of pulmonary micrometastasis seeded from breast carcinoma. *Biochim. Biophys. Acta Mol. Basis Dis.* 1864(11), 3574–3584 (2018). <https://doi.org/10.1016/j.bbadis.2018.08.022>
- [37] Kumar, S. S. R. *UV-VIS and Photoluminescence Spectroscopy for Nanomaterials Characterization*; Springer: Berlin, Germany, 2013.
- [38] Alshehawy, A. M., Mansour, D.-E. A., Ghali, M., Lehtonen, M., & Darwish, M. M. F. (2021). Photoluminescence Spectroscopy Measurements for Effective Condition Assessment of Transformer Insulating Oil. *Processes*, 9(5), Article 732. <https://doi.org/10.3390/pr9050732>

Chapter III: Techniques for characterizing the physical properties of porous silicon layers

- [39] Usha Shukla and Samreen Bari Study on the Photoluminescence Journal of Pure Applied and Industrial Physics, Vol.8(5),25-31, May 2018. Usha Shukla, et al. Vol.8 (5), 25-31 (2018)
- [40] T. H. Gfroerer, "Photoluminescence in Analysis of Surfaces and Interfaces," in Encyclopedia of Analytical Chemistry, R. A. Meyers, Ed., John Wiley & Sons, 2006, pp.92099231227979265
- [41] H. Khan, A. S. Yerramilli, A. D'Oliveira, T. L. Alford, D. C. Boffito, and G. S. Patience, 2020.
- [42] B. Fultz and J. Howe, Transmission Electron Microscopy and Diffractometry of Materials, Springer, Berlin/Heidelberg, 2013.
- [43] D. G. Lamas, M. D. O. Neto, G. Kellermann, and A. F. Craievich, "X-ray Diffraction and Scattering by Nanomaterials," in Nano Characterization Techniques, William Andrew Publishing, Oxford, UK, 2017, pp. 111–182.
- [44] P. Sarrazin, D. Blake, S. Feldman, S. Chipera, D. Vaniman, and D. Bish, "Field deployment of a portable X-ray diffraction/X-ray fluorescence instrument on Mars analog terrain," Powder Diffr., vol. 20, no. 2, pp. 128–133, 2005, doi:10.1154/1.1913719
- [45] V. V. Chernyshev, "Structural Characterization of Pharmaceutical Cocrystals with the Use of Laboratory X-ray Powder Diffraction Patterns," Cryst., vol. 13, no. 4, p. 640, 2023, doi:10.3390/cryst13040640.
- [46] V. S. Vinila et al., "XRD Studies on Nano Crystalline Ceramic Superconductor PbSrCaCuO at Different Treating Temperatures," Cryst. Struct. Theory Appl., vol. 3, no. 1, pp. 1–9, 2014, doi:10.4236/CSTA.2014.31001
- [47] C. Scheuerlein, M. Di Michiel, and F. Buta, "Synchrotron radiation techniques for the characterization of Nb₃Sn superconductors," IEEE Trans. Appl. Supercond., vol. 19, no. 3, pp. 2653–2656, 2009, doi:10.1109/TASC.2009.2019101.
- [48] N. K. Subramani, "Revisiting Powder X-ray Diffraction Technique: A Powerful Tool to Characterize Polymers and their Composite Films," Res. Rev. J. Mater. Sci., vol. 4, no. 4, 2016, doi:10.4172/2321-6212.1000158.

Chapter III: Techniques for characterizing the physical properties of porous silicon layers

- [49] R. J. Rodbari, R. Wendelbo, L. C. L. Agostinho Jamshidi, E. Padrón Hernández, and L. Nascimento, "Study of physical and chemical characterization of nanocomposite polystyrene/graphene oxide high acidity can be applied in thin films," *J. Chil. Chem. Soc.*, vol. 61, no. 3, pp. 3120–3124, 2016, doi:10.4067/S0717-97072016000300023.
- [50] B. Lavina, P. Dera, and R. T. Downs, "Modern X-ray Diffraction Methods in Mineralogy and Geosciences," *Rev. Mineral. Geochem.*, vol. 78, no. 1, pp. 1–31, 2014, doi:10.2138/RMG.2014.78.1,
- [51] A. Ghasemi, "Ferrite characterization techniques," in *Magnet. Ferrites Relat. Nanocomposites*, Jan. 2022, pp. 49–124, doi:10.1016/B978-0-12-824014-4.00002-0.
- [52] Bruker AXS, "D8 Advance X-ray Diffractometer: Principles and Applications," Technical Manual, 2020. [Online]. Available: bruker.com.

Chapter IV: Practical Study
“Results and Discussion

IV-1 Introduction

Over the past few years, silicon materials have become a major focus of scientific research worldwide. Owing to their importance in nanotechnology, they have been thoroughly explored, particularly in optoelectronic applications. The increasing fascination with silicon materials arises from their plentiful availability and varied physicochemical attributes, including significant chemical stability and notable electrical and optical features. Etching silicon substrates to produce porous silicon films is among the most promising approaches [1]

This substance displays distinctive characteristics that render it appropriate for numerous uses. In areas like solar cells, photoluminescence, micromachining, photovoltaics, gas sensors, biosensors, and biomedical uses, porous silicon films could tackle many issues. Many research efforts have focused on this material, extending Canham’s work on photoluminescence (PL) phenomena. [2]. Various scientific fields are engaging in extensive studies on porous silicon. Its notable attributes consist of a sizable surface area, tunable porosity, and suitability for electrical and optoelectronic devices [3] In this chapter, we outline several experiments conducted to enhance porous silicon and its application in the photovoltaic industry

1. **First experiment:** Magnetic fields can change The composition and appearance of layers of porous silicon, improving their functional characteristics and allowing for new technological uses. This interaction is able to change the setup and size of magnetic nanostructures within porous silicon, affecting their magnetic behaviours. The superconductivity of quantum nanostructures results in enhanced magnetic permeability, which is not present in porous silicon. Investigating interactions within magnetic fields may result in novel optoelectronic uses and memory technologies. A perpendicular magnetic field can produce p-Si structures with lateral dendritic pores, leading to materials with enhanced coercive strength and magnetic anisotropy. The unique structural characteristics of porous silicon make it highly suitable for a variety of electrical applications, including lithium-ion batteries. We intend to create porous silicon applying a magnetic field, concentrating on the influence of the magnetic field on the properties, structure, or manufacturing method. This may involve modifying pore size, shape, or

arrangement; improving The mechanical, optical, or electrical properties of the substance; and developing new synthesis methods for creating complex magnetic nanostructures in silicon matrices [4]

2. **Second experiment:** Erbium is a rare earth ion that has attracted significant attention due to its remarkable ability to enhance light emission in the near-infrared region. This characteristic makes erbium particularly valuable for optoelectronic and photonic applications. At the same time, extensive research on silicon-rich oxide structures has shown that these materials contain a higher concentration of silicon compared to stoichiometric oxides, which gives them distinct optical and electronic properties. Solar energy represents one of the most important and widely accessible renewable energy sources. However, the efficiency of solar cells is limited by several loss mechanisms. Among the most important are optical losses caused by light reflection at the surface of the cell, as well as thermal losses resulting from the conversion of ultraviolet and infrared radiation into heat rather than usable electrical energy. To reduce these effects, solar devices are commonly coated with anti-reflective layers designed to improve light absorption. In recent years, materials doped or co-doped with rare earth elements have been extensively studied because of their potential use in advanced optoelectronic applications. These materials are also being explored as alternative solutions in photovoltaic technologies, mainly due to their favorable optical properties, including down-conversion and up-conversion processes that can improve the utilization of the solar spectrum. Within this context, porous silicon films have emerged as a promising alternative to conventional silicon doping approaches. Porous silicon offers a flexible platform for incorporating rare earth elements, particularly erbium, through various fabrication techniques. The interaction between erbium ions and the porous silicon matrix can significantly influence the material's physical and optical behavior. This research is therefore focused on gaining a deeper understanding of the relationship between porous silicon structures and erbium incorporation, as well as the resulting modifications in their properties, with the aim of supporting future developments in optoelectronic and photovoltaic applications. his objective is pursued through the use of various experimental approaches, including structural characterization techniques and spectroscopic analyses, which allow for a comprehensive evaluation of the material properties. In addition, the

study explores the potential technological applications of erbium-infiltrated porous silicon, particularly in optoelectronic devices such as light-emitting diodes, lasers, and optical amplifiers. Special emphasis is placed on photoluminescence behaviour, as it provides essential insight into the mechanisms responsible for light emission and its optimization for practical applications. In this work, an electrochemical method is employed to introduce erbium ions into the porous silicon matrix. The incorporation process is influenced by several controllable parameters, including the concentration of the solution, the choice between constant current or constant voltage modes, the applied electrical values, and the duration of the deposition process. By adjusting these factors, it is possible to tailor the resulting material properties. From another perspective, erbium-doped porous silicon exhibits the ability to support both up-conversion and down-conversion processes. These optical effects are of particular interest for photovoltaic applications, as they can contribute to improved photo conversion efficiency in silicon-based solar cells by enabling more effective utilization of the solar spectrum. [3]

3. **Third experiment:** This research focuses on the morphological characterization and optical properties of porous silicon layers developed for photovoltaic applications. Despite extensive research in this field, the underlying physical mechanisms are not yet fully understood, mainly due to the strong relationship between the nanoscale structure of porous silicon and the conditions under which it is fabricated. Variations in fabrication parameters can lead to significant changes in the material's properties, making systematic investigation essential. Among the different fabrication parameters, the etching current density is considered one of the most influential factors, as it directly affects key structural features such as pore depth, pore size, and overall porosity. In this study, porous silicon layers are prepared using p-type silicon wafers with low resistivity, following a carefully controlled substrate cleaning procedure to ensure reproducibility and material consistency. High-purity materials are used throughout the experimental process to minimize contamination and external effects. The main objective of this work is to examine how the emission spectra intensities evolve as a function of porosity, layer thickness, and refractive properties. Understanding these relationships is essential for optimizing the optical behavior of porous silicon and enhancing its performance in photovoltaic devices. [2].

4. **Fourth experiment:** The present work investigates the temperature dependence of photoluminescence in porous silicon layers fabricated on an n-type silicon substrate. Such an examination involves analyzing how variations in temperature influence the photoluminescence response of the material. This type of research is important for enhancing the understanding of the optical and electronic characteristics of porous silicon, which are critical for its integration into advanced technological applications. Porous silicon has emerged as a promising material for optoelectronic, sensing, and photovoltaic applications, leading to considerable scientific interest. In particular, understanding its temperature-sensitive photoluminescence characteristics supports the development of highly efficient silicon-based photonic devices, including those integrated within a-SiN_xO_y systems. Temperature-dependent behavior provides valuable insight into carrier dynamics and material stability under operating conditions. This study primarily focuses on analyzing the temperature dependence of the photoluminescence properties of porous silicon layers. To achieve this, both the ambient temperature and the corresponding photoluminescence response are systematically measured and recorded. Analyzing the resulting photoluminescence data makes it possible to identify emission features and gain insight into the recombination processes that control light emission in porous silicon [1].

IV -2 Experimental Section

IV -2-1 Design of the Anodizing Pod

An anodizing cell was designed to fabricate porous silicon layers with controlled dimensions, featuring a circular opening that allows the formation of layers approximately 10 mm in diameter figure IV-1 presents a schematic of the anodization setup, showing the cell configuration along with a stabilized power supply that maintains a constant current throughout the process. In this arrangement, the silicon wafer is provided with a metallic contact on its rear side, which is carefully isolated from the HF/ethanol electrolyte by an HF-resistant O-ring. This arrangement ensures that the electrolyte only interacts with the front surface of the wafer, preventing unintended etching or damage to other areas. Consequently, the diameter of the porous silicon region is primarily determined by the size

of the O-ring, demonstrating precise control over the spatial extent of the porous layer while minimizing the influence of edge effects [5].

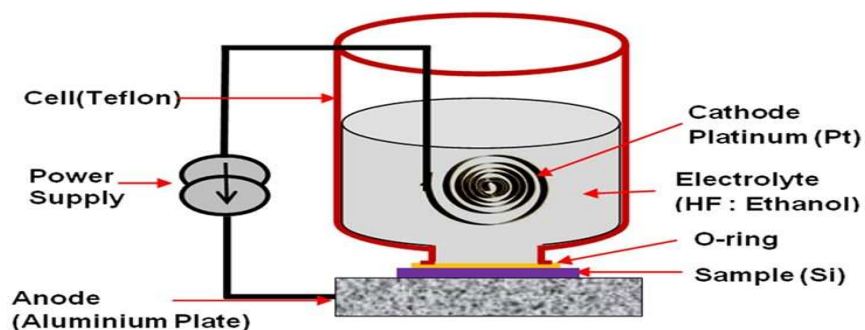


Figure IV.1. Representation of the electrochemical cell configuration used for the formation of porous silicon layers [1].

IV -2-2 Preparing the Substrate

The porous silicon samples were prepared using the electrochemical anodization technique, a widely adopted method that allows for the controlled fabrication of uniform porous layers. This approach offers the advantage of precise regulation over the structural properties of the resulting layers, including both porosity and thickness, which are critical for optimizing their optical and electronic behaviour. In this study, both p-type and n-type monocrystalline silicon substrates with crystallographic orientations of (100) and (111) were employed to investigate the influence of substrate type on the resulting porous structures. Prior to anodization, an aluminium plate was attached to the back of each substrate to ensure reliable electrical contact, which is essential for maintaining a stable current during the electrochemical process [5].

IV -2-3 Cleaning Procedure of Si Substrates

Prior to any processing, the silicon substrates were thoroughly cleaned to ensure the removal of contaminants and to achieve reproducible results. The cleaning procedure followed a standardized protocol to prepare the substrates for porous silicon fabrication. Initially, The wafers were treated with a commercial detergent at 50 ± 1 °C for 15 minutes and then rinsed in deionized water under ultrasonic agitation. The substrates were then immersed in ethanol at 50 ± 1 °C for an additional 15 minutes to further remove organic residues. Subsequently, the wafers were cleaned with acetone and deionized water and then vacuum-dried at 100 °C for 90 minutes to eliminate any remaining moisture. Finally,

immediately before each experiment, the substrates were exposed to a flow of dry nitrogen gas to ensure a clean and inert surface for the anodization process [4].

IV -2-4 Preparation of Porous Silicon Samples

Porous silicon films were fabricated using the electrochemical etching technique, following a well-established and carefully controlled procedure. Silicon samples were immersed in an electrolyte consisting of a 1:1 volume mixture of hydrofluoric acid (HF, 40%) and ethanol (C_2H_5OH , 98%) at room temperature for a predetermined etching duration. The inclusion of ethanol in the solution facilitated the formation of a uniform porous layer and minimized the formation of hydrogen bubbles on the surface, ensuring consistent layer homogeneity. To produce porous silicon layers with a diameter of approximately 10 mm, a custom anodization cell with a circular aperture was employed. A schematic diagram of the anodization setup, including the anodizing tray, is presented in figure IV-1. The cell was equipped with a stabilized power supply that maintained a constant current during the etching process. The silicon wafer was provided with a metallic contact on its backside, which was insulated from the HF/ethanol solution using an HF-resistant O-ring. This configuration ensured that the electrolyte interacted exclusively with the front surface of the wafer. As a result, the diameter of the resulting porous silicon region was effectively determined by the size of the O-ring, even when edge effects were neglected. During the etching process, a current was applied between the electrodes to ensure reproducibility of the porous layer geometry and to precisely control both the porosity and thickness. Both constant and variable current intensities were employed, allowing for systematic investigation of their effect on the structural and optical properties of the resulting porous silicon films.

