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Advancements in Passivation and Metallization Techniques for n-Type Monocrystalline Silicon Solar Cells

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ABSTRACT

Crystalline n-type silicon (n-Si) solar cells are emerging as promising candidates to overcome the efficiency limitations of current p-type technologies, such as PERC cells. This article explores recent advances in passivation and metallisation techniques for monocrystalline n-Si solar cells, focusing on their impact on improving conversion efficiency and reducing manufacturing costs. The paper begins with a discussion of the importance of base material quality for n-Si cells.

The impact of metallic impurities, oxide precipitates and thermal donors on minority carrier lifetime is analysed, as well as n-type silicon purification and passivation strategies, such as gettering. Next, the paper explores different contact passivation technologies, including silicon heterojunctions (SHJs), poly-Si and tunnel oxide TOPCon/POLO contacts, and metal oxide and organic compound contacts. The performance, advantages and manufacturing challenges of each technology are compared and discussed. Metallization techniques such as silver screen printing and more cost-effective and sustainable alternatives such as screen printing and copper plating are also examined. The impact of plating technologies on the performance of bifacial cells is also discussed. The paper then looks at n-Si bifacial solar cells and their potential to increase the energy efficiency of PV systems. Different bifacial cell concepts and their performance under real-world conditions are discussed, as well as the challenges and opportunities for their future development. Silicon-based tandem and multifunction solar cells are presented as a promising way to overcome the efficiency limits of single-junction cells. Perovskite-silicon tandems and III-V/silicon tandems, with their respective advantages and challenges, are examined in detail. Finally, the article discusses the economic and environmental aspects of n-type PV technologies,

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including cost of ownership (COO), discounted cost of energy (LCOE) and life cycle assessment (LCA). The importance of improving efficiency and reducing material use for the economic viability and sustainability of n-Si solar cells is highlighted. In conclusion, the paper highlights the crucial role of n-Si solar cells for the energy transition and highlights the opportunities and challenges for their development and large-scale deployment in the future.

التقدم في تقنيات التخميل والتعدين للخلايا الشمسية السليكونية أحادية البلورية من النوع n.

ملخص: تظهر الخلايا الشمسية المجردة من النوع n المصنوعة من السيليكون (n-Si) كمرشحين واعدين للتغلب على قيود الكفاءة في تقنيات النوع p الحالية، مثل خلايا PERC. تستكشف هذه المقالة التطورات الحديثة في تقنيات التخميل والتعدين للخلايا الشمسية أحادية البلورية n-Si، مع التركيز على تأثيرها على تحسين كفاءة التحويل وتقليل تكاليف التصنيع.
يتم أيضًا فحص تقنيات المعدنة مثل طباعة الشبكة الفضية والبدائل الأكثر فعالية من حيث التكلفة والاستدامة مثل طباعة الشبكة وطلاء النحاس. وتناقش أيضا تأثير تقنيات الطلاء على أداء الخلايا ثنائية الوجه. ثم تتناول الورقة الخلايا الشمسية ثنائية الجانب n-Si وقدرتها على زيادة كفاءة استخدام القدرة في المنظومة الكهروضوئية. تتم مناقشة المفاهيم المختلفة للخلايا ثنائية الجانب وأدائها في ظل الظروف الحقيقية، بالإضافة إلى التحديات والفرص لتطويرها في المستقبل. يتم تقديم الخلايا الشمسية من نوع Tandem ومتعددة الوظائف القائمة على السيليكون كوسيلة واعدة للتغلب على حدود كفاءة الخلايا أحادية الوصلة. يتم فحص ترادفات البيروفسكايت والسيليكون وترادفات III-V /السيليكون، مع مزاياها وتحدياتها، بالتفصيل. أخيرًا، يناقش المقال الجوانب الاقتصادية والبيئية للتقنيات الكهروضوئية من النوع n، بما في ذلك تكلفة الملكية (COO)، وتكلفة الطاقة المخفضة (LCOE)، وتقييم دورة الحياة (LCA). يتم تسليط الضوء على أهمية تحسين الكفاءة وتقليل استخدام المواد من أجل الجدوى الاقتصادية والاستدامة للخلايا الشمسية n-Si. وفي الختام، تسلط الورقة الضوء على الدور الحاسم للخلايا الشمسية n-Si في تحول الطاقة وتسلط الضوء على الفرص والتحديات لتطويرها ونشرها على نطاق واسع في المستقبل.

الكلمات المفتاحية – الخلايا الشمسية من النوع n، التخميل، التعدين، الكفاءة، التكلفة، التصنيع.

1. INTRODUCTION

The transition to renewable energy sources has become a global priority to combat climate change and ensure a sustainable energy future. Among the various renewable energy technologies, solar Photovoltaics (PV) is playing an increasingly important role thanks to its ability to convert sunlight directly into electricity, providing a clean and abundant source of energy.

Crystalline silicon (c-Si) solar cells currently dominate the PV market, accounting for over 95% of global production [1]. However, p-type (p-Si) c-Si cell technologies, such as passive emitter back-contact (PERC) cells, are approaching their theoretical efficiency limits [2]. In addition, the growing demand for high performance PV modules for applications such as bifacial systems, high power density installations and perovskite-silicon tandems requires more efficient cell technologies. In this context, n-type silicon (n-Si) solar cells are emerging as promising candidates for overcoming the efficiency limitations of current p-type technologies. N-Si cells have several intrinsic advantages over their p-type counterparts, including:

Superior electronic properties: n-Si cells have a higher minority carrier (hole) lifetime than p-Si cells, leading to higher open circuit voltages (Voc) and fill factors (FF), and therefore higher conversion efficiency [3].

Improved defect tolerance: n-Si cells are less susceptible to light-induced degradation (LID) related to boron-oxygen defects, a common problem in p-Si cells [4].

Higher efficiency potential: n-Si cells have a higher theoretical efficiency potential than p-Si cells, paving the way for significant performance improvements [2].

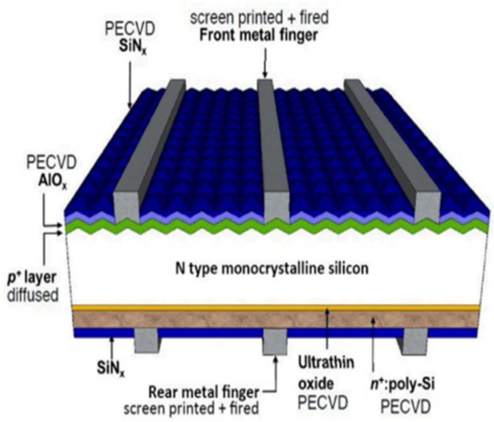

Figure 1. A schematic image of an n-Si solar cell with a description of its different layers [5].

