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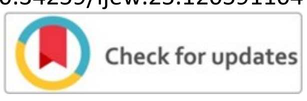

Future Prospect & Challenges on Cu/Ni Metallization Techniques in Photovoltaic Cells

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***Abstract*—** A key component of achieving higher efficiency is improving the process of metalizing silicon solar cells. Due to its simplicity and speed, contact realization by screen printing is now the most popular technology in the silicon-based photovoltaic sector. The issue with this type of metallization is that it has a higher contact resistance and a smaller aspect ratio, which restricts the efficiency of solar cells. Silicon solar cell producers are encouraged to develop new metallization techniques that use less silver and do not rely on the pressing process of screen printing due to the rising cost of silver pastes and decreasing silicon wafer thicknesses. Recently, a metallization technique that might address these problems is nickel/copper (Ni/Cu) based metal plating. In this review, we will describe the progress of electroplating techniques, mainly for the deposition of nickel/copper by laser deposition for nickel and the light-induced copper plating process. The metallization of the front-side silicon solar cells using a copper stack system is integral to achieving superior efficiency. The formation of a Ni seed layer by applying laser-assisted deposition has the advantage of using a single step for opening the ARC and the seed layer formation. Cu conducting layer using a light-induced plating (LIP) as the primary stack system, after applying a nickel seed layer to stop copper from diffusing into silicon, we also check tin as a top layer stack to protect it from oxidation. Moreover, we finally addressed the future advanced challenges and the issue of copper diffusion, background plating, and cost reductions.

***Keywords*—** Copper, Nickel, Metallization, LIP, Silicide

I. INTRODUCTION

Improvement of Silicon Solar Cell Metallization. Since a better methodology was observed for higher efficiency that had to be developed, contact formation by screen printing remains the dominating technology due to its simplicity and high processing speed in the conventional silicon-based photovoltaic industry[1]. This metallization method has a lower aspect ratio and higher contact resistance, reducing solar cell efficiency. The rising cost of silver pastes and thinner silicon wafers drives silicon solar cell firms to use less silver without screen printing. According to the International Technology Roadmap for Photovoltaics, solar cells must perform better with less silver paste[2]. Improved metallization of silicon solar cells is key to commercializing solar cells efficiently. However, the rising cost of silver and the need for higher efficiency have driven the search for alternative metallization techniques. Silicon solar cells have undoubtedly been the fundamental backbone of the entire global photovoltaic industry, representing a significant share of more than 95% of all the solar modules produced worldwide. These solar cells were massive, and widespread adoption has been driven mainly by their notable reliability, impressive scalability, and continuing advancements that have improved their efficiency and overall cost-effectiveness[3]. The metallization of silicon solar cells—forming conductive contacts on the surface of a solar cell to gather and transport the generated electricity—has been one of the most vital parts of the manufacturing process. Among many metallization methods, nickel-copper (Ni-Cu) electroplating has proven to be the most promising due to its superior performance, longer lifespan, and lower production cost[4]. This chapter will focus on the role of Ni-Cu electroplating techniques in silicon solar cell manufacturing and review their application in increasing efficiency, lowering costs, and paving the way toward advanced silicon solar cells.

Copper is considered one of the best metals to replace silver in the photovoltaic (PV) industry. On the other hand, it represents a glamorous alternative to silver in the photovoltaic industry since it is significantly cheaper, more abundant, and highly conductive; it has good compatibility with existing technologies. Copper metallization is expected to be introduced for mass production in 2020, and a market share of about 10% is expected by 2028. As innovation within the industry continues to evolve and solves the challenges that exist with copper, it will be more important in the future of solar energy[5]. Copper has some limitations when used alone, including its high diffusivity and solubility in silicon and copper contamination in silicon solar cells, which reduces device performance due to minority

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carrier recombination centres. Nickel is often used as a diffusion barrier to remove Cu from silicon[6]. Nickel/copper (Ni/Cu) plating has emerged as a viable solution, offering lower material costs, higher conductivity, and the potential for finer line widths, which reduce shading losses and improve cell efficiency. A good solution to enhance precision and low contact resistance in efficient metallization is to use Ni/Cu plating. This can be realized in lower material costs and can be used in the mass production process. The standard processing sequence of Ni/Cu contact formation is a three-step process, wherein first, (i) Ni metal film is plated onto the silicon substrate, (ii) the second step of plating a copper metal film on top of the Ni, (iii) then the final step by capping with tin. Ni as a seed layer enables metals to be plated on semiconducting or non-conducting materials[7]. The electroless plating process of Ni involves a complexing agent, a buffering agent, and a reducing agent that reacts with metal ions to form a metal film. Besides the conventional electroless plating of the Ni seed layer, it is plated in the presence of illumination, known as light-induced electroless plating. After the Ni seed layer formation on a silicon substrate, copper is conventionally electroplated to increase the metal line conductivity. Also, narrower metallization lines (10–30 μm) result in smaller shading effects and lower specific contact resistivity[8]. The light-induced plating (LIP) methodology, developed by the Fraunhofer Institute for Solar Energy Systems (ISE), has been adopted and widely used by many research groups for the deposition steps of silicon solar cells. In carrying out the LIP method, a sample with an n/p junction and an aluminium back contact screen printed is immersed in a plating bath. Increasing applied bias forces increases the operating current density of the cell, and consequently, plate rates rise [9]. The LIP arrangement is helpful in controlling plating height because a modification of the process velocity results in the variation of light intensity or, conversely, vice versa. Furthermore, the LIP is believed to be promising for the metallization of solar cells since metallization for the front grid and the fully aluminium-doped rear side can be realised simultaneously[10]. Such Cu-based LIP plating process is schematically shown in Figure 1.

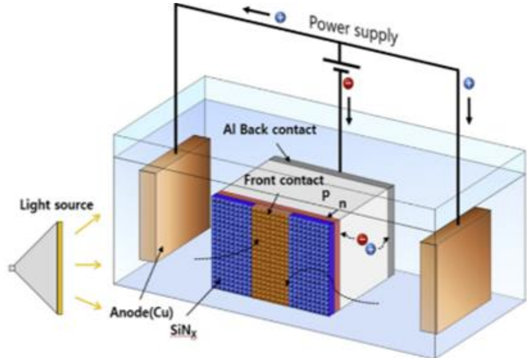

Fig. 1 Schematic Diagram of Light-induced Plating (LIP) based on copper platin

This review focuses on the Ni/Cu plating technique, specifically the deposition of nickel as a seed layer, copper plating for conduction, and tin capping for protection. The review will cover the various methods of nickel deposition, the copper plating process, and the challenges associated with this metallization technique, including adhesion, background plating, and long-term reliability.

