A review of technologies for high efficiency silicon solar cells

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Abstract. Solar power, an emerging representative of sustainable resources, remains a critical solution to the growing requirement for energy. In recent years, huge efforts have been devoted to developing solar power conversion, leading to the rapid development of the global photovoltaic (PV) market. As the first-generation solar cells, silicon solar cells, particularly crystalline silicon (c-Si) solar cells, still dominate the PV industry. However, many factors constrain their efficiency to a great extent, including the surface recombination of photogenerated electrons and holes and the reduction of light absorption on the front surface. To overcome these problems, many techniques have been investigated. This paper presents an overview of high-efficiency silicon solar cells’ typical technologies, including surface passivation, anti-reflection coating, surface texturing, multi-junction solar cell, and interdigitated back contact solar cell. The working principles, characteristics, and some recent research of these techniques are discussed in this article.

1. Introduction
Over the past few decades, the energy consumption caused by the economic growth around the world has reached an unprecedented level. Traditional fossil energy is unable to meet the needs of energy expenditure in our daily lives. Still, the burning emission of it, which is called greenhouse gases, becomes the main culprit of global warming at present. To cope with such situations, clean alternative energy sources are being popularized worldwide. Therefore, electric energy, in particular, has grown rapidly as an effective component of total energy demand. One useful path to generate electric energy is the conversion from solar energy, leading to the solar cell industry’s development.

The basic working principle of solar cells is given as follows: among all the photons absorbed by solar cells, those with energy greater than the width of the semiconductor bandgap can excite valence electrons of the atoms in the semiconductor. Such photons can also generate photogenerated electrons, which are known as photogenerated charge carriers [1]. These carriers thus formed will migrate in all directions due to thermal motion [2]. This process will also leave corresponding holes in the P region, space charge region, and N region simultaneously [1]. Furthermore, the electron-hole pairs produced in the space charge region are immediately separated by the built-in electric field. Simultaneously, the
electrons are pushed into the N region and the holes are pushed into the P region [3]. Therefore, both positive and negative charges will be accumulated on both sides of the p-n junction, forming a photogenerated electric field opposite to the built-in electric field. In addition to partially counteracting the built-in electric field, this newly introduced electric field also allows the p-type layer to be positively charged and the n-type layer negatively charged, which creates the photovoltaic (PV) effect.

Silicon based solar cells are the first-generation solar cells normally produced on silicon wafers [5]. They can be divided into crystalline silicon (c-Si) solar cells and thin film silicon solar cells according to silicon wafers’ thickness [6]. At present, silicon solar cells still take over most of the PV market, especially for c-Si cells. More than 90% of the worldwide PV industry is occupied by c-Si solar cells [7]. However, the cost of fabricating silicon solar cells is relatively high compared with using fossil energy. Therefore, one of the most critical points in the PV industry is to improve the efficiency of solar cells. A solar cell’s efficiency is determined as the ratio of the output energy from the solar cell (the energy converted to electricity) to the incident energy from the sun. It is defined as:

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

Where $V_{OC}$ is the open circuit voltage, $I_{SC}$ is the short circuit current, $FF$ is the fill factor and $P_{in}$ is the input power. Optical loss and electric loss are the main factors leading to the constraint of efficiency. The reflection and lack of absorption of incident light result in optical loss, while the carrier recombination loss is one of the main components of electric loss [8].

In recent years, great efforts have been devoted to developing high efficiency solar cells, particularly based on silicon. This paper mainly discusses the basic principles and characteristics of some vital technologies to enhance the efficiency of silicon solar cells, including surface passivation (based on SiO$_2$, Al$_2$O$_3$ and SiO$_2$/Al$_2$O$_3$ stack), anti-reflection coating, surface texturing, multi-junction solar cell and interdigitated back contact cell (IBC). Surface passivation is able to suppress the recombination of photogenerated electrons and holes effectively, which reduces the electric loss. The other techniques are based on decreasing the optical loss to improve the efficiency through enhancing the light absorption. Some recent research progress on these technologies is also reviewed in this paper. This article aims to provide readers with a concise overview of both some conventional mature technologies (surface passivation, anti-reflection coating, surface texturing), which have already been widely used, and two relatively emerging techniques (multi-junction solar cell, interdigitated back contact cell), which have broad prospects in the PV industry. It is also likely to present guidance for the development of improving the efficiency of silicon solar cells. Figure 1 illustrates the structure of this paper, followed by a detailed description of each section.