We prepared the samples in the same way, but each sample was subjected to different parameters.

IV -2-4-A In the presence of a magnetic field

The first sample was exposed to a controlled magnetic field during the fabrication of porous silicon structures. For this purpose, a single-crystal n-type Si(111) wafer with dimensions of 1 cm $\times$ 1 cm and a resistivity of 0.75 $\Omega \cdot \text{cm}$ was employed. The experimental setup for the etching process is illustrated in figure IV-2. During anodization, the sample was illuminated with an incandescent lamp to enable optical monitoring of pore formation.

The specific experimental conditions used in this study are summarized in table IV-1. A stabilized voltage generator was used as the power supply to drive the anodization process. Accurately quantifying the magnetic field presents technical challenges but is vital for achieving reproducible and controlled experimental conditions. A teslameter with 0.01 mT resolution was employed to measure the field generated by the coils. The system featured a Hall effect sensor, a supporting rod, and a digital display console, facilitating precise and consistent monitoring of the applied magnetic field.

Table IV.1. Sample preparation and processing conditions [4].

Samples	[HF]%	J(mA/cm ²)	t(m)	B(Tesla)	P%
S1	20	50	5	0.3	37.53
S2	20	50	5	0.5	43.58
S3	20	50	5	0.7	58.82
S4	20	50	5	0.9	69.74

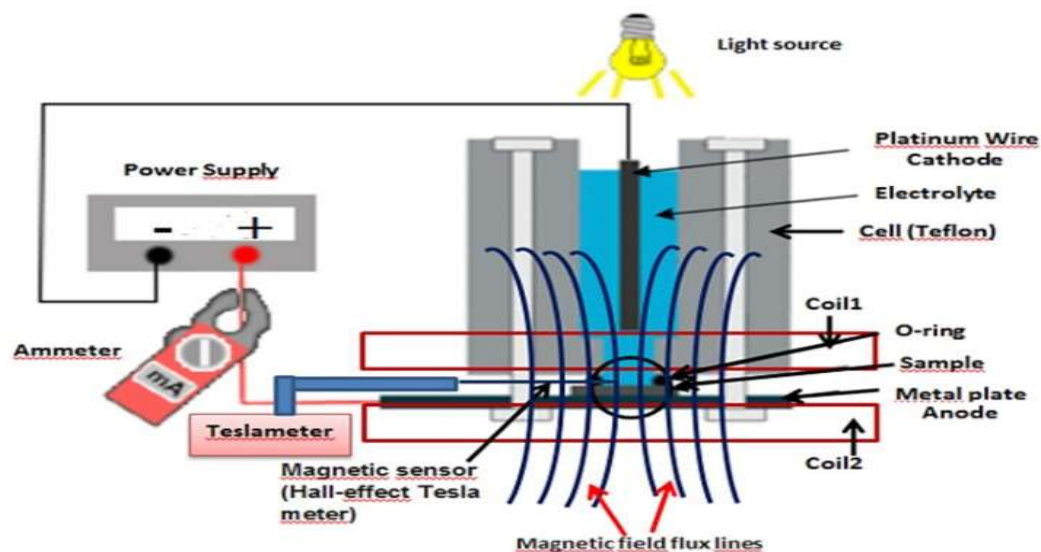


Figure IV.2. Schematic representation of the electrochemical setup applied to form PSi layers while subjected to a magnetic field [4].



Figure IV.3. Picture of the experimental system in its entirety [4].

IV -2-4 B In the presence of Erbium ions

Porous silicon samples were additionally prepared from a p-type silicon substrate with (100) orientation, a resistivity of $1\text{--}10\ \Omega\cdot\text{cm}$, and a surface area of $0.64\ \text{cm}^2$. The etching solution for these samples contained a combination of erbium oxide (Er_2O_3) and hydrochloric acid (HCl) at a concentration of $0.1\ \text{mol/L}$, as reported in previous studies. To incorporate erbium ions into the porous silicon matrix Samples were introduced into a saturated $\text{ErCl}_3\cdot 6\text{H}_2\text{O}$ /ethanol solution and electrically polarized negatively in relation to a platinum electrode. This procedure allowed for controlled deposition of erbium within the porous network. The specific anodization and doping conditions used for each substrate are summarized in table IV-2 [3], providing a clear overview of the experimental parameters applied in this study.

Table IV.2. Conditions under which the substrates were anodized.

Samples	Current density (mA/cm^2)	Etching times (s)	Volume ratio(HF: $\text{C}_2\text{H}_5\text{OH}$)	Annealed ($^\circ\text{C}/\text{Hours}$)	$\text{Er}_2\text{O}_3(\text{mg})$	HCl (ml)
S ₁	15	240	1:1	400	200	5
S ₂	20	240	1:1	400	200	5
S ₃	25	240	1:1	400	200	5
S ₄	30	240	1:1	400	200	5

IV -2-4-C Use only alternating current

The optical properties of porous silicon films fabricated via electrochemical etching of doped p-type silicon substrates with (100) orientation were systematically examined. In particular, photoluminescence and ellipsometry measurements were performed to evaluate the films' optical behavior. The results indicated that key fabrication parameters, such as the etching current density and the duration of electrical contact during anodization, had a significant influence on the optical characteristics of the porous silicon layers. Understanding these dependencies is essential for optimizing the material's performance in optoelectronic and photonic applications [2].

IV -2-4-D Influence of Temperature on the Photoluminescence Properties of Porous Silicon Films

This work seeks to investigate the influence of temperature on the photoluminescence (PL) band and to elucidate the energy levels associated with the emission. and to gain insight into the underlying radiative recombination mechanisms. A key objective of the investigation was to analyze changes in the PL intensity, as well as the integrated PL intensity, across a wide temperature range from 10 K to 300 K. The sample selected for this study was an n-type silicon wafer with (100) orientation, which was subjected to controlled experimental conditions to systematically evaluate the effects of temperature on its photoluminescence behavior : [HF] = 20%, $t = 3$ min, and $j = 25$ mA/cm² [1].

IV -3 Characterization of Porous Silicon Layers

Each porous silicon sample was systematically characterized using a combination of scanning electron microscopy (SEM), photoluminescence (PL) spectroscopy, and Fourier-transform infrared (FTIR) spectroscopy to obtain a comprehensive understanding of their structural, optical, and chemical properties. Photoluminescence measurements were conducted at room temperature using a conventional lock-in detection method. A Jobin-Yvon 250 mm high-resolution monochromatic coupled with a GaAs photomultiplier was used to record the PL spectra. The samples were excited with a solid-state laser operating at a wavelength of 447 nm and a laser power of 7.66 mW, ensuring sufficient excitation while minimizing thermal effects. The chemical composition and bonding characteristics of samples, particularly those exposed to a magnetic field, were investigated using a Bruker Optics VERTEX 80 FTIR spectrometer. these studies offered in-depth

characterization of the material’s chemical composition and confirmed that erbium and other elements were successfully incorporated into the porous silicon framework [4].

The microstructure and morphology of the porous silicon layers, particularly in the erbium-doped samples, were examined using a SEM (TESCAN VEGA), providing detailed imaging of the pore structures and surface features. In addition, X-ray diffraction (XRD) analysis was performed to investigate the crystalline structure of the porous silicon films. Using a Panalytical X’pert Pro diffractometer with a nickel filter and back monochromatic, diffraction patterns were acquired. The configuration blocked the $K\beta$ line and allowed the $K\alpha_1$ and $K\alpha_2$ copper lines, with wavelengths of 1.5406 Å and 1.5444 Å, respectively, to pass. These measurements offered valuable information on the crystallinity and structural alterations in the porous silicon layers due to erbium incorporation [3].

IV-4 Results and discussion

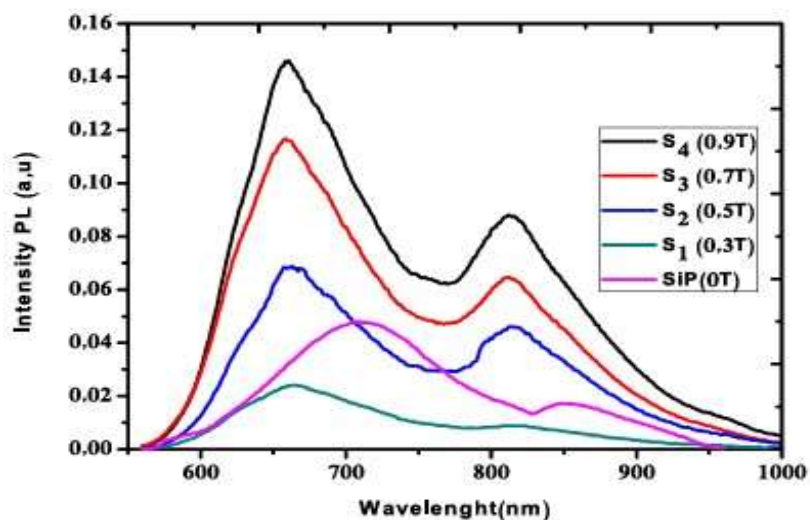
IV-4-1 PL Measurements

IV-4-1 A In the presence of a magnetic field.

This study aims to gain a deeper understanding of the radiative recombination mechanisms in porous silicon, to assess the influence of a magnetic field on the photoluminescence (PL) band and to determine the characteristics of the energy levels contributing to the emission. The investigation primarily focused on how both the overall PL intensity and the oscillations induced by the magnetic field are affected. Experimental results indicate that the applied magnetic field can significantly influence the photoluminescence behavior, either by altering the intensity of the emission or by causing shifts in the PL spectrum, as illustrated in figure IV-4. Quantitative analysis of the PL peaks, summarized in table IV-3, shows measurable changes in both peak intensity and spectral position, Demonstrating the impact of the magnetic field on the optical characteristics of the porous silicon layers [4].

Table IV.3. The spectral positions of the photoluminescence emission peaks [4].

Samples	B(Tesla)	Peak 1(nm)	Peak 2 (nm)
S ₁	0.3	665	820
S ₂	0.5	662	814
S ₃	0.7	658	810
S ₄	0.9	660	812

**Figure IV.4. Photoluminescence spectra evolution of N-type porous layers obtained under varying magnetic field conditions [4].**

The first peak in the photoluminescence (PL) spectrum of porous silicon provides critical information about its electronic configuration and energy states. In samples fabricated from doped n-type substrates, additional peaks—such as the second peak—originate from dopant-induced energy levels, leading to extra radiative transitions in the PL spectrum. The appearance and intensity of these peaks depend on both the nature and concentration of the dopants incorporated into the porous silicon lattice. When a magnetic field is applied, Energy states of electrons and holes in silicon nanostructures can be split as a consequence of the Zeeman effect, as illustrated in figure IV-4. This splitting can alter the recombination dynamics of carriers, affecting the PL spectrum. The magnetic field influences carrier behaviour by modifying mobility, recombination rates, and diffusion properties, which can either enhance or suppress photoluminescence depending on the field's strength and orientation. A magnetic field can also affect the spin states of electrons

and holes, where spin-flip processes alter recombination pathways and influence the intensity and efficiency of PL emission. Furthermore, quantum confinement in porous silicon gives rise to discrete energy levels, which may shift under an applied magnetic field, resulting in changes in the emitted light's wavelength and intensity. Collectively, these effects demonstrate that the optical response of porous silicon is highly sensitive to magnetic field interactions, which can be exploited to tailor its photoluminescence properties for advanced optoelectronic applications [4].

IV-4-1-B In the presence of Erbium ions

In erbium-infiltrated porous silicon, the presence of sharp PL peaks is mainly attributed to electronic transitions between erbium ion energy levels. Quantum confinement within silicon nanocrystals governs visible emission, while surface-related states provide supplementary radiative recombination channels that influence PL behavior. Defects such as impurities and dangling bonds also act as effective recombination centers. The oxidation of porous silicon can significantly modify its electronic structure, often enhancing PL intensity. Moreover, localized bandgap states caused by structural instability or contamination may contribute to the emission process. Typically, porous silicon exhibits broad visible photoluminescence spanning blue to red wavelengths, depending on the size and distribution of silicon nanocrystals within the pores. (Figure IV-5). Crystalline silicon has an indirect bandgap of 1.1 eV, and both chemical and electrochemical etching of silicon wafers can induce visible PL at room temperature. This emission is commonly associated with freestanding silicon quantum wires, in which two-dimensional quantum confinement increases the effective bandgap. As the etching duration increases, the porosity of the silicon layer grows, and the reduction in crystallite size can explain the observed shift of the PL spectrum toward shorter wavelengths (blue shift). Luminescence is also observed shortly after the formation of highly porous layers (~85% porosity). When erbium is incorporated into the porous silicon matrix, the silicon framework absorbs the excitation radiation and transfers the energy to the erbium ions, resulting in additional PL features characteristic of erbium transitions. This energy transfer process enhances the overall emission and provides opportunities for tailoring the optical properties of porous silicon for advanced optoelectronic applications [3].

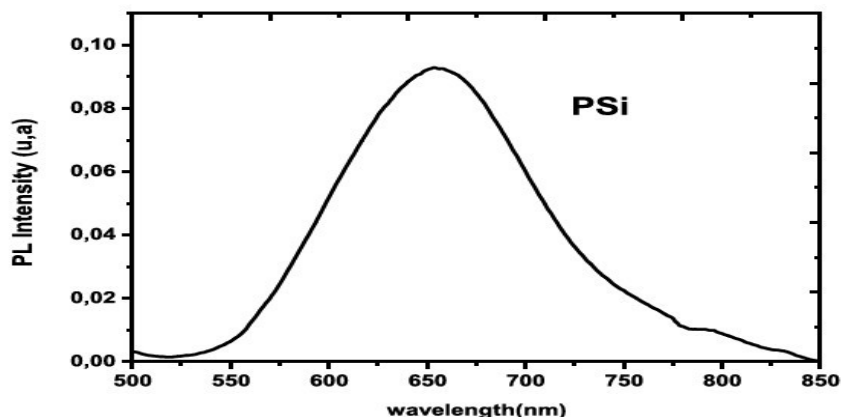


Figure IV.5. Photoluminescence spectrum of a p-type porous silicon layer fabricated on a (100) silicon substrate [3].

The increased surface area of porous silicon, combined with stronger coupling between the silicon matrix and erbium ions, results in a notable enhancement of photoluminescence intensity. In undoped porous silicon, however, PL mainly arises from quantum confinement effects that influence the electronic and optical behavior of silicon nanocrystals. This confinement increases the effective bandgap, promotes efficient radiative recombination, and enables strong visible photoluminescence. While quantum confinement is the dominant mechanism, surface states and structural defects also contribute to the emission. In erbium-doped porous silicon, the PL spectrum exhibits distinct peaks associated with erbium-related transitions, as shown in figure IV-6. The presence of erbium enhances emission in both the visible and near-infrared regions, increasing the overall PL intensity of the porous silicon layer. This enhancement is particularly evident in green and red emission bands under ultraviolet and near-infrared excitation, resulting in a more pronounced and unique PL spectrum compared to undoped samples. The interplay between quantum confinement in the silicon nanocrystals and the erbium-related emissions is critical for interpreting the observed PL spectra. The size and spatial distribution of silicon nanocrystals within the porous structure influence both the broad silicon emission and the sharper erbium-related peaks. Successful incorporation of erbium ions is indicated by the appearance of sharp PL peaks corresponding to erbium energy levels and by the overall increase in emission intensity. In particular, the green emission observed in the S4 spectrum of erbium-doped porous silicon (PSi:Er) is primarily driven by energy transfer from the silicon matrix to erbium ions, followed by successive

no-radiative decay from the upper $\Psi_{G11/2}$ level. Additionally, the $\Psi_{F4/2}$ state is populated through radiationless decay from the green-emitting $\Psi_{S3/2}$ level, with minor contributions from phonon-assisted cross-relaxation and energy transfer processes. Red emission arising from transitions between the $^4F_{3/2}$ and $^4F_{4/2}$ levels to the $^4I_{13/2}$ state also influences the dynamics of the $\Psi_{F4/2}$ level. According to the Stark sublevel diagrams for Er^{3+} -doped crystals provided by R. Kelai et al. and Méndez-Ramos J. et al., a significant Stark splitting effect around 550 nm must be considered. The resulting emission bands are broad due to the crystal field environment of erbium ions, overlapping with the intrinsic silicon emission bands. Finally, the rotational vibration observed around 550 nm during annealing is attributed to oxygen diffusion and its interaction with erbium within the porous silicon matrix. These combined effects demonstrate the complex interactions between quantum confinement, erbium doping, and the local chemical environment, which together define the unique photoluminescence properties of PSi:Er [3].