II. Reasons to Replace Silver

Crystalline silicon solar cells are the most common type used worldwide. In the laboratory, a single solar cell has been produced with an efficiency of 25%, and multiple cells with 20%. The market-available cells under standard test conditions (STC) have an 18%–22 % efficiency. Crystalline solar cells can be either monocrystalline or polycrystalline[11]. Since the beginning of the photovoltaic (PV) industry, silver screen printing has been utilized to establish electrical connections on solar cells. It is necessary to apply silver paste to the surface of the cell to generate conductive grids that are capable of collecting and moving electrical current. Despite the fact that it is effective, there are a number of difficulties associated with the utilization of silver. These drawbacks include higher material costs, vulnerabilities in the supply chain, and environmental problems. As the demand for solar energy continues to grow, there is an urgent need to explore alternative materials and methods to replace silver screen printing in PV cells. This shift is critical to reducing production costs, improving sustainability, and ensuring the scalability of solar technology to meet global energy needs[12]. This review highlights the necessity of transitioning from silver screen printing and explores potential innovations that could revolutionize the PV industry. Solar panels are typically between $8,500 and $30,500; the median is about $12,700 for a 6kW solar system. Naturally, these estimates should properly include the effects of incentives and tax credits in the equation. Our research shows that the price of solar panels depends on location, system size, panel type, and other variables. With the numerous variables that go into the final cost of solar panels, a knowledge of the particular areas in which costs can be incurred can ensure efficient budgeting for installing solar panels and thus enhance the potential for energy savings[13]

As you're budgeting for a solar panel system, you may come across three types of solar panels. Each can come with a price tag, so consider the following differences before choosing.

A. *2.1 Monocrystalline Solar Panels*

Monocrystalline solar panels, the most common type, cost $1–1.5 per watt. As its name implies, monocrystalline cells use one silicon crystal. To maximize efficiency, laboratory-made crystal ingots are sliced into thin octagonal discs and meticulously fastened to the panel. Monocrystalline solar panels cost more to buy and install than heterocrystalline ones. Thus, their efficiency comes at a cost.

Fig 2. Monocrystalline Solar panel

B. 2.2 Polycrystalline Solar Panels

The average cost for polycrystalline solar panels ranges from $0.90 to $1.50 per watt. Both polycrystalline and monocrystalline solar panels are photovoltaic (PV) solar panels. They convert sunlight into electricity. Unlike monocrystalline cells, however, the polycrystalline variety comprises fragmented silicon crystals cut into wafer-like shapes. This shortcut makes for a cheaper product that is faster to produce, but also less efficient.

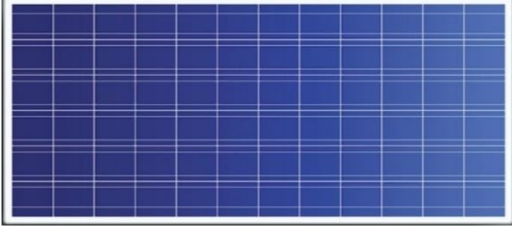

Fig 3. Polycrystalline Solar panel

C. 2.3 Thin-Film Solar Panels

The thin-film solar panels are the most cost-effective type of solar panels, with prices ranging from $0.50 to $1.50 per watt. Although the vast majority of thin-film cells use amorphous silicon, which is not crystalline, these solar panels also make use of photovoltaic materials. Thin-film solar panels are more environmentally friendly than other types of solar panels due to the fact that they are less expensive to manufacture and use materials that are easily accessible.

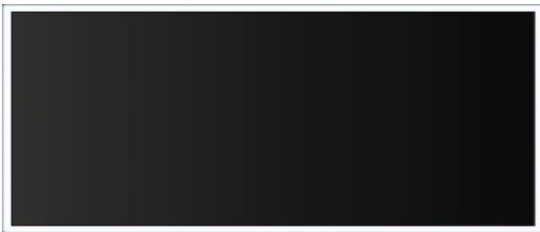

Fig 4. Thin-Film Solar Panel

Because solar panels are often less efficient than other types of energy production systems, they require a bigger space to generate the same amount of electricity. To add insult to injury, their lifespan is only ten to twenty years, which is ten to fifteen years shorter than that of photovoltaic panels. On the other hand, we believe that thin-film solar panels are a fantastic alternative for RVs because of their lightweight nature. This is especially true if you are continuously on the move.

TABLE I AVERAGE COST BY PANEL TYPE

Panel type	Cost/ Watt	6KWsystem Cost
Monocrystalline	$1.00-$1.50	$6,000-$9,000
Polycrystalline	$0.90-$1.50	$5,400-$6,000
Thin-film	$0.50-$1.50	$6,000-$9,000

Assessment of the world efficiency record reported for different thin-film-based solar cell methods, including mono-cell devices. Note: Polycrystalline-based solar cells are not included in this evaluation.

III. NICKEL COPPER METALLIZATION

Using Ni-Cu plated contacts, it is possible to overcome the challenges associated with silver paste technology. The plated metal has the bulk conductivity of copper, making it twice as conductive as the silver paste. The nickel seed layer is annealed to form a thin nickel silicide layer, which has a low resistivity of 10-20 μΩ.cm. This low resistivity facilitates good ohmic contact with lightly doped silicon. A contact opening of less than 10 μm can be achieved using femtosecond laser ablation of the dielectric[14]. However, recent developments in equipment and processes related to plated contacts are not adequately prepared for this challenge, either unreliable enough or generating excessive waste in the processing involved (e.g., using a full seed layer in the lithography patterning technique). The formation of these contacts involves multiple steps, including anti-reflection coating removal, Ni plating, Cu plating, and tin capping, as shown in Figure 6. This literature review examines the existing processes and their effects on contact formation, as well as emerging technologies that need to be optimised in advance for a cost-effective realisation of Ni/Cu-plated contacts in PV.

(i) Remove the ARC to expose the emitter regions.
(ii) Ni Plating
(iii) Cu Plating
(iv) Tin Capping

Removing the anti-reflection coating to expose the emitter regions is the pre-plating of Ni/Cu plating, while Tin Capping is the post-plating step. In the Ni/Cu plating technique, Ni can serve as a seed layer, while Cu can be deposited as a main conducting layer by electroplating.

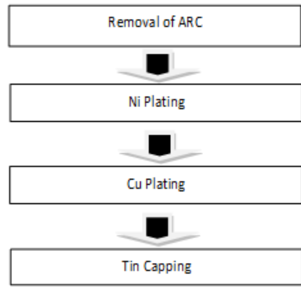

Fig 5. The Process involved in the formation of Ni/Cu-based metallization

The development of nickel/copper (Ni/Cu)-plated contacts has gained significant attention for silicon solar cells due to their potential to replace conventional silver contacts, offering reduced material costs and improved electrical performance. The formation of these contacts involves multiple steps, including anti-reflection coating removal, Ni plating, Cu plating, and tin capping.

A. 3.1 Nickel Formation

Initially, a nickel metal seed layer can be established through electroless plating, light-induced plating, or laser-assisted deposition. Other transition metals like tungsten (W) or titanium (Ti) may also serve as seed layers. Nickel is the optimal choice due to its efficacy as a diffusion barrier and its ability to maintain low contact resistance with doped silicon. The electroless deposition of nickel, coupled with low-temperature annealing, facilitates the formation of low-resistivity ohmic contacts. As long as the oxidation-reduction reaction principle is considered, there are numerous ways to execute the electroless plating process. The plating rates can be significantly altered by using a technique called light-assisted plating (LIP) [15]. Furthermore, the laser-aided nickel deposition method is another extremely effective strategy for creating the nickel seed layer. Considering that the anti-reflection coating (ARC) and ablation step may be carried out simultaneously with the production of the Ni seed layer, this approach offers a great deal of competitive advantage[16]. To deposit an efficient nickel barrier layer, the fundamental requirements include a sufficient thickness and an evenness that has been achieved across the entire front side patterned grid. The efficiency of the barrier layer is determined by the degree to which it can contain copper and prevent its diffusion over a specified amount of time. On the other hand, a thinner covering of nickel is preferred because the conductivity of nickel is lower than that of coppe[17].

