monoPoly™ to biPoly™: Low-cost passivating contact technologies for efficiencies towards 25%

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Abstract

Passivated emitter and rear cell (PERC) technology continues to dominate the solar industry as the standard in large-scale production. However, conventional PERC is limited to efficiencies below 23% in production. There is a need to push past this efficiency in high-volume manufacturing with low-cost technological improvements. In recent years, the emergence of screen-printed and fired polysilicon-based rear-side passivating contacts, such as in SERIS' monoPoly™ technology platform, have proved effective in achieving cell efficiencies of near 24% with an attractive low-cost upgrade to most PERC/PERT production lines. The significant reduction in carrier recombination at the rear contacts has enabled cell open-circuit voltages V_{oc} greater than 705mV. To boost V_{oc} and efficiencies beyond 24%, this paper presents preliminary results of SERIS' biPoly™ cell: the bifacial application of polysilicon-based passivating contact stacks with front and rear screen-printed and fired metallization. Both monoPoly and biPoly technologies can be integrated into existing manufacturing lines, enabling cell efficiencies above 24% to be obtained in mass production.

Background

The global c-Si cell and PV module production capacity at the end of 2019 increased to ~200GWp as a result of continued passivated emitter and rear cell (PERC) capacity expansions [1]. The implementation of half-cell interconnections and the use of larger wafers have led to higher average PERC module powers. Today's mainstream p-type mono-Si-based modules reach efficiencies of ~20%. Improvements in the wafer material and the front and rear sides of the cells and the introduction of bifacial cell concepts are needed in order to boost module efficiencies further. It is likely that in the next few years, double-side contact cell concepts (e.g. PERC/PERT/TOPCon) will dominate the market, with passivating contacts on n-type mono-Si gaining market share over standard PERC technologies.

Passivating contact stacks consisting of polycrystalline silicon (poly-Si) on silicon oxide (SiO_x) show considerable promise, with cell efficiencies of 25.7% being achieved on laboratory-scale (<100cm^2) solar cells, and up to 24.8% on industrial-scale (≥239cm^2) solar cells, as presented in Fig. 1 [2–4].

SERIS' monoPoly™ platform for the monofacial application of poly-Si-based passivating contact stacks offers an ideal low-cost process that: 1) can be retrofitted to current solar cell lines; 2) is compatible with screen-printed and fired bifacial contacts; and 3) is cost competitive with standard PERC technology [5,6]. The monoPoly technology has achieved conversion efficiencies close to 24% on M2-sized wafers, with open-circuit voltages (V_{oc}) near 710mV and short-circuit current densities (J_{sc}) greater than 41mA/cm^2, as a result of the semitransparent nature of the layers (shown in Table 1). Note that the 23.2% reported was independently measured by ISFH.

As the PV industry progresses towards cell efficiencies in excess of 24%, the need for double-side passivating contacts, which significantly reduce front- and rear-contact recombination, becomes increasingly important. Current passivating contact cell technologies mainly deploy poly-Si stacks on the rear side, because of high parasitic absorption in the doped poly-Si layers and because of the inability to form screen-printed contacts to very thin poly-Si layers.

