Technology requirements for Ni/Cu plating metallization in commercial PV

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Abstract

Until now, Ni/Cu-plated contacts have not been widely favoured in the PV industry despite them being more cost-effective than screen-printed Ag/Al contacts, and the possibility of their further enhancing the cell efficiency in many concepts. One of the main challenges is that moving from one mature technology to another requires putting a great deal of intense effort in equipment and process development. Several fabrication aspects need to be considered in order to ensure the quality of Ni/Cu-plated contacts: 1) generation of contact patterns; 2) plated contact growth; and 3) post-processing for reliable cell and module performance. This paper reviews those associated fabrication technologies for the mass production of Ni/Cu-plated contacts. The technologies currently in use in the PV industry for plated contacts, as well as the developing technologies having high scaling-up potential, will be reviewed. In addition, the future requirements for plating metallization will be discussed.

Introduction

The PV market has been steadily growing during the last few decades. The continuous advancements in PV technology have made solar energy become more efficient and affordable. Since 2019, the price of electricity from large-scale PV power plants without any government subsidies has already been cheaper than from coal-fired power plants [1]. Although the record lab cell efficiencies are approaching theoretical limits, the mass production of such high-efficiency solar cells needs to consider more concepts, particularly in manufacturing reliability and overall cost. This generally leads to a delay in efficiency improvements which is reflected on conventional solar cells. Currently, passivated emitter and rear cell (PERC) devices are the industry-dominating technology, with a market share of over 80%, while tunnel oxide passivated contact (TOPCon) and silicon heterojunction (SHJ) solar cells are usually considered promising candidates for the next-generation high-efficiency solar cells [2,3].

In addition, screen-printing metallization by Ag/Al and Al paste is the mainstream process used in the PV industry for forming metal contacts, mainly because of its simplicity and high throughput [4]. However, there are several concerns around screen-printing technology remaining the major metallization method. First, the evolution of thinner and larger silicon wafers greatly increases the mechanical impact of screen-printing paste on the cell precursors, thereby leading to greater risks of wafer bowing and breakage. Second, TOPCon and SHJ solar cells typically rely on an ultrathin oxide or an a-Si layer to achieve excellent passivation, and therefore high efficiency [5]. The firing process in screen-printing metallization, however, has a high risk of damaging their selective passivation function. Finally, and most importantly, the high silver consumption could become a major disadvantage, limiting the future development of PV [6]. By 2020, the PV industry had already used more than 10% of the global silver supply, mainly for contact formation. In contrast, PERC solar cells mainly use Ag just for the front contacts, while TOPCon and SHJ solar cells need Ag for both the front and the rear contacts – approximately double the Ag consumption [7–9]. As global PV is expected to dramatically increase from ~135GW in 2020 to ~70TW in 2050, there will not be enough Ag for solar PV usage [9–12]. In the pursuit of higher efficiencies and cheaper solar energy, it is necessary to seek out other possible alternatives to metallization.

Among the various metallization technologies, Ni/Cu plating should be seriously contemplated, as it could fundamentally meet the previously mentioned challenges while having scaling-up potential [13–15]. From the early 1990s, plating was used in BP Solar’s buried contact (BC) solar cells, and those plated contacted solar cells showed less degradation than screen-printed solar cells after 20 years’ use [16–19]. This result implied that solar cells with plated contacts could be sufficiently durable. In the period 2009–2013, Suntech’s Pluto technology adopted plating metallization and came up with the world’s first p-type commercial solar cell having an efficiency of more than 20% [20–22]. SunPower also used plating in interdigitated back contact (IBC) solar cells, achieving an efficiency above 20% in

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solar panels integration [4, 23].

In recent years, there has been more and more research looking into the potential of plated metallization in solar cells with passivated contacts and other structure/material devices [24, 25]. Despite the consistent reports of challenges in adhesion and reliability, the highest efficiency of commercial solar cells now created by SunDrive use plated contacts without any Ag involved [26]. In fact, for several years the ITRPV has highlighted the potential of plated contacts, yet there has been no notable growth in this particular market [2, 3]. The reason for this is, perhaps, because starting up a newly built production line demands a certain amount of effort and financial investment in order to make its resulting product quality, reliability and process throughput superior to that of the existing technology [27]. However, the current equipment and process development for plated contacts do not yet seem to be fully ready for this — either lacking in reliability or generating too much waste in associated processing (i.e. use of a full-area seed layer in lithography patterning approach).