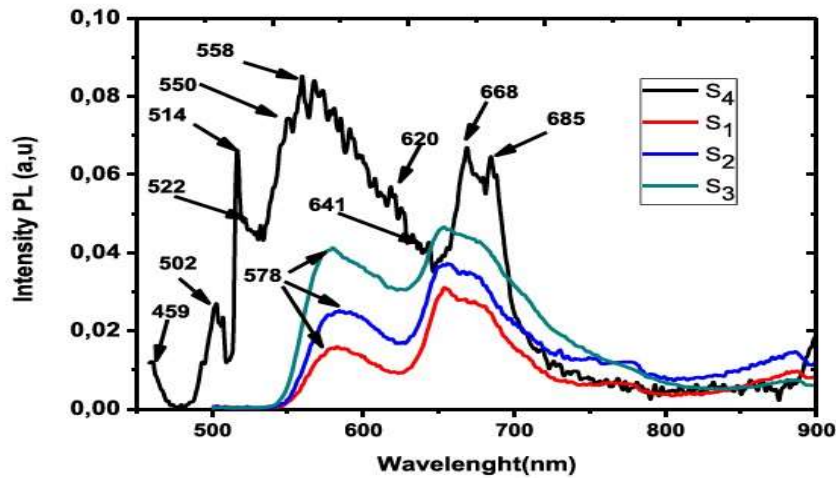


Figure IV.6 Photoluminescence emission spectrum of a porous silicon layer after infiltration with Er^{3+} ions [3].

IV-4-1-C Use only alternating current

All of the fabricated porous silicon (PS) samples (see Table 4) exhibited detectable photoluminescence (PL) at room temperature. Figure IV-7 presents the PL spectra of p-type PS samples prepared under varying etching current densities and etching durations. The data indicate that the PL intensity is strongly influenced by the applied current density, showing a clear proportional relationship. Specifically, the PL intensity increased markedly from 2.59 to 11.72 (a.u.) as the current density increased, reaching a maximum when the highest current density, $J_{\text{max}} = 20 \text{ mA/cm}^2$, was applied. This enhancement in PL intensity

can be attributed in part to the oxidation of porous silicon during the etching process. Oxygen incorporation into the porous layer breaks Si–H bonds and oxidizes the silicon crystallites, resulting in a shift of the PL spectrum toward higher energies, commonly referred to as a "blue shift." This observation is consistent with a quantum confinement effect, whereby the effective size of the silicon nanocrystallites is reduced. Structural analysis of the porous layer formed on p-type silicon wafers reveals a combination of spherical and cylindrical crystallites, indicating that the material consists of a mixture of quantum wires and quantum wells with varying sizes and concentrations. Ellipsometry measurements further confirm that increasing the anodization current density leads to a significant increase in porosity, ranging from 34.53% to 78.23%. Correspondingly, both the PL integrated intensity and the overall emission intensity increase with higher current densities (Figure IV-7), as summarized in table IV-4. Additionally, extending the etching time in conjunction with higher current densities further enhances the PL intensity of the porous silicon layers, demonstrating that both etching parameters play a critical role in controlling the optical properties of the material [2].

Table IV.4 he parameters derived from the recorded PL spectra under the applied operating conditions show good agreement with the theoretical curves corresponding to porous silicon samples formed at varying etch current densities and an etching time of 180 s [2].

Samples	Current Density (mA/ Cm2)	λ_{Peak} (nm)	FWHM (meV)	IPLMax (u, a)	Eg (eV)
S ₁	5	682	249	2.59	1.81
S ₂	10	665	210	4.12	1.87
S ₃	15	652	122	6.81	1.91
S ₄	20	655	111	11.72	1.90

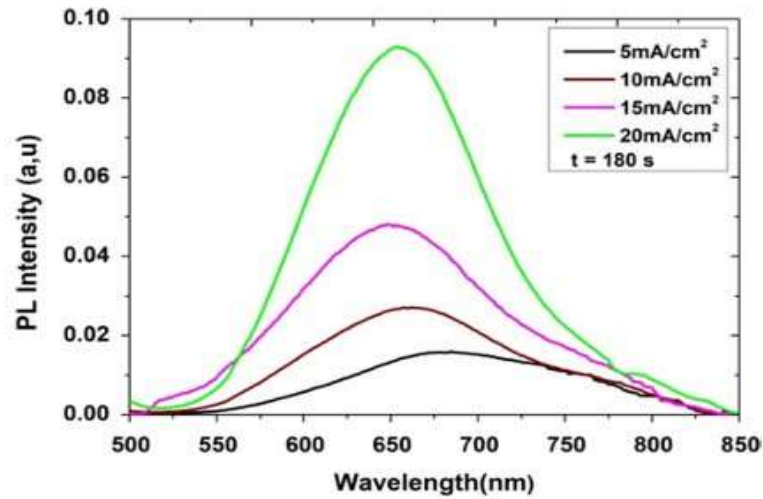


Figure IV.7 Changes in the photoluminescence response of p-type porous layers as a function of etch current density [2].

IV-4-1-D Evolution of Photoluminescence as a Function of Temperature in Porous Silicon Films

IV-4-1-D-1 Low-Temperature Photoluminescence Study

Low-temperature photoluminescence spectroscopy is a well-established experimental technique in condensed matter physics and materials science, providing detailed insight into the optical and electronic properties of solid-state materials. By analyzing the light emitted following photon excitation under controlled low-temperature conditions, this method enables the observation of radiative processes that are often masked at higher temperatures. The objectives of this study are to investigate the temperature-dependent evolution of the photoluminescence (PL) band, to identify and characterize the energy levels responsible for the emission, and to gain a deeper understanding of the radiative recombination mechanisms governing luminescence in porous silicon films. Particular attention is given to analyzing variations in both the PL intensity and the integrated PL intensity as a function of temperature over a range from 10 K to 300 K. The studied porous silicon sample was fabricated from an n-type silicon substrate with (100) orientation and used for all measurements. The sample was subjected to controlled experimental conditions, enabling a systematic evaluation of the influence of temperature on its photoluminescence behavior and the underlying recombination processes: $t = 3$ min, $j = 25$ mA/cm² [HF] = 20% (Figure IV-8 and IV-9) [1].

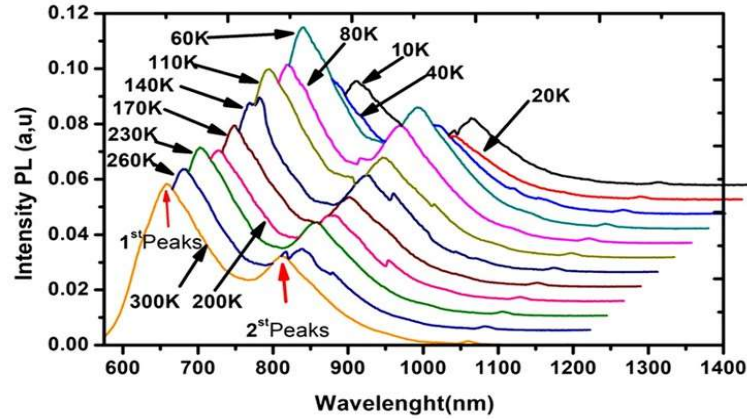


Figure IV.8 Porous silicon samples exhibit photoluminescence spectra with a type N(100) at 10K to 300K [1].

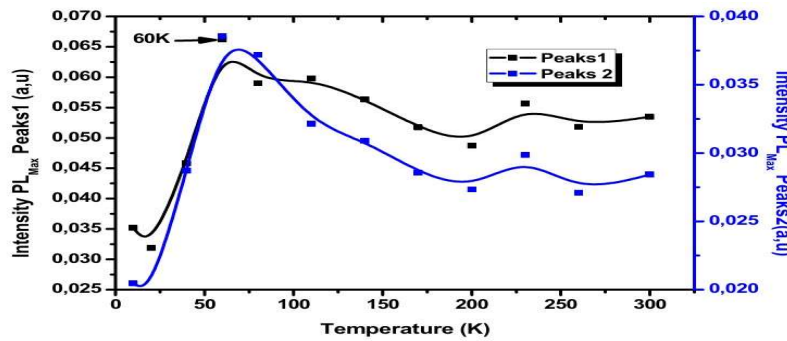


Figure IV.9 Temperature-dependent changes in the photoluminescence intensity of a PSi layer on an n-type (100) substrate [1].

IV-4-1-D-1-1 Correlation Between Temperature and Photoluminescence Intensities

Temperature variations have a significant influence on the photoluminescence (PL) spectrum of porous silicon, particularly on the peak wavelength and emission intensity. Spectral shifts in the PL emission are influenced by carrier–phonon coupling, thermal expansion, and quantum confinement-induced bandgap changes. Higher temperatures enhance non-radiative recombination via carrier thermal activation and surface-state trapping, leading to a reduction, or quenching, of PL intensity. At low temperatures, typically around 60 K, the PL spectra of porous silicon often exhibit sharper and more intense emission peaks due to reduced thermal broadening of energy levels. Enhanced spectral resolution permits precise characterization of emission energies arising from quantum confinement effects and other electronic transitions in the porous silicon structure. In addition, defect-related or impurity-induced emission peaks may become more

apparent at low temperatures, and their intensity and spectral position can vary with temperature. The excitation wavelength also plays an important role in determining the temperature-dependent PL response. Different excitation energies can selectively activate specific electronic states within the porous silicon matrix, resulting in temperature-dependent alterations in the observed photoluminescence spectra. Quantum confinement effects are especially pronounced in porous silicon nanostructures, where discrete energy levels emerge due to nanoscale dimensions. Temperature-dependent PL studies provide valuable insight into the behavior of these confined states and their contribution to light emission. Furthermore, when specific impurities are introduced into the n-type porous silicon substrate, Energy levels arising from dopants influence the photoluminescence spectrum of the material. Additional emission peaks may arise from electronic transitions involving these dopant states, and their presence can provide information about the type and degree of doping. Overall, PL spectroscopy serves as an effective tool for evaluating porous silicon structures, as it offers critical insight into their optical and electronic properties. At low temperatures, surface states, pore morphology, and surface functionalization play a particularly important role in shaping the PL characteristics. Variations in fabrication conditions, pore size distribution, and surface chemistry can strongly affect the emission behavior, highlighting the complex interplay between structural and electronic factors in porous silicon systems [1].

IV-4-1-D-1-2 Temperature-Dependent Evolution of Photoluminescence (PL) Intensity

Temperature variations have a pronounced effect on photoluminescence (PL) intensity in porous silicon. In general, the PL intensity decreases as temperature increases, mainly due to the increasing dominance of non-radiative recombination mechanisms that compete with radiative recombination at elevated temperatures. Because the observed changes in PL intensity are influenced not only by temperature but also by additional structural and material-related factors, this study examines the variation of PL intensity over a wide temperature range within a consistent experimental framework. The temperature dependence of PL intensity is closely related to the rates of charge carrier generation and recombination within the porous silicon lattice. At lower temperatures, radiative recombination processes are favored, leading to an enhancement in PL intensity. In contrast, at higher temperatures, With rising temperature, non-radiative pathways—such as thermal carrier excitation and recombination at surface states—become more pronounced,

resulting in PL quenching. The decrease in PL intensity with increasing temperature, particularly below 50 K, can be explained by the thermal activation of excitons to higher-energy non-radiative states. In the temperature range of approximately 50–60 K, The suppression of non-radiative processes leads to extended carrier lifetimes and more frequent radiative recombination, contributing to an increase in photoluminescence intensity. According to this model, excitons thermally migrate to lower-energy localized states, where they recombine radiative, producing stronger interband photoluminescence. Compared to room temperature (300 K), porous silicon typically exhibits significantly higher PL intensity at around 60 K. This enhancement is associated with reduced thermal broadening, longer carrier lifetimes, and a higher probability of radiative recombination. As a result, the PL emission peaks appear sharper and more pronounced at lower temperatures. However, the specific PL behavior at 60 K is strongly influenced by factors such as surface chemistry, pore size, fabrication conditions, and overall structural quality of the porous silicon layer. At higher temperatures ($T > 60$ K), Increasing thermal activation facilitates the conversion of confined excitons into free carriers, which can diffuse through the structure without undergoing radiative recombination. Consequently, the PL intensity decreases due to enhanced non-radiative recombination. At room temperature, increased thermal excitation further reduces PL intensity and leads to broader emission peaks. The PL intensity maximum observed in the corresponding figure occurs at a specific intermediate temperature, reflecting the balance between radiative and non-radiative recombination processes., $T_m = 60$ K [1].

IV-4-1-D-2 Variation of Photoluminescence Intensity with the Reciprocal of Temperature

Quantum confinement effects provide an effective means of modifying Energy gap of silicon in its porous nanostructured form. Within the porous matrix, the bandgap energy is strongly dependent on the size of the silicon nanocrystals; as the nanocrystal dimensions decrease, quantum confinement becomes more pronounced, leading to an increase in the effective bandgap energy. Variations in temperature, especially when considered in terms of reciprocal temperature, influence the bandgap energy and thereby modify the photoluminescence emission of the material. Previous studies by D. Zhao et al. and G. E. Weng et al. have identified two primary exciton transfer mechanisms that contribute to the temperature-dependent behavior of PL intensity. The first mechanism involves tunneling

transfer, which is effective even at relatively low temperatures. The second mechanism is associated with thermal dissociation, which becomes significant only at higher temperatures and is negligible at low temperatures. The coexistence of these two transfer processes provides a plausible explanation for the observed temperature dependence of PL intensity. It has been reported that temperature variation can enhance the tunneling process, as suggested by Ten et al., while thermal dissociation of excitons increases with rising temperature, as demonstrated by Jin Hua et al. This thermal dissociation promotes exciton migration from quantum dots (QDs) to quantum wells (QWs), which possess lower energy states. As a result, the balance between radiative and non-radiative recombination pathways is altered, affecting the overall PL intensity. In this study, the integrated PL intensity is plotted as a function of the reciprocal temperature, as shown in Figure IV-10. To interpret the experimental results, a two-energy-level model was employed to fit the observed behavior while accounting for both exciton transfer mechanisms. The corresponding analytical expression is given in equation (IV-1). The activation energies associated with the recombination processes were extracted by fitting the experimental data using OriginPro 8 software, based on the model proposed by G. Saint-Girons et al. This analysis provides valuable insight into the role of exciton dynamics and quantum confinement effects in governing the temperature-dependent photoluminescence of porous silicon [1].