1) 3.1.1 Laser Nickel Deposition

Laser-based front-contact openings and metal deposition are considered to constitute the most appropriate method for fabricating cells with Ni/Cu contacts on the industrial scale. In 1990, laser-based contact patterning was done for EFG polycrystalline silicon solar cells. At the University of New South Wales (UNSW), which is located in Australia, laser-grooved buried contact (LGBC) solar cells were manufactured through the application of the laser process. Following that, BP Solar became involved in the production of LGBC solar modules for commercial use[18]. Several studies have indicated that laser ablation and laser-doping procedures are both effective contact opening methods for plating metallization in PERC and TOPCon solar cells. Both approaches have received widespread acceptance.

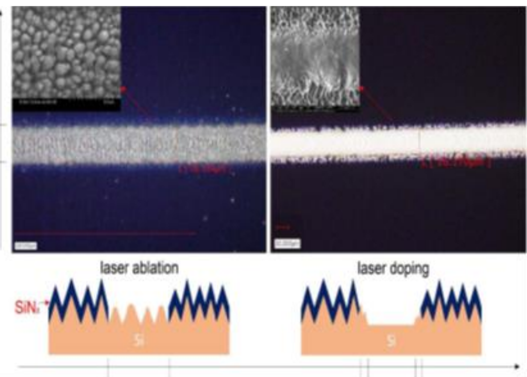

Fig. 6 Sample cross-section schematic and microscope and SEM photos for (a) laser ablation and (b) doping

Several opening approaches 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 [19]Fig.6(a). Demonstrates a cross-sectional schematic that is indicative of the whole, as well as images obtained from a microscope and a scanning electron microscope (SEM) for laser ablation on a surface that has been coated with SiN

Dopants can be present as chemical liquids or solid films. At a high temperature, molten Si decomposes surface dielectrics, triggering the 'doping' process, where dopant and disintegrated dielectrics rapidly diffuse into the molten zone. Recrystallisation causes the melt front to advance toward the surface, leading to epitaxial growth in the molten zone[20]. Representative cross-section schematic, microscope, and SEM pictures for laser doping on SiNx-coated textured surface are shown in Fig.6 (b). Several studies have indicated that laser ablation and laser-doping procedures are both effective contact opening methods for plating metallization in PERC and TOPCon solar cells. Both of these approaches have received widespread acceptance[21]. The ARC ablation step and laser chemical metal deposition (LCMD) Ni deposition procedure can help commercialize Ni/Cu metallization for silicon solar cells. Ni was deposited using the LCMD technique at Fraunhofer ISE, followed by nitride ablation and Cu plating. Laser transfer contact (LTC) was utilized to deposit a Ni seed layer through optically transparent glass with finger widths of less than 30 nm[22].

2) 3.1.2 Electroless Plating of Nickel

The adherence and surface coverage of the metal that is being deposited are two of the most important challenges that must be taken into consideration. In the past, Boulord and his colleagues have reported that in order to satisfy these conditions, electroless nickel must have a pH value that has high requirements[23]. Electroless nickel plating is a recognized technique, particularly appropriate for depositing the seed layer on semiconducting surfaces, as electroplating necessitates a conductive substrate for deposition. The anti-reflective coating of the solar cell will serve to mask and prevent deposition in unpatterned areas. A critical element of solar cell metallization is that nickel diffusion through the emitter and bulk material can result in shunt formation and a decrease in minority carrier lifetime[24]. For the purpose of depositing the nickel, both electroless and LIP techniques are utilized. The nickel is subsequently annealed in order to produce silicide. It is found that there are adhesion issues, notably with electroless nickel; however, LIP nickel works better, obtaining efficiencies of up to 17.4% and highlighting the necessity of surface roughness for adhesion. In order to assess the influence that contact formation has on the junction, a pseudo-fill factor, also known as pFF, is utilized. The results are more favorable when the temperatures are lower[24]. The plating bath for nickel electroless plating is made up of the following bath compositions, one of which is a reducing agent consisting of sodium hypophosphite[25].

- Nickel chloride, ($NiCl_2 \cdot 6H_2O$) or nickel sulfate, ($NiSO_4[H_2O]_6$) as a main source of Ni
- Triammonium citrate [$(NH_4)_3C_6H_5O_7$] as a buffer and mild complex agent for Ni

•Sodium hypophosphite, (NaH2PO2·H2O) as a reducing agent

$$\text{Step (1)}\ \ H_2PO_{\overline{2}} + H_20 \rightarrow HP\frac{2}{3} + 2H^+ + H^- \quad (1)$$

$$\text{Step (2)}\ \ 2H^- + Ni^{2^+} \rightarrow N\dot{i} + H_2 \quad (2)$$

$$\text{Sum:}\ \ 2H_2P_{\overline{2}} + 2H_2O + Ni^{2+} \rightarrow Ni + \dot{H}_2 + 4H^+ + 2HPO_{\overline{2}} \quad (3)$$

Optimizing Ni/Cu metallization involves balancing deposition techniques, material interactions, and cost. Electroless and electrolytic plating are the dominant methods, with electroless plating favored for its simplicity and uniformity. Su et al. (2012) [26] investigated light-induced nickel plating on p-type silicon, elucidating mechanisms that enhance deposition selectivity and reduce background plating. Similarly, Russell et al. (2012) [27] proposed a simple copper metallization process achieving high efficiencies, emphasizing process streamlining for industrial adoption.

3) 3.1.3 Light-Induced Plating (LIP) of Nickel

Light-induced plating (LIP) is an electrochemical deposition technique employed to metalize silicon solar cells to create nickel (Ni) seed layers and contacts. This method utilizes the photovoltaic impact of the solar cell to facilitate the plating process, allowing for accurate, cost-effective, and scalable metallization. The following is a comprehensive analysis of its concepts, benefits, and applications in photovoltaic cells[28]. With the help of the photovoltage produced by the PN junction and the electronegativity of the substrates, the electron migration at the surface may be appropriately controlled[29]. Additionally, the diffusion of these photo-generated electrons at the surface helps in the reduction of Ni2+ ions and contributes to the formation[30]. A new batch of Cz material was able to produce an even greater efficiency of 17.2% by the time the first trial was completed. The use of a nickel layer that was deposited by LIP rather than electroless plating did not have any impact on the performance of the cell[31].

