Roadmap towards 1 mg/W Silver Consumption for Industrial High-Efficiency Screen-Printed Silicon Solar Cells

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Introduction

To solve climate change and decarbonise the energy sector, the installation capacity of photovoltaic (PV) technologies need to reach 60 TW by 2050[1], corresponding to a sixty time increase from what has been deployed to date. Such aggressive growth in the deployment rate of PV technologies subsequently requires a TW scale, if not multi-TW scale production capability per annum to be established by next decade. A key concern for TW scale PV deployment is the sheer volumes of raw materials required in the PV manufacturing, including not only those rare elements, such as silver, indium, and bismuth[2], but also more abundant materials like silicon[3], copper, and aluminium[4]. Such substaintially increased material demand will inevitably raise concerns over the unsustainable material consumption and potential depletion of the resources. In addition, this could also negatively impact the manufacturing costs of PV technologies if the material supply chain was disrupted by the aggressively increased demand from the PV industry. Therefore, reducing the material consumption will be a critical mission for the PV industry to ensure the sustainable manufacturing of PV technologies on a rapidly approaching TW era.

For the mainstream silicon solar cell technologies, screen printing has been used as the industrially preferred metallization technique for more than half a century. The low equipment costs, simple and robust process of screen printing has contributed significantly to the large-scale deployment of silicon solar cells and the reductions in manufacturing costs. In addition, the continuous improvements in the screen-printing technology and paste performance also played a crucial role in the remarkable increases in cell efficiencies that occurred in the past two decades. Despite being such a mature and widely adopted technology with more than 99% of the market share in the PV industry, the screen-printing technology still faces major challenges to support an upcoming TW manufacturing scale of silicon solar cells. Even though each solar cell only uses 50-150 mg of silver in screen-printed contacts, to deploy 240 GW of PV in 2022, the PV industry fabricated approximately 30-50 billion solar cells. This has already consumed over 14% of the global silver supply in 2022[5]. To ensure the sustainable consumption of silver rand responsible production of silicon solar cells for TW scale manufacturing, substantial reductions in silver consumption of screen-printed solar cells are required. If the PV industry is to limit silver demand to 20% of the current global primary silver supply, less than 5 mg/W[6] is urgently required for a 1 TW market using existing industrial screen-printing technology. However, when considering the possibility of multi-TW scale markets (eg. 3 TW p.a.), a long-term target of <2 mg/W[2] is required.

Historically, the PV industry has demonstrated its strong capabilities and determination in reducing silver consumption of screen-printed solar cells. Since 2010, the average silver consumption of typical industrial silicon solar cells has been reduced by a factor of 6 from almost 60 mg/W to around 10 mg/W[7]. Such a remarkable achievement can be largely attributed to the progress in fine-line printing technology, the use of a multi-busbar configuration, and gradual improvements in cell efficiencies. Despite that, the silver consumption of existing industrial screen-printed solar cells is still well above the 5 mg/W and 2 mg/W targets, calling for more advancements in the screen-printing technology for further reductions in silver consumption. In the meantime, although the development of several alternative metallization techniques, such as Cu plating, parallel dispensing, and pattern transfer printing has gained significant interest from the PV industry for silver reductions, each of these technologies is still facing its own challenges in mass production, and the dominance of the screen-printing technology is still expected in coming decades. Therefore, to allow the sustainable manufacturing of silicon solar cell technologies on a multi-TW scale, a pathway to reduce silver consumption of screen-printed contacts towards 5 mg/W or even 2 mg/W will be critically needed.

In this paper, we highlight silver reduction roadmaps towards an ultra-low level of 1 mg/W with interim approaches to allow 5 mg/W and 2 mg/W targets to be reached based on industrial standard screen-printing technology and modified silver-lean metallization design.