In recent years, considerable progress has been made in the development of high-performance n-Si solar cell technologies. Advances in contact passivation techniques, such as silicon heterojunctions (SHJs) [6] and Topcon/POLO contacts [7], have resulted in n-Si cell efficiencies in excess of 26%[8]. In addition, n-Si cells have been shown to be particularly suitable for bifacial cell designs, further increasing the energy efficiency of PV systems [9].
However, despite these promising advances, the large-scale manufacture of n-Si cells still presents challenges, including:
Cost of base material: n-Si wafers are generally more expensive than p-Si wafers due to the complexity of the manufacturing process.
Process complexity: Some n-Si cell technologies, such as SHJs, require more complex and expensive manufacturing processes than PERC cells.
Silver consumption: n-Si cells often use more silver for metallisation, which increases their cost and raises sustainability issues.
To overcome these challenges, ongoing research and development efforts are needed to improve efficiency, reduce manufacturing costs and minimise the environmental impact of n-Si solar cells.

2. PROPERTIES OF N-TYPE SILICON MATERIALS

The performance of n-type silicon (n-Si) solar cells is highly dependent on the quality of the base material, specifically the silicon substrate. This chapter explores key aspects of n-Si material properties, focusing on the impact of impurities and defects on solar cell efficiency, as well as material characterisation and purification methods.

2.1. Importance of the quality of the base material (substrate) for solar cell performance

The n-type silicon used for solar cells is generally obtained by the Czochralski (Cz) process [10]. The quality of the Cz material is influenced by a number of factors, including the purity of the starting silicon, ingot growth conditions and the presence of impurities and defects.
• **Silicon purity:** The presence of metallic impurities, even at low concentrations, can degrade the lifetime of minority carriers and therefore the efficiency of solar cells [3]. The use of high-purity silicon is therefore essential for optimum performance.
• **Ingot growth:** Ingot growth parameters, such as pulling speed and temperature gradient, influence the distribution of impurities and the formation of defects [10]. Controlled ingot growth is necessary to obtain a homogeneous, high-quality material.

• **Defects:** Crystalline defects, such as dislocations and stacking faults, can also act as recombination centres and reduce the efficiency of solar cells [11]. Minimising defect density is therefore an important objective for the manufacture of high-performance n-Si cells.
Table 1. This table shows the coefficients of severance to the equilibrium of the main dopants in silicon, highlighting the challenge associated with gallium and phosphorus doping.

Table 1. Main dopants' optimal segregation coefficients in Si.

Element	**k0**
Boron	0.8
Gallium	0.008
Aluminium	0.002
Indium	0.0004
Phosphorus	0.35
Arsenic	0.3
Antimony	0.023

Figure 2 demonstrates how the performance of high-efficiency solar cells can be impacted by transition metals, even at concentrations as low as 1 108 cm^3. Such diluted faults cannot be found using standard defect spectroscopy methods like For standard solar cell materials, deep level transient spectroscopy (DLTS) has a sensitivity limit of 1~1010 cm~3 (about 1~105 cm~3 below the doping). However, these materials affect efficiency and can be detected (albeit not identified) using lifetime spectroscopy[12].

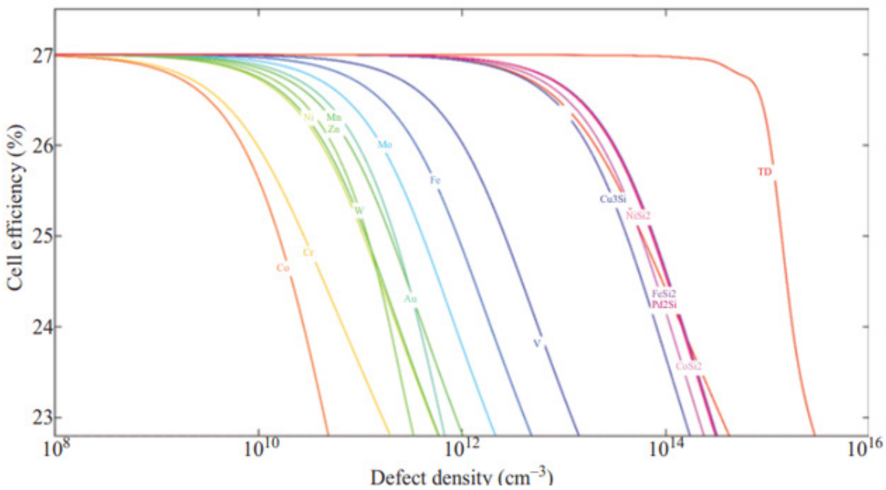

Figure 2. Cell efficiency in relation to the number of impurity defects[12].

2.2. Impact of metallic impurities, oxide precipitates and thermal donors on minority carrier lifetime and cell efficiency

Metallic impurities: Metallic impurities, such as iron (Fe), chromium (Cr) and nickel (Ni), introduce deep energy levels into the silicon bandgap, which promotes carrier recombination and reduces minority carrier lifetime [3]. The impact of metallic impurities on n-Si cells is generally less significant than on p-Si cells, but remains a limiting factor for efficiency [13]. The minority carrier lifespan in an n-type ingot following five regrowth is depicted in Figure 3.
Following repeated regrowth toward sub-ms lifetimes, the minority lifetime deteriorates. Along the ingot, the lifetime also declines.

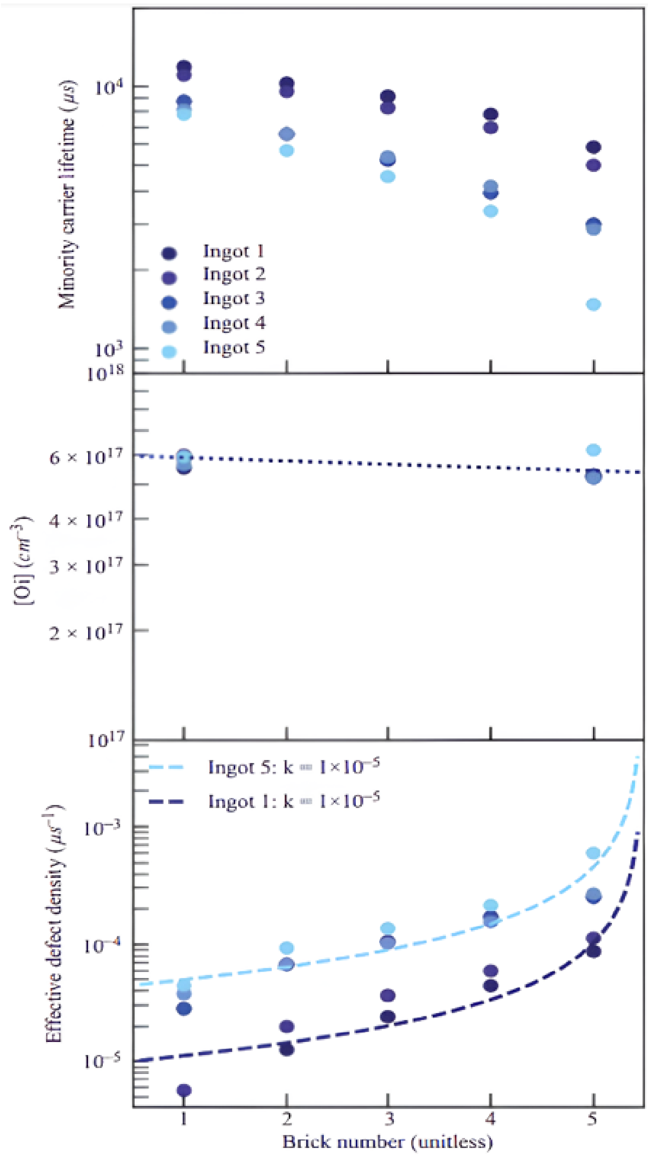

Figure 3. shows the effective defect density, interstitial oxygen concentration, and minority carrier lifespan in an n-type ingot after five recharges[12].