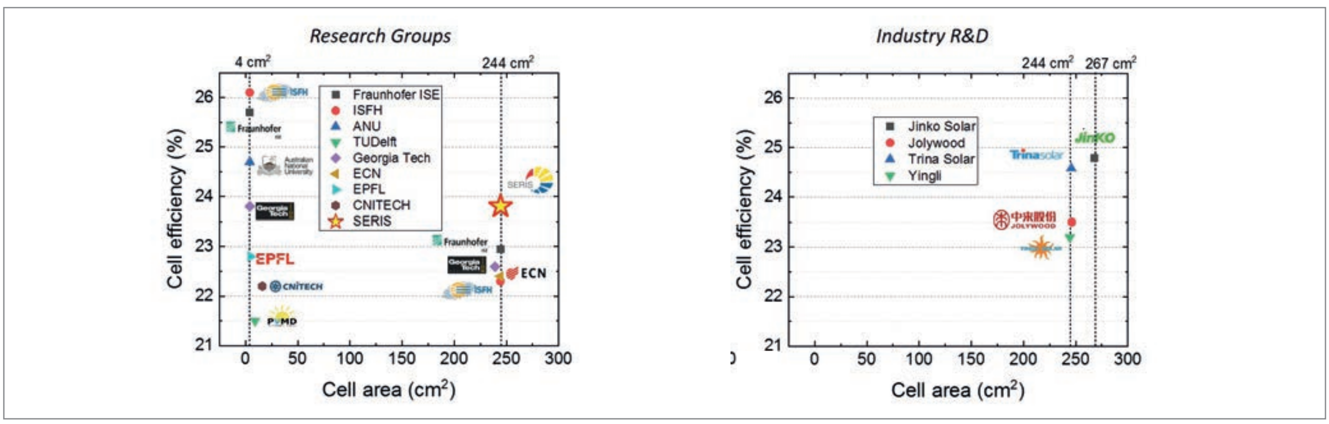

Figure 1. Overview of solar efficiencies achieved with single-side poly-Si/SiO_x passivating contact stacks on small-area (<100cm^2) and large-area (≥239cm^2) silicon wafer solar cells for various groups and industrial players, as reported at scientific conferences and in the press.

This paper presents SERIS' biPoly™ technology platform, a follow-up to monoPoly; it incorporates the double-side (bifacial) application of poly-Si-based passivating contact stacks. Preliminary studies demonstrate recombination current density (J_o) values less than 5fA/cm² for both phosphorus-doped (n^+:poly-Si) and boron-doped (p^+:poly-Si) layers on an ultrathin interfacial SiO_x layer.

Furthermore, silicon solar cell precursors fabricated with a front n^+ poly-Si/SiO_x emitter and rear p^+ poly-Si/SiO_x back-surface field (BSF), as shown in Fig. 2, have demonstrated implied V_{oc} values of up to 730mV before metallization.

biPoly layer properties

The front and rear biPoly stacks consist of an ultrathin (~2nm) interfacial oxide (iO_x) layer that is capped by either n^+- or p^+-doped poly-Si layers [7]. The stack can be deposited by either low-pressure chemical vapour deposition (LPCVD), atmospheric chemical vapour deposition (APCVD) or plasma-enhanced chemical vapour deposition (PECVD). The iO_x is grown in situ in both cases (with no break in vacuum).

Doping of the poly-Si layers is achieved ex situ (LPCVD, APCVD) or in situ (PECVD), where the doped layers can be fabricated using a single-side high-throughput system, for example, in the case of PECVD. The properties of the poly-Si stacks are developed and optimized to meet the requirements for high-performing biPoly solar cells. The dopant profiles for the n^+ and p^+ poly-Si/SiO_x stacks are presented in Fig. 3. Optimized peak dopant concentrations of $4\times10^{20}cm^{-3}$ for n^+ poly-Si and $3\times10^{19}cm^{-3}$ for p^+ poly-Si were found to be ideal for industrial screen-printed and fired metal contacts on the poly-Si. The optimized thickness of the poly-Si further ensures semitransparency at the front side of the biPoly solar cells.

	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
Record batch	697	41.4	81.3	23.5
Record V_{oc}	707	40.4	81.2	23.2

Table 1. Best-performing monoPoly *J–V* parameters.

Solar cell process flow

The introduction of passivating contacts to large-scale solar cell manufacturing is very appealing but at the same time challenging. High-throughput, low-cost deposition schemes are necessary for successful deployment of front and rear passivating contact stacks in mass manufacturing.

The typical process flows for standard pPERC and nPERT are presented in Fig. 4 for comparison. The pPERC process has a laser step after passivation, whereas the nPERT process has an additional n^+ diffusion to form the BSF on the rear. The pPERC process is representative and does not take into consideration any selective emitter process or the mandatory 'stabilization' process included in most PERC production lines today. Both pPERC and nPERT processes use standard screen-printed metallization with high-temperature firing to form the metal contacts.