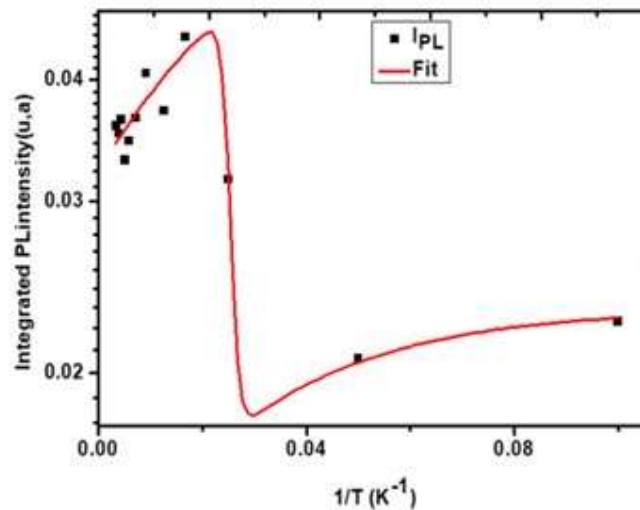


Figure IV.10 Temperature Dependence of the Integrated Photoluminescence Intensity Represented as a Function of the Reciprocal Temperature [1].

Table IV.5 The parameter values calculated from the corresponding equation [1].

Parameters	Values
I_{PL}	2.32 E-2
a_1	4.01 E-1
e_1	$36.60 \times 8.33 \text{ E-5} = 3050 \mu\text{eV}$
A	1.72
a_2	11.54 E14
e_2	$1205.84 \times 8.33 \text{ E-5} = 100440 \mu\text{eV}$

$$I_{pL}(T) = \left[I_{pL}(0) \frac{1}{1 + a_1 \exp\left(\frac{-e_1}{kT}\right)} \right] * \left[1 + A \frac{a_2 \exp\left(\frac{-e_2}{kT}\right)}{1 + a_2 \exp\left(\frac{-e_2}{kT}\right)} \right] \dots\dots\dots (IV.1)$$

Where the initial thermal activation energy is represented by the variable e_1 and the subsequent thermal activation energy is represented by the variable e_2 . Table IV-5 and figure IV-10 show the evolution of PL intensity values against the reciprocal of temperature $1/T$. The fitting parameters are A , a_1 , and a_2 . At elevated temperatures, the electrical properties of porous silicon, such as the effective bandgap and charge carrier mobility, may be modified, thereby influencing the recombination mechanisms responsible for photoluminescence. Increased atomic vibrations (phonons) and enhanced carrier diffusion can activate non-radiative recombination pathways, while a higher density of surface defects may act as trapping centers for excited carriers, leading to a reduction in PL intensity. Since the investigated sample is n-type, dopants and impurities also play a significant role in the observed photoluminescence behavior. At high concentrations, these impurities can promote non-radiative recombination processes, resulting in PL quenching. The inverse dependence of PL intensity on temperature is mainly attributed to the thermal activation of charge carriers. As temperature increases, carriers acquire sufficient thermal energy to overcome potential barriers and participate more effectively in non-radiative recombination, causing a decrease in PL intensity. The experimental results further indicate that different energy levels within the porous silicon structure exhibit distinct thermal activation energies. With increasing temperature, tunneling-assisted transfer mechanisms become more prominent, contributing to the observed PL behavior. Phonons in porous silicon are characterized by specific thermal activation energies and significantly affect carrier relaxation dynamics. Due to its nanoscale nature, porous silicon exhibits strong quantum confinement effects, where quantum wells predominantly contribute to low-energy emissions, while quantum dots play a major role in high-energy emissions. Each

confined structure is associated with different activation energies, reflecting their distinct recombination mechanisms [1].

IV-4-2 Morphological Studies

IV-4-2 A In the presence of a magnetic field.

The position, symmetry, pore arrangement, and homogeneity of porous silicon layers are strongly influenced by the applied magnetic field, as illustrated in figures IV-11 and IV-12. The magnetic field can modify both the growth direction and spatial distribution of nanopores, leading to a more uniform pore structure. In addition, the interaction between the magnetic field and the electrochemical etching process enables control over the pore morphology. The structural characteristics of the pores, such as size and depth, are determined by both the strength and orientation of the magnetic field applied during fabrication. Depending on the etching conditions, an increased magnetic field may either enhance or suppress pore enlargement. Figure IV-13 presents scanning electron microscopy cross-sectional images of porous silicon layers formed under different magnetic fields. At 0.7 T (Figure IV-13a), the pore depth ranges from 21.14 to 36.71 μm , as determined using Motic Plus software. When the magnetic field is increased to 0.9 T (Figure IV-13b), the pore depth increases to values between 26.63 and 42.88 μm . Pore diameters were observed to vary from 0.094 to 2.31 μm , owing to the influence of the magnetic field on the local electric field distribution during the fabrication process, which can enhance or reduce the etching rate in specific regions of the silicon substrate, thereby modifying pore depth and morphology [4].

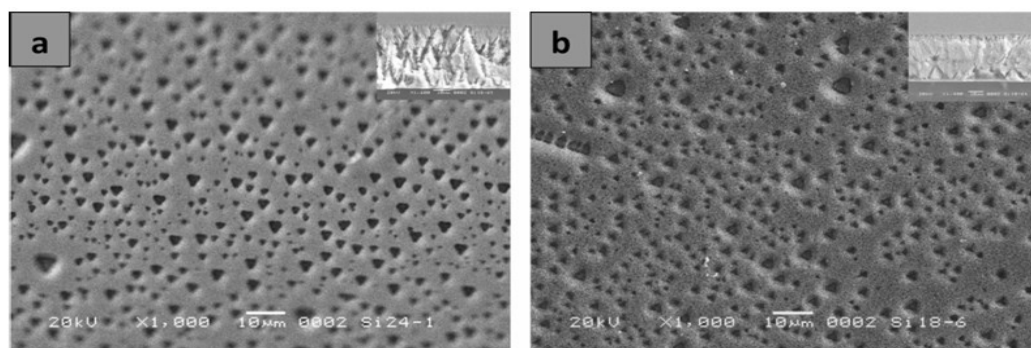


Figure IV.11 Morphology of porous silicon layers produced under magnetic fields of (a) 0.9 Tesla and (b) 0.7 Tesla [4].

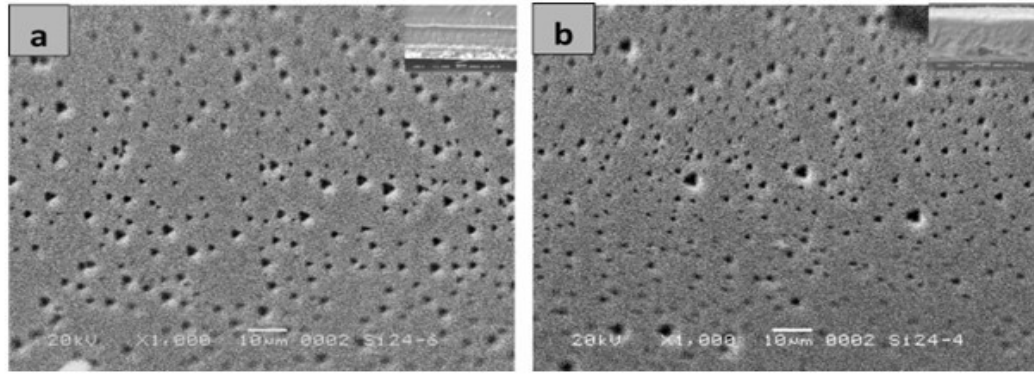


Figure IV.12 Morphology of porous silicon layers produced under magnetic fields of (a) 0.5 Tesla and (b) 0.3 Tesla [4].

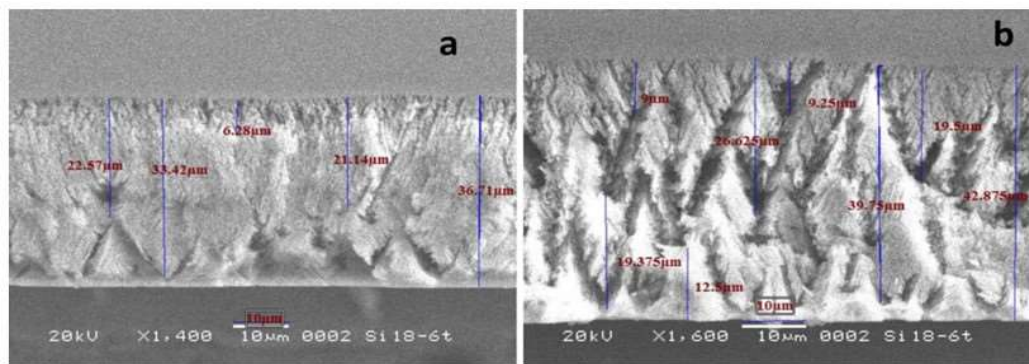


Figure IV.13 Morphology of porous silicon layer slices imaged by SEM under magnetic fields of (a) 0.7 Tesla and (b) 0.9 Tesla [4].

It is important to note that porosity is an average parameter and that different microstructures and pore morphologies can correspond to the same porosity value. In this work, porosity was controlled by adjusting both the anodization parameters listed in the table below and the applied magnetic field intensity. The porosity (P) of the porous silicon layers was determined using the gravimetric method, which evaluates the fraction of voids (air) within the nanocrystalline porous layer. This method is based on measuring the mass of the silicon sample before and after anodization, as well as after removal of the porous layer. The porosity was then calculated using the standard gravimetric equation:

$$P = \frac{m_1 - m_2}{m_1 - m_3} * 100 \dots\dots\dots (IV.2)$$

In the gravimetric method, m_3 represents the sample weight in potassium hydroxide (KOH) after the porous layer has been removed, while m_1 and m_2 correspond to the sample weight before and after anodization, respectively. The influence of the magnetic field on

ion mobility and charge carrier dynamics becomes more pronounced as the field intensity increases. As shown in figure IV-13, this can lead to an approximately linear relationship between porosity and magnetic field strength, with porosity rising as the field intensity increases.

The structural porosity is affected by both the current direction and the magnetic field orientation relative to the silicon surface. A magnetic field applied normal to the surface encourages the formation of vertically aligned pores, thereby increasing porosity. Additionally, the field can modify the spatial distribution of pores, producing a more uniform arrangement, and can influence pore size by deflecting moving charges via Lorentz forces during etching.

It is important to note that the relationship between magnetic field and porosity is strongly dependent on other etching parameters, including temperature, current density, and electrolyte composition. Optimizing these factors in combination with magnetic field strength is essential for achieving controlled and uniform porosity in porous silicon layers [4].

IV-4-2 B In the presence of Erbium ions

Silicon is a widely used material in semiconductor technology, and when processed to form a porous structure, it contains nanoscale pores or voids. Erbium, a rare-earth element, is extensively employed in photonics and optical applications due to its ability to enhance light emission. Incorporation of erbium ions into porous silicon can significantly modify its optical properties. The topographical changes induced by erbium infiltration are evident in scanning electron microscopy (SEM) images. Figure IV-14 depicts the uniform distribution of erbium ions and indicates whether concentration gradients are present. Scanning electron microscopy (SEM) characterization allows for the assessment of surface irregularities, which can significantly affect material properties such as optical behavior and carrier dynamics. Furthermore, SEM provides detailed information on the structure, spatial distribution, and interactions of erbium ions within the porous silicon matrix. Such microscopic analysis is crucial for understanding the physical characteristics of the material, optimizing fabrication protocols, and tailoring the properties of erbium-infiltrated porous silicon for targeted applications in optoelectronic and photonic devices [3].

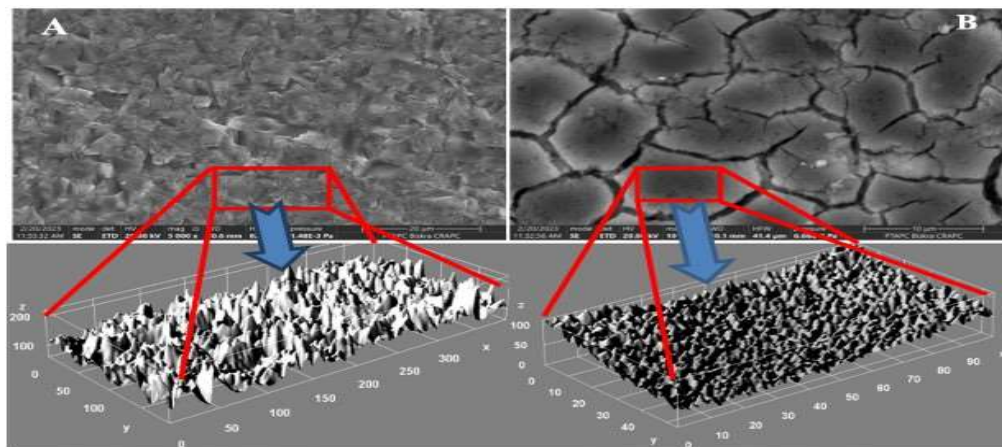


Figure IV.14 Scanning electron micrographs showing porous silicon layers (A) before and (B) after infiltration with erbium ions [3].

IV-4-2 C Use only alternating current

Scanning electron microscopy (SEM) is a key technique for analyzing the surface morphology of thin films, providing direct two-dimensional imaging of the surface as well as the ability to estimate average particle or pore sizes. Due to the adequate electrical conductivity of doped silicon, SEM is particularly well suited for observing and characterizing the structure of porous silicon layers [2].

Table IV.6 The various parameters correspond to the samples prepared with a 180 s etching time under different current densities [2].

Samples	Current density (mA/cm ²)	n	k	P (%)	α (cm ⁻¹)	d (μm)	(a) penetration factor (μm)	I _{PLMax} (u.a)
S ₁	5	1.77	0.0035	34.53	644.90	0.1162	15.5	2.59
S ₂	10	1.43	0.0022	61.45	415.72	0.6322	24.05	4.12
S ₃	15	1.33	0.0018	70.20	346.92	0.9058	28.82	6.81
S ₄	20	1.22	0.0014	78.23	268.59	1.2118	37.23	11.72

The porous silicon samples can be directly imaged by SEM without prior metallization. For detailed visualization of the pores, a field-emission SEM is required to achieve the necessary resolution. The front-view and cross-sectional SEM images (Figure IV-15) reveal that the fabricated samples possess a porous surface morphology, with a variety of pore sizes and depths.

Adjusting the anodization parameters allows control over the pore architecture, producing either straight, vertically aligned channels (Figure IV-15a) or more self-similar, scale-invariant structures (Figure IV-15b).

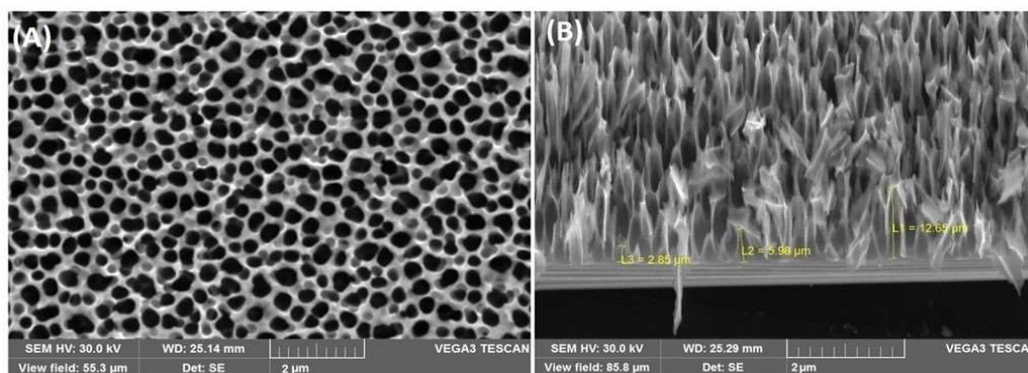


Figure IV.15 Front and cross-sectional SEM pictures of porous silicon grown on a Type P100 substrate [2].