Oxide precipitates: Interstitial oxygen present in silicon Cz can aggregate and form oxide precipitates during ingot cooling or heat treatment of solar cells. These precipitates can act as recombination centres and reduce carrier lifetime [14]. Managing oxygen concentration and minimising precipitate formation are therefore essential for n-Si cells.

Thermal donors: Thermal donors are oxygen defects that form during the heat treatment of silicon at moderate temperatures (350-500°C) [15]. They can influence the resistivity of the material and, at high concentrations, degrade the lifetime of the carriers, thus affecting the efficiency of solar cells [15].

2.3. Techniques for characterising defects and material quality

A variety of characterisation techniques are used to assess the quality of n-Si material and identify any defects present. The most commonly used methods include:

• Carrier lifetime spectroscopy (CLS): This technique measures the lifetime of minority carriers in silicon, providing a direct indication of the quality of the material and the impact of defects [16].

• Photoluminescence spectroscopy (PL): PL detects defects and impurities in silicon by analysing the light emission spectrum of the material [17].
• Transmission electron microscopy (TEM): TEM is used to visualise the microstructure of silicon and identify crystalline defects, such as dislocations and oxide precipitates [18].
• Fourier transform infrared absorption spectroscopy (FTIR) : FTIR is used to determine the concentration of oxygen and carbon in silicon [19].

2.4. Purification and passivation methods for n-type silicon (e.g. gettering)

• Gettering is a technique used to remove metallic impurities from silicon by attracting them to specific areas where they have less impact on solar cell performance [20]. Various gettering methods exist, including :
• Gettering by phosphorus diffusion: High-temperature phosphorus diffusion creates a highly doped zone that acts as a gettering sink for metallic impurities [21].
• Gettering by ion implantation: Ion implantation of phosphorus or boron can also be used to create gettering wells [22].
• Gettering by dielectric layers: Dielectric layers, such as silicon nitride (SiNx) and aluminium oxide (AlOx), can also act as gettering wells for metallic impurities [23].

3. CONTACT PASSIVATION TECHNOLOGIES

Surface and interface passivation is crucial for minimising recombination losses in solar cells, thereby contributing to improved conversion efficiency. This chapter explores the different contact passivation technologies available for n-type silicon (n-Si) solar cells, focusing on their operating principles, performance and manufacturing challenges. As shown in Figure 4, a summary diagram shows the various architectural structures of n-type silicon solar cells. This diagram illustrates the technological progress made in the field of contact passivation for these solar cells.

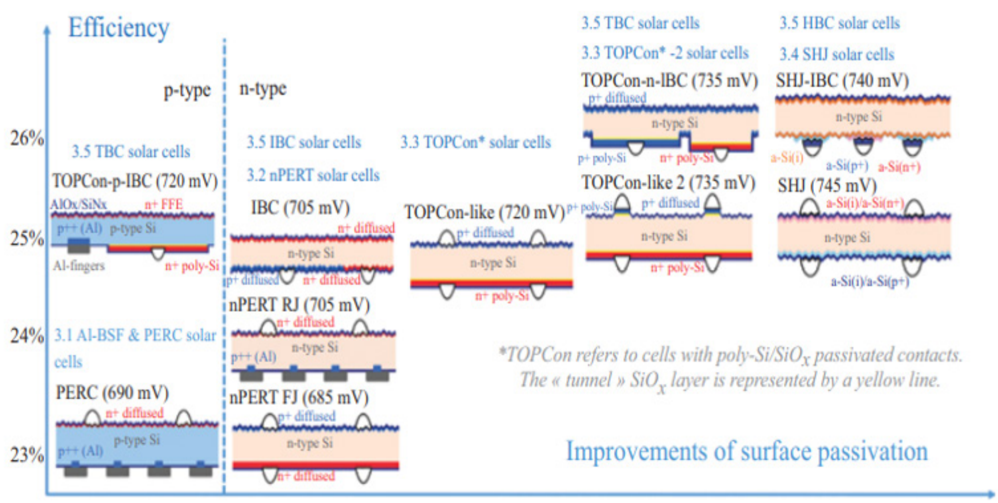

Figure 4. Diagrammatic illustrations of the many solar cell technologies discussed in this chapter. The advances in surface passivation are represented by the x-axis. With respect to the conversion efficiency, the y-axis[12].

3.1. Importance of surface and interface passivation to minimise recombination losses

The surfaces and interfaces of solar cells are areas where the crystalline structure of silicon is interrupted, creating defects and surface states that act as recombination centres for charge carriers (electrons and holes) [24]. Carrier recombination reduces the lifetime of minority carriers and limits the open circuit voltage (Voc) and fill factor (FF) of solar cells, thus affecting their conversion efficiency [25]. Surface and interface passivation aims to reduce the density of these defects and surface conditions, thereby minimising recombination losses and improving solar cell performance.

3.2. Review of contact passivation technologies

Several contact passivation technologies have been developed for n-Si solar cells, each offering specific benefits and challenges.

3.2.1. Silicon heterojunctions (SHJ)

Silicon heterojunction (SHJ) solar cells use thin films of hydrogenated amorphous silicon (a-Si:H) to passivate the crystalline silicon (c-Si) surface and form selective carrier contacts [6]. a-Si:H has a wider bandgap than c-Si, creating band gaps at the interface that promote carrier separation and reduce recombination [26]. SHJ cells are characterised by excellent surface passivation, enabling high Voc and FFs in excess of 80% to be achieved [27].
Advantages: Excellent passivation, high Voc, high FF, compatible with thin wafers.
Challenges: Cost of base material, complexity of a-Si:H deposition process, indium consumption for TCO layers.

3.2.2. Passivated tunnel oxide (TOP Con)/Poly-Si on oxide (POLO) contacts

Topcon/POLO solar cells use an ultra-thin layer of silicon oxide (SiOx) as the interfacial passivation layer between the c-Si wafer and a layer of heavily doped poly-Si [7]. The SiOx layer provides chemical passivation of the c-Si surface, while the poly-Si layer provides field-effect passivation and carrier selectivity [28]. Topcon/POLO cells have demonstrated efficiencies in excess of 25% and offer a good compromise between performance and manufacturing cost [29]. Figure 5 illustrates the band diagram of a poly-silicon passivating contact, highlighting the impact of the SiOx layer thickness on the doping profile and surface passivation.