In recent years, SERIS and its key industry partners have extensively developed the proprietary monoPoly passivating contact solar cell technology platform for mass production, which has produced efficiencies up to 23.5% (shown in Table 1), and also more recently close to 24%, where an independent verification of the results is ongoing at the moment. The monoPoly process – presented in Fig. 4 – is an eight-step simple and lean process flow that can be easily adapted to existing PERC/PERT production lines, with one additional tool required while maintaining the same number of total process steps. This passivating

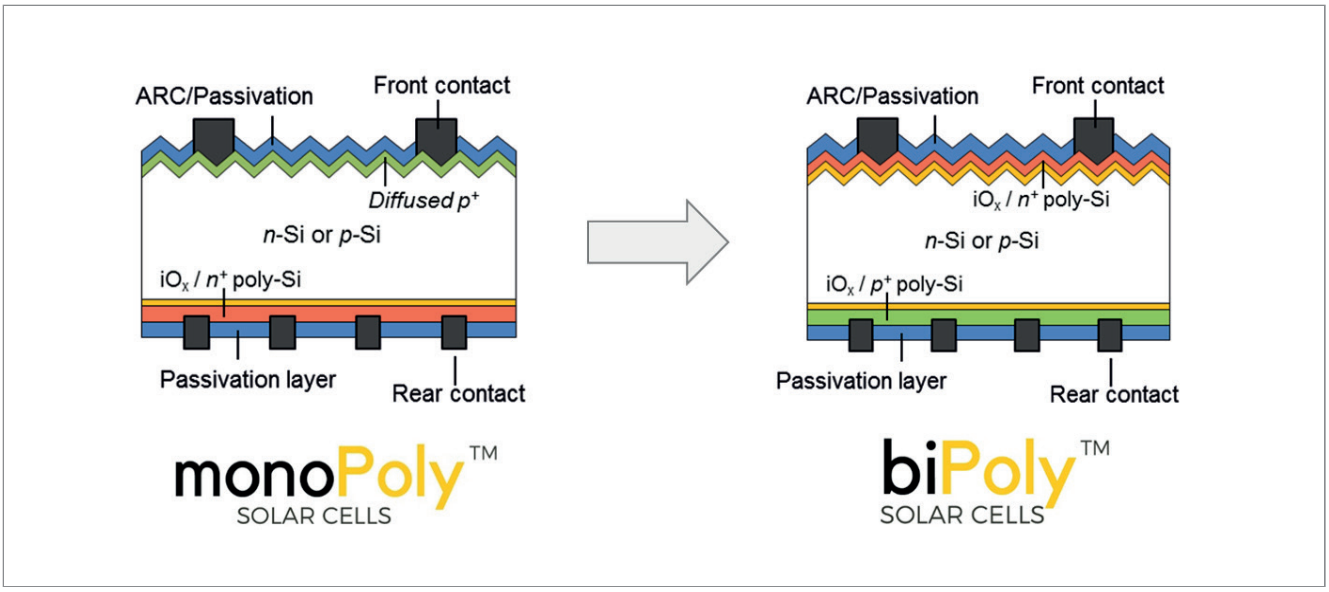

Figure 2. Transition from a bifacial monoPoly cell to a bifacial biPoly cell with a front semitransparent electron-selective passivating contact stack and a rear hole-selective passivating contact stack.