![Figure 1. Structure of this paper.](image)

2. Surface passivation
The electric recombination on the interface between the absorber layer and contact leads to a significant reduction in silicon solar cells’ efficiency [9, 10]. Moreover, as the thickness of silicon solar cells is further reduced to save cost, it may become close to or even smaller than the diffusion length of minority carriers, resulting in more carriers diffusing to the surface and enhancing the recombination [11]. Surface passivation, a critical enabler for high-efficiency silicon solar cells, is a
vital technology to effectively reduce recombination losses [9, 10]. Several important surface passivation techniques are reviewed in this paper, including passivation based on SiO\(_2\), passivation based on Al\(_2\)O\(_3\) and passivation based on SiO\(_2\)/Al\(_2\)O\(_3\) stack. All of those are important components of high efficiency silicon solar cells.

2.1. Surface passivation based on silicon oxide

SiO\(_2\) passivation layer has been widely used in high efficiency silicon solar cells due to the intrinsic great interfacing quality between Si and SiO\(_2\) [9]. It is able to passivate the dangling bonds on the silicon surface effectively and thus significantly reduce the interface defect density [12]. Therefore, SiO\(_2\) provides a high level of chemical passivation which can be achieved on both n-type and p-type silicon surfaces combing with insufficient field-effect passivation due to the comparatively low value of fixed charges [10, 12]. A slow velocity of surface recombination (less than 10 cm/s) can be achieved by applying SiO\(_2\) as the passivation layer [9, 10].

The most widely used method to deposit SiO\(_2\) layer are silicon oxidation by high-temperature thermal annealing and low-temperature plasma-enhanced chemical vapor deposition (PECVD) [9, 11]. In thermal oxidation, SiO\(_2\) is deposited in rapid thermal annealing (RTA) in either a wet environment (H\(_2\)O vapor with temperature from 850 to 900\(^\circ\)C) or a dry environment (O\(_2\) with temperature from 950 to 1000\(^\circ\)C) [9, 10]. SiO\(_2\) formed through thermal annealing is considered to have one of the ideal passivation qualities. In 2019, Yadav et al. [13] compared the passivation quality of silicon oxide deposited via various methods capping with a layer of SiN\(_x\):H. The result showed that the solar cell based on p-type, 2 \(\Omega\)-cm, Czochralski (CZ) silicon wafers with silicon oxide prepared by thermal oxidation achieved the highest average open circuit voltage (633.9 mV) and the highest average efficiency (18.6%). However, oxidizing at such a high temperature leads to a reduction in silicon bulk carrier lifetime, so it is unsuitable for industrial solar cell production [13, 14]. The low-temperature PECVD method, which generally utilizes SiH\(_4\) and N\(_2\)O gas flow in a special PECVD system reacting under specific temperature, pressure, and radio frequency power, overcomes this disadvantage. It also has a high deposition rate, leading to a short process time, enabling low production costs and high throughput [14]. Nevertheless, this type of layer has worse passivation quality and higher recombination velocity than the one produced through thermal oxidation [9].

To further optimize the deposition of the silicon oxide passivation layer, some techniques have been proposed by different research groups. Moldovan et al. [15] investigated ozone-based oxidation techniques to generate the ultrathin silicon oxide layer, including UV/O\(_3\) photo-oxidation and wet chemical oxidation in ozonized DI-H\(_2\)O (DIO\(_3\)). The UV source was used to dissociate the molecular oxygen into atomic oxygen to have a reaction with the silicon surface directly or to form O\(_3\) and those O\(_3\) was mixed in DIO\(_3\) for various time duration with invariant concentration to oxide the silicon surface. Those ozone-grown silicon oxides have shown improved electrical properties because of the non-destructive oxidation on the silicon surface and fewer defects on the interface due to more saturated Si-O bonds. Furthermore, using DIO\(_3\) is able to form a film with higher thermal stability [15]. Another cost-effective, low-temperature, and simple method with high deposition speed to deposit silicon oxide was demonstrated by Chen et al. [16]. This technique was called liquid phase deposition (LPD). An ideal concentration of H\(_2\)SiF\(_6\) (1.5 M) reacted with water to produce SiO\(_2\) under an optimal temperature of 50\(^\circ\)C. The layer generated through this method was likely to have a better passivation quality on n-type silicon wafers, and it was able to achieve a conversion efficiency of 19.5% on a p-type, 1 - 3 \(\Omega\)-cm CZ silicon wafer with an area of 156 mm \(\times\) 156 mm. Table 1 summarizes these deposition processes of silicon oxide.
Table 1. Summary of different silicon oxide deposition processes.