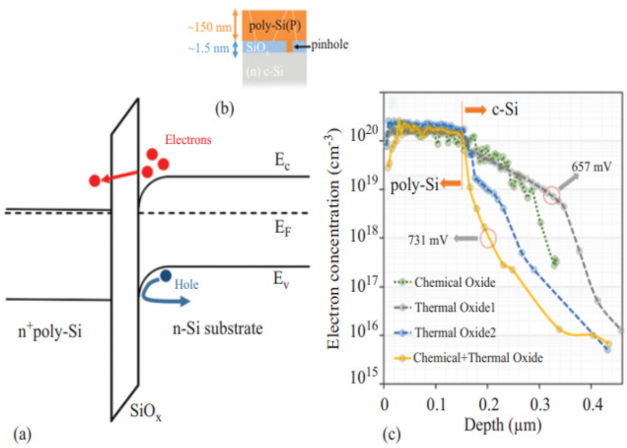

Figure 5. The study presents a schematic band diagram and electron concentration profiles of a poly-Si(n+)/SiOx passivated contact, highlighting the influence of the SiO_x layer on dopant diffusion into the c-Si substrate and its effect on surface passivation level[7], [12].

This diagram explains how Topcon/POLO contacts work and highlights the crucial importance of precise control of the SiOx layer thickness. Precise adjustment of this thickness is essential to optimise passivation and thus improve the performance of these high-efficiency passivating contacts.
Advantages: Good passivation, high efficiencies, relatively low manufacturing cost, compatibility with screen-printing metallisation processes.
Challenges: Precise control of the thickness and quality of the SiOx layer, complexity of the poly-Si deposition process.

3.2.3. Contacts based on metal oxides and halogenated compounds

Contacts based on metal oxides and halogen compounds represent an alternative to doped silicon contacts [30]. These materials generally have a wide bandgap and a high or low work function, allowing carrier selectivity for holes or electrons, respectively [31]. Solar cell efficiencies in excess of 23% have been achieved with contacts based on metal oxides such as MoO3 and V2O5[32].
Advantages: Simplicity of the deposition process, potential for cost reduction.
Challenges: Lower passivation performance than doped silicon contacts, parasitic light absorption, stabilitychallenges.

3.2.4. Organic contacts

Organic contacts represent another promising route for contact passivation in n-Si solar cells[33]. Materials such as PEDOT:PSS have been successfully used as hole-selective contacts, achieving solar cell efficiencies in excess of 20% [34]. Organic contacts offer the potential to reduce costs and simplify manufacturing processes.
Benefits: Potential for cost reduction, process simplicity,
Advantages: Potential for cost reduction, simplicity of process, compatibility with flexible substrates.
Challenges: Lower passivation and carrier selectivity performance than inorganic contacts, long-term stability challenges.

3.2.5. Comparison of the performance and manufacturing challenges of each technology

The choice of contact passivation technology depends on a number of factors, including the desired level of efficiency, manufacturing cost and stability requirements. SHJ cells offer the best passivation performance and efficiency, but are more expensive to manufacture. Topcon/POLO cells offer a good compromise between performance and cost, while contacts based on metal oxides and organic compounds offer the potential to reduce costs, but still require improvements in terms of performance and stability.

4. METALLIZATION TECHNOLOGIES

The metallisation of solar cells plays a crucial role in the efficient extraction of photo generated current, while minimising optical losses. This chapter explores the different metallisation techniques used for n-Si solar cells, focusing on the challenges and opportunities related to cost reduction, durability and bifacial cell performance.

4.1. Influence of metallisation on solar cell efficiency and optical losses

The metallisation of solar cells has a dual impact on efficiency:
Current extraction: The metal contacts must efficiently collect the current photo generated in the silicon and transport it to the cell terminals. The resistance of the contacts and grid lines

influences the fill factor (FF) and therefore the conversion efficiency.
Optical losses: Metal contacts absorb and reflect part of the incident light, reducing the short-circuit current (Jsc) of the cell. Minimising optical losses is essential to maximising efficiency.

4.2. Traditional metallisation techniques and their limitations (e.g. silver screen-printing)

Silver screen printing is the most commonly used metallisation technique in the photovoltaic industry. It involves depositing a silver paste on the surface of the cell through a screen printer, followed by a baking step to form the contacts [35]. Figure 6 highlights the reduction for silver required for the metallisation of solar cells over time. It also shows an example of a knot-free screen mesh, allowing finer metallic lines to be printed. This illustration reflects the industry's efforts to reduce the consumption of expensive silver, while at the same time reducing the optical losses caused by metallisation. These advances aim to increase the efficiency and profitability of photovoltaic cells by optimising their design[36]. Cell performance is affected by metallization, particularly by shading and electrical losses. A compromise has to be found between the width and number of fingers, as well as their resistance. The development of interconnections, from 3 to 9 bus bars, then to cells without bus bars, has reduced the impact of finger resistance. Advances in silver pastes and screen-printing screens have made it possible to achieve finger widths of less than 40 μm. The use of low-temperature pastes and new interconnection processes such as Smart Wire have also reduced silver consumption[37].

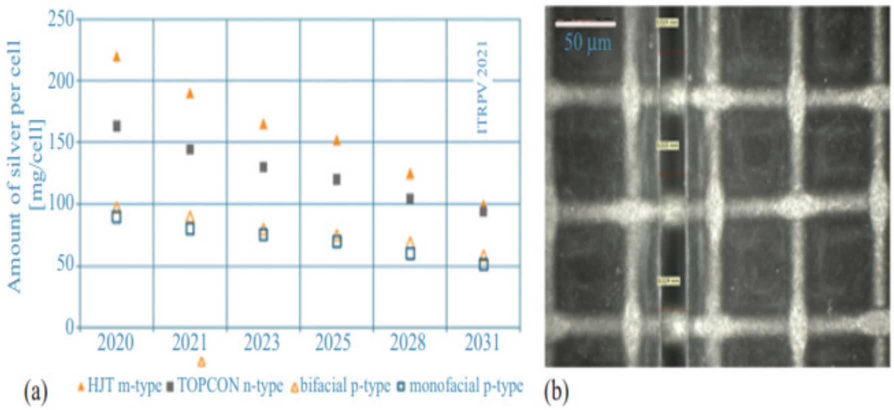

Figure 6. (a) For different cell technologies, the quantity of silver deposited on both the front and rear surfaces of each cell. (a) An image of a knotless screen with a 24 mm aperture[38].

Advantages: Mature process, relatively low cost, good silver conductivity.
Limitations: High cost of silver, thickness of grid fingers limiting efficiency, risk of cracking and delamination.

4.3. Alternatives to silver for cost reduction and durability

The search for alternatives to silver for the metallisation of solar cells is driven by the high cost of silver and sustainability concerns related to its limited availability.

4.3.1. Copper screen-printing

Copper screen-printing is a promising alternative to silver screen printing. Copper has an electrical conductivity comparable to that of silver and is much cheaper [39].
Advantages: Low cost, good electrical properties.
Challenges: Copper oxidation, solder ability challenges, need to develop copper pastes with improved printability.

4.3.2. Copper plating

Copper plating is another alternative metallisation technique, which involves depositing a layer of copper on the cell surface by electrolysis [40]. As shown in Figure 7, cross-sectional images of metallic fingers obtained by copper electroplating are presented, captured with a scanning electron microscope. On the left, a Topcon solar cell with nickel, copper and silver-plated fingers. On the right, a silver seeding grid screen-printed with a copper electrodeposited finger. This approach has recently made it possible to achieve fingers 12 µm wide and 5-7 µm high, offering an absolute 0.4% gain in efficiency for Topcon compared with silver references. The excellent barrier to copper diffusion provided by the transparent conductive oxide simplifies application to silicon hybrid cells.