This paper presents a review of the existing and emerging technologies that need to be optimized in advance for a cost-effective realization of Ni/Cu-plated contacts in PV.

In general, the formation of Ni/Cu-plated contacts on well-passivated samples entails the following steps:
1. Generation of the contact patterns via opening the surface dielectrics
2. Ni plating
3. Cu plating

The application of Ni sinter used to be the standard process between steps 2 and 3 for forming nickel-silicide as the ohmic contact and Cu diffusion barrier. In recent years, however, there has been an increasing trend to skip this step, or to shift it to the end of the fabrication process [13, 14, 27]. Here, PERC cell precursors are selected as the main topic of discussion in the plating metallization process, as they are expected to continue to dominate the market in the next 10 years [2]. However, some of the fabrication processes might not be well suited to other emerging cell structures with passivation contacts, in which case alternative strategies will be discussed.

**Generation of plated contact patterns**

Prior to plating, metal contact patterns need to be developed on the well-passivated surface. Among the various methods for creating contact openings, laser scribing might be the fastest and simplest.

**Figure 1.** A representative cross-section schematic, and the microscope and SEM images for (a) laser ablation and (b) laser doping. The laser ablation was performed by a ps-UV laser, and laser conditions were chosen with the aim of only removing surface dielectrics; however, a slight morphology change in the underlying Si pyramids is often unavoidable. The laser doping was performed by a CW-green laser; because the laser used has a Gaussian disturbed power density, the edges of the opening are usually not very well defined, since the laser power in this region melts only the surface dielectric and not the underlying Si.
one, indeed, the high throughput might be its most attractive feature to manufacturers. Moreover, in recent years, the laser-doped selective emitter (LDSE) has steadily become a standard on the PV production line, which suggests a lower initial investment and smoother technology transfer when laser scribing is used for contact patterning.

There are several opening approaches that could be performed by laser scribing. Possibly the most straightforward one is laser ablation, which makes use of laser irradiation to remove only the surface dielectrics and leave most of the underlying microstructure unchanged. Fig. 1(a) shows a representative cross-section schematic, and the microscope and scanning electron microscope (SEM) images for laser ablation on a SiN$_x$-coated textured surface.

The surface dielectrics that need to be removed consist of typically a ~70–80nm SiN$_x$, a ~100–110nm SiO$_2$, a ~70–80nm-SiN$_x$/~6–15nm-SiO$_2$ stack layer, a ~50–60nm-SiN$_x$/~10nm-AlO$_x$ or other similar combination stack layers [4,28,29]. Those materials and thicknesses are normally chosen taking into consideration the anti-reflection coating (ARC) and passivation purposes. To achieve such opening patterns, the focus of the laser beam should be on the interface between the surface dielectrics and the silicon. Laser irradiation is mostly absorbed by the surface silicon and eventually converts into heat. Depending on the characteristics of the laser used (wavelength, operation types, etc.), this heat can result in melting or vaporization of the silicon [29–31]. The former case leads to a transfer of heat, thereby decomposing the dielectrics, while the latter case results in thermal stress, causing the dielectrics to lift off. For a textured surface, laser ablation has been reported to enhance the contact adhesion because of the increase in Si/metal interface area [32,33].

A laser can also be used to both remove the surface dielectrics and selectively dope the underlying Si. This approach is called laser doping (LD), which is based on the LDSE technology developed at UNSW in 2007. It involves four steps:

1. Melting of Si
2. Removal of dielectric layers
3. Diffusion of dopants
4. Recrystallization of molten Si

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The entire laser doping process takes place in less than one microsecond [30]. In this process, the laser energy needs to be high enough to melt the surface Si but not so high as to ablate/vaporize the Si substrate.

