SCREEN PRINTED SELECTIVE Emitter FORMATION AND METALLIZATION
SCREEN PRINTED SELECTIVE_EMITTER FORMATION AND METALLIZATION

ABSTRACT
Selective emitter (SE) technology is a strategic way for c-Si photovoltaic manufacturers to improve cell efficiency and drive down cost per watt at the same time. To date, the adoption of SE technology for high-volume production of cells with SE technology has been inhibited by material cost and process complexity. Applied Materials is focused on supporting cost-effective approaches for selective emitter (SE) mass production. The approach reported here seamlessly integrates into a conventional cell production line using Baccini screen printing and drying, diffusion of p-type wafers, glass removal and pre-qualified consumables. Additionally, we describe how high precision metallization tools based on Baccini® Esatto Technology™ are used to ensure the maximum efficiency benefits from SE cells.

INTRODUCTION
Photovoltaic manufacturers must drive costs down and efficiencies up to win in the market. Selective emitter (SE) technology is one method that crystalline silicon (c-Si) solar cell producers are implementing to achieve these objectives. To boost the absolute efficiency of c-Si solar cells in a cost-effective way, SE must be implemented with minimal additional capital investment and changes to the existing cell design and factory hardware. A number of different approaches, varying in complexity, cost and efficiency gain, have been developed and tested to form selective emitters. Implementing SE includes a number of technical challenges, including the formation of the SE junction profile, alignment of the metallization to remain within the narrow SE region, and optimization of the emitter between the metal grid pattern to maximize the SE benefits. Successful SE solutions must be cost effective, implementable in existing fabrication lines, technically optimized to increase cell efficiency, and scalable to a high-volume production environment without compromising module quality and reliability. At the same time they should be low risk.

WHY SELECTIVE_EMITTER?
Cell efficiency improvements with SE cell technology have been the focus of much design and development over many years, but high-volume implementation has been inhibited by cost and complex processes. Current homogeneous emitter technology has reached practical design limits. Shallow homogeneous emitters with sheet resistance >80 Ω/sq can improve short wavelength light response, but have a constrained contact firing process window because of their shallow junction depth through which increased shunting and / or contact resistance losses become highly probable. Emitters with sheet resistance of <60 Ω/sq have generally lower contact resistance, but also increased recombination losses in the field region. SE allows the metallized and non-metallized regions to be independently optimized (Figure 1). High doping regions under the glass-silver metal fingers improve ohmic contact, reduce shunting, and provide a more robust firing process window. Lower dopant concentrations in the non-metallized areas have better short wavelength response and lower recombination loses (higher Isc and Voc).
SE efficiency gains over conventional homogeneous emitter designs of up to 0.7% are expected for practical factory conditions (Figure 2), while 0.3% to 0.6% are typical gains observed on mono-crystalline Cz and multi-crystalline silicon cells. The model uses the dependence of surface recombination on the surface concentration, Ns as published by A. Cuevas, 2003 [1], and short circuit current density and open circuit voltage calculated using PC1D [2] with idealized profiles. Assuming a typical average efficiency gain of 0.5%, a fabrication line of 10 million cells per year could yield over one million additional watts. One challenge is to realize this gain while minimizing the additional cost. This is a key consideration in selecting a method to form and integrate the SE into a production operation.
Many approaches exist to generate this common cell concept in Si cells with varying degrees of complexity and cost. Figure 3 contains a summary of some of the more well-known SE formation methods in the industry. SE solutions should meet certain requirements to be able to help drive down the cost per watt by increasing cell efficiency. The method must be cost-effective, with minimal complexity and additional steps.

We will now focus our discussion on screen printed SE approach which leverages the industry’s huge existing installed base of screen printers and enables a low-risk fabrication process flow (Figure 3).

**SCREEN PRINTING SELECTIVE EMITTER**

The screen printed SE approach provides a straightforward, cost-effective way to implement selective emitter. The simple addition of a screen printing step to create highly doped regions under the grid uses screen printing technology already widely applied in c-Si solar cell fabrication. Though screen printing is a simple way to integrate a low cost SE into an existing manufacturing line, there are critical considerations that must be taken into account to ensure maximum benefit in cell performance with selective emitter design. Below are design and process challenges to integrating a high efficiency screen printed SE in a crystalline silicon solar cell fabrication process.
Device Design

![Device Design Diagram]

Figure 4: Standard cell (a) and optimized Selective Emitter cell (b) design specifications (Target $J_0$ 50-70 fA/cm$^2$ Emitter saturation current density after development of diffusion)

To work in an existing cell line with minimum disruption and maximum efficiency gains from SE, some considerations to device design must be made (Figure 4). These include grid design, emitter engineering and line width consideration. Grid design needs to take into account finger spacing for optimum fill factor and reduced shading, and the number of fingers optimized for high emitter $R_{sheet}$. Optimum selective emitter engineering, as shown in Figure 4, results in the N++ region for low contact resistance and the N+, shallow emitter, region for improved blue response. The screen printed SE line width is optimized to maximize shallow junction areas while allowing sufficient tolerances for metallization alignment.

Saw Damage Etch and Texturization Challenges

Whether the incoming substrate is mono-crystalline silicon or multi-crystalline, silicon high efficiency cells start with good saw damage etch and texturization. These steps ensure a clean, uniform, high surface area foundation to begin fabricating a solar cell. In order to achieve high efficiency gains with selective emitter these process steps must be optimized to a low reflectance specification for mono and multi. Without consideration to these steps efficiency is lost due to trade-offs between overall light absorption and absorption in the short wavelength region (Figure 6).