| Technique type          | Basic process                                                                 | Advantages and disadvantages                                                                 |
|-------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Thermal annealing       | Deposit in an RTA in a wet environment (H$_2$O, 850 - 900°C) or a dry environment (O$_2$, 950 - 1000°C) | 1. High passivation quality<br>2. High thermal budget which reduces the silicon bulk carrier lifetime |
| PECVD                   | Several gas sources react with each other (generally SiH$_4$ and N$_2$O) under specific conditions to form silicon oxide | 1. Relatively low temperature condition and significantly high deposition rate<br>2. Poorer passivation quality compared with thermal annealing |
| Ozone-based oxidation   | Utilize UV/O$_3$ (photooxidation) or DIO$_3$ (wet chemical oxidation) to react with the silicon surface | 1. It does not damage the silicon surface and generates fewer defects on the interface resulting in an enhanced electrical property<br>2. Using DIO$_3$ can achieve higher thermal stability |
| LPD                     | H$_2$SiF$_6$ with a concentration of 1.5M reacts with H$_2$O at 50°C            | Cost-effective, low temperature condition and simple with a high deposition rate             |

According to [17], the single passivation layer is likely to suffer from firing stability issues. It can achieve a high passivation quality during cell processes, but this effect is hardly maintained when the whole fabrication is completed. Hence, SiO$_2$ is often combined with other layers to improve the passivation level. One of the most frequently used combinations is SiO$_2$/SiNx. A SiNx capping layer can not only enhance the firing stability of SiO$_2$, but also improve the passivation quality [18]. Gong et al. [11] stated that a 100 nm or thicker silicon oxide layer was capped by a SiN$_x$ layer, the effective minority carrier lifetime could reach more than 2 ms, which was significantly higher than that of a single silicon oxide layer. Another common structure is based on the ultrathin silicon oxide and doped polycrystalline silicon layers in a metal/poly-Si/silicon oxide/Si structure [19]. Poly-Si can help provide an extremely low contact resistivity [20] and enhance the contact quality combing with silicon oxide because of the Fermi level depinning [21]. Moreover, Kale et al. [19] explained that the heavily doped poly-Si was also able to enhance the field-effect passivation of silicon oxide, so combining the original chemical passivation with this newly introduced field-effect passivation results in a very low $J_{0e}$. Additionally, they illustrated that the optimal thickness of the silicon oxide in this structure was around 1.4 - 1.6 nm, and the ideal contact annealing temperature was approximately 850°C.

2.2. Surface passivation based on aluminum oxide

Another frequently used surface passivation mechanism is based on Al$_2$O$_3$. The most notable characteristic of Al$_2$O$_3$ is the high negative fixed charge density in the range of $\sim 10^{12} - 10^{13}$ cm$^{-2}$ [22]. This results in the decrease of the types of charge carriers in the underlying silicon, which is able to reduce the surface recombination velocity. Therefore, Al$_2$O$_3$ offers excellent field-effect passivation [12]. Additionally, it also provides a low interface defect density (less than $10^{11}$ eV$^{-1}$ cm$^{-2}$) indicating a good level of chemical passivation [22]. Due to the fixed negative charges, Al$_2$O$_3$ passivation layer overcomes the parasitic shunting, so it can passivate both the diffused and undiffused p-type silicon effectively [9]. However, this feature of Al$_2$O$_3$ leads to the limited effect while passivating the highly
doped n⁺ silicon surfaces since it triggers the increase of the minority charge carrier density on these surfaces, which leads to enhanced surface recombination [22].

A frequently used technique to deposit the Al₂O₃ passivation film is called atomic layer deposition (ALD). Two types of precursors are used during this process which is Trimethylaluminum (TMA) as a source of Al and H₂O, O₂ or O₃ particles as oxidants [9]. These two precursors react with the silicon surface alternately till the end of the process [10]. When O₂ is used, the process is known as thermal ALD, while when O₃ is applied, the process is called plasma ALD [13]. ALD has become a preferred method for the production of Al₂O₃ film not only owing to the great uniformity, pin hole free deposition and single layer thickness control [23], but the layer produced through this method holds the best passivation properties. In 2019, Bansal et al. [23] demonstrated that the surface passivation properties of Al₂O₃ layer deposited using ALD were closely related to the process parameters including substrate temperature, annealing temperature and layer thickness. They illustrated that the film achieved by plasma ALD performed better than the one prepared via thermal ALD in terms of the effective minority carrier lifetime while the former reached 335 µs and the latter only obtained 259 µs. Furthermore, they compared the quality of Al₂O₃ layers produced by plasma ALD with different parameters. The result showed that the optimal values of substrate temperature, annealing temperature and layer thickness were approximately 200°C, 425°C and 10-20 nm respectively [23].