Industrial Screen-Printed Silicon Solar Cells

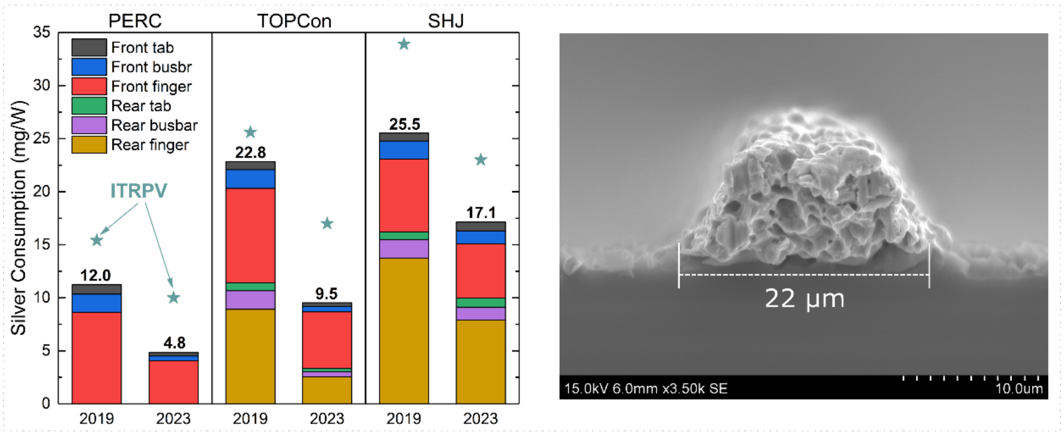

Figure 1. (left) Silver consumption measured on industrial screen-printed PERC, TOPCon and SHJ solar cells manufactured in 2019 and 2023. Stars depict the silver consumption values reported by ITRPV[1]. (right) Cross-sectional SEM image of a screen-printed silver finger with 22 µm finger width.

The silver consumption of industrial screen-printed PERC, TOPCon, and SHJ solar cells is shown in Fig. 1. According to ITRPV, despite higher efficiency potential of n-type TOPCon and SHJ solar cells, their silver consumption is almost twice higher than p-type PERC solar cells (10 mg/W), at 17 and 23 mg/W, respectively. This can be explained by the need of silver contacts on both front and rear side in those n-type solar cell structures. Assuming 20% of the global silver supply is open to the PV industry, the current supply will only tolerate up to 300 GW annual production of TOPCon or 230 GW for SHJ, fall short of the target TW manufacturing scale. With an aggressive shift from PERC to TOPCon production currently occurring in the PV industry, reducing silver consumption of screen-printed contacts will be even more detrimental, particularly for TOPCon solar cells, to avoid the unsustainable growth in the silver demand from the PV industry. Notably, a silver consumption level of 5 mg/W has been measured on industrial PERC solar cells produced in 2023 with 22 µm finger width (see Fig. 1), which represents a major milestone that the current implementation of the screen-printing technology in PERC could already meet the 5 mg/W target for TW scale manufacturing.