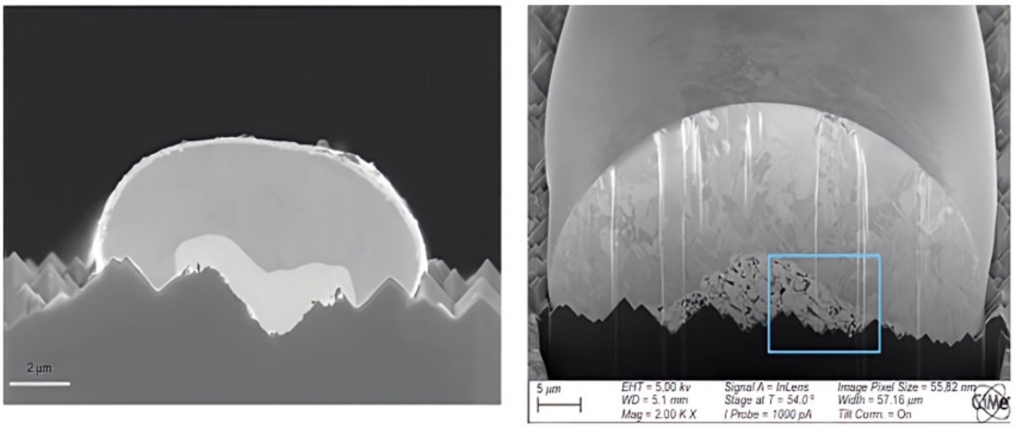

Figure 7. Cu-plated finger cross-sectional pictures taken using a scanning electron microscope. Left: A Topcon solar cell with fingers plated in Ni, Cu, and Ag. Right: A screen-printed Ag seed-grid application with a Cu-plated finger[40], [41].

Advantages: Low cost, grid finger thickness can be reduced, good adhesion.
Challenges: Complexity of the process, need a barrier layer to prevent diffusion of copper into the silicon.

4.3.3. Other emerging techniques

Other emerging metallisation techniques are also being developed, including:
Inkjet printing: This technique enables metal patterns to be deposited with great precision, thereby reducing optical losses [42].
Laser metallisation: Laser metallization can create localized contacts with high resolution, offering the potential for improved efficiency [43].

4.4. Impact of metallisation technologies on bifacial cell performance

Bifacial solar cells are sensitive to incident light on both sides of the cell, requiring appropriate metallisation technologies to minimise optical losses on the backside. Low-shading metallisation techniques, such as fine-line screen-printing and copper plating, are particularly attractive for bifacial cells [9].

5. BIFACIAL N-TYPE SOLAR CELLS

Bifacial solar cells, capable of converting sunlight incident on both sides of the cell, offer the potential to increase the energy efficiency of PV systems. This chapter explores the benefits of bifacial cells, the different manufacturing concepts and technologies, their performance under real-world conditions, and the challenges and opportunities for their future development.

5.1. Benefits of bifacial cells for increasing energy efficiency

Bifacial solar cells offer several advantages for increasing the energy efficiency of PV systems:
Harvesting reflected light: Bifacial cells can absorb light reflected from the ground or other surrounding surfaces, increasing energy production compared to nonofficial cells [44]. The gain in bifacial efficiency depends on factors such as ground albedo, module installation height and system design.
Better use of diffuse light: Bifacial cells are more efficient at capturing diffuse light, which can account for a significant proportion of total solar radiation, particularly in cloudy climates [45].
Reduction of shading effect: The active rear side of bifacial cells can partially compensate for losses in energy production due to shading on the front side[46].

5.2. Bifacial cell concepts and manufacturing technologies (bifacial PERC, bifacial Topcon, bifacial SHJ, etc.)

Different solar cell technologies can be adapted to bifacial designs:
PERC bifacial: PERC cells can be made bifacial by replacing the full-surface aluminium layer on the back with an aluminium grid, allowing light to reach the back of the cell[47].
Topcon bifacial: Topcon cells can also be designed to be bifacial by using transparent passivation layers on the back and a metal grid optimised for current collection on both sides [48].
Bifacial SHJ: SHJ cells are naturally bifacial due to their symmetrical structure and the excellent surface passivation provided by the a-Si:H layers [49].

5.3. Performance of bifacial n-type PV systems under real-life conditions

Numerous studies and pilot projects have demonstrated the energy efficiency benefits of bifacial n-type PV systems under real-world conditions [50]. Typical bifacial efficiency gains are between 10 and 30%, depending on cell technology, ground albedo and system design [9].
Soil albedo: The albedo of the soil, i.e. its ability to reflect light, has a significant impact on bifacial yield. Surfaces with a high albedo, such as white sand or snow, considerably increase energy production on the rear side.
Installation height: Increasing the installation height of the modules improves the collection of light reflected from the ground and reduces the effect of shading.
System design: The design of the system, including the spacing between rows of modules and the orientation of the modules, also influences bifacial performance.

5.4. Research and development challenges and opportunities for bifacial n-type cells

Despite the progress made, several challenges and opportunities remain for the future development of bifacial n-type cells:
Energy performance modelling: More accurate and reliable simulation models are necessary to accurately predict the energy performance of bifacial PV systems under various conditions [51].
Standardisation and certification: Standards and certification procedures for bifacial modules are being developed to ensure product quality and comparability [52].
Metallization technologies: Research efforts are necessary to develop low-shading, low-cost metallization technologies for bifacial cells to maximize efficiency and durability.
New applications: The integration of bifacial cells into emerging applications, such as agri-voltaics and building-integrated PV installations, offers interesting opportunities for market expansion.

6. SILICON-BASED TANDEM AND MULTI-JUNCTION SOLAR CELLS

Single-junction solar cells, even with the most advanced passivation and metallisation technologies, are limited by the Shockley-Queisser efficiency limit. Tandem and multi-junction structures offer the possibility of overcoming this limit by combining several absorber materials with different band gaps. This chapter explores the possibilities, the state of the art and the manufacturing challenges of silicon-based tandem and multi-junction cells.

6.1. Opportunities to exceed the efficiency limit of single-junction solar cells using tandem and multi-junction structures

The Shockley-Queisser efficiency limit for a single-junction solar cell is around 33% under an AM1.5G solar spectrum [53]. This limit is due to thermalization, i.e. the loss of energy from incident photons whose energy is greater than the band gap of the absorbing material [54]. Tandem and multi-junction structures circumvent this limitation by stacking several solar cells with different band gaps, enabling better use of the solar spectrum and higher conversion efficiency. The potential of high-energy photons is exploited more effectively by adding additional solar cells with higher band gaps. The simplest implementation of this idea is a tandem solar cell. Here, a pair of sub-cell combinations share the solar spectrum (see figure 8) and result in higher energy conversion rates through optimal selection of the forbidden bands[55][56].