4) 3.1.4 The Formation of Nickel Silicide

Nickel silicide formation is a critical step in Ni/Cu processes, enhancing adhesion and electrical contact. Mondon et al. (2013) [32] through the examination of the microstructure of nickel silicide that was formed through thermal processing identified, the perfect conditions for contact stability. Following the deposition of nickel, the sintering process produces a silicon and nickel alloy by heating nickel in nitrogen gas. The alloy is responsible for the seeding of copper, which is created at higher temperatures. (300–400 °C). Metal semiconductor contact resistance decreases[33]. The Ni creates numerous phases with varied compositions when heated at various temperature ranges, such as Ni2Si (200–300 °C), NiSi (300–700 °C), and NiSi2 (700–900 °C)[34]. Raval et al. (2015) explored the production of silicides and how they affect fill-factor losses, offering solutions to decrease the consequences of recombination. These findings underscore how critical process control is to manufacturing high-performance Ni/Cu contacts shown in Fig.7.

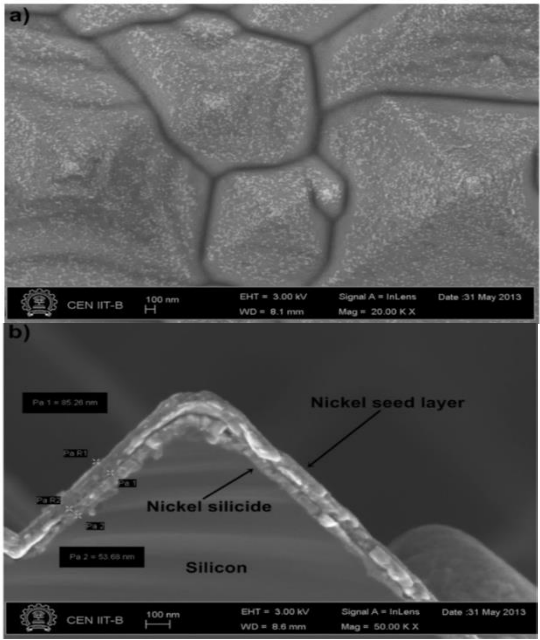

Fig. 7 Manufacturing high-performance Ni/Cu contacts

5) 3.2 Electroplating of Copper

Copper plating has emerged as a transformative technique in the metallization of silicon solar cells, offering a cost-effective and high-performance alternative to traditional silver-based contacts[35]. As the photovoltaic industry seeks to reduce manufacturing costs while maintaining or improving efficiency, copper's high conductivity, abundance, and compatibility with plating processes have made it a focal point of research and development[36]. The main source of Cu is copper sulfate (CuSO4 ・ 5H2O), which produces copper ions (Cu^{+2}) in the bath. High copper concentration produces high current density in the solution[37]. However, if copper from the anode contributes to exceeding the solubility limit of 240 g/L, copper sulfate recrystallises in the plating bath. Also, sulfuric acid (H2SO4) was added to the solution to enhance conductivity

$$\mathrm{Cu} + 2e^+ \rightarrow \mathrm{Cu}^{+2} \quad (4)$$

$$CU + 2e^+ \rightarrow Cu^{2+}$$
$$H_2SO4 \rightarrow 2H^+ + SO_4^{2-} \quad (5)$$

$$\mathrm{Cu}^{2+} + 2e^- \rightarrow \mathrm{Cu} \quad (6)$$

The above equations show the reaction at the anode (4), in the solution (5), and at the cathode (6). Figure 1 shows the Cu LIP process

The Ni/Cu front contact was formed by plating, as shown in Fig. 8, an FE-SEM image. Sang-Hee Lee et al. at the Green Strategic Energy Research Institute measured the thickness and surface of the deposited nickel using an FE-SEM (JSM-7100F) and the adhesion using a universal testing machine (UTM, H5KT) with a 90° angle.

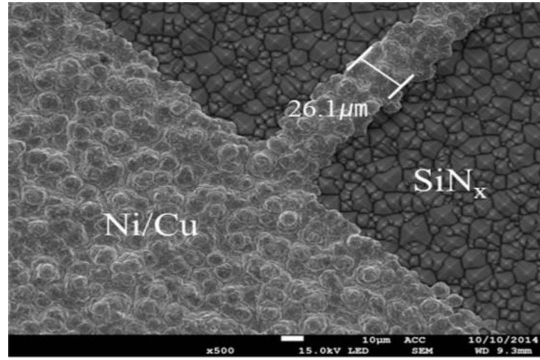

Fig. 8 FE-SEM image of Ni/Cu front contact was formed by Plating[38]

IV. Experimental Details

Manufacturing the seed layer can be accomplished by various methods, such as chemical plating, tampon printing, or spray printing, for instance. The substrate must be thoroughly cleaned before nickel can be electroplated onto a solar cell component (often a silicon wafer or a conductive layer like a metal contact). This is critical because contaminants, such as dirt, grease, oxides, or organic residues, can prevent the nickel from adhering correctly or lead to uneven plating, affecting the solar cell's performance. Before completing the Ni electroless plating process, the ARC (anti-reflection coating) must be opened. There are a variety of methods that can be used to open the ARC. One such method is the mask and etch sequence or laser ablation. It all starts with a photolithography procedure for patterning the photoresist mask. After that, the emitter area is exposed by etching away the unprotected ARC. Hydrofluoric acid is often used to etch ARC, and then an organic solvent is used to peel the mask layer. Patterning lines with smaller widths is possible using the photolithography method, which can be applied to the mask layer. Process: (i) Degreasing: The substrate is cleaned with an organic solvent (e.g., acetone or isopropyl alcohol) or an alkaline solution to remove oils and organic residues. (ii) Rinsing: The surface is rinsed with deionized water to remove any remaining solvent or cleaning agents. (iii) Acid Etching (if needed): A mild acid solution (e.g., dilute sulfuric...

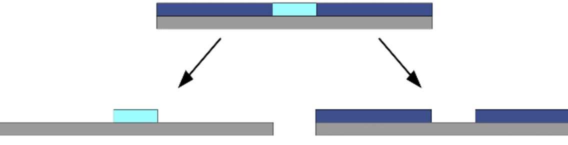

Fig. 9 Schematic mask and etch sequence. Mask patterning is done initially to open ARC, followed by a process of photoresist removal

One of the capabilities of the ARC opening process, which is founded on photolithography, is the ability to pattern lines with lesser widths. Due to the large number of processing steps that are involved in such a system, however, the high throughput that is required for commercialization may be hampered. The photolithography method is simply one of several possible approaches that can be taken to unlock the ARC. Among the components of the technique are etching pastes, laser-transferred nickel seed layers, mechanical scribing to open arc-reflective coatings, and aerosol jet etching[38]. The LCMD technique, which stands for laser chemical metal deposition, is often regarded as the gold standard for industrial applications. The approach streamlines the process by combining nitride ablation and seed layer production into one step, making it easier to implement. The laser chemical metal deposition methods developed by N. Wehkamp et al. at Fraunhofer ISE were used to create a 40 µm wide line for solar cells made on p-type CZ silicon substrates. The team reported an efficiency of 17.9% using this technique[7].