The dopant can be present in the form of a chemical liquid or a solid deposited film. When the molten Si rises to a sufficiently high temperature to decompose the surface dielectrics, the ‘doping’ process begins – both dopant and decomposed dielectrics will then rapidly diffuse into the molten region. Upon recrystallization, the front of the melt moves back towards the surface, then the molten regions undergoes epitaxial growth. A representative cross-section schematic, and the microscope and SEM images for laser doping on a SiN$_x$-coated textured surface are shown in Fig. 1(b). The laser doping approach can effectively create contact openings for the subsequent plating process and is beneficial for selective emitters (SEs) in terms of contact performance (contact resistance, $J_t$, etc.) [30,31].

The laser-ablation and laser-doping approaches have both been widely reported in many studies as contact opening methods for plating metallization in PERC and TOPCon solar cells [29,32–38]. Although the resulting efficiencies might not yet be superior to those of current industrial cells, it should be noted that there are usually a few processing parameters that have not been fully explored and optimized for cells with plated contacts in those trials. Furthermore, the use of different laser conditions (e.g. laser power, scanning speed, etc.) could significantly influence the plating metallization results, and hence the cell performance [39–42]. Detailed investigations in laser conditions particularly for plated contacts therefore need to be conducted before introducing plating metallization into the production line.

Laser structuring might not be ideal, however, for SHJ solar cells [43]. First, in SHJ solar cells, the metal contact is formed on a transparent conductive oxide (TCO), such as indium tin oxide (ITO). This TCO can act as a Cu diffusion barrier, thereby relaxing the stress in Ni plating, but direct Cu plating on TCO has poor adhesion. Moreover, the areas between the fingers must be isolated to avoid parasitic plating, as TCO is conductive. Finally, the doped a-Si layer plays an essential role in SHJ solar cell passivation, but it is unlikely that the TCO can be completely removed by laser scribing without affecting this underlying layer. Consequently, a different contact patterning approach is necessary for SHJ solar cells.

In general, the contact patterning in SHJ solar cells typically involves a lithography process (mask deposition and removal, etc.), despite the variety of processing routes that have been reported [43–53]. In most approaches, a thin seed layer is first deposited on the TCO by physical vapour deposition (PVD). Then a series of mask layer stacks, which could consist of photosensitive organic material, resin solution, hotmelt ink or even dielectric/metal layers, are formed on top of the seed layer by screen-printing, spraying, inkjet printing or plasma-enhanced chemical vapour deposition (PECVD). Depending on the mask technique used, the contact patterns would later be developed by photobiography, inkjet or laser structuring. After plating, the mask and unwanted metal are removed by wet-chemical etching.

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The overall process flow is clearly more complex than that for PERC and TOPCon cells where laser scribing is applicable. Fig. 2 shows a typical process flow comparison of laser scribing and the lithography patterning approach for Ni/Cu-plating metallization. Most importantly, the need for a full-area seed layer on the TCO to improve contact adhesion could be the most unappealing part of those approaches, because it means there is a large amount of material waste (~95%) and extra cost involved [9,52]. The latter consequence leads to the metallization costs for SHJ cells becoming even greater than for PERC cells, thus resulting in SHJ cells being less competitive in the PV market [9,49]. The insufficient adhesion of direct plating on TCO contacts, however, might also relate to inappropriate plating approaches (e.g. vertical plating), which will be discussed in the next section.

**Growth of plated contacts**

There are several different plating methods available for contact formation in solar cells. According to the way the plating circuit is connected, the contact can be formed by electroplating, light-induced plating (LIP) or bias-assisted LIP. A detail review of the working principles related to those plating circuits can be found in the literature [14], but here, more about the plating technologies will be reviewed, namely plating layout, equipment design and applications.

Vertical continuous plating (VCP) is currently the mainstream technology used in mass production plating, for example in printed circuit board (PCB) manufacturing. Nowadays, most conventional PV plating equipment also adopts this design layout [27,52]. Basically, metal clips are used to hold the cell precursors by the edges, which are then immersed in the plating bath and removed when the desired thickness has been deposited. Fig 3 shows a schematic of the vertical plating approach.

Different techniques have been developed (pulse plating, high-throw DC plating, etc.) to improve the plating results and processing reliability [54]. The major advantages of the vertical plating approach are its simple processing, low floor space requirement and reduced fume emissions. Empirically, the vertical plating works well in...
solar plating when a thin metal seed layer is pre-deposited on the cell precursors [55,56]. However, to accommodate the growing need for high aspect ratios and complex surfaces (black-silicon, etc.), horizontal plating might be the best option.