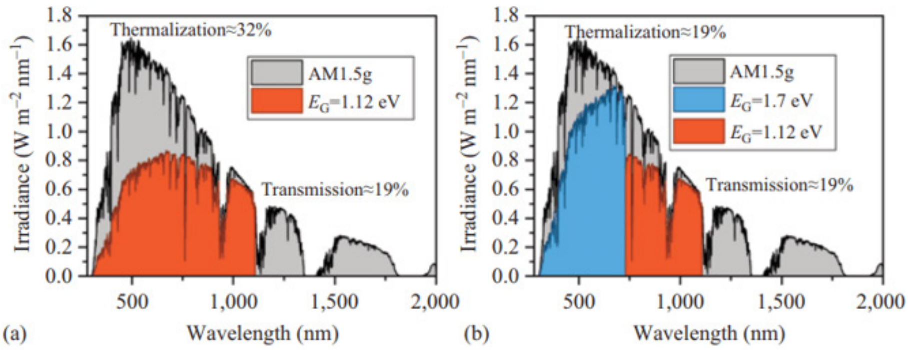

Figure 8. The AM1.5g spectrum fraction can be used in single-junction solar cells with 1.12 eV bandgaps like silicon or combined with materials with 1.7 eV and 1.12 eV bandgaps. In tandem solar cells, high energy photons absorb in the top cell, reducing thermalization losses to 19%[55].

6.2. Perovskite-silicon tandems and III-V/silicon tandems: state of the art and prospects

Two main types of silicon-based tandem cell are currently being developed: perovskite-silicon tandems and III-V/silicon tandems. Perovskite-silicon tandems: Metal halide perovskites are emerging semiconductor materials with exceptional optoelectronic properties for PV applications, including a tunable bandgap, high absorption coefficient and low temperature fabrication [57]. Perovskite-silicon tandems combine a perovskite top cell with a bandgap of around 1.7 eV and a silicon bottom cell with a bandgap of 1.12 eV. These tandems have made rapid progress in terms of efficiency, reaching records of over 32% [58], [59].

III-V/silicon tandems: III-V semiconductors, such as GaAs and GaInP, offer a wide range of band gaps and high carrier transport properties, making them suitable for high-performance solar cells. III-V/silicon tandems combine an upper III-V cell with a lower silicon cell. The efficiencies of III-V/silicon tandems have reached records of over 35% for triple-junction structures [60].

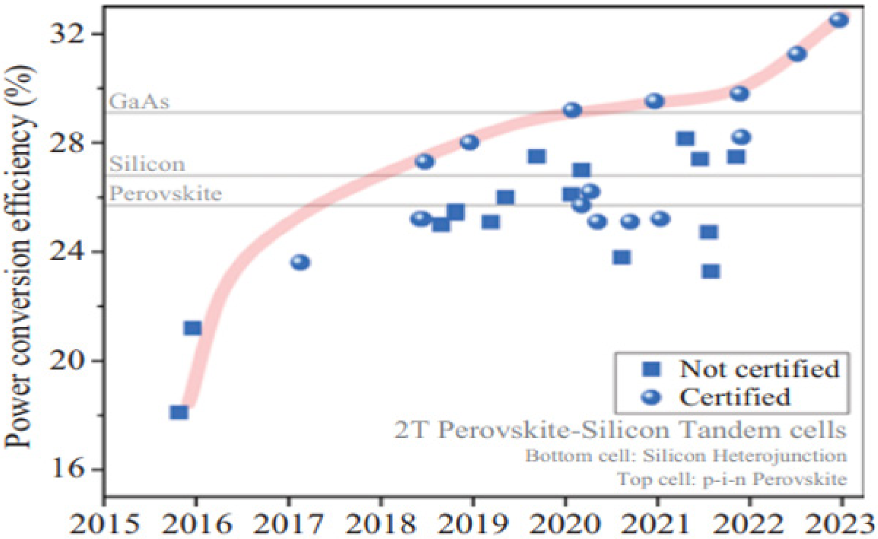

Figure 9. The study demonstrates the highest power conversion efficiencies of two-terminal perovskite-silicon tandem solar cells, surpassing the record efficiencies of other single junction technologies under the global AM1.5 spectrum.

Among all solar cell technologies, this quick and remarkable improvement in PCE for tandem pedo-silicium solar cells is unmatched. A graph showing the temporal evolution of the best power conversion rates is shown in figure 9. The scientific community is focusing more on improving tandem cell stability, examining how sensitive perovskite sheets are to heat and humidity, and examining behavior under real-world settings as a result of the rise in PCE [61][62]. Furthermore, it may be anticipated that the implementation of "tandem upgrades" for current PERx technologies will become a significant topic, as shown by Messmer et al. based on simulations [166]. The first tandems of PERC/POLO/perovskites were recently completed as part of a partnership between the ISFH and the Helmholtz Center Berlin [63].

6.3. Challenges in manufacturing and integrating tandem and multi-junction cells

The manufacture and integration of tandem and multi-junction cells present a number of challenges:
Material and process compatibility: The manufacture of tandem cells requires compatibility between the materials and processes used for the different sub-cells. Differences in processing temperatures, thermal constraint taken into account.
Sub-cell interconnection: The electrical and optical interconnection of sub-cells is crucial to tandem performance. Various interconnection approaches, such as recombination layers, inter-band tunnels and mechanical stacking, are being studied.
Manufacturing cost: The manufacturing cost of tandem and multi-junction cells is generally higher than that of single-junction cells, due to the complexity of the processes and materials used.

7. ECONOMIC AND ENVIRONMENTAL ANALYSIS

Assessing the economic viability and environmental impact of n-type PV technologies is essential for their large-scale deployment and contribution to the energy transition. This chapter explores key aspects of the economic and environmental analysis of n-type solar cells and modules, focusing on cost of ownership (COO), discounted cost of energy (LCOE) and life cycle assessment (LCA).

7.1. Cost of ownership (COO) for solar cells and n-type modules

COO represents the total cost associated with manufacturing a product, taking into account all cost factors including raw materials, equipment, utilities, labour and yield losses [64]. As shown in Figure 11, the cost of cell transformation is presented from two angles. Figure 6.1 gives the cost per cell, while Figure 11 gives the cost per Watt-peak (Wp), taking cell efficiency into account. Comparing the four technologies studied, several key points emerge n-type cells require more expensive metal pastes on both sides, compared with only one for PERCs. They also have a higher lost yield cost, mainly due to the cost of the wafer and the back silver metallisation. In addition, Topcon and ZEBRA require more steps that impact yields. Finally, the amortisation of investments is slightly higher for Topcon/ZEBRA and much higher for SHJ, due to the additional equipment and larger cleanrooms.