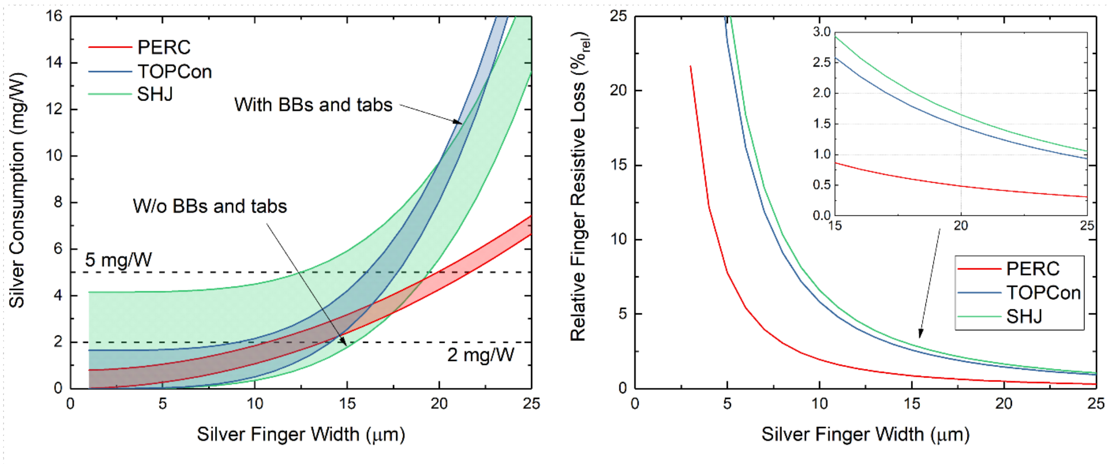

Figure 2. Impact of finger width on (left) silver consumption and (right) finger resistive losses in screen-printed PERC, TOPCon, and SHJ solar cells.

Although significant reductions in finger width have been achieved with industrial screen-printing technology, silver consumption in fingers still accounts for more than 75% of the total silver consumption in existing screen-printed industrial solar cells. Therefore, further reductions in the finger width will be essential to reducing the silver consumption of TOPCon and SHJ solar cells towards a sustainable target level. For both TOPCon and SHJ, achieving a finger width in the range of 17-20 µm would be sufficient to lower the finger silver consumption to 5 mg/W (see Fig. 2 (left)). It should be noted that even though a finger width of ~22 µm has already been achieved in PERC, the finger width of TOPCon and SHJ was found to be larger than PERC, at 26 and 35 µm, respectively. This suggests that the advancements in fine-line printing technology have yet to be fully transferred from PERC to TOPCon and SHJ solar cells, and reducing the finger width in those n-type solar cell structures requires more effort.

In addition, to achieve a total silver consumption of 5 mg/W, the silver usage in busbars and soldering tabs also needs to be reduced, especially for TOPCon and SHJ solar cells. With current busbar and soldering tab designs, 5 mg/W total silver consumption will only tolerate a finger width of ~ 15.5 µm for TOPCon and 12.5 µm for SHJ. It remains unknown if such a small finger width is achievable with the screen-printing technology. However, substantial reductions in finger cross-sectional area will likely raise concerns over the reliability of such fine-line fingers in mass production and significantly increases finger series resistance. As shown in Fig. 2 (right), reducing the finger width from 20 µm to 15 µm could attract up to $1\%_{rel}$ increases in finger resistive losses for both TOPCon and SHJ solar cells, corresponding to over $0.25\%_{abs}$ losses in efficiency. To avoid those issues, reducing or eliminating busbar and soldering tab silver consumption will be a mandatory requirement, particularly for SHJ solar cells, of which the silver consumption in busbars and soldering tabs is significantly higher than other solar cell technologies.

Ultra-low silver consumption towards 1 mg/W

Alternatively, the use of silver-lean or silver-free paste materials provides an immediate solution to greatly reduce the silver consumption without relaying on improvements in the fine-line printing technology. However, with existing metallization designs, the screen-printed contacts need to play several roles simultaneously, such as forming direct metal/Si interfaces with the silicon surface, current transport, and cell interconnection, which strongly limits the choice of paste materials that can be used as substitute of silver. For instance, although the relatively cheap and abundant copper has been widely used as a conducting material in IC industry and electrical engineering, it introduces deep-level impurities to silicon solar cells, which subsequently prevents the use of copper as screen-printing material in the PV industry. It was not until recently that the industry starts using silver-coated copper pastes as alternative paste materials to reduce silver consumption. However, the application of such copper pastes is only limited to SHJ solar cells, where a low-temperature curing process is used instead of firing at 700-800 °C and no direct metal/Si interfaces are required. Similarly, despite the advantageous use of aluminium to form back-surface field regions on the rear surface of traditional Al-BSF and PERC solar cells, the formation of heavily doped p^{++} regions with aluminium pastes cannot be tolerated on PERC front nor the front and rear side of TOPCon solar cells.