As mentioned in 2.1, a single Al₂O₃ layer has a weak firing stability similar to a single silicon oxide layer [17], so it is also often combined with other layers like SiNx to improve the firing stability. Lin et al. [24] concluded that SiNx is suitable for acting as a capping and insulating layer of Al₂O₃ due to the low deposition rate and the negative charges of Al₂O₃ can be retained although Al₂O₃ and SiNx have different charge polarities. Additionally, SiNx has the ability to protect the Al₂O₃ film from being disintegrated by metal pastes and thus improve the chemical stability [10]. Al₂O₃/SiNx stack is widely applied as the rear passivation layers of p-type passivated emitter rear cells (PERC). PERC structure is an upgrade of Al-BSF cell (aluminum-back surface field) containing the deposition of an extra rear passivation film and a local contact formation by laser processing as shown in Figure 2 [10, 25]. The SiNx layer over Al₂O₃ can prevent the rear passivation layer from being metallized. Additionally, SiNx can further increase the thickness of rear passivation stack to ensure sufficient internal reflection on the rear side of the cell to improve the short circuit current density [25]. In 2017, industrial PERC cells featuring Al₂O₃/SiNx as the rear passivation stack have obtained great performance with efficiencies of 20.5% and 20.8% corresponding to open circuit voltages of 660 and 666 mV, respectively [26].

![Figure 2. Structure of the PERC [26].](image)

2.3. Surface passivation based on silicon oxide/aluminum oxide stack

Another different approach of surface passivation is to use Al₂O₃ as a covering layer of SiO₂. SiO₂/Al₂O₃ stack exhibits a weaker field-effect passivation and an enhanced chemical passivation due to the introduction of SiO₂ compared with a single Al₂O₃ layer [17] since the SiO₂ film prevents the injection of electrons from the silicon bulk into the Al₂O₃ resulting in the decrease of negative charges [22]. Hence, it will not lead to the increase of the minority charge carrier density in n-type silicon, enabling the resulting stack to be well suited for various types of silicon surfaces, especially for the n⁺
surface, which is impractical for a single Al₂O₃ layer [22]. Loo et al. [27] investigated the passivation quality of the SiO₂/Al₂O₃ stack on the n⁺ surface of a p-type CZ silicon wafer. They found that for all the cases in which the SiO₂ is applied (thickness varying from 1 nm - 14.4 nm), J₀e was reduced compared with single Al₂O₃ layers. When the thickness became 3.6 nm, the improvement in J₀e was significant, decreasing from 81 fA/cm² to 50 fA/cm². They also concluded that the SiO₂/Al₂O₃ stack performed better than a single Al₂O₃ layer in a large range of phosphorous doping concentration, most remarkably in the range from 5×10¹⁷ - 10²⁰ cm⁻³. Furthermore, with the application of the Al₂O₃ capping layer, the passivation properties of SiO₂ prepared through the low-temperature method is significantly improved [10]. Therefore, the SiO₂/Al₂O₃ stack may become an effective substitute for high-temperature thermal annealing SiO₂ since it avoids the shortcomings caused by the high temperature and also remains the advantage of high passivation quality. In summary, the SiO₂/Al₂O₃ passivation stack has the potential to replace single passivation layers (SiO₂ or Al₂O₃) in the photovoltaic industry.

2.4. Summary
Overall, SiO₂ and Al₂O₃ are widely used to passivate the surface of solar cells. Both of them enable the passivation quality to reach a high level. However, their passivation mechanisms are different: SiO₂ performs well in chemical passivation but it has a weak field-effect passivation while Al₂O₃ has not only a good chemical passivation, but also an excellent field-effect passivation because of its high negative fixed charge density. In addition, SiO₂ is more flexible than Al₂O₃ since single Al₂O₃ film is not suitable for n-type silicon. Furthermore, both single SiO₂ and Al₂O₃ layers suffer from a critical issue of firing stability, so they usually combine with other types of material which is generally SiNₓ in order to further enhance the passivation quality.

The SiO₂/Al₂O₃ stack, which is the combination of those two materials, is likely to be an ideal choice for surface passivation. Firstly, its firing stability is higher than the single-film structure. Moreover, it is able to passivate the surface of n⁺ silicon effectively unlike Al₂O₃ or Al₂O₃/SiNₓ. It also offers a passivation quality as high as the SiO₂ deposited through thermal annealing without affecting the lifetime of silicon bulk carriers. Table 2 presents a brief summary of the characteristics of these three types of passivation layer reviewed in the first section.

Table 2. A brief summary of the features of different types of passivation layer.

| Surface passivation type | Passivation mechanism | Firing stability | Flexibility |
|--------------------------|-----------------------|-----------------|-------------|
| Single layer of SiO₂     | Strong chemical passivation with weak field-effect passivation | low             | Perform well on both n-type and p-type silicon surfaces |
| Single layer of Al₂O₃    | Excellent field-effect passivation with good chemical passivation | low             | Perform well on p-type silicon surface; Not suitable for n-type silicon surface especially for highly doped n-type silicon surface |
| SiO₂/Al₂O₃ stack         | Better chemical passivation and weaker field-effect passivation compared with single Al₂O₃ | high            | Well suited for both n-type and p-type silicon surfaces |

3. Conventional technologies to improve light utilization
Besides the surface recombination loss, another major source bringing about the losses of silicon solar cells’ efficiency is the reflection of the incident photons by the silicon surface [28]. Bare silicon has a surface reflection of over 30% resulting in a great waste of the incident light. Therefore, some
conventional techniques, including anti-reflection coating (ARC) and surface texturing, are widely used to fabricate silicon solar cells to promote the light utilization.