V. Advancements in Cu Plating

Only six businesses have chosen to license the technology, including BP Solar, but they are the only ones who have seen the process through to commercial use. Mason 131 has examined the evolution of the industrial laser and the grooved buried grid. Following an Australian laboratory development phase (1986-1989) [39]. The first commercial cells were exported in 1992 after a pilot facility was set up in Alcobendas, Spain. These techniques involve replacing silver, which is expensive and scarce, with copper, which is relatively abundant and substantially cheaper[40]. As of March 20, 2025, the following is a comprehensive analysis of more than ten businesses and institutes that have recently made important contributions to implementing copper plating in solar cells. Note that this analysis is based on advances that have occurred.

Fraunhofer ISE in Germany has been a pioneer in Cu plating for silicon solar cells, particularly in tunnel oxide passivated contact (TOPCon) and silicon heterojunction (SHJ) technologies. Their work focuses on replacing silver with Ni/Cu stacks, achieving efficiencies exceeding 24%[41]. At the 52nd IEEE Photovoltaic Specialists Conference (PVSC) in 2024, they reported a TOPCon cell with a Cu-plated front contact, achieving 24.0% efficiency and reducing silver usage by over 90%[42] (IEEE PVSC, 2024 proceedings). SunDrive, an Australian solar technology company, has been a pioneer in Cu plating for solar cells. In December 2024, the company achieved a copper plating production yield exceeding 99% at its commercial pilot facility, a milestone supported by an AUD 11 million grant from the Australian Renewable Energy Agency (ARENA). SunDrive's technology replaces silver with copper, reducing costs by leveraging copper's abundance and conductivity. Earlier, in 2022, they recorded a 26.41% efficiency in a full-size silicon heterojunction (HJT) cell, verified by the Institute for Solar Energy Research in Hamelin (ISFH). This demonstrates their leadership in scaling Cu-based metallization for commercial applications[43].

UNSW in Australia has conducted influential research on Cu plating's potential to replace silver in solar cells. A 2021 study by Brett Hallam and colleagues explored copper plating as a sustainable alternative for terawatt-scale PV production, highlighting its cost advantages and compatibility with technologies like PERC and HJT. Their work emphasizes the need for industry shifts toward Cu-based metallization to address silver supply constraints, influencing global PV roadmaps[44].

Historically a leader in PV innovation, Siemens Solar has contributed to Cu-based solar cells through its work on copper indium diselenide (CIS) thin-film modules. Recent efforts,

building on collaborations with the U.S. Department of Energy's Thin-film Photovoltaics Partnership Program, have improved efficiencies beyond 12% in large-area CIS modules. While not exclusively focused on Cu plating, their advancements in copper-based semiconductors have informed modern Cu metallization techniques[45]. Maxwell, a key equipment supplier, has supported Cu plating advancements by providing cutting-edge chemical vapour deposition (CVD) and physical vapour deposition (PVD) tools. In 2022, their equipment enabled SunDrive to enhance HJT cell performance, achieving a 26.41% efficiency by improving passivation and contact resistance with Cu-plated electrodes. Maxwell's innovations in manufacturing tools are critical for scaling Cu plating processes[46]. SunPower, a U.S. solar company, has long used Cu plating in its Maxeon cell technology, particularly for rear-side contacts. Their 24.4%-efficient interdigitated back contact (IBC) cells use copper's conductivity and cost to achieve efficiency[47]. Imec, a leading research hub in Belgium, has advanced Cu plating for industrial-scale SHJ cells. Their research emphasizes optimizing seed layers (e.g., Ni or Ti) and plating processes to enhance contact reliability. A key contribution is documented in the IEEE Journal of Photovoltaics, where Horzel et al. demonstrated SHJ cells with Cu-plated contacts achieving efficiencies above 22% and improved fill factors[48].

NREL, a U.S. research institution, has contributed to Cu plating in SHJ and tandem PV cells, focusing on contact formation and long-term stability. Their work on alternative seed layers for Cu plating was presented at the 38th IEEE PVSC (2012), achieving efficiencies above 19% in early prototypes[49].

Oxford PV, a UK-based company, has extended Cu plating to perovskite-silicon tandem cells, targeting efficiencies above 29%. Their metallization innovations reduce reliance on expensive materials, with their work reflected in broader IEEE PVSC discussions on tandem cell advancements[50]. Tongwei Solar, a Chinese PV giant, has implemented Cu plating in TOPCon and SHJ cells for mass production. Their collaboration with research partners has yielded efficiencies above 23%, with findings presented at recent IEEE PVSC conferences emphasizing Cu's role in sustainable PV manufacturing[51]. TU Delft in the Netherlands has developed innovative Cu-plating techniques for carrier-selective contact cells. Their research, published in the IEEE Journal of Photovoltaics, demonstrated a 19.6% efficiency TCO-free cell with Cu-plated contacts, improving fill factor and cost-effectiveness[52]. REC Group, a Singapore-based company, has explored Cu plating in its Alpha series SHJ cells, achieving efficiencies above 21%. Their efforts focus on durability and scalability, with related advancements discussed in IEEE forums on SHJ cell optimization[53]. Panasonic has advanced Cu plating in its HIT (Heterojunction with Intrinsic Thin-layer) solar cells, achieving efficiencies of up to 24.7%. Their work integrates nickel/copper (Ni/Cu) stacks to enhance fill factors and reduce costs, demonstrating copper's potential in high-performance PV modules. Panasonic's contributions underscore Cu plating's reliability in industrial settings[54]. South Korea's Shinsung Solar Energy has achieved over 19% efficiency in commercial selective emitter solar cells with Ni/Cu-plated contacts. Their 2012 demonstrations at the European Photovoltaic Solar Energy Conference highlighted copper's ability to lower contact resistance and improve performance, paving the way for broader adoption in crystalline silicon cells[55]. A major player in the photovoltaic copper plating equipment market, Kunshan Dongwei Technology (China) has driven the adoption of Cu plating in high-efficiency cells like HJT and TOPCon. Their equipment supports vertical and horizontal plating processes, contributing to a projected market growth from $150 million in 2025 to $2,217.1 million by 2030, with a CAGR of 72%. Their focus on precision and automation has made Cu plating viable for mass production, and the latest advancement is shown in Table II below.

TABLE II. LATEST RESULTS FROM THE RESEARCH INSTITUTIONS AND MANUFACTURING COMPANIES.

R&D Center	type	Efficiency	
Fraunhofer (ISE)	SHJ & TOPCon	24 %	[56]
SunDrive Solar	HJT	26.4 %	[43]
REC Group	SHJ	21%	[53]
Siemens Solar Group	CIS	12%	[45]
Imec	SHJ	22%	[48]
SunPower	IBC	24.4%	[47]
NREL	Tandem PVC	19%	[49]
Oxford PV	PVSC	29%	[50]
Tongwei Solar	TOPCon	23%	[51]
TU Delft	TCO-free cell	19%	[52]
Panasonic	HIT	24%	[54]
Shinsung Solar Energy	CSE	19%	[55]

The shift to Cu plating addresses the PV industry's need to reduce reliance on silver, which is both expensive and subject to supply chain volatility. Fraunhofer ISE and Imec have set benchmarks by demonstrating high-efficiency cells with Cu, supported by rigorous IEEE-documented testing. Companies like Meyer Burger and Tongwei Solar have bridged the gap between research and industrial application, scaling Cu plating for mass production. SunPower and Panasonic have leveraged their expertise in high-efficiency cells to integrate Cu without compromising performance, while NREL and TU Delft have provided critical insights into material science challenges, such as Cu diffusion and contact adhesion

Emerging players like Oxford PV and REC Group highlight Cu's versatility across PV technologies, from tandems to thin films. Hanwha Q CELLS and Solar Frontier exemplify how established manufacturers adapt Cu plating to existing platforms, enhancing competitiveness. UNSW's foundational work continues to influence these advancements, ensuring Cu plating meets the stringent reliability standards of modern PV systems.