Furthermore, the use of metal clips for sample holding and acting as a cathode has caused many problems in PV plating. First, holding the point contacts increases the mechanical impact on the cell precursors. Nowadays, PV manufacturers continue to push Si wafers to thinner and larger sizes at a rapid rate [2]; this makes the issues of microcracks worse and even leads to wafer breakages in the plating process. Second, in the direct plating case (plating without the use of a metal seed layer), the inhomogeneous current distribution between the metallic clips and the semiconductor/TCO surface can decrease the plating uniformity, especially in cell precursors requiring bifacial plated contacts [52]. This is because the area having a low chemical potential (i.e., low resistance) tends to be more easily plated, thereby resulting in directional plating – from the area close to the metal clips towards to area away from the metal clips [57,58]. The finished plated contacts are therefore usually too thick at the edges and more prone to peeling away. Moreover, uneven plating extends the plating processing time, and cell precursors need to be soaked in the plating bath for longer, which leads to the risk of surface dielectrics being over-etched. In consequence, there is an emerging interest in horizontal plating, despite the increased complexity associated with operation, maintenance and equipment development.

Horizontal plating line was first introduced to PCB manufacturing in the late 1980s and is generally only used when the vertical plating approach is not practical or is unable to satisfy the technical requirements (high aspect ratio, complex multilayer structures, etc.) [59]. In the case of solar cells, the basic operation concept involves immersing only the surface to be plated in the plating solution, and the opposite side directly contacts the cathode. A schematic of the horizontal plating approach is presented in Fig. 4.

The full back contact characteristics greatly promote the plating uniformity, thereby making plating without a metal seed layer both viable and reliable, which is beneficial with regard to material cost and manufacturing complexity [27,42,60,61]. However, careful selection of the contact patterning concepts is also important in such direct plating cases. For example, the surface conditions (surface morphology, doping density, etc.) of the contact opening area are modified, and as a result may not be very uniform in terms of electrochemical potential after laser scribing. Regardless of whether this occurs, even though

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the desired plating approach is used, the plating quality is still limited by poor laser scribing [37,39,42,62,63].

Furthermore, because of the use of a larger tank in horizontal plating, the requirements of plating solution agitation and replacement are usually greater (to reduce the temperature gradient, to balance the high evaporation rate, etc.). In some designs, swiping or rotation of the cell precursors is even utilized; however, with those treatments there are also difficulties in maintaining the precursor at the same level during plating, and therefore undesirable rear-side wetting or floating of the precursors cannot be completely avoided [27]. Nevertheless, in conjunction with an appropriate contact patterning approach, several successful direct plating results using a horizontal plating line have been reported for TOPCon and SHJ cells [25,52,60,61,64]. This supports the potential of plated contacts for meeting the criteria of not only achieving higher efficiencies but also reducing costs.

So far, the reported horizontal plating approaches generally treat one side of the cell precursor at a time. As bifacial designs become more and more popular, the single-side plating characteristic will certainly become a concern: the processing time for plating is doubled, as well as there being the additional risk of breakage through samples flipping over [27,65]. To address such concerns, equipment development for simultaneous bifacial plating via the horizontal plating approach was recently revealed by UNSW [65]. This inline design utilizes a ‘dripping’ supply of plating solution, as well as a discontinuous plating bath, to allow LIP and electroplating to be performed simultaneously. Despite the reported best efficiency results not yet reaching the levels of current industrial PERC cells, a satisfactory contact performance demonstrates its feasibility and potential.

In summary, the horizontal plating approach is more suited to solar cell plating, as it allows viable direct plating, but further investigation to satisfy the requirements of both reliability and high throughput, perhaps through simultaneous bifacial plating, is needed in order to meet the rapidly growing market share of bifacial solar cells.

Other associated considerations
Apart from the standard contact formation procedure, other aspects need to be seriously considered, such as efficiency gain, modules and interconnection. Despite Ni/Cu-plated contacts often being acknowledged for their potential for efficiency enhancement on account of their reduced shading and low contact resistance, further improvements through appropriate methods are always desirable. For example, by integrating UNSW hydrogenation technology in between the Ni sintering and the Cu-plating steps, up to $\sim 0.6\%$ increase in efficiency has been recently reported for bifacial PERC cells with plated contacts [37,42,66]. Other possible techniques capable of providing similar benefits could be explored.