3.1. Anti-reflection coating
ARC consists of one or multiple thin layers of dielectric material. It aims to enable the wave reflected from the top surface to be out of phase with the one reflected from the silicon surface. Destructive interference occurs between these out-of-phase reflected waves, leading to zero net reflected energy. Generally, SiNx is widely used as the material of ARCs. A single-layer SiNx is able to suppress the minimum reflection point to less than 1% at the wavelength of 600 nm for normal incident light [29]. In addition, some types of transition metal oxide (TMO) including ZnO, MgO and Al₂O₃ can also be utilized as the material of single-layer structured ARCs [30]. In 2020, Sagar and Rao [30] stated that these TMOs could offer a great optical transparency and a proper refractive index to suppress the reflection loss. After applying ZnO, MgO and Al₂O₃ layer to the n-type emitter of silicon solar cells, the short circuit current density was increased by around 5.08, 5.70 and 5.67 mA/cm² respectively compared with the solar cells without an ARC; the cell efficiency also rose by 1.35%, 1.48% and 0.74% respectively [30].

Furthermore, some designs of multi-layer structured ARCs have been investigated. In 2019, Yan et al. [29] proposed an improved double-layer structure by adding a layer of SiOₓ over SiNx. They applied various ARCs to a 20 nm AlOₓ passivation layer on an n-type front and back contact solar cell. The result showed that the use of a 50/50 nm SiNx/SiOₓ stack enhanced both the open circuit voltage and short circuit current density compared with a 50 nm single-layer SiNx ARC by 3 mV and 0.3 mA/cm² respectively. The average cell efficiency also showed an increase from 21.11% to 21.30% [29]. Additionally, Sarker et al. [28] also investigated the performances of a double-layer structure based on 50/60 nm ZnS/MgF₂ (refractive indexes are 2.34/1.38 respectively) and a multi-layer structure based on 45/10/80 nm ZnS/Si₃N₄/MgF₂ (refractive indexes are 2.34/2.02/1.38 respectively) as shown in Figure 3. The resulting reflection loss was lower than 8.46% and 5.71% respectively [28]. In this study, this multi-layer structure was an optimal choice of the ARC since it formed a refractive index gradient which effectively helped minimizing the reflection by placing a thin film in the middle whose refractive index is in between the other two layers. Therefore, the material of the middle film can be changed to any type as long as the refractive index satisfies this condition. In summary, ARC can be composed of different types of material with a variety of structures and it is a critical technique for high efficiency silicon solar cells. Generally, multi-layer structured ARCs perform better than single-layer structured ARCs.

3.2. Surface texturing
Surface texturing is another familiar method to enhance the absorption rate of the incident sunlight. It can be used to minimize the reflection since the rough surface reduces it effectively by increasing the

![Figure 3. Schematic diagram of multi-layer structures with corresponding refractive indexes (left: 50/60 nm ZnS/MgF₂; right: 45/10/80 nm ZnS/Si₃N₄/MgF₂).](image)
chances of reflected light bouncing back onto the surface instead of out to the surrounding air. At present, the inverted pyramid has become an ideal structure to boost cell efficiency as the development of the photovoltaic industry. Comparing with the micro-pyramid structure, the inverted nano-pyramid structure is able to achieve a better performance considering the thickness and light trapping comprehensively [31]. Furthermore, the inverted pyramid structure has the ability to enable the incident light to bounce triple or more times on the surface before being reflected away, which is one or more bounces than the traditional upright pyramid structure [32].

The anisotropic alkali chemical etching is one of the methods to form the inverted pyramid structure. It is based on low-concentration strong-alkaline solutions such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) texturing the surface at about 80°C [33]. There also exists an optimal texturing time at about 30 minutes to prevent the surface from lacking or over etching [34]. Another cost-effective and efficient chemical etching method to generate the inverted pyramid structure in industrial production is metal-assisted chemical etching (MACE) [35]. This process aims to form a metal ion layer on the silicon surface through physical or chemical means and take advantage of the catalytic performance of it to realize the induced corrosion by the mixed acid etching fluid of hydrofluoric acid (HF) and an oxidizing agent such as hydrogen peroxide (H₂O₂) and nitric acid (HNO₃). The commonly used material of the metal is argentum. Furthermore, the property of the textured surface indicates a strong connection with the size of the inverted pyramids, which means a larger size is able to produce a better light capture performance [36]. Changing the proportion of those reactants can realize the size control of the inverted pyramids [37].