The fabricated porous silicon films exhibit a clear accumulation of uniformly sized pores on their surface, providing a basis for characterizing the pore formation process. For p-type layers, increasing the anodization current leads to pore enlargement, consistent with the typical etching behavior observed in electropolishing (Figure IV-16). Both the depth [2].

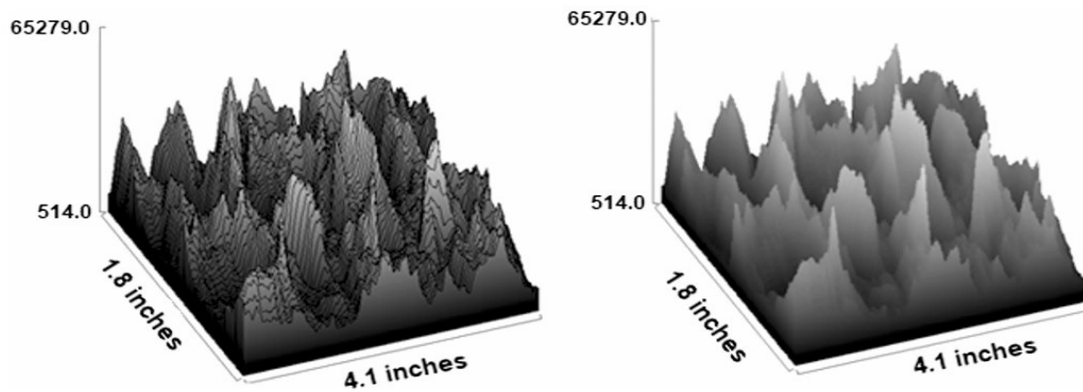


Figure IV.16 SEM photo study of the pore distribution on porous silicon produced from a P100 type substrate using Image-J software [2].

IV-4-2 D Effect of Temperature Variation on the Photoluminescence of Porous Silicon Films

Examination of porous silicon layer morphology on n-type (100) substrates provides valuable insights into the physical and structural properties of the material. Using advanced techniques such as scanning electron microscopy (SEM), the porous structure was successfully visualized at multiple scales, allowing assessment of surface topography and pore size distribution. The relationship between etching parameters and the resulting morphology offers insight into how fabrication conditions influence the formation of the porous network.

SEM images reveal that the nanoporous silicon layers possess a homogeneous structure with uniformly distributed pores across the film. The pores are oriented along the substrate's intended crystallographic direction (100). Variations in silicon doping concentration can affect both the width of the depletion region and the observed morphological features. The number and distribution of pores on the surface are also influenced by the silicon type (p- or n-type) and its resistivity. Representative SEM images are shown in figure IV-17 [1].

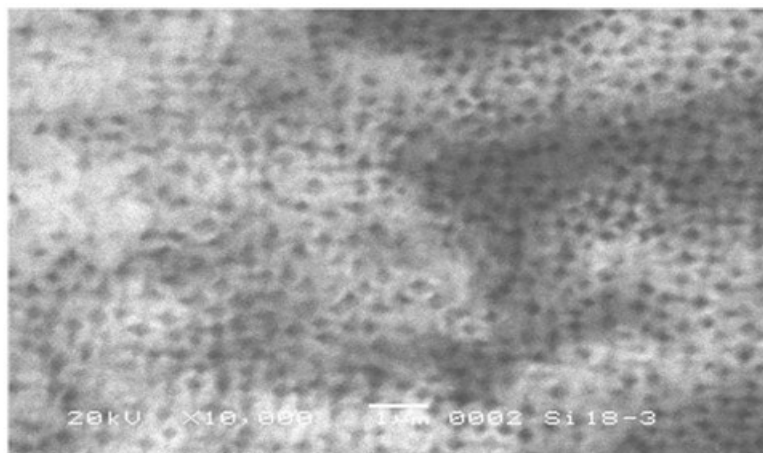


Figure IV.17 Morphological Characteristics of Porous Silicon on n-Type (100) Substrates observed by SEM [1].

Figures IV-18a and IV-18b show homogeneous, transparent nanopores with diameters in the nanometer range. Other porous silicon layers can exhibit varied morphologies due to differences in silicon–electrolyte contact, which generate a depletion region resembling a junction. In N-type nanoporous silicon, incident light can influence hole injection, with the intensity and carrier flow of the light controlling the injection process. The hole injection is primarily concentrated near the pore tips, which act as hole collectors, and this process affects the local pore widening. As a result, the pores expand uniformly and regularly during etching. Building on this structural understanding, our study next focused on examining the optical characteristics of these nanoporous silicon layers, particularly at low temperatures [1].

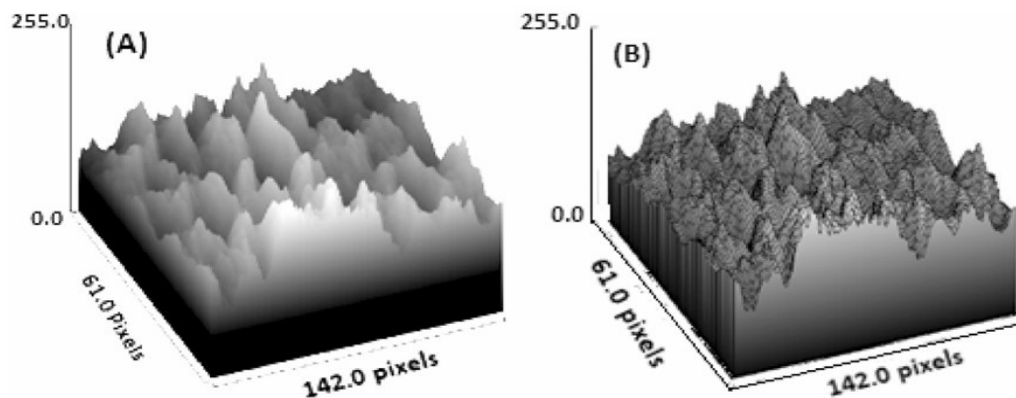


Figure IV.18. SEM-based evaluation of pore distribution in porous silicon prepared from an n-type (100) substrate, processed with ImageJ software: (A) smooth filter and (B) wireframe filter applied [1].

A comprehensive evaluation of the morphological and structural quality of the porous silicon layers was performed. Subsequent work may explore the relationship between morphological parameters and optical performance. The Full Width at Half Maximum (FWHM) of the PL emission spectrum, calculated from the primary peak of highest intensity, served as a quantitative measure of layer uniformity. As illustrated in figure IV-19, the FWHM remains nearly constant across different temperatures, reflecting the regularity and uniformity of the pores in the fabricated layers. A lower FWHM value indicates a more homogeneous material with a narrow size distribution, whereas a higher FWHM suggests a broader size distribution and reduced uniformity. This analysis confirms the high structural consistency of the produced porous silicon layer [1].

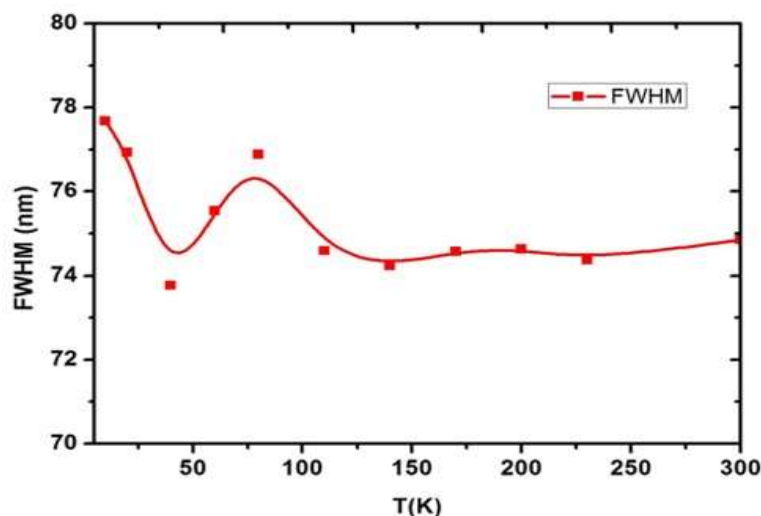


Figure IV.19 FWHM as a function of temperature[1].

IV-4-3 FTIR Characterization

IV-4-3 A In the presence of a magnetic field

Fourier transform infrared spectroscopy (FTIR) is a key tool for analysing the chemical composition of porous silicon layers. In samples fabricated from n-type (111) silicon wafers, FTIR reveals important details regarding surface oxidation, hydride groups, and bonding structures. The spectra reveal the vibrational modes of chemical species present on the porous silicon surface. Figure IV-20 shows the FTIR spectra of porous silicon layers prepared under different magnetic field intensities, plotted against wavenumber (cm^{-1}). A peak around 625 cm^{-1} corresponds to the Si–H wagging mode associated with surface Si–H bonds. The band between 490 and 520 cm^{-1} is attributed to Si–O bending vibrations, indicating the presence of silicon-oxygen bonds (SiO_2) formed during surface oxidation. A peak at 850 cm^{-1} arises from Si–O–Si bending vibrations, characteristic of initial oxidation. The broad band between 960 and 980 cm^{-1} is assigned to SiH_2 bending modes, while the peak at 1080 – 1225 cm^{-1} corresponds to the asymmetric stretching of Si–O–Si bonds, which intensifies with increased surface oxidation. Additionally, the bending mode of H–O–H is observed between 1615 and 1640 cm^{-1} , indicating adsorbed water or humidity. A broad band between 2850 and 2920 cm^{-1} is associated with C–H stretching, reflecting possible organic contaminants or residues from processing. Finally, the Si–OH stretching of hydroxyl groups, formed during partial oxidation, appears between 3205 and 3550 cm^{-1} .

This FTIR analysis provides comprehensive insight into the surface chemistry of porous silicon layers and highlights the influence of magnetic field intensity on chemical bonding and oxidation behavior [4].

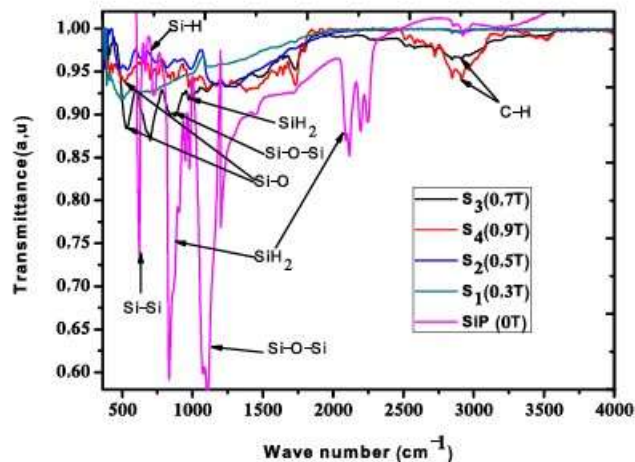


Figure IV.20 Porous silicon layers' FTIR spectra acquired in a magnetic field [4].

IV-4-3 B In the presence of Erbium ions

FTIR analysis can also be used to determine the chemical composition of materials and to identify specific bonds associated with erbium and porous silicon-related compounds. By examining the vibrational modes, FTIR provides insight into how the incorporation of erbium ions influences the structural and chemical characteristics of the porous silicon matrix. Figure IV-21 shows the FTIR spectra of erbium-infiltrated porous silicon (PSi) samples. A strong peak around 470 cm^{-1} corresponds to the Si–O–Er bond, indicating interaction between erbium ions and the silicon oxide network. Peaks at 1099 and 1121 cm^{-1} are attributed to Si–O–Si bonds, confirming the formation of surface oxide layers, while the peak at 1179 cm^{-1} corresponds to O–Si–O bonding. The broad band at $3480\text{--}3499\text{ cm}^{-1}$ is associated with Si–OH groups, and the broad absorption near 2050 cm^{-1} is linked to SiH₂ bonds. Absorption in the range of $1200\text{--}4000\text{ cm}^{-1}$ can be attributed to the surface activity of erbium oxide, which was annealed at $400\text{ }^{\circ}\text{C}$. The small size of the erbium oxide particles results in a high specific surface area, enhancing interactions with the porous silicon matrix. This analysis confirms the successful incorporation of erbium and its influence on the vibrational and chemical properties of the porous silicon structure [3].

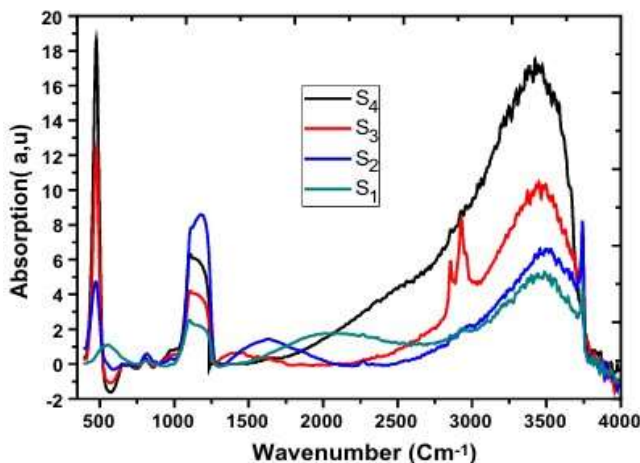


Figure IV.21 FTIR spectra of silicon samples (S1, S2, S3, and S4) acquired following infiltration with varying current densities [3].

IV-4-3 C Use only alternating current

Figure IV-22 presents the FTIR spectra of two porous silicon films fabricated at different current densities (10 and 15 mA/cm²). The spectra reveal three distinct absorption bands at 615 cm⁻¹, 905 cm⁻¹, and 2105 cm⁻¹, corresponding to Si-H₂ vibrations. The band at 1105 cm⁻¹ is attributed to the asymmetric stretching vibration of Si-O-Si. The intensity of both Si-O-Si and Si-H₂ bands increases with higher current density, indicating a correlation between the growth of porous silicon and hydrogen passivation. Additionally, a small peak at 2921 cm⁻¹ is observed, which corresponds to the asymmetric stretching mode of CH₂, likely arising from residual organic species [2].

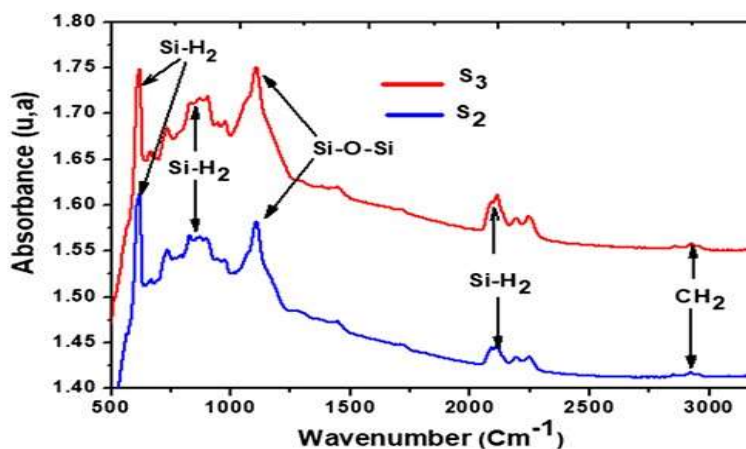


Figure IV.22 Porous silicon (PS) sheets' infrared spectra at various current densities (10, 15 mA/cm²). (2) [2].