VI. FUTURE CHALLENGES

Nickel/Copper (Ni/Cu) metallization in silicon solar cells is gaining attention due to its potential to create affordable, efficient, and dependable electrical contacts. This approach could help meet the growing worldwide need for solar energy. However, there are still some hurdles to overcome, including improving how well the metals stick to the silicon (adhesion), preventing the unwanted spread of the metals into the silicon (diffusion), and simplifying the manufacturing process (process

complexity). Solving these issues could make Ni/Cu metallization a key player in advancing solar cell technology.

Cost Reduction and Replacement of Silver

The shift toward nickel/copper (Ni/Cu) metallization in silicon solar cells is propelled by a critical economic incentive: reducing dependence on silver, a traditionally dominant but increasingly expensive material for solar cell contacts. Research such as Posthuma et al. (2009) and Mason et al. (2003) emphasize this advantage, illustrating how Ni/Cu can deliver comparable electrical performance—low contact resistance and high conductivity—while slashing material costs. Despite its superior properties, Silver is plagued by price volatility and supply chain vulnerabilities, often tied to mining constraints and geopolitical factors[57]. In contrast, Ni/Cu leverages copper's abundant availability and excellent conductivity, paired with nickel's role as a robust seed layer and diffusion barrier, making it an attractive substitute for cost-conscious solar manufacturers[58].

The trajectory of Ni/Cu metallization points toward further advancements in plating processes to amplify its economic edge and industrial viability. Historically, we have explored rapid deposition techniques, such as optimized electroplating or light-assisted methods, which could boost production speeds while maintaining quality, crucial for meeting the solar industry's growing demand. Complementing this, Cimiotti et al. (2009) investigate practical, large-scale approaches, including refinements in plating bath compositions, temperature controls, and automation to ensure uniformity and minimise defects across expansive production lines[32]. These efforts aim to lower energy inputs, reduce chemical waste, and enhance process reliability, all of which are pivotal for integrating Ni/Cu into high-volume manufacturing environments.

The potential for Ni/Cu to become the industry standard hinges on both market dynamics and technological progress. Should silver prices surge, driven by commodity market fluctuations or dwindling reserves, or if supply chains face disruptions, Ni/Cu's cost-effectiveness could make it the default choice for industrial solar cells[59]. Ongoing research is sharpening this prospect by targeting key areas: minimizing copper thickness to cut material use without compromising performance, improving adhesion to diverse substrates, and developing closed-loop systems to recycle plating chemicals[60]. Innovations like these could reduce the levelized cost of electricity (LCOE) for solar power, aligning with the industry's push for affordability and sustainability. If successful, Ni/Cu metallization could not only supplant silver in mainstream silicon cells but also adapt to next-generation designs, cementing its role as a cornerstone of future photovoltaic production.

A. *Improved Efficiency and Performance*

The application of nickel/copper (Ni/Cu) metallization has demonstrated its capability to achieve impressive efficiencies in silicon solar cells, positioning it as a formidable competitor to traditional silver-based systems. The research by Tous et al. (2012) showcases how Ni/Cu plating can deliver high-performance outcomes across large-scale cells, leveraging copper's excellent conductivity and nickel's stability to optimize current collection[61]. Similarly, Glunz et al. (2013) underscore the potential of Ni/Cu to rival or even surpass silver in terms of efficiency thanks to its ability to form reliable, low-resistance contacts[62]. These studies indicate that Ni/Cu is not merely a cost-saving alternative but a pathway to enhancing overall cell performance.

Efforts to refine Ni/Cu metallization have zeroed in on improving electrical characteristics through innovative design approaches. For instance, Bartsch et al. (2011) explore the use of fine-line contacts, which reduce shading losses on the cell surface while maintaining robust electrical connectivity—an essential factor in boosting efficiency[63]. Meanwhile, Kuzma-Filipek et al. (2012) demonstrate how Ni/Cu can be paired with selective-emitter architectures, where doping levels are tailored to minimize recombination losses at the contacts and enhance carrier collection[64]. These advancements highlight a concerted focus on optimizing contact geometry and material interfaces to extract maximum performance from Ni/Cu-based systems.

Looking forward, the prospect of integrating Ni/Cu metallization with advanced cell architectures offers a tantalizing glimpse into its role in next-generation photovoltaics. Studies like Li et al. (2020) illustrate its compatibility with heterojunction (HJT) cells, which are prized for their high open-circuit voltages and low-temperature processing requirements. Similarly, its application to Passivated Emitter and Rear Contact (PERC) cells—already a mainstay in commercial production—could further elevate efficiencies beyond the 20% threshold, a benchmark for premium solar technologies[65]. Achieving this could involve tailoring Ni/Cu processes to reduce series resistance, enhance adhesion to diverse substrates like amorphous silicon or textured surfaces, and mitigate long-term degradation under environmental stress. As tandem cells and other cutting-edge designs emerge, Ni/Cu's versatility, combined with ongoing refinements in plating precision and material efficiency, could solidify its position as a scalable, high-efficiency solution, driving the photovoltaic industry toward greater performance and sustainability.

B. *Enhanced Reliability and Long-Term Stability*

Reliability remains a pivotal focus in the development of nickel/copper (Ni/Cu) metallization for silicon solar cells, as evidenced by foundational and contemporary research spanning decades. Early work done by Lee et al. (1981) established the groundwork for assessing the durability of Ni/Cu contacts under operational conditions, identifying key factors like contact adhesion and resistance to environmental degradation[66]. More recent studies, like Kraft et al. (2014), build on this legacy, providing detailed insights into how these metallization systems perform over extended periods, including their resilience against humidity, temperature cycling, and mechanical stress[67]. These investigations underscore reliability as a cornerstone for Ni/Cu's adoption, ensuring it can meet the rigorous demands of real-world solar applications.

A primary challenge to reliability is copper diffusion into the silicon substrate, which can introduce recombination centers and degrade cell efficiency over time. This issue has been

systematically tackled through the development of nickel diffusion barriers, as detailed by Chen et al. (2018). Here, nickel serves as a protective layer, preventing copper atoms from penetrating the silicon while maintaining electrical integrity at the contact interface[68]. Kale et al. (2018) explore the behavior of these contacts under elevated temperatures, a critical factor given the thermal cycles solar cells endure during manufacturing and field operation[69]. These studies highlight solutions like optimizing nickel layer thickness, improving deposition uniformity, and enhancing barrier robustness to ensure long-term performance stability.