However, for multi-crystalline silicon (mc-Si) solar cells, it is impractical to apply such an etchant to texturing process as the crystallographic grains on the surface have random orientations [38]. Instead, laser engraving is applicable for this type of solar cell. During this process, IR laser is typically used under a specific pulse frequency to etch the surface, and the optical effect obtained from different laser wavelengths is slightly different [38]. After the laser engraving, a small quantity of residue is left on the surface, so the surface cleaning process is required, which is achieved using 1% KOH at room temperature or ultrasonic for 5 minutes [39].

3.3. Summary

Therefore, both anti-reflection coating and surface texturing play an important role in suppressing the reflection losses and thus improve the photovoltaic conversion efficiency of silicon solar cells [40]. They have the same mechanism, which is to reduce the reflection of the incident light. However, ARC intends to construct a destructive interference between different reflected waves, which significantly reduces the reflected energy while surface texturing aims to increase the bounces of reflected light onto the surface.

Various types of dielectric material can be made into ARCs with single- or multi-layer structures. In general, multi-layer ARCs hold better performances than single-layer ARCs. A three-layer ARC can form a refractive index gradient to lessen the reflection loss effectively by choosing these materials with proper refractive indexes. For surface texturing, an inverted nano-pyramid structure is one of the optimal schemes due to its great performance. Many methods can be applied to generate this structure, such as anisotropic alkali chemical etching, MACE, and laser engraving. Additionally, mc-Si solar cells can only apply laser engraving to form inverted nano-pyramids on their surfaces because of the random orientations of crystallographic grains. Table 3 summarizes the effects of these surface texturing methods on solar cells.

Table 3. Summary of the effects of various types of surface texturing methods.

| Surface texturing method                  | Effect                                                                 |
|------------------------------------------|------------------------------------------------------------------------|
| Anisotropic alkali chemical etching      | The reflection of the diamond-wire-sawn single-crystalline silicon cells applying |
this method is only about 5%, and this can be put into use on a large scale in the PV industry [33].

Comparing with the 182 μm thick crystalline-Si in the spectral range of 300 - 1100 nm, solar energy materials can achieve the same average absorptance value with the material usage reducing over 3.6-fold [37].

The surface reflectivity of 355 nm laser performing on a mc-Si cell can be reduced to between 11% and 8% over the spectral range from 400 nm to 1 μm [41].

4. Advanced structures of solar cells

In addition to these commonly used technologies, some emerging techniques also occupy prominent positions in improving the efficiency of silicon solar cells. Two typical advanced structures are introduced in this section which are multi-junction solar cell and interdigitated back contact solar cell. Both of them aim to increase the absorption of sunlight through different approaches in order to reduce optical loss.

4.1. Multi-junction solar cell

Comparing with the single-junction structures in the industrial standard silicon solar cells, multi-junction (MJ) solar cells are able to ameliorate their 30% limitation of the intrinsic efficiency and thus obtain a higher solar-to-electrical transfer efficiency [42]. Therefore, MJ has become an alternative approach to enhance the efficiency of solar cells by absorbing the whole solar spectrum under AM 1.5 solar spectrum illumination. It can get an efficiency of over 30% [43]. It can also decrease the thermal losses caused by absorbing photons with additional energy and the transmission losses of photons with inadequate energy. Generally, there are two different methods to implement MJ cells. Firstly, the integration of different solar cells is realized in an optical system, which divides the incident light into various wavelength bands and then reorients to the cells with proper bandgaps. Another approach is to stack the individual solar cells using independent contacts on each cell mechanically, which is called multi-terminal. All the industrial MJ solar cells up to present utilize a two-terminal structure since the fabricating process is simpler [44].

Si has been widely applied as the substrate of MJ solar cells instead of Ge or GaAs due to the lower cost [45]. Silicon MJ solar cells are generally obtained via a set of semiconductor absorbers majorly from III-V with various energy bandgaps, which enable them to utilize the electromagnetic energy at specific frequencies [44, 46]. One of the most common structures of silicon MJ solar cells is the triple-junction with a structure of GaInP/GaAs/Si. The top GaInP layer can absorb the wave with a wavelength of 300 - 670 nm, and the middle GaAs layer is able to absorb the wave having a wavelength of 500 - 890 nm, while the bottom silicon is responsible for absorbing the wave whose wavelength is 650 - 1180 nm and converting it into electricity. Therefore, the resulting device is specially designed to absorb most of the frequencies of sunlight, thus generate more energy.