IV-4-3 D Effect of Temperature Variation on the Photoluminescence of Porous Silicon Films

For the FTIR investigations, porous silicon films fabricated from single-crystal n-type (100) silicon substrates were utilized. The resulting FTIR spectrum, plotted as a function of wavenumber (cm^{-1}), is presented in figure IV-23. A prominent peak observed at 611 cm^{-1} is attributed to Si-Si bonding (bonding mode), while a broad band near 905 cm^{-1} corresponds to SiH_2 bonds (shear mode). Additionally, the peak at 1105 cm^{-1} is assigned to the Si-O-Si. Additionally, a broad band at 2108 cm^{-1} is associated with the SiH_2 bond (stretching mode). These features confirm the presence of surface hydrides and oxide formation on the porous silicon films, reflecting the chemical structure of the fabricated layers [1].

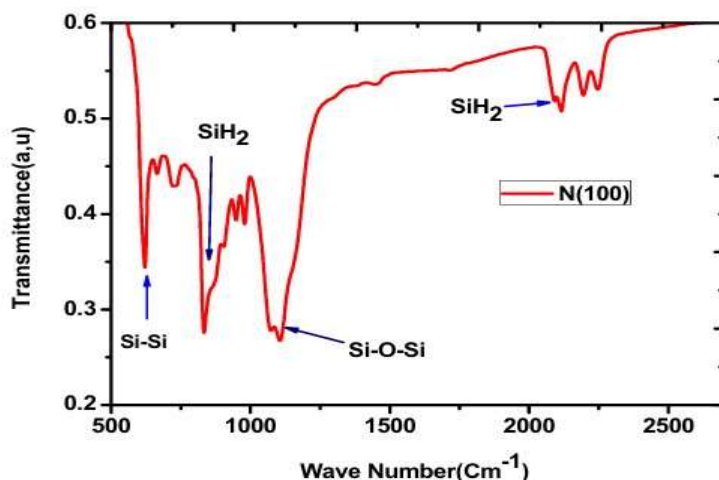


Figure IV.23 A porous silicon layer's FTIR spectrum [1].

IV-4-4 Characterization by XRD

X-ray diffraction (XRD) analysis was performed to investigate the crystal structure of porous silicon (PSi) layers before and after infiltration with erbium ions. This technique provides insights into structural alterations caused by erbium incorporation and allows identification of the various phases present in the material. By analyzing the XRD patterns, lattice parameters can be determined, crystallite size variations can be assessed, and the impact of erbium ions on the structural properties of PSi layers can be evaluated. Figure IV-24 presents the diffractograms of the studied samples. Sample S1 shows that the thin film crystallizes with a fraction of amorphous material, and four phases— $\text{Er}_2\text{Si}_2\text{O}_3$, Er_2O_3 , $\text{Er}_2\text{Si}_3\text{C}$, and $\text{Er}_2\text{Si}_2\text{O}_4$ —are observed, with Er_2O_3 identified as the predominant phase. Sample S2 exhibits three main phases: $\text{Er}_2\text{Si}_3\text{C}$, Er_2O_3 , and $\text{Er}_2\text{Si}_2\text{O}_3$, with $\text{Er}_2\text{Si}_2\text{O}_4$ being

dominant. Sample S3 shows four prominent peaks at 28.41° , 28.80° , 29.33° , and 47.50° , corresponding to Er_2O_3 , Er_2SiO_2 , $\text{Er}_2\text{Si}_2\text{O}_2$, and $\text{Er}_2\text{O}_3\text{C}_3$, respectively, with Er_2O_3 as the main phase. Sample S4 demonstrates five diffraction peaks at 28.47° , 28.86° , 29.35° , 47.56° , and 48.13° , corresponding to $\text{Er}_2\text{Si}_2\text{O}_4$, $\text{Er}_2\text{Si}_2\text{O}_2$, Er_2O_3 , $\text{Er}_2\text{Si}_3\text{C}$, and Er_3Si , with $\text{Er}_2\text{Si}_2\text{O}_4$ being the dominant phase. In all samples, the presence of amorphous material is noted, but samples S3 and S4 show highly crystalline structures. Overall, XRD results indicate that all samples consistently contain Er_2O_3 and $\text{Er}_2\text{Si}_2\text{O}_4$ phases in significant proportions, highlighting the stability of erbium oxide after infiltration. These findings, combined with FTIR analysis, reveal important details about the chemical composition, bonding interactions, crystallinity, and structural changes induced by erbium ions in porous silicon layers. Such information is essential for tailoring the material's properties for applications in optoelectronics and advanced materials science [3].

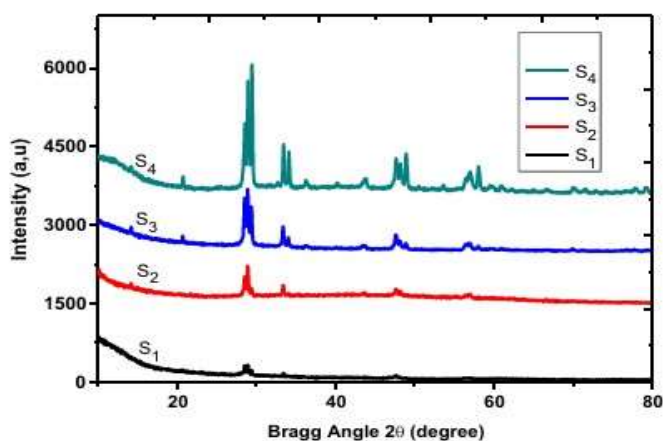


Figure IV.24 X-ray diffraction analysis of porous silicon (PSi) samples exhibiting varied current densities and erbium ion infiltration (samples S1 through S4) [3].

Table IV.7 X-ray diffraction analysis of porous silicon layers (S1–S4) after Er³⁺ infiltration, with each sample fabricated under distinct etching current conditions [3].

Samples	Phases	$2\theta_{exp}$	$2\theta_{hoe}$	$ 2\Delta\theta $	Intensity (u a)	phases Percentage (%)
S ₁	$Er_{2856}C_{3.24}Si_{15}$	28.4131	28.589	0.1759	340	27.22
S ₁	$Er_2Si_2O_7$	28.8018	28.921	0.1192	349	27.94
S ₁	Er_2O_3	29.3337	29.256	0.0777	428	34.26
S ₁	Er_5Si_3C	47.5013	47.548	0.0467	132	10.56
S ₂	Er_5Si_3C	28.4131	28.253	0.1601	907	36.31
S ₂	$Er_2Si_2O_7$	28.8222	28.921	0.0988	827	23.99
S ₂	Er_2O_3	29.3133	29.256	0.0573	1713	49.69
S ₃	$Er_{2856}C_{3.24}Si_{15.96}$	28.4335	28.589	0.155	1096	21.90
S ₃	$Er_2Si_2O_7$	28.8222	28.921	0.0988	1255	25.08
S ₃	Er_2O_3	29.2928	29.256	0.0368	1522	30.42
S ₃	Er_2SiO_5	33.3027	33.400	0.0973	1130	22.58
S ₄	$Er_{2856}C_{3.24}Si_{15.96}$	28.4744	28.589	0.1146	1507	11.18
S ₄	$Er_2Si_2O_7$	28.8623	28.921	0.0587	5509	40.88
S ₄	Er_2O_3	29.3542	29.256	0.0982	4921	36.52
S ₄	Er_5Si_3C	47.5626	47.548	0.0146	825	5.27
S ₄	Er_3Si_5	48.1355	48.114	0.0215	711	6.12

IV-5 Conclusion

Because of its advantageous physical and chemical properties, porous silicon (PSi) is a popular element for many different applications. Studying how magnetic fields impact the morphology of porous silicon layers and how these fields can alter the structural properties of porous silicon is an intriguing field. Pore size and surface morphology of porous silicon layers can be affected by the strength and direction of the magnetic field. It influences the etching process and pore formation by interacting with charged particles through the Lorentz force. The process can be accelerated or slowed down by the field, which can also change the wavelength and intensity of the light that is released. Examining how magnetic fields affect porous silicon layers may result in nanostructured materials with better characteristics.

Porous silicon (PSi) has recently attracted a lot of attention because of its unique optical and structural properties as well as its adaptability. Because of the importance of silicon, we have investigated the penetration of trivalent erbium ions (Er^{3+}) into silicon-generated holes using the electrochemical approach. The results showed that during the electrochemical reaction, photoluminescence emission in porous silicon, Er silicate, and Er oxide developed inside the silicon pores, creating an erbium-rich environment. Due to their exceptional optical characteristics, such as their long lifespan and distinct emission lines, rare earth ions were introduced. The study shows that because porous silicon has a wider energy gap than monocrystalline silicon, it provides an advantageous host matrix for Er complexes during the emission process. Higher Er^{3+} ion incorporation in porous silicon enhances luminosity. Understanding the behavior and possible uses of porous silicon films infused with rare earth ions depends on their optical characteristics. The results of the study provide a foundation for further investigation and development.

Conversely, we have investigated how etching current densities affect the optical characteristics of porous silicon sheets. The study intends to investigate chemical changes to enhance the material's physicochemical characteristics, possibly opening up possibilities in molecular separation, photovoltaics, and micro-energy. The penetration factor rose as a function of current density, whereas the absorption coefficient decreased as porosity increased. Furthermore, the results of this study indicate that the development of photovoltaic application layers has more potential.

Additionally, examining the temperature-dependent photoluminescence (PL) features of porous silicon (PSi), an intriguing material with special optical and electrical characteristics, may provide important insights into its behavior. We investigated the evolution of the PL band as a function of temperature in order to shed light on luminescence. In order to comprehend the characteristics of a porous silicon layer derived from an N-type silicon substrate, such as electronic structure and quantum confinement effects, researchers are examining the temperature-dependent behavior of the layer. Scientists can learn more about the special characteristics of porous silicon and its possible uses in optoelectronics and other domains by examining photoluminescence, electrical, and structural studies. The study intends to open up new avenues for investigation.

References

- [1] S. Rahmouni, H. Boubekri, H. Bendjeffal, H. Mamane, N. Boukhenoufa, I. Tifouti, B. Mariane, N. Nasri, L. Zighed, and R. Chtourou, “The temperature effect on the photoluminescence of porous silicon films obtained from an N-type silicon substrate,” *Silicon*, 2024. doi: 10.1007/s12633-024-02996-9.
- [2] S. Rahmouni, N. Boukhanoufa, I. Tifouti, H. Bendjeffal, and B. Mariane, “Influence of etching current density on the structural and optical properties of porous silicon films developed for photovoltaic applications,” *Silicon*, 2022. doi: 10.1007/s12633-022-02261-x.
- [3] D. Kehil, S. Rahmouni, N. Boukhenoufa, A. Djebli, H. Mamane, N. Nasri, and H. Bendjeffal, “Infiltration of Erbium ions (Er^{3+}) in porous silicon layer synthesized by electrochemical method: Structural and optical properties studies,” *Silicon*, 2024. doi:10.1007/s12633-024-03136-z.
- [4] N. Nasri, N. Boukhenoufa, S. Rahmouni, and H. Bendjeffal, “Morphological and structural investigation of porous silicon layers obtained under magnetic field,” *Silicon*, 2025. doi:10.1007/s12633-025-03242-6.
- [5] S. Rahmouni, Study, design, and fabrication of antireflection coatings for improving photovoltaic conversion, Ph.D. dissertation, University of 20 August 1955–Skikda, 2017.

General Conclusion

General Conclusion

General Conclusion

Our work has enabled us to identify the following points:

- We studied the effect of a magnetic field on the depth of the pores as a result of changes in the electric field it generates. The magnetic field induces shifts in these energy levels, altering the wavelength and intensity of the emitted light. Investigating the effects of magnetic fields on the morphology and properties of porous silicon layers represents a promising research area that could lead to significant advances in the production of nanomaterials with enhanced properties for diverse technological applications
- We studied the effect of Er^{3+} infiltration on porous silicon films, revealing that porous silicon is an advantageous host matrix for Er complexes in the emission process due to its wider energy gap compared to single-crystal silicon. The presence of pores allows for greater incorporation of Er^{3+} ions, potentially enhancing luminescence. The optical properties of porous silicon layers infiltrated with rare earth ions are essential for understanding their behavior and potential applications. These findings form the basis for future research and improvements.
- we investigated in this study the optical properties of porous silicon films fabricated on p-type Si(100) wafers using varying etching current densities. The results showed good agreement between PL and SE measurements for different etching times and current densities. The absorption coefficient decreased with increasing porosity, and the penetration factor increased with current density. We aimed to explore chemical surface modification to improve the material's physical and chemical properties, which could enable potential applications in photovoltaics, microenergy, and molecular separation.
- We studied the temperature-dependent photoluminescence (PL) properties of porous silicon films, focusing on time-resolved spectra recorded over a temperature range of 10–300 K. The study revealed that the main cause of photoluminescence emission in porous materials is primarily related to transitions across surface states. The choice of an N-type substrate and the concentration and type of dopant in both substrates can affect carrier mobility, density, and recombination rates, thereby impacting the photoluminescence intensity. This research may pave the way for future research in advanced optoelectronic physics and devices.



Morphological and Structural Investigation of Porous Silicon Layers Obtained under Magnetic Field

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Received: 15 October 2024 / Accepted: 31 January 2025
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Abstract

Due to its good physical and chemical properties, porous silicon (PSi) is a highly favored element for several applications. In this paper, we report an evaluation of the structural and morphological layers of porous silicon of a 111-oriented N-doped silicon substrate created via electrochemical etching under the effect of a magnetic field. The electrochemical technique enabled meticulous regulation of porous silicon characteristics, including average pore diameter range from 0.094 μm to 2.31 μm , average pore depths range between 21.14 μm and 42.87 μm , and porosity from 37.53 μm to 69.74%. The influence of the magnetic field on the morphological structure and optical properties of porous silicon layers was assessed using various analytical approaches, including the Fourier Transform Infrared (FTIR) spectroscopy, scanning Electron Microscopy (SEM), and (PL) spectroscopy. The impact of magnetic fields on the morphology of porous silicon layers is a compelling research subject investigating how magnetic fields can alter the structural properties of porous silicon.

Keywords Porous silicon · Magnetic field · Electrochemical etching · SEM · FTIR · PL

1 Introduction

Porous silicon (PSi) is distinguished by its modifiable microstructure and elevated surface area. Porous silicon has diamagnetic behavior, with the paramagnetic component altered by additional dangling bonds; hence, porosity significantly influences the material's magnetic characteristics [1]. The interaction between the magnetic field and the porous silicon layers can result in precise pore architecture and metal deposition alterations, enhancing the material's functional properties and facilitating novel technological applications. Research indicates that the magnetic field can alter the configuration and dimensions of magnetic nanostructures embedded in porous silicon, influencing their magnetic responses [2]. It can also be noted that the superconductivity associated with quantum nanostructures of silicon leads to increased magnetic permeability, a property absent in porous

silicon [3]. It is also worth noting that porous silicon, especially microporous silicon, has been the subject of extensive research, especially concerning electrical conductivity, photoluminescence, electroluminescence, photovoltaics, optoelectronics [4–6], thermal [7] and mechanical [8]. The investigation of the essential mechanisms by which magnetic fields affect the structure and morphology of porous silicon layers must not be overlooked. Comprehensive investigations of quantum confinement effects with magnetic interactions might enhance understanding of the underlying physical phenomena, paving the path for novel optoelectronic applications and memory devices [9–11]. The researchers applied a perpendicular magnetic field to the silicon sample during oxidation. This process created lateral dendritic porous *p*-Si structures. This process led to the deposition of nickel in these templates, which produced compounds with increased coercive strength and magnetic anisotropy, indicating that magnetic field-assisted etching can improve both the structural and magnetic properties of *p*-Si/Ni composites [12]. A novel synthesis route involved doping silicon with manganese atoms through ion implantation and anodization to create *p*-Si. This method successfully induced magnetic properties in the *p*-Si, suggesting potential applications in magnetic sensing and data storage [13]. Combining luminescent *p*-Si with ferromagnetic nickel aimed to modify both

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photoluminescence and magnetic properties. The study found that incorporating nickel nanostructures into *p*-Si matrices influenced the material's magnetic characteristics, which could be beneficial for developing multifunctional optoelectronic devices [14]. Investigations into the impact of magnetic fields during the formation of macroporous silicon revealed changes in structural and optical properties. Applying a magnetic field during electrochemical etching affected pore morphology and distribution, influencing the material's optical behavior [15].