Diffusion Optimization

Once the doped region is printed and dried, the wafers proceed to the Phosphorous diffusion. In conventional cell formation this step must balance the field emitter performance with that under the grid. A shallow, lightly doped field region delivers less recombination in the emitter but poor contact resistance and a narrow firing process window for the grid region. Selective emitter decouples this trade-off, allowing the lightly doped region in the open area to have improved diffusion carrier collection. One expects to see higher “blue” to visible response on quantum efficiency charts (Figure 5). P diffusion is independent of forming the highly doped regions under the grid. This is done through the SE formation step to create a doped region followed by diffusion tuned for time and temperature to achieve the active surface dopant concentration and profile.

Failure to optimize the diffusion for field and selective emitter can result in low current and open circuit voltage with poor fill factor, which result in lower efficiency cells. Typical sheet resistances using a four-point probe for field and selective emitters are shown in Figure 4. Both the surface concentration and junction depth should be optimized for each region to ensure that the desired profile has no dead layer/phosphorus precipitates left on the surface after PSG removal. SIMS and SRP’s measurements can be used to evaluate the diffuse profile, concentrations, and percent of active surface dopant. Multi-crystalline silicon has a lower thermal budget than mono due to impurities, therefore making few approaches compatible with multi.
However, screen printed SE formation can be adapted to multi-Si, provided that temperature is held below 840º C.

Figure 5: Internal Quantum Efficiency (Source: Applied Solar R&D, Mono c-Si)

ARC and Passivation

Selective emitter can be sensitive to surface passivation and antireflective layer. Cells benefit from a passivation layer that is optimized for low reflectivity to realize the full gain of the SE design. Front side Silicon Nitride (SiN) must be tuned to make the film more nitrogen rich. The average weighted reflectivity can be used to elevate the Silicon Nitride (SiN) concentration for a target refractive index of 2.05-2.10 (Figure 6).

Figure 6: Average weighted reflectivity (source: Applied Solar R&D)
Materials

Materials present a primary challenge to implementing a screen printed SE approach. Applied Materials is working with multiple suppliers to ensure the right printing materials are available for printed SE.

Quality screens compatible with printed SE have been thoroughly investigated. Non-metallic screens and compatible emulsions are used for SE printing. It is also important to use optimized screen material for metallization to achieve aligned SE and metal printed patterns. Precise placement of the metal pattern over the SE region allows for a narrower SE region. It is also important to ensure similar SE screen lifetime performance to that of the metallization printing steps. Certain conventional screen technologies may deform over the lifetime of the screen. Because multiple screen printing steps will be in sequence with each other, it is important to eliminate or minimize deformation over the screens’ lifetime for SE printing as well as metallization, to ensure pattern matching from one print step to the next.

The screen printer’s squeegee should also be made of a material compatible with the SE consumables. Non-reactive material optimized for best printing properties is critical. The combination of squeegee material hardness and screen emulsion can interact. Optimal combinations have been validated for robust repeatable performance to meet stringent manufacturability performance criteria.

METALLIZATION

All SE formation methods are compatible with printed metallization technology and other cell fabrication steps, however superior alignment capability is required for all SE formation methods to locate and precisely print metal fingers and bus bars over the SE areas without extending to the adjacent shallow emitter regions.

For metal print, the primary challenge to integrating the SE is locating the selective emitter region. SE doped regions can be visible to the naked eye but depend on wafer texture. Because of the poor contrast between differently doped areas, traditional vision systems are not efficient in pattern alignment over SE. It is critical to reliably locate this region for metal printing. Applied Baccini® has identified specific lighting sources, optics and cameras that give a robust window for locating the SE region, so that the metal grid and bus bars can be precisely printed over the doped region to maximize efficiency gains. Misalignment can result in high series resistance, and will likely short out if printed over the lower doped field region with traditional metallization.

Use of an advanced vision system developed for pattern alignment over SE can overcome the contrast issue (Figure 7); this technology also can be used as post printing inspection to assure that the metallization does not go beyond the SE width. Some examples of the Applied Baccini Esatto Technology SE image recognition on mono and multi c-Si with various SE formation approaches are provided in Figure 8. The vision system is critical to precise detection of the SE region for accurate metal alignment, to overcome typical issues of SE cells such as lack of fiducials for improved yield.
VALIDATION OF PRINTED SE PERFORMANCE

As expected, the improved blue light response and optimized P-diffusion resulted in >0.5% efficiency enhancement to 18.9% compared to the baseline (Figure 9). Mono-crystalline solar cells were fabricated using a low cost dopant paste. Dopant line width control has been demonstrated to be within ±30µm of screen opening. Metallization was carried out using Applied Baccini Esatto Technology. Conventional POCl₃ diffusion at < 840°C was optimized for field emitter junction depth, low saturation current density and overall device performance. Internal quantum efficiency showed improvements in blue response to 92% at 400nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
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<tr>
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<tr>
<td>Efficiency (%)</td>
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</tr>
</tbody>
</table>

Figure 9. Screen printed SE cell performance Printed SE Champion Cell IV Curve

Literature references have also reported cell efficiencies up to 19.2% in production and 6% efficiency gains in modules due to screen printed SE [4].

CONCLUSION

One of the challenges with implementing efficiency improvement solutions in a solar manufacturing environment is to make sure the technology works in existing cell lines with minimal disruptions. Screen printed SE is a fast, straightforward and low-risk way to higher cell efficiencies. Applied Materials has demonstrated a cost-effective screen printed approach to form the SE that includes process optimization and hardware for accurate metal alignment. Testing in both laboratory and customer fabs has shown that
SE cells fabricated using Applied Materials equipment can increase absolute conversion efficiency by >0.5% on mono c-Si SE cells compared to conventional cells.

REFERENCES

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