A specific two-terminal GaInP/GaAs/Si triple-junction structure was proposed by Feifel et al. [45]. The schematic diagram is shown in Figure 4. In this study, the corresponding III-V semiconductor absorbers were formed through a direct epitaxial growth process, which was metalorganic vapor-phase epitaxy (MOVPE), resulting in a huge cost decrease. The front contacts were generated through evaporation and photolithography. A prominent characteristic of this structure is the extra stack of layers between the silicon surface and III-V semiconductors. As shown in Figure 4, the additional GaP layer featuring a low lattice mismatch to silicon acts as a transition layer from Si to III-V materials and
a growing template for III-V absorbers [47]. The capping layer (GaN\textsubscript{0.024}P\textsubscript{0.976}) of it is used to protect GaP from being relaxed to minimize the defect density at the GaP/Si interface [45]. Furthermore, a GaAs\textsubscript{y}P\textsubscript{1-y} buffer enables the lattice constant from silicon to GaAs to increase and the above overshooting Al\textsubscript{0.1}Ga\textsubscript{0.86}In\textsubscript{0.04}As film relax the resulting buffer to achieve the in-plane lattice constant of GaAs [45, 47]. This triple-junction silicon-based solar cell achieved a high AM1.5g conversion efficiency of 22.3% [45].

Figure 4. Schematic diagram of the triple-junction structure proposed in [45].

Although the MJ solar cells have been investigated rapidly in a recent development, realizing a four-junction structure (InGaP/GaAs/InGaAs/InGaAs) with an efficiency of over 45% at a high solar concentration [48], the shortage of the metal used in this structure should be confronted. The core elements of the high-efficient PV module concept (III-V/Si), such as gallium, indium, and arsenic, are likely to face supply risks and shortages in the next 30 years if extensively used [49] and the alternative solutions remain to be discovered.

4.2. Interdigitated back contact solar cell

Interdigitated back contact (IBC) solar cell is a technology to move both positive and negative metal contacts to the back side of the cell and enable these metal grids to locate in an interdigitated structure along with the emitter and the back surface field doping layer on the rear side of the cell so that the front side of the cell is completely black. Most of the metal fingers on the front side are invisible, eliminating the optical shading losses on the front side to improve efficiency [25]. Moreover, IBC solar cells enable the interconnection process to be simplified at a module level, leading to the high conversion efficiency of over 24% at the cell level and more than 23% at the module level [50]. A schematic diagram of an IBC cell is shown in Figure 5.

Figure 5. Structure of an IBC solar cell with n\textsuperscript{+} back surface field and p\textsuperscript{+} emitter [25].

The process flow of fabricating the IBC solar cell is much more complicated than that of traditional solar cells. Besides, it is more optimal to fabricate the IBC solar cell on n-type silicon wafers rather than p-type since n-type silicon is more tolerant to common impurities compared with p-type silicon [51]. One of the critical steps is the formation of cross-arranged p\textsuperscript{+} and n\textsuperscript{+} regions on the back of the
cell with metallization contact on the top featuring a high quality and good interdigitated distribution [25, 51]. Therefore, the fabrication of IBC cells requires local doping, such as lithography or laser formation to form the desired pattern, followed by two separate diffusion processes to form the p-type and n-type regions. Generally, an extra process is required to avoid the problem of tunnel junction shunting that happens at the interface between heavily doped p⁺ and n⁻ regions, which is to generate an undoped gap between those two sections [52]. However, this process is complicated. Dong et al. [52] proposed an alternative method to avoid this issue. They stated that the tunnel junction shunting could be reduced effectively through the control of the boron-doping concentration of p⁺ region. If the boron concentration is controlled under a threshold value, the tunnel junction shunting will be restrained [52].

The average efficiency of the mass production of IBC solar cells is able to reach 23% [53]. With the introduction of the layer selective laser process in manufacturing polo-IBC solar cells, the power conversion efficiency can achieve as high as 26.1% [54]. Although the IBC solar cell has such high efficiency, it is one of the most complex structures among commercial crystalline silicon solar cells. This technique requires high-quality silicon wafers with a relatively complicated manufacturing process, resulting in a high cost twice as much as ordinary cells, restricting the large-scale application [55]. Utilizing industrial technologies such as screen printing, tubular diffusion, or ion implantation is able to reduce the cost effectively [56]. The commercial application and popularization of IBC cells have a wide prospect.

4.3. Summary
Although these two structures have a similar mechanism which is to promote light absorption, their working principles are totally different. MJ solar cell integrates various solar cells together via individual semiconductor contacts. A two-terminal triple-junction silicon solar cell based on GaInP/GaAs/Si is one of the most common structures. The use of this technology enables solar cells to absorb the entire solar spectrum under the illumination of AM 1.5 solar light, which is great progress in improving light utilization. IBC solar cell elevates the efficiency by moving both positive and negative metal contacts to the back side of the cell to increase the area of the absorption region of the incident light. The back surface field, emitter, and metal fingers are located in an interdigitated structure on the rear surface. The major factors limiting the industrial application of MJ solar cells and IBC solar cells are their complicated fabrication process and high cost. However, these two burgeoning techniques still have the potential to become vital components in the PV industry due to their great performances in enhancing efficiency.