The future of Ni/Cu metallization hinges on advancing these reliability enhancements to align with the solar industry's stringent expectations, particularly the 25–30-year warranties that have become standard for photovoltaic modules. Ongoing research is likely to focus on refining nickel barrier layers—perhaps through alloying with other metals or adopting multi-layer structures—to further suppress copper diffusion while minimizing material costs. Plating techniques, too, stand to evolve, with innovations like electroless deposition or pulsed plating potentially improving layer adhesion and reducing defects such as voids or microcracks. Environmental testing will play a key role, simulating decades of exposure to moisture, UV radiation, and thermal fluctuations to validate durability. By achieving these improvements, Ni/Cu contacts could not only match but exceed the longevity of silver-based systems, offering a reliable, cost-effective alternative that supports the industry's push for sustainable, long-lasting solar energy solutions.

C. Process Optimization and Scalability

The evolution of nickel/copper (Ni/Cu) metallization in silicon solar cells is closely tied to advancements in manufacturing processes, with a clear emphasis on streamlining production for industrial scalability. Metz et al. (2014) focus on fine-tuning plating parameters—like bath chemistry, current density, and deposition rates—to enhance efficiency and uniformity, making Ni/Cu viable for high-volume production[70]. Similarly, Hsiao et al. (2018) delve into cutting-edge methods to improve the quality of deposited layers, addressing challenges such as adhesion, thickness control, and defect reduction[71]. These efforts reflect a broader push to adapt Ni/Cu metallization to the fast-paced, cost-sensitive demands of modern solar manufacturing.

Innovative techniques are further expanding the toolkit for Ni/Cu applications. For instance, Ochoa-Martínez et al. (2013) highlight the use of laser-assisted deposition to precisely pattern nickel seed layers, enabling finer contact lines that reduce shading losses and boost cell efficiency[72]. This approach enhances scalability by offering a controlled, repeatable process compatible with large-area cells. Meanwhile, Knauss et al. (2006) showcase electroless plating—a chemical deposition method that eliminates the need for external electrical current—as a way to achieve uniform metallization over expansive surfaces[73]. This technique simplifies equipment requirements and improves accessibility for complex cell designs, paving the way for broader industrial adoption.

Looking ahead, the prospect of fully automated, high-speed Ni/Cu plating lines integrated into gigawatt-scale solar factories holds transformative potential for the photovoltaic industry. Such systems could leverage robotics and real-time monitoring to optimise every stage of the plating process, from nickel barrier deposition to copper layer buildup, slashing production times from hours to minutes while maintaining stringent quality standards. Advances in conveyorised plating setups and machine learning to dynamically adjust parameters could minimise material waste and energy use, driving down costs per watt. Compatibility with existing infrastructure, such as that used for Passivated Emitter and Rear Contact (PERC) or heterojunction cells, would further ease adoption. By achieving this level of automation and precision, Ni/Cu metallization could become a cornerstone of next-generation solar manufacturing, delivering high-quality, low-cost cells at unprecedented scale to meet global energy demands.

D. Adaptation to Thin and Flexible Wafers

As the solar industry pursues cost reduction through the use of thinner silicon wafers, nickel/copper (Ni/Cu) metallization is being specifically adapted to meet the challenges and opportunities presented by these delicate substrates. Early research, such as Sudagar et al. (2013), explored the feasibility of applying Ni/Cu contacts to wafers significantly thinner than the standard 180–200 micrometers, demonstrating that this metallization system could maintain electrical performance while minimizing mechanical stress[74]. Building on this, Oh and Lee et al. (2003) further refined the process, optimising plating techniques to ensure uniform deposition and strong adhesion on wafers as thin as 50–100 micrometres [75]. This adaptability stems from Ni/Cu's ability to form robust, low-resistance contacts without requiring the high-temperature firing processes associated with silver pastes, which can warp or crack fragile, thin substrates[76].The versatility of Ni/Cu metallization positions it as a promising solution not only for conventional thin-wafer applications but also for emerging flexible and lightweight solar technologies. Thin silicon wafers are a stepping stone toward more pliable photovoltaic designs, and Ni/Cu's compatibility with low-temperature processing and its potential for fine-line plating make it well-suited for these innovations[77]. For instance, the nickel layer's role as a diffusion barrier and adhesion promoter, combined with copper's flexibility and conductivity, could enable the creation of durable contacts on substrates that bend or flex without compromising performance[78]. This adaptability opens the door to applications beyond rigid panels, extending Ni/Cu's relevance to cutting-edge markets where lightweight, conformable solar cells are increasingly in demand.

The prospect of Ni/Cu playing a pivotal role in emerging markets like flexible photovoltaics and building-integrated photovoltaics (BIPV) is particularly compelling. In flexible PV, where silicon or other thin semiconductor layers might be mounted on polymer or metal foils, Ni/Cu contacts could provide the durability and conductivity needed to withstand repeated bending while keeping weight to a minimum—an essential feature for portable or wearable solar devices. In BIPV, where solar cells are integrated into windows, facades, or roofing materials, the lightweight nature of thin wafers paired with Ni/Cu's cost-effective metallization could enable seamless incorporation into architectural designs without sacrificing longevity. Future advancements might focus on tailoring plating

processes to enhance flexibility, perhaps through nanostructured nickel layers or hybrid coatings, while ensuring resistance to environmental factors like moisture and UV exposure. By meeting these demands, Ni/Cu could become a cornerstone of lightweight, versatile solar solutions, driving growth in niche markets and broadening the reach of photovoltaic technology.

E. Sustainability and Environmental Impact

Although not always explicitly highlighted in research titles, the transition from silver to nickel/copper (Ni/Cu) metallization in solar cells aligns seamlessly with the photovoltaic industry's broader sustainability objectives. While effective, silver is a relatively scarce and resource-intensive material to extract, with mining processes often involving significant energy consumption, water use, and environmental disruption. In contrast, copper and nickel are far more abundant in the Earth's crust—copper being roughly 1,000 times more plentiful than silver—and their extraction and refining typically demand fewer resources per unit of material[79]. Moreover, ongoing research into Ni/Cu plating efficiency, such as optimising deposition rates and minimising excess material use, promises to further curtail waste, reducing the ecological footprint of solar cell production[80]. This shift reflects a strategic move toward more sustainable manufacturing practices without compromising performance.

The environmental benefits of Ni/Cu extend beyond resource abundance to the potential for greener production processes. Traditional silver screen-printing relies on high-temperature firing and organic binders that release volatile compounds, whereas Ni/Cu plating—often achieved through electrochemical or electroless methods—can operate at lower temperatures and with fewer hazardous byproducts[81]. Studies improving plating techniques, such as refining bath compositions or reducing chemical overuse, contribute to a leaner process that generates less waste and consumes less energy. This inherent compatibility with sustainability goals positions Ni/Cu as a forward-thinking choice, capable of supporting the solar industry's aim to produce clean energy in a manner that minimizes environmental harm from cradle to grave.

By integrating such innovations, Ni/Cu could solidify its role as an environmentally responsible alternative, amplifying photovoltaics' green credentials in an era increasingly defined by climate consciousness.