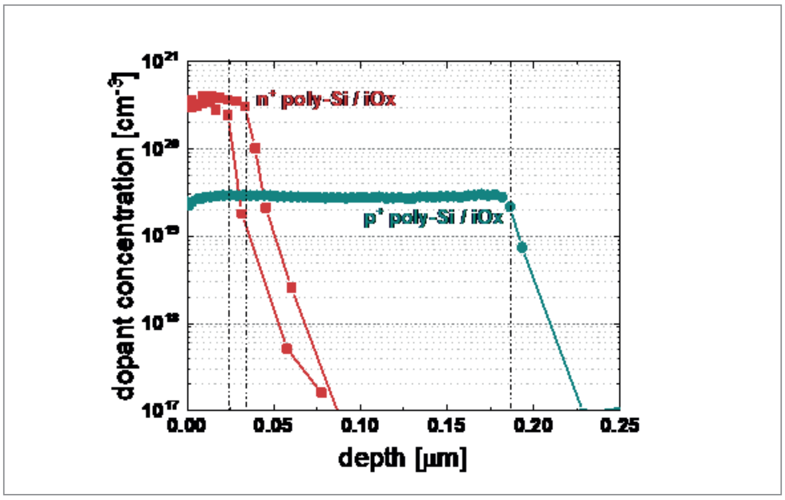

Figure 3. Dopant profiles for ultrathin n+ poly-Si (25 and 35nm) and p+ poly-Si (180nm) on iO_x stacks developed for the biPoly cell structure.

"High-throughput, low-cost deposition schemes are necessary for successful deployment of front and rear passivating contact stacks in mass manufacturing."

contact process uses a unique PECVD process and set of equipment, enabling a streamlined method of manufacturing. The same lean process is now used for front-side application of a poly-Si on the oxide stack in the biPoly cell process – also presented in Fig. 4. With a single-side in situ process, the deposition of the front-side passivating contact stack simply replaces the emitter diffusion step in the monoPoly process.

Efficiency potential

The preliminary passivation quality and implied solar cell performance of biPoly cell precursors is presented in Fig. 5. A 'first-attempt' iV_{oc} of 710mV (at 1 sun) was achieved using an industrial process flow with front and rear poly-Si layers. Further optimization of the process, with improvements in the rear surface roughness, passivating contact stack properties and front layer thickness, pushed the iV_{oc} to 730mV. These cell precursors have a thin front electron-selective n^+ poly-Si/iO_x stack and a rear hole-selective p^+ poly-Si/iO_x stack on a large-area M2-size low-resistivity n-type Cz-Si substrate. A corresponding total surface J_o of 10fA/cm² and an implied fill factor (*iFF*) of more than 84.5% indicate very low device recombination at maximum power point (MPP) conditions. Low device recombination (i.e. high excess carrier density) at MPP not only helps to increase the upper *FF* limit but also increases the lateral carrier conductivity in the silicon base [8].

With the measured properties of iV_{oc} and i*FF*, assuming an attainable J_{sc} of 40mA/cm² for ultrathin ~25nm front n^+ poly-Si layers, the biPoly cell precursor has an implied cell efficiency (unmetallized) of close to 25%. This brings biPoly cell efficiencies on par with silicon heterojunction cells while retaining high-temperature stability, which is not possible with silicon heterojunction technology. Furthermore, existing PV production lines can be adapted for biPoly fabrication with cost-effective upgrades while retaining most of the existing PERC process steps (e.g. wet chemical steps, SiN_x passivation, screen-printing and firing).

Some challenges remain, however, when fabricating a high-efficiency solar cell – in particular, the screen-printed metallization of the ultrathin biPoly layers using commercially available (non-optimized) metal pastes. With the rapid development of rear-side passivating contact technologies in the PV community (e.g. TOPCon, monoPoly, etc.), metal paste manufacturers are demonstrating continuing improvements in paste that can contact ultrathin poly-Si layers. It will not be long before improved paste formulations will help realize the efficiency potential of cell technologies with front and rear poly-Si passivating contacts, such as biPoly.

Outlook and roadmap towards 30%

The current record efficiency for Si single-junction solar cells is 26.7% [9], with a theoretical efficiency limit of 29.56% [10] for single-junction Si cells because of unavoidable spectral losses and Auger recombination in the silicon material. The only way to surpass this limit is by adding a second solar cell in tandem – for example, multijunction cells with a silicon bottom cell and either a III-V semiconductor or a perovskite-based top cell.