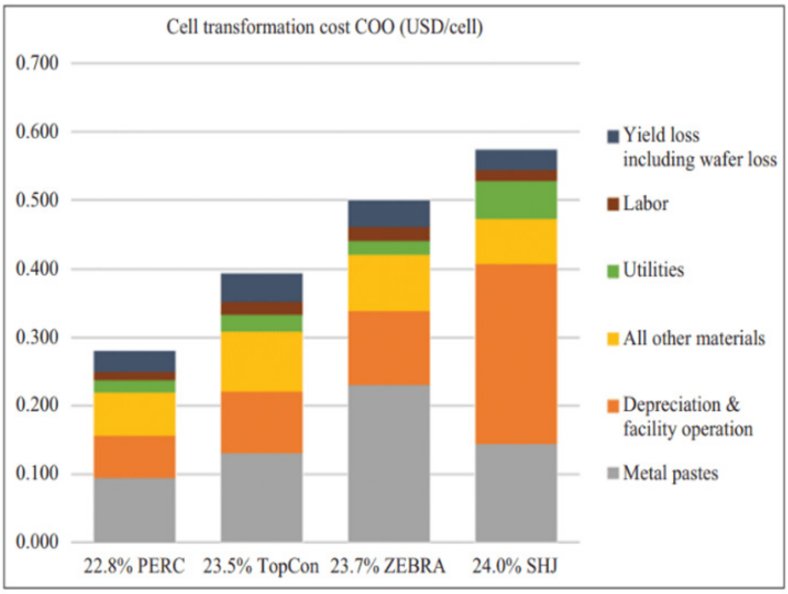

Figure 10. USD/cell transformation cost.

The COO of n-type solar cells and modules is generally higher than that of established p-Si technologies, such as PERC cells, due to several factors:
Wafer cost: n-Si wafers are generally more expensive than p-Si wafers due to the complexity of the manufacturing process.
Cost of metallisation: n-Si cells often use more silver for metallisation, which increases their cost.
Process complexity: Some n-Si cell technologies, such as SHJs, require more complex and expensive manufacturing processes.

7.2. Calculating the discounted cost of energy (LCOE) for n-type PV systems

LCOE is a key economic indicator that compares the lifetime cost of electricity produced by different power generation technologies. It takes into account initial investment costs, operating and maintenance costs, and expected energy output [65]. Although the Cost of ownership of n-Si modules is generally higher, their higher conversion efficiency and better performance under real-life conditions (e.g. bifaciality, temperature coefficient) can lead to a lower LCOE than p-Si technologies [9]. As shown in Figure 12, the performance ratio (PR) depends on cell technology (Pmpp temperature coefficient) and location (ambient temperature and radiation). For hot, sunny climates such as Malaga, the advantage of SHJs - with the lowest temperature coefficient - is clearly more visible than for cooler, less sunny climates such as Copenhagen. Furthermore, for each site, the PR increases as the temperature coefficient of the cells decreases. For the same technology, the PR is better in cooler climates. The energy production simulations, based on the assumptions in Table 6.5, give the LCOE values in Figure 12. These results are based in particular on the assumptions of ground-mounted installations (low surface BOS costs), bifacial systems with high albedo (30%), and medium-high WACC (8%). Different assumptions would alter the relative advantages of each technology.

Table 2. The economy and technological assumptions for Life Cycle Cost Estimates.

	PERC	TOPCon	ZEBRA-IBC	SHJ
System lifetime	25 years			
WACC, discount rate	8%			
Area-related BOS cost (module area)	47.15 USD/m^2			
Power-related BOS cost	0.196 USD/Wp			
O&M cost	1% of PV system CAPEX			
Inverter lifetime	25 years			
Inverter replacement cost	35 USD/kWp			
Temperature coefficient Pmpp (%/°C)	−0.35	−0.30	−0.30	−0.25
Bifacial factor of module	0.7	0.8	0.7	0.9
Bifacial gain	12%	13.7%	12%	15.4%
Initial degradation	2%	1%	1%	1%
Yearly degradation	0.4%			
PV module cost USD/Wp	0.209	0.224	0.236	0.242
Module area (with frame) m^2	2.58	2.58	2.57[1]	2.58
Module power Pmpp	542 Wp	558 Wp	563 Wp	570 Wp
Module efficiency	21%	21.6%	21.9%	22.2%
Total cost of installed system (including PV modules)	0.622	0.630	0.640	0.644

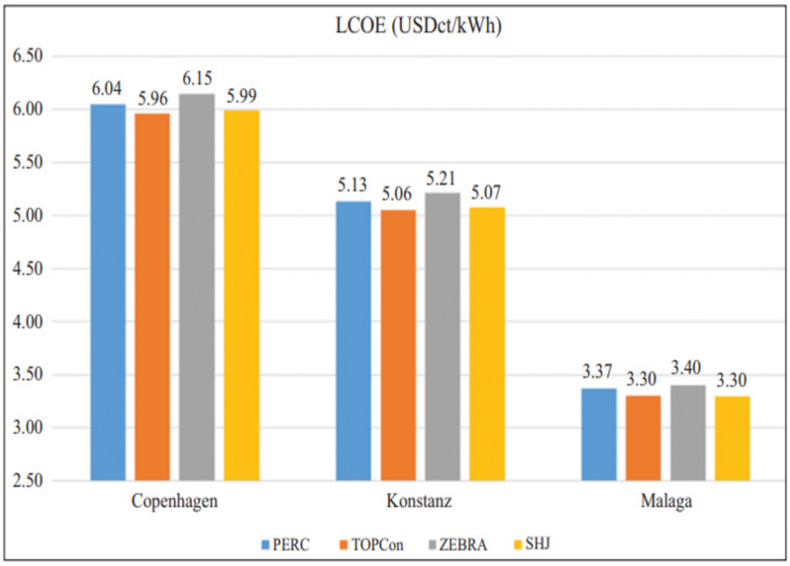

Figure 11. Outcomes of the module COO-based LCOE computations for the four cell technologies.

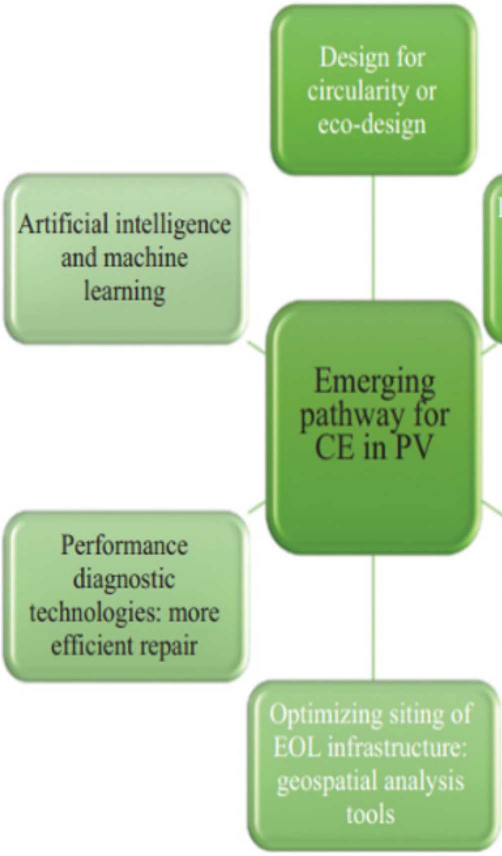

Figure 12. An overview of the essential components of PV technologies to implement a successful circular economy plan[12].

7.3. Life Cycle Assessment (LCA) of n-type PV technologies

LCA is a method of assessing the environmental impact of a product throughout its life cycle, from the extraction of raw materials to manufacture, use and end of life [66]. The LCA of n-type PV technologies is influenced by several factors, including:

Energy consumption: The manufacture of n-Si cells and modules can require higher energy consumption than p-Si technologies, particularly for low-temperature processes.