F. Integration with Emerging Technologies

The application of nickel/copper (Ni/Cu) metallization to advanced solar cell architectures, such as Passivated Emitter and Rear Contact (PERC) cells and heterojunction (HJT) cells, demonstrates its remarkable versatility and potential for broader adoption in next-generation photovoltaic technologies[61]. For instance, research like Lee et al. (2002) highlights how Ni/Cu contacts can enhance the efficiency and reliability of PERC cells, which are widely valued for their improved rear-side passivation and increased energy conversion efficiency[58]. Similarly, studies such as Hatt et al. (2020) showcase the successful integration of Ni/Cu metallization with heterojunction cells, known for their high open-circuit voltages and low-temperature processing advantages, further underscoring the adaptability of this metallization approach across diverse cell types[82].

As the solar industry continues to innovate, with tandem cells and other novel designs gaining momentum, Ni/Cu metallization stands out as a promising candidate for meeting the unique demands of these emerging technologies. Tandem cells, which stack multiple semiconductor layers to capture a broader spectrum of sunlight, require metallization schemes that ensure low contact resistance, minimal recombination losses, and compatibility with varied material systems—attributes where Ni/Cu has already shown promise. The use of nickel as a barrier layer combined with copper's excellent conductivity offers a cost-effective alternative to traditional silver-based contacts while maintaining high performance. Moreover, Ni/Cu's potential for fine-line printing and plating techniques could address the precision and scalability needs of these advanced designs. As research progresses, tailoring Ni/Cu processes, such as optimizing adhesion, reducing thermal stress, or enhancing durability under diverse operating conditions, could further expand its role, making it a cornerstone in the evolution of efficient, affordable, and adaptable solar cell technologies

VII. CHALLENGES TO OVERCOME

Ni/Cu metallization in silicon solar cells could lead to cost-effective, high-efficiency, and dependable connections that can scale to satisfy global demand. If adhesion, diffusion, and process complexity are addressed, Ni/Cu could replace silver in mainstream PV production. Research is still refining methods and adapting them to new cell designs. With plating, material science, and production integration advances, the technology should be industrially viable by the late 2020s.

A. Adhesion and Interface Issues

The 1971 study by Walker et al. and the 2013 study by Mondon et al. demonstrate the ongoing difficulty of achieving robust contact adhesion in metalised silicon-based systems. Walker and colleagues investigated early nickel-copper plating on silicon solar cell adhesion methods in 1971, revealing poor interfacial bonding and mechanical instability under thermal and environmental stress[83]. This basic work showed that surface preparation and plating must be improved to reduce delamination risks. In 2013, Mondon et al. examined the microstructural characteristics of thermally produced nickel silicide surfaces, using advanced analytical methods to quantify adhesion strength and failure mechanisms[62]. Their research showed that phase changes, interfacial tension, and material incompatibilities still compromise reliability. These publications demonstrate the ongoing issue of optimising metal-semiconductor interactions. As solar cell and microelectronic efficiency and endurance increase, future research must develop creative deposition procedures, refine material compositions, and use nanoscale engineering to assure permanent adhesion.

B. Background Plating

In semiconductor and solar cell manufacturing, background plating—the unintended deposition of metal on areas outside the designated contact regions—can cause defects, reduced electrical performance, and compromised reliability. Recent developments in plasma-based methods have underlined even

more its adaptability in handling plating problems. For instance, the capacity of plasma treatments to selectively functionalize surfaces—whether by adding oxygen-rich species, as in the N2O process, or by other means—provides a tuned approach to regulate where and how metal sticks. With reference cells averaging an average efficiency of 17.4% and a fill factor of 73.5% without the treatment, the Raval et al. study ascribed the improvement in FF to the reduction of recombination losses caused by background plating, hence producing further benefits post-treatment. These findings imply that plasma treatments could be modified to other materials or systems where undesired deposition causes a bottleneck, providing a route to improve both yield and efficiency over a spectrum of technologies[14]. The study demonstrated that this technique nearly eliminates background plating, improving the fill factor by mitigating resistance-limited defect recombination, a key factor in lowering efficiency. Furthermore, the authors found that a post-treatment step with N2O plasma enhances performance even further by oxidizing the ARC surface, which helps suppress unwanted nucleation sites for metal plating. This straightforward yet impactful process has the potential to overcome one of the longstanding barriers to adopting Ni-Cu contacts in commercial solar cell production, where issues like adhesion and background plating have historically limited progress. The significance of minimizing unwanted plating extends beyond solar cells to other applications, such as microelectronics and thin-film technologies, where precision in metal deposition is paramount. Uncontrolled plating can lead to short circuits, increased parasitic resistance, or degraded device lifetimes, all of which reduce manufacturing yield and increase costs. In the case of Ni-Cu metallization, background plating is particularly problematic because it can shunt the junction, impairing the electrical characteristics of the device. The N2O plasma treatment approach offers a promising solution by leveraging the reactive properties of plasma to alter surface chemistry without requiring complex or costly modifications to existing production lines. This aligns with the broader industry trend toward developing efficient, scalable, and environmentally friendly processes that maintain high-performance standards.

C. Copper Diffusion

"Quick Determination of Copper-Metallization Long-Term Impact" by Kamp et al. (2009) highlights the need to protect silicon-based semiconductor devices against copper deterioration. Copper, used in metallization due to its high electrical conductivity, can diffuse into silicon and generate deep-level traps, limiting device performance. One promising technique is robust nickel silicide (NiSi) barriers, which prevent copper transport into the silicon substrate. Thermal stability, low resistivity, and compatibility with existing production methods make nickel silicide an effective interlayer to decrease copper-induced deterioration[84]. Besides nickel silicide, several solutions are being studied. Tantalum (Ta) or tantalum nitride (TaN) barriers' high melting temperatures and copper diffusion resistance make them promising mechanical and chemical shields. Ultra-thin, homogenous barrier layers can be created using contemporary deposition processes like atomic layer deposition (ALD), boosting protection without increasing resistance or process complexity[85]. Copper can be alloyed with aluminium or magnesium to lower its diffusion coefficient and atomic contact with silicon. These methods are critical because the semiconductor industry seeks reduced feature sizes and higher performance, where even minor deterioration can cause reliability issues. Research balances efficacy and manufacturability to improve these methods. Significant research supports this conversation:

CONCLUSION

The cost of making silicon solar cells can be lowered by using cheap metals for metallization and a thinner silicon base. The perspective of the Ni/Cu plating method for silicon solar cell metallization has been followed in this work. With several innovative plating processes, using Ni to enhance the adhesion and as a barrier to Cu shows considerable promise. As a reasonably cheap material for next-generation metallization systems for silicon solar cells, copper has great potential to become a main player. Over the past few years, promising achievements in terms of greater fill factors and open circuit voltage have come about. The growth of plating techniques has also led to the development of new patterning methods, such as the utilization of light-induced plating, electroless, and laser-based chemical metal deposition. These techniques have been utilised increasingly in recent years. A reduction in the complexity of the process may be achieved by utilizing a combination of nitride ablation and producing a Ni seed layer.

Metallization based on copper plating appears to be a good alternative to the current screen-printing technology in terms of material costs and cell performance. However, a standard industrial process is still constrained by several issues; adhesion, background plating, and copper diffusion issues have been somewhat resolved, but it is believed that long-term reliability is the primary barrier to a manufacturing technology that's sustainable.

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