Module reliability might be the most important concern for PV metallization in the transfer from screen printing to plating. PV modules normally provide a 25-year performance warrantee ($\approx 80\%$ nameplate power after 25 years’ usage, which equates to $<0.5\%$ degradation rate per year) and
other associated safe operation guarantees [67]. To reach such a standard, enormous efforts have been made on developments in solar cell design and fabrication, as well as advancements in module and interconnection technologies.

More challenges are expected when Ni/Cu-plating metallization is introduced into the production line, as material and fabrication methods are different [27,68]. For example, standard soldering is not well suited to plated contacts because of the concerns about stress. Approaches such as SmartWire, ribbon gluing and wire interconnection are emerging to address such issues, and even further improve module performance. New concerns, however, are also becoming apparent: for example, the additional usage of scarce metals (such as bismuth) in SmartWire technology may limit the supply chain [9]. Moreover, issues such as the large quantity of hazard waste produced by plating and reliable characterization technologies for inline plating of samples and finished products should also be carefully considered and standardized [9,27,68].

Conclusions
In 2021 the global PV generating capacity achieved the terawatt (TW) level and is estimated to reach ~70TW by 2050, which means that a production capacity of ~3TW will be required per year by the PV industry. Despite the price of large-scale PV power plants, there are concerns around further development possibly being limited by the scarce metal usage, particularly Ag, in metallization. To significantly reduce, or even eliminate, the necessary use of Ag, shifting the currently dominated screen-printing technology to plating metallization could be a promising solution. However, to introduce new technology into large-scale manufacturing, new challenges arise and need to be overcome first before that technology can stand alone in the market. In this paper, several technologies have been reviewed that need to be comprehensively investigated and developed for the large-scale manufacturing of Ni/Cu-plated contacts in PV.

With regard to the requirement for contact pattern generation, the laser scribing approach is expected to be the most suitable because of its simple and rapid processing capability. Laser scribing can be carried out by either laser ablation or laser doping, and has been successfully implemented on PERC and TOPCon solar cells. While the former would promote better adhesion on a textured surface in view of the larger Si/metal interface, the latter could enhance cell performance by using selective emitters. It has to be emphasized that in either approach, the laser scribing conditions need to be chosen carefully, as the resulting surface conditions (morphology, doping, etc.) can significantly influence the plated contact formation. However, in the case of SHJ solar cells, the lithography process would be preferable owing to its unique layer structure. Different processing routes have been reported and have delivered satisfactory results, but the common use of a PVD seed layer could create additional financial concerns, and therefore warrants further investigation.

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Figure 4. (a) Schematic of the horizontal plating line used in solar cell plating. (b) Photographic examples of cell precursors in the plating process.
Currently, vertical continuous plating is the mainstream method used in PV manufacturing. Although such a layout offers the convenience of bifacial plating by a relatively low space requirement, it generally results in poor plating uniformity when a metal seed layer is not used. Consequently, there is an emerging trend of using the horizontal plating approach to resolve such issues and achieve a better aspect ratio. Several successful direct plating results for almost all types of cell structure have been reported by using the horizontal plating approach, and some are already in pilot line development. However, most existing (and under development) horizontal plating equipment only plate a single side at a time, which could be a concern, as the market share of bifacial cells is expected to grow rapidly in the next decade. It might be worthwhile, therefore, to look into a specific horizontal plating design layout that allows both sides of the cell precursors to be plated simultaneously.

Besides the technologies directly related to contact formation, there are other issues that should also be seriously considered. These include techniques for further cell efficiency enhancement, module and interconnection reliability, waste hazard processing and standard characterization development. In conclusion, it is never simple to move from one mature technology to another, especially when there is a need for complex process integration. A comprehensive investigation of each necessary concept is necessary. In order to encourage a wide adoption of Ni/Cu-plated contacts in commercial PV, developments in technology and equipment (e.g. reliability, throughput and cost-effectiveness) will first have to reach a certain level.

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References

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