Use of materials: The use of critical materials, such as silver and indium, has a significant impact on the LCA of n-Si cells.

Recycling potential: Recycling PV modules at the end of their life is essential to reduce their overall environmental impact.

7.4. Impact of cell efficiency and manufacturing technologies on LCOE and Life Cycle Assessment

Improving solar cell efficiency has a direct impact on reducing LCOE and LCA. Increased efficiency means that more energy can be produced per unit area of module, thereby reducing the installation and operating costs of PV systems. In addition, reducing the consumption of materials, particularly critical materials, helps to minimise environmental impact.

Manufacturing technologies: The and LCA of n-Si development of more efficient and less energy-intensive manufacturing technologies is essential for reducing the Cost of ownership cells.

Reducing the use of materials: Finding alternatives to critical materials and minimising the overall consumption of materials are important objectives for the sustainability of n-type PV technologies.

8. FUTURE PROSPECTS AND CHALLENGES

As n-Si solar cells gain in popularity and their technology rapidly advances, it is crucial to examine future market trends, research and development opportunities, as well as sustainability and social acceptance challenges. This chapter explores these key aspects to illuminate the way forward for the successful and sustainable deployment of n-type PV technologies.

8.1. Future market trends for n-type solar cells

The literature on the circular economy (CE) identifies 10 strategies ranging from R0 to R9. The challenge associated with the estimated growth of photovoltaics to 3 TW by 2030 is to mitigate the environmental impact. Two EC strategies - refuse and reduce - are applied in the photovoltaic manufacturing phase[67].

Recycling end-of-life materials is another way of mitigating supply challenges, but it faces three major challenges: the absence of integrated processes, costs, and the lack of end-of-life market projections.

Another EC approach is the repairable design of photovoltaic modules to extend their life. Technical guidelines for safe reuse are also proposed[68].

Figure 13 summarises the emerging digital pathways for an effective photovoltaic CE strategy. The integration of digital technologies is essential throughout the life cycle. Digital modelling optimises design for improved durability, repair ability and recyclability. Digital tracking provides improved traceability to inform CE strategies. Analysis of massive Internet of Things data facilitates predictive maintenance and materials recovery[69]. In this way, the judicious deployment of digital technology is catalysing the achievement of a sustainable circular economy in photovoltaics.

The n-Si solar cell market is expected to grow significantly in the coming years, driven by several factors:

Growing demand for high performance PV modules: Global demand for electricity continues to grow, driving the search for more efficient PV technologies. N-Si cells, with their superior efficiency potential, are well positioned to meet this demand [70].

Reduced manufacturing costs: Continued advances in manufacturing technologies, such as the use of thinner wafers and low-cost metallisation techniques, are helping to reduce the cost of producing n-Si cells, making them more competitive in the marketplace [71].

Integration into emerging applications: n-Si cells are increasingly being integrated into emerging applications such as bifacial PV systems, agri-voltaics and building-integrated PV installations, expanding their market [9].

8.2. Research and development opportunities to improve efficiency and reduce costs

There are several research and development opportunities for n-Si solar cells to improve efficiency and reduce costs:

New contact materials and structures: The search for more transparent and efficient contact materials and new contact structures, such as carrier selective contacts (CSPCs) based on metal oxides or organic compounds, offers the potential to improve efficiency [72].

Optimisation of manufacturing processes: Optimisation of existing manufacturing processes, such as thin-film deposition, metallisation and passivation, can help to reduce production costs and improve cell efficiency.

Integration of advanced technologies: Integrating advanced technologies, such as artificial intelligence and machine learning, into solar cell manufacturing and design processes can optimise performance and reduce costs [73].

8.3. Sustainability and circular economy challenges for n-type PV technologies

Sustainability and the circular economy are major concerns for the photovoltaic industry. N-Type PV technologies face several challenges to ensure their sustainability:
Reducing the use of critical materials: The use of critical materials, such as silver and indium, raises sustainability and cost issues. The search for alternatives and the minimisation of material consumption are essential.
End-of-life module recycling: The development of efficient and cost-effective recycling technologies for end-of-life PV modules is crucial to reducing their environmental impact. Module eco-design: The design of PV modules should take into account their environmental impact throughout their life cycle, from material selection to manufacture, use and end-of-life [74].

8.4. Social impact and market acceptance of n-type solar cells

The social acceptance and market impact of n-Si solar cells is influenced by several factors:
Cost: The cost of n-Si modules remains an important factor in their market uptake. Reducing manufacturing costs is essential to make n-Si technologies more competitive.
Public awareness: Raising public awareness of the benefits of n-Si PV technologies is key to their social acceptance and market uptake.
Landscape integration: The design and installation of PV systems must take into account their impact on the landscape and the environment, in order to minimise negative impacts and promote social acceptance.

9. CONCLUSION

N-Silicon (n-Si) solar cells have emerged as strong candidates for the next generation of photovoltaic technologies, offering the potential for higher conversion efficiency and better performance than the dominant p-Si technologies. This review article explored the significant advances made in passivation and metallisation techniques for monocrystalline n-Si solar cells, as well as the challenges and opportunities for their future development.
The importance of base material quality and the impact of impurities and defects on n-Si cell performance were highlighted. Techniques for characterising and purifying n-type silicon, such as gettering, play a crucial role in minimising recombination losses and maximising cell efficiency. Various contact passivation technologies, including silicon heterojunctions (SHJs) and Topcon/POLO contacts, have demonstrated their ability to achieve record conversion efficiencies. Contacts based on metal oxides and organic compounds offer the potential to reduce costs, but still require improvements in terms of performance and stability.
Alternative metallisation techniques to silver, such as screen-printing and copper plating, are essential to reduce costs and improve the durability of n-Si cells. The impact of metallisation on the performance of bifacial cells was also highlighted. Economic and environmental analysis of n-type PV technologies has shown that, despite a higher COO, their higher efficiency and better performance can lead to a lower LCOE and reduced environmental impact. Reducing the use of materials and improving manufacturing processes are essential for large-scale, sustainable adoption.
In conclusion, n-type silicon solar cells are becoming a key technology for the energy transition and building a sustainable energy future. Continued advances in passivation and metallisation techniques, together with efforts to improve sustainability and social acceptance, are paving the way for significant market expansion and a leading role in clean, affordable electricity generation.

Future prospects: Continued research into new materials and contact structures, optimisation of manufacturing processes and integration of advanced technologies are expected to further improve the efficiency and reduce the cost of n-Si cells.

Bifacial n-type solar cells offer significant potential for increasing the energy efficiency of PV systems. The various bifacial cell concepts and their performance under real-life conditions were discussed, along with the challenges and opportunities for their future development.

Silicon-based tandem and multi-junction solar cells, in particular perovskite-silicon tandems, have made spectacular progress in terms of efficiency, exceeding the Shockley-Queisser limit for single-junction cells. The development of more efficient recycling technologies and the adoption of eco-design principles will play a crucial role in ensuring the sustainability of n-type PV technologies.

Public awareness efforts and the harmonious integration of PV systems into the landscape will promote social acceptance and market expansion.

N-Si solar cells have the potential to revolutionise the photovoltaic industry and make a significant contribution to the transition to a sustainable energy future.

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