5. Conclusion
Solar energy has the advantages of no exhaustion risks, pollution-free, and high energy quality. Silicon solar cell is one of the most fundamental and widely used devices utilizing solar energy effectively. Thus, improving the efficiency of silicon solar cells remains an important research topic in the energy industry. As discussed in the previous sections, the conversion efficiency of a silicon solar cell can be improved via several methods, which are surface passivation, anti-reflection coating, surface texturing, multi-junction solar cells, and interdigitated back contact cell.

The surface passivation technique has various methods with different materials, utilizing single or multiple layers based on SiO₂ and Al₂O₃ or their combination are the basic ones. Each of them has its own technological process, characteristics and performance. The SiO₂/Al₂O₃ stack is able to remedy some disadvantages of SiO₂ and Al₂O₃ including the low passivation quality of low-temperature deposited SiO₂ and the low flexibility of Al₂O₃ which has become one of the optimal passivation mechanisms. No matter now or in the future, surface passivation will remain to be an eternal way to increase the life span of solar cells.

Anti-reflection coating (ARC) and surface texturing are both based on decreasing the reflection light to increase η. For the ARC, the typical single-layer material is SiNₓ while multi-layer ARC structures combining with several different materials achieve better performances. One of the optimal
results shows the reflection loss is reduced to less than 6%. The development of ARC is based on discovering proper materials. For instance, for poly-crystalline silicon solar cells, the optical transmittance of garnet nano-microfilm has a perfect performance at 97% in the 300-800 nm wave range and is appropriate to be used for ARC material. For surface texturing, the chemical etching is applied extensively compared with laser engraving due to its advantages of convenience and low-cost, and the reflection rate can be attenuated to about 10%. In addition, there are no obvious shortcomings in these two techniques, so is the surface passivation. They can be applied to almost all the solar cells and have become essential steps while fabricating solar cells.

The principle of multi-junction (MJ) solar cell is also to enhance the absorption of the solar light by combining different solar cells together through the semiconductor contacts. It is a lateral increase in efficiency by absorbing a wider range of the solar spectrum. At present, major MJ solar cells have three junctions, and the efficiency can easily break 30%. Although the lattice mismatch is a tough problem, MJ solar cells will occupy high efficiency market dominance by upgrading different materials. In the future, solar cells with more junctions will be designed. A configuration called super-multi-junction cell is connected by up to 10 junctions and has strong robustness, which owns a maximum potential efficiency at 50% in realistic spectrum fluctuation.

The interdigitated back contact (IBC) solar cell has a high efficiency based on its elaborate design. It is the first back-junction cell that increases efficiency by increasing the light-receiving area of the front surface. The further development of IBC solar cells can be based on decreasing the contact resistance and increasing the lifetime of minority carriers. Nevertheless, the complicated structure and high-cost manufacturing process of IBC solar cells may lead to a limited domain of application. Both multi-junction solar cells and IBC solar cells are relatively fresh compared with the first three techniques. Therefore, they have not been utilized in the PV industry as widely as those three technologies. With the further development of solar cells, MJ solar cells and IBC solar cells will become more critical in improving the efficiency of silicon solar cells.

At the present stage of developing solar cells, the main goal is to increase efficiency and performance. However, it is different from the commercial process in assembly lines. Price is an important consideration in industrial production, and it is reasonable to sacrifice some efficiency in order to save costs. For instance, for industrial single-crystalline silicon and multi-crystalline silicon solar cells, the MACE nano-texture process is used with transfer efficiencies of 19.4% and 18.7%, respectively. Although the efficiencies are lower than the designs in the laboratory, the simplification of production lines brings the advantage of lower costs.

In the future, solar photovoltaic will continue to become a clean source for generating electric power because of its feasibility and cost-effectiveness. In particular, crystalline silicon solar cells will proceed to replace conventional fuel since it is regarded as a vital resource that is economically and environmentally sustainable. With the comprehensive utilization and future development of these technologies, it is expected that silicon solar cells’ efficiency will approach the ultimate theoretical value. Moreover, according to Solarbe, the single crystal PERC technology held the best performance in cell conversion efficiency and output power compared with other technologies. In 2022, 40% of the mitigation of greenhouse gases will be contributed from PERCs, and it will be expected to become much higher in the late 2020s. Furthermore, the combination of established and emerging technologies will become a highlight, such as the cross fertilization between GaAs and GaInP. This motion seems to be unstemmed though it is indistinct which technologies will integrate to take the supercells’ shape.

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