In this work, a new metallization design (see Fig. 3) has been developed based on the well-established industrial dual-print process to substantially reduce the silver consumption of screen-printed solar cells to an ultra-low level of 1 mg/W. The key feature of this design is that the conventional silver pastes is only printed in localized regions to form direct metal/Si interfaces with the silicon surface, and silver-free or silver-lean fingers and busbars with a H-pattern design is subsequently printed on top of localized silver contacts just for the purpose of current collection and transport. Since floating fingers and busbars will not fire through dielectric layers to make direct contact with silicon, the risk of undesirable interaction between pastes and silicon will be largely mitigated regardless of the choice of paste materials. As for localized silver contacts, the silver consumption in those regions can be reduced by lowering the coverage area of the contact. With industrial standard metallization design, the coverage area of silver fingers and busbars is typically in the range of 3-5% of the total cell area. By reducing the coverage area to ~1% with localized contacts, an immediate reduction in silver consumption to 3 mg/W and 6.5 mg/W can be expected for PERC and TOPCon solar cells, respectively. Furthermore, since such silver contacts mostly play a role of contact formation, the lateral conductivity of them become less crucial, which allows further silver reduction by reducing the printed height of these silver contacts without harming the cell efficiency. With a reduced printed height of ~ 5 μm compared to 15 μm in standard screen-printed contacts, an ultra-low silver consumption of only 1 mg/W will become feasible for PERC (see Fig. 3 (right)) and less than 2 mg/W for TOPCon.

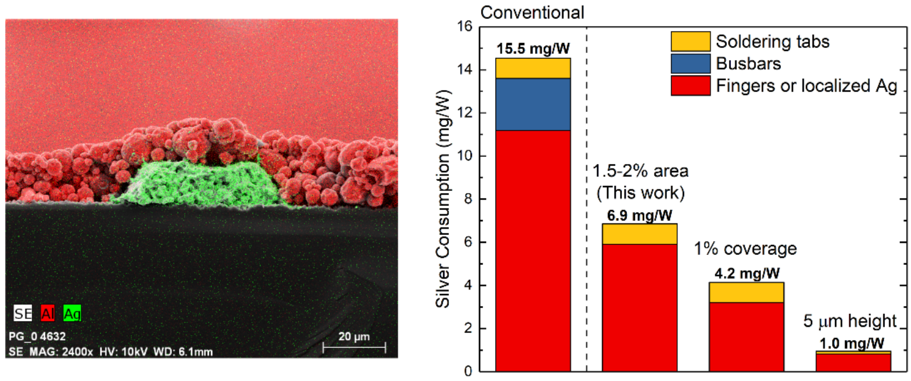

Figure 3. (Left) Cross-sectional SEM-EDS image of silver-lean screen-printed contacts with floating aluminium fingers on top of localized silver contacts. (Right) Roadmap towards 1 mg/W silver consumption for industrial screen-printed PERC solar cells with the silver-lean metallization design.

Preliminary testing has demonstrated in more than 50% reductions in silver consumption of PERC (from 15 to less than 7 mg/W) with 1.5% coverage area of localized silver contacts and floating aluminium fingers and busbars (**Toyo TTC-22A series Al pastes**). By reducing the printed height and improving the efficiency with optimized fabrication process, further reductions in silver consumption towards 1 mg/W target will face no major challenges for industrial PERC. The implementation of such silver-lean metallization designs on both front and rear surface of TOPCon solar cells could subsequently lead to an ultra-low silver consumption of less than 2 mg/W compared to 10-15 mg/W in current industrial TOPCon. In the meantime, other silver-lean and silver-free paste materials are currently being evaluated for floating fingers and busbars. In addition to significantly broaden choices of paste materials, the requirements on paste development based on alternative non-silver materials will be substantially relaxed given that the formation of high-quality ohmic contacts with silicon is no longer needed with this silver-lean metallization design. An extra benefit of reduced contact coverage area was found to be substantially reduced carrier recombination losses at direct metal/Si interface areas. By reducing the metal/Si interface area from 3-4% to 1%, up to 12 mV improvements in implied V_{OC} and up to 8 mV increases in device V_{OC} have been demonstrated experimentally on PERC. This will provide additional scope of efficiency improvements to solar cells manufactured with such low-area silver-lean metallization design.

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