The distinct structural characteristics of porous silicon render it appropriate for various electrical applications [16], including its utilization as an anode in lithium-ion batteries. Moreover, porous silicon is utilized in gettering techniques to remove impurities from electronic devices' active portions, improving their performance and dependability [17]. The pronounced photoluminescence shown by porous silicon has facilitated its implementation in various photonic technologies, including optical waveguides, distributed Bragg reflectors, and photonic crystals [18]. This enables us to assert that porous silicon is a multifaceted material in photonics. Examining magnetic fields on the structure and morphology of porous silicon layers offers multiple prospects for future research. Our aim is to produce porous silicon using a magnetic field, which likely focuses on exploring how the magnetic field affects the properties, structure, or fabrication process of the porous silicon. This could include Altering pore size, morphology, or distribution, enhancing the material's electronic, optical, or mechanical properties, and investigating new techniques or mechanisms to control the

formation process. Furthermore, advancing novel synthesis strategies for fabricating sophisticated magnetic nanostructures within silicon matrices is imperative. Contemporary techniques like electrochemical deposition and atomic layer deposition provide avenues for integration but could improve by investigating innovative fabrication processes that reduce harm to the fragile porous silicon architecture while enhancing magnetic characteristics.

2 Experimental Section

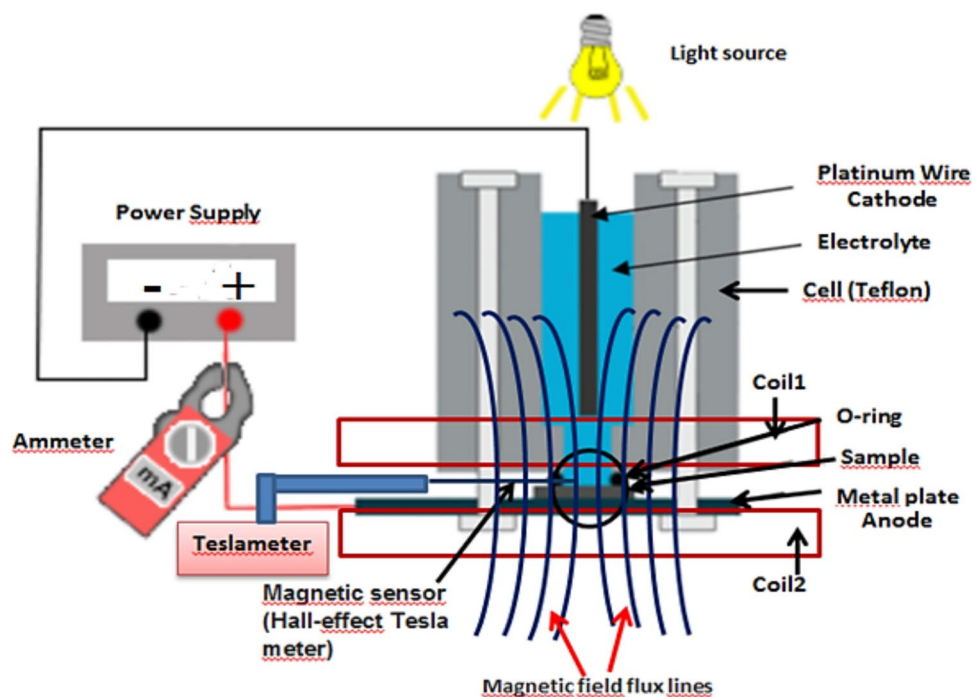
2.1 Cleaning Procedure of Si Substrates

The Si substrates (1 cm/1 cm) were carefully cleansed in accordance with a well-defined protocol before the preparation of PSi samples. They were cleaned with a commercial detergent at 50 ± 1 °C for 15 min, followed by a wash with deionized water in an ultrasonic bath and subsequent immersion in ethanol at 50 ± 1 °C for 15 min. After being cleansed with acetone and deionised water, the substrates were dried in a vacuum at 100 °C for 90 min. Lastly, the substrate samples were subjected to a dry nitrogen gas flow prior to each experiment.

2.2 Preparation of Porous Silicon Samples

This study utilized N-type Si(111) with a resistivity of 0.75 Ωcm as a single crystal to manufacture PSi structures. Figure 1 illustrates the experimental configuration of the etching

Fig. 1 Detailed diagram of the applied electrochemical cell to produce PSi layers under a magnetic field



procedure. A Teflon cell, equipped with an O-ring and a metal plate, contained the sample and electrolyte during the etching procedure. The silicon sample was positioned between the O-ring and the metal plate (Fig. 2). The front edge of the sample was placed in contact with the electrolyte, comprising a 1:1 volumetric combination of HF and ethanol. This electrolyte has been frequently utilized to produce PSi. The platinum wire functioned as the cathode during the etching process, whereas the metal plate served as the anode. The existing supply is sourced from a voltage generator, and an incandescent lamp lit the specimen during the etching procedure to create holes optically; the conditions used are gathered in Table 1. Measuring the magnetic field is a technically challenging endeavor. It is essential to define the specific magnetic field of interest. The telemeter, featuring a resolution of 0.01mT, facilitates the measurement of the magnetic field generated during electromagnetic research involving coils. The package includes a Hall effect probe, a stand rod, and a display console, including a digital display. All samples were characterized by utilizing scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and photoluminescence (PL). Photoluminescence (PL) spectroscopy experiments were conducted at ambient temperature utilizing a *JobinYvon* 250 mmHR monochromator paired with a GaAs photomultiplier, employing a conventional lock-in procedure. A laser power of 7.66 mW was delivered to the sample's surface, and the

photoluminescence (PL) spectrums were performed using a solid-state laser at 447 nm as an excitation wavelength. The Bruker Optics VERTEX 80 FTIR spectrometer was utilized to determine chemical compositions and bonding.

3 Results and Discussions

3.1 Morphological Study

Figures 3 and 4 illustrate that the magnetic field strength can affect the uniformity of the resultant layers and the pores' location, symmetry, and configuration. The spatial distribution of pores can be altered, and nanopores' orientation and development direction in porous silicon can be influenced to achieve a more uniform distribution. The interaction between a magnetic field and porous silicon layers can result in regulated alterations to the pore structure. The intensity and orientation of the magnetic field may affect the pore size. A powerful magnetic field can diminish or augment pore size, contingent upon the particular synthesis conditions.

Figure 5 shows a scanning electron microscope image of a slice of a porous layer obtained under a magnetic field. Figure 5(a) shows a cross-section of a porous layer created in a 0.7 Tesla magnetic field. MOTIC PLUS software indicates that the pore depths range from 21.14 μm to 36.71 μm . Figure 5(b) shows a porous layer created in a 0.9 Tesla magnetic field. MOTIC PLUS measurements indicate that the pore depths range from 26.625 μm to 42.875 μm , with an average pore diameter range from 0.094 μm to 2.31 μm .

The magnetic field can modify the distribution of the electric field during etching. This alteration can augment or diminish the electric field in certain silicon areas, consequently affecting the depth of the pores. The augmented electric fields may facilitate more profound etching in

Table 1 Forming conditions for the samples used

Samples	[HF]%	J(mA/cm ²)	t(m)	B(Tesla)	P%
S1	20	50	5	0.3	37.53
S2	20	50	5	0.5	43.58
S3	20	50	5	0.7	58.82
S4	20	50	5	0.9	69.74



Fig. 2 Photograph of the complete experimental setup

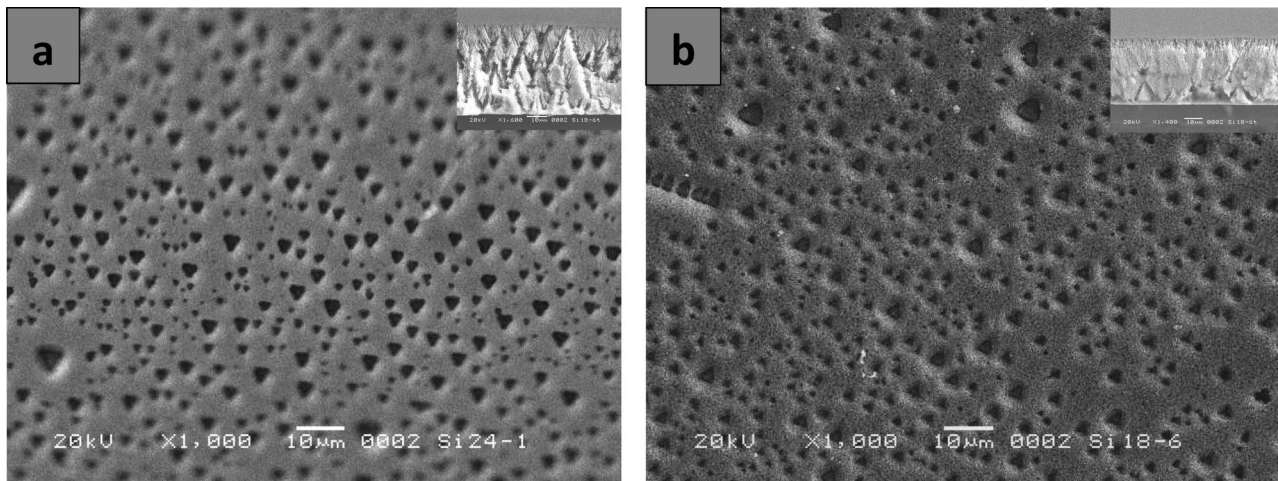


Fig. 3 Porous layer obtained: (a) with 0.9 Tesla and (b) using 0.7 Tesla

Fig. 4 Porous layer obtained: (a) with 0.5 Tesla and (b) using 0.3 Tesla

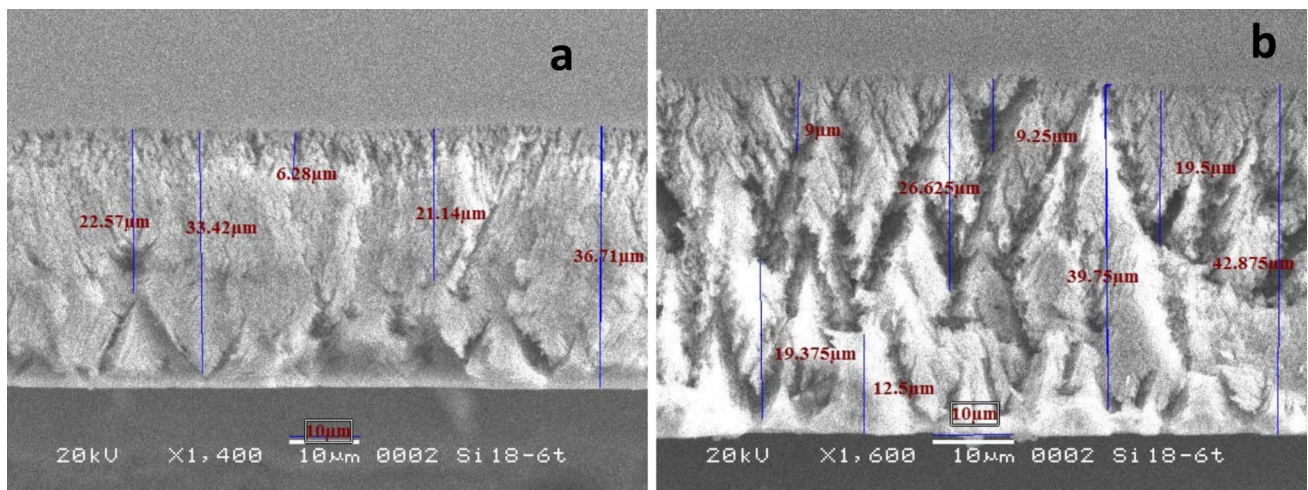
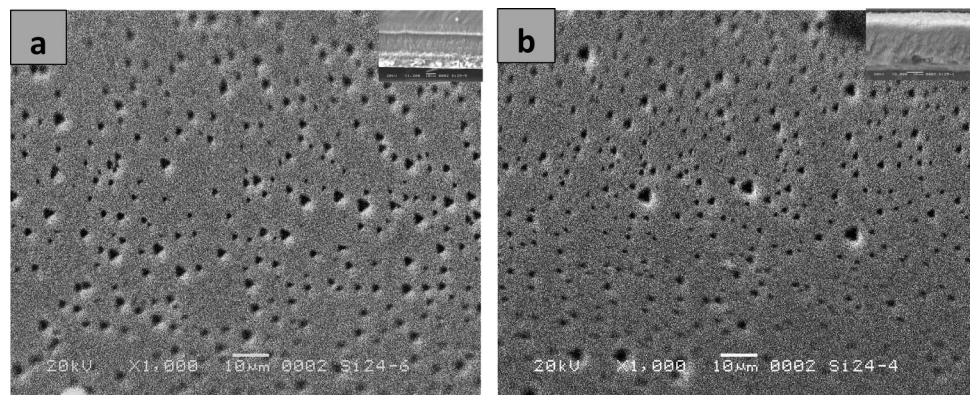


Fig. 5 SEM photograph of a slice of a porous layer obtained under a magnetic field of (a) 0.7 Tesla and (b) 0.9 Tesla

specific regions, resulting in deeper pores. The identical field-induced effect on ion transport in the electrolyte and variations in the local concentration of etching species on the silicon surface influence pore depth. Efficient ion transport results in deeper pores, whereas hindered transport results in shallower pores [19]. As influenced by the magnetic field, porosity can exhibit intricate variations based on its effects on charge carrier dynamics, etching rates, mass transport, and anisotropy in pore formation. It is essential to recognize that porosity is an average measurement and that varying material morphologies can be achieved with the same porosity level [20]. In our study, we employed the anodizing parameters listed in the table below in conjunction with the fluctuation in magnetic field density. Porosity (P) is ascertained by the gravimetric approach, utilizing the relationship [21], wherein P is defined as the ratio of voids (air) present within the nanocrystalline porous layer. The porosity is ascertained by the gravimetric approach utilizing the connection:

$$P = \frac{m_1 - m_2}{m_1 - m_3} \times 100 \quad (1)$$

where m_1 and m_2 denote the sample weight before and after anodization, respectively, m_3 symbolizes the sample weight after stripping off the porous layer in potash (KOH).