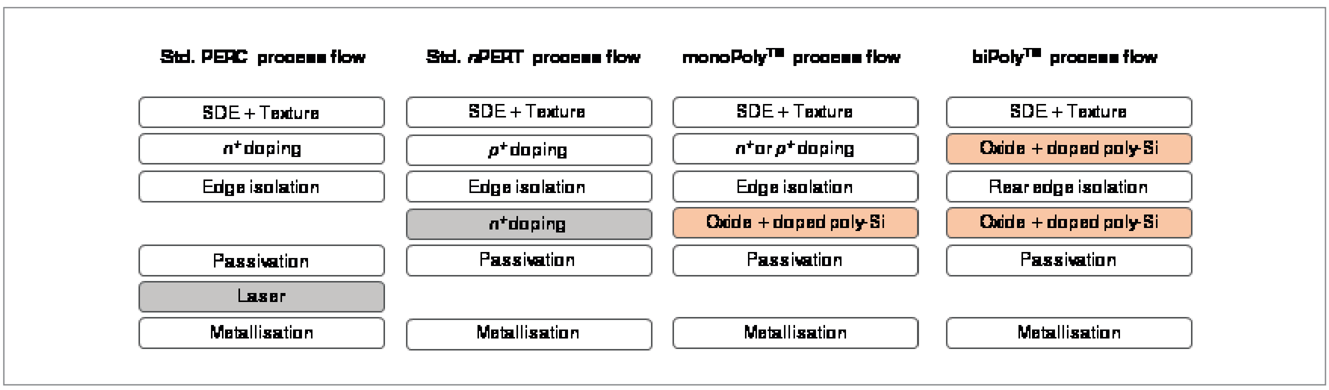

Figure 4. Comparison of the standard PERC and PERT process flows with the simple eight-step process flows for the fabrication of monoPoly and biPoly solar cells, where the oxide and doped poly-Si can be deposited by PECVD, LPCVD or APCVD.

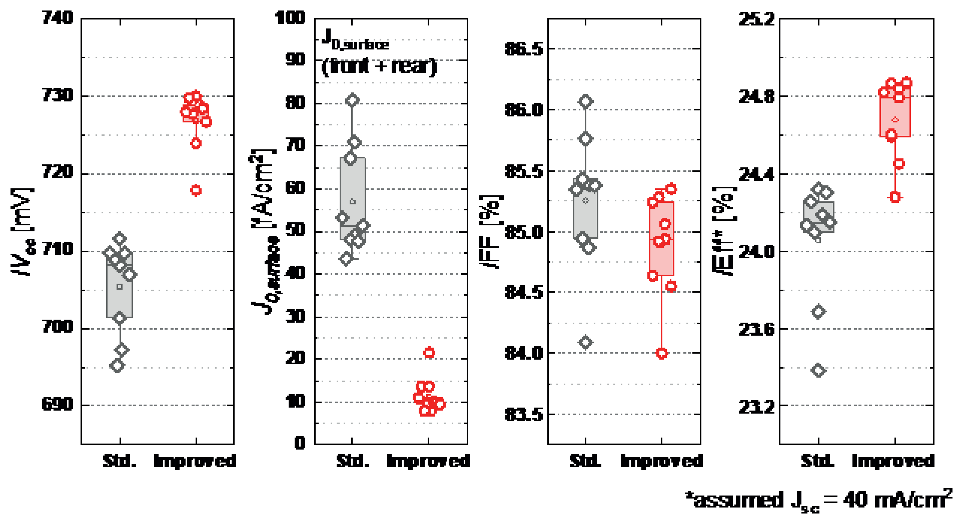

Figure 5. Implied open-circuit volage (iV_{oc}) at 1 sun, total surface recombination current density ($J_{o,surface}$), implied fill factor (i*FF*) and implied efficiency (i*Eff*) of biPoly cell precursors fabricated at SERIS. Parameters are measured prior to metallization for standard and optimized process flows. A J_{sc} of 40mA/cm² is assumed for i*Eff* estimations.