As the field strength escalates for each sample, the impact on charge carrier dynamics and ion mobility becomes increasingly evident. This may result in a linear correlation between magnetic field strength and porosity, with porosity augmenting as field strength increases, as illustrated in Fig. 6. The alignment of the magnetic field concerning the silicon surface and the current flow direction may influence porosity. Applying a perpendicular field to the surface can facilitate the development of vertical pores,

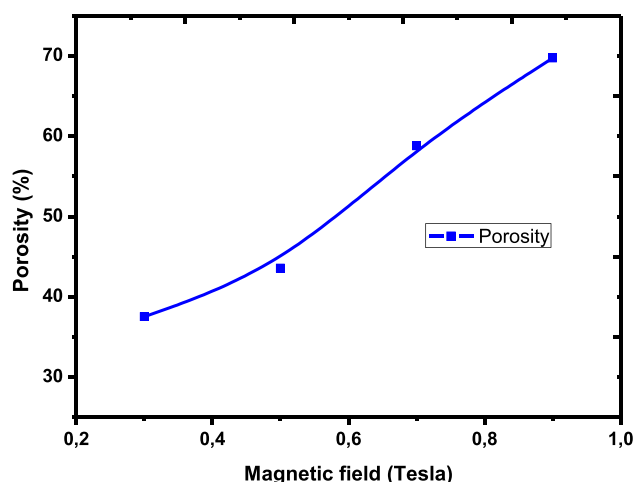


Fig. 6 Variation of porosity according to magnetic field

thereby enhancing porosity, as demonstrated in our study. It is important to note that the spatial distribution of pores can be modified in the presence of a magnetic field. Pores may be more uniformly distributed. The magnitude and direction of the magnetic field can also affect the size of the pores. Charges moving within the material can be deflected by Lorentz forces, affecting the formation of pores. All these elements can affect the porosity of layers formed under a magnetic field. Certain etching parameters, such as electrolyte composition, current density, and temperature, significantly influence the correlation between magnetic field and porosity. Optimizing these parameters alongside the magnetic field is essential for attaining optimal porosity.

3.2 PL Measurements

This work seeks to investigate the evolution of the PL band's magnetic field, clarify the energy levels' features linked to this photoluminescence (PL), and understand the radiative recombination mechanisms involved [5]. The inquiry concentrated on analyzing the variations in intensity and the aggregate intensity of the magnetic field. It can be said that the field influences the photoluminescence spectrum either on the intensity or the shift of the PL spectrum, as shown in

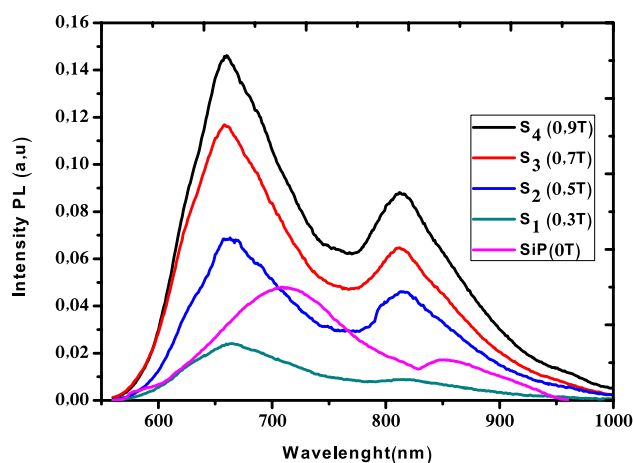


Fig. 7 Evolution of photoluminescence spectra of the as-obtained N-type porous layers fabricated at different magnetic field densities

Table 2 Positioning of peaks on the wavelength of the photoluminescence spectra

Samples	B(Tesla)	Peak1 (nm)	Peak2 (nm)
S ₁	0.3	665	820
S ₂	0.5	662	814
S ₃	0.7	658	810
S ₄	0.9	660	812

Fig. 7. We notice a variation in the intensity and shift of the peaks, as shown in the following Table 2.

Porous silicon's photoluminescence spectrum (peak1) offers critical insights into the material's electrical structure and energy levels [22]. Doping the N-type substrate with particular impurities might introduce dopant-related energy levels that contribute to the photoluminescence (PL) emission spectrum, as observed in our samples (peak 2). These supplementary peaks in the PL spectra arise from energy transitions involving dopant states within the porous silicon structure. The existence of these states can indicate the degree of doping and the specific dopants employed.

Figure 7 shows that the energy levels of electrons and holes in silicon nanostructures can split in the presence of a magnetic field due to the Zeeman effect. This splitting can change the recombination rates of electrons and holes, influencing the photoluminescence spectrum. The magnetic field can change the carrier dynamics (mobility, recombination, and diffusion) in porous silicon. Depending on the field strength and direction, it can change the radiative and non-radiative recombination rate, potentially enhancing or quenching the photoluminescence. The magnetic field can affect the spin states of the charge carriers (electrons and holes). Spin flip processes, where the magnetic field causes a change in the spin of an electron or hole, can impact the recombination processes, thereby influencing the photoluminescence. Finally, Quantum confinement in porous silicon creates discrete energy levels for electrons and holes. A magnetic field can cause these energy levels to shift, changing the wavelength and intensity of the emitted light.

3.3 FTIR Characterization

Fourier transform infrared spectroscopy (FTIR) is widely used to characterize porous silicon (PS) layers, especially to identify surface chemical species and bonding structures. For porous silicon layers grown from N(111) silicon substrates, FTIR can provide crucial information on the oxidation state, surface hydrides, and other chemical bonds on the porous silicon surface. FTIR spectra are collected to detect the chemical species' vibrational modes on the porous silicon's surface.

The FTIR spectra obtained according to the wave number m (in cm^{-1}) are presented in Fig. 8 of the porous silicon layers obtained from a monocrystalline silicon substrate of type N(111) under a magnetic field of different intensities. The spectra are marked by the presence of a peak around 625 cm^{-1} associated with the Si-H bond (wagging) concerning the Si-H surface bonds (Si-H wagging vibrations) [21]. A band is observed around $(490 \text{ to } 520) \text{ cm}^{-1}$, that of a Si-O bond (bending), due to the silicon-oxygen bonds in SiO_2 [23–25], often formed by surface oxidation. The peak around 850 cm^{-1} is due to Si-O-Si bonding (bonding) due

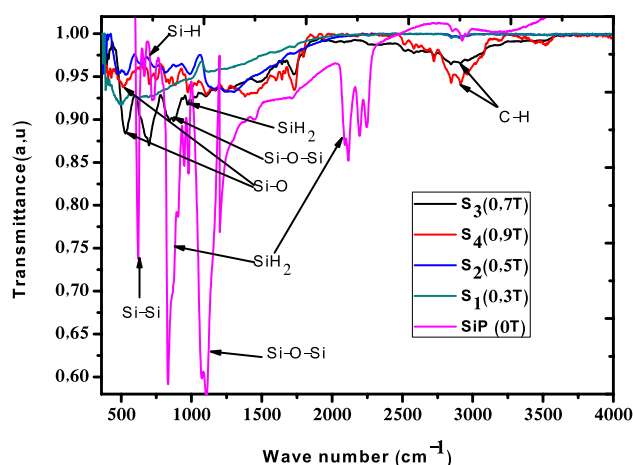


Fig. 8 FTIR spectrum of porous silicon layers obtained under magnetic field

to the bending of the silicon-oxygen bond associated with initial oxidation. A peak around $(1080 \text{ to } 1225) \text{ cm}^{-1}$ (asymmetric stretching) due to the stretching mode of Si-O-Si bonds [26, 27], increasing with surface oxidation, leading to the formation of oxide on the surface and a noisy band at $(960 \text{ to } 980) \text{ cm}^{-1}$ confirmed refers to SiH_2 bonding (bending modes) surface hydride species [28, 29]. From $(1615 \text{ to } 1640) \text{ cm}^{-1}$ (adsorbed water), H-O-H bending related to adsorbed water or humidity. A noisy band around $(2850 \text{ to } 2920) \text{ cm}^{-1}$ is associated with C-H stretching (organic contaminants) and potential organic residues from processing or the environment. From $(3205 \text{ to } 3550) \text{ cm}^{-1}$, we note the Si-OH stretching hydroxyl groups from partial oxidation.

4 Conclusion

We aim to successfully produce porous silicon layers by employing a magnetic field as an extra anodizing parameter and to analyze their characteristics for potential applications in renewable energy. All endeavors focus on enhancing the efficiency of PSi solar cells and their application in the optoelectronic domain. The intensity and orientation of the magnetic field may affect the pore size. The magnetic field interacts with moving charged particles (ions and electrons) via the Lorentz force. The magnetic field can significantly impact the surface morphology of the etched material by influencing the dynamics of charged species and the uniformity of the etching process. The magnetic field can either accelerate or decelerate the etching process by modifying photogenerated carriers' transport and recombination rates. The magnetic field can help align the growth of pores along specific crystallographic directions or influence their size distribution by controlling the local electric field and ion dynamics. The

magnetic field affects pore depth due to variations in the electric field generated by the magnetic field. The magnetic field induces shifts in these energy levels, altering the wavelength and intensity of the emitted light. Investigating magnetic fields' effects on the morphological structure and optical characteristics of porous silicon layers represents a promising research domain that may yield substantial progress in producing nanostructured materials with enhanced properties for diverse technological applications.

Acknowledgements We thank the Algerian MESRS Ministry for its support.

Author Contributions Nihal Nasri, Noureddine Boukhanoufa, and Salah Rahmouni, Conceptualization, Methodology and Investigation, Hacene Bendjeffal writing-Original draft, Reviewing and Editing.

Funding Not applicable.

Data Availability No datasets were generated or analysed during the current study.

Declarations This work's authors confirm that this study's results do not involve humans or animals in this work.

Ethics Approval The work described in this publication has not been impacted by any known conflicting financial interests or personal relationships.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

References

- Rumpf K, Granitzer P (2014) Diamagnetic behavior of porous silicon. In: Canham L (ed) Handbook of porous silicon. Springer, Cham. https://doi.org/10.1007/978-3-319-05744-6_29
- Zulkifli F, Radzali R, Abd Rahim AF, Mahmood A, Mohd Razali NS, Abu Bakar A (2022) Influence of different etching methods on the structural properties of porous silicon. *Microelectron Int* 39(3):101–109. <https://doi.org/10.1108/MI-01-2022-0009>
- Bagraev NT, Gehlhoff W, Klyachkin LE, Malyarenko AM, Romanov VV, Rykov SA (2006) Superconductivity in silicon nanostructures. *Phys C* 437:21–24. <https://doi.org/10.1016/j.physc.2005.12.011>
- Rahmouni S, Boukhanoufa N, Tifouti I et al (2023) Influence of etching current density on the structural and optical properties of porous silicon films developed for photovoltaic applications. *Silicon* 15:3261–3268. <https://doi.org/10.1007/s12633-022-02261-x>
- Rahmouni S, boubekri H, Bendjeffal H et al (2024) The temperature effect on the photoluminescence of porous silicon films obtained from an N-type silicon substrate. *SILICON*. <https://doi.org/10.1007/s12633-024-02996-9>
- Ram SK (2018) Electrical transport in porous silicon. *Handbook of Porous Silicon*. Springer, Cham, p. 263–79
- Zhao Y, Yang L, Kong L, Nai MH, Liu D, Wu J et al (2017) Ultralow thermal conductivity of single-crystalline porous silicon nanowires. *Adv Func Mater* 27(40):1702824. <https://doi.org/10.1002/adfm.201702824>
- Canham L (2018) mechanical properties of porous silicon. In: Canham LT (ed) Handbook of porous silicon. Springer, Cham, pp 213–220
- Granitzer P, Rumpf K (2015) Physical properties of semiconducting/magnetic nanocomposites. *Front Mater* 2:4. <https://doi.org/10.3389/fmats.2015.00004>
- Granitzer P, Rumpf K (2020) Metal filled nanostructured silicon with respect to magnetic and optical properties. *Front Phys* 8. <https://doi.org/10.3389/fphy.2020.00121>
- Issaadi HK, Baouz T, Levesque A, Douglad J, Rehamnia R, Chopart JP (2024) Effect of applied magnetic field on ZnFe alloy electrodeposition. *J Indian Chem Soc* 101226. <https://doi.org/10.1016/j.jics.2024.101226>
- Granitzer P, Rumpf K, Ohta T et al (2012) Porous silicon/Ni composites of high coercivity due to magnetic field-assisted etching. *Nanoscale Res Lett* 7:384. <https://doi.org/10.1186/1556-276X-7-384>
- Aouassa M, Jadli I, Zrir MA et al (2017) Fabrication and characterization of magnetic porous silicon with curie temperature above room temperature. *J Porous Mater* 24:1139–1144. <https://doi.org/10.1007/s10934-016-0353-2>
- Granitzer P, Rumpf K, Poelt P, Reissner M (2019) Magnetic characteristics of Ni-filled luminescent porous silicon. *Front Chem* 7:41. <https://doi.org/10.3389/fchem.2019.00041>
- Antúnez EE, Estevez JO, Campos J, Basurto M, Agarwal V et al (2013) Effect of magnetic field on the formation of macroporous silicon: structural and optical properties. *MRS Online Proceedings Library (OPL)* 1617:63–68. <https://doi.org/10.1557/opl.2013.1165>
- Kehil D, Rahmouni S, Boukhenoufa N et al (2024) Infiltration of Erbium ions (Er³⁺) in porous silicon layer synthesized by electrochemical method: structural and optical properties studies. *SILICON*. <https://doi.org/10.1007/s12633-024-03136-z>
- Karbassian F (2018) Porous silicon: porosity - process, technologies and applications. *Intechopen*. <https://doi.org/10.5772/intechopen.72910>
- Mourdikoudis S, Pallares RM, Thanh NTK (2018) Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties. *Nanoscale* 10(27):12871–12934. <https://doi.org/10.1039/c8nr02278j>
- Rumpf K, Granitzer P, Hilscher G, Albu M, Poelt P (2012) Magnetically interacting low dimensional Ni-nanostructures within porous silicon. *Microelectron Eng* 90(C):83–87
- Gille Lerondel (1997) Propagation de la lumière dans le silicium poreux application photonique. (Thèse de doctorat) université Joseph Fourier –Gronoble I, p 9–13–15
- Bisi O, Ossicini S, Pavesi L (2000) Porous silicon: a quantum sponge structure for silicon based optoelectronics. *Surf Sci Rep* 38(1–3):1–126. [https://doi.org/10.1016/S0167-5729\(99\)00012-6](https://doi.org/10.1016/S0167-5729(99)00012-6)
- Egeberg RC, Veje E, Da Silva AF, Pepe I, Alves AS (2000) The energy-band structure of porous silicon studied with photoluminescence excitation and photoacoustic spectroscopy. *J Porous Mater* 7:173–176. <https://doi.org/10.1023/A:1009674401781>
- Arce RD, Koropecski RR, Olmos G, Gennaro AM, Schmidt JA (2006) Photoinduced phenomena in nanostructured porous silicon. *Thin Solid Films* 510(1–2):169–174. <https://doi.org/10.1016/j.tsf.2005.08.376>
- Zhao Y, Yang D, Li D, Jiang M (2005) Annealing and amorphous silicon passivation of porous silicon with blue light emission. *Appl Surf Sci* 252:1065–1069. <https://doi.org/10.1016/j.apsusc.2005.01.176>
- Pap AE, Kordás K, George TF, Leppävuori S (2004) Thermal oxidation of porous silicon: study on reaction kinetics. *J Phys Chem B* 108:12744–12747. <https://doi.org/10.1021/jp049323y>

26. Pong KL, Chen SC, Cheah KW (1996) Photoluminescence of laser ablated silicon. *Solid State Commun* 99:887–890. [https://doi.org/10.1016/0038-1098\(96\)00336-5](https://doi.org/10.1016/0038-1098(96)00336-5)
27. Dimova – Malinovska D (2000) Application of stain etched porous silicon in c-Si solar cells. *Optoelectron Rev* 8:353–355
28. Ruiz F, Vazquez-Lopez C, Gonzalez-Hernandez J et al (1994) Mesostructure of Photoluminescent porous silicon. *J Vac Sci Technol A Vacuum, Surfaces, Film* 12:2565–2571
29. Koropecski RR, Arce R (1986) Infrared study of the kinetics of oxidation in porous amorphous silicon. *J Appl Phys* 60(5):1802–1807. <https://doi.org/10.1063/1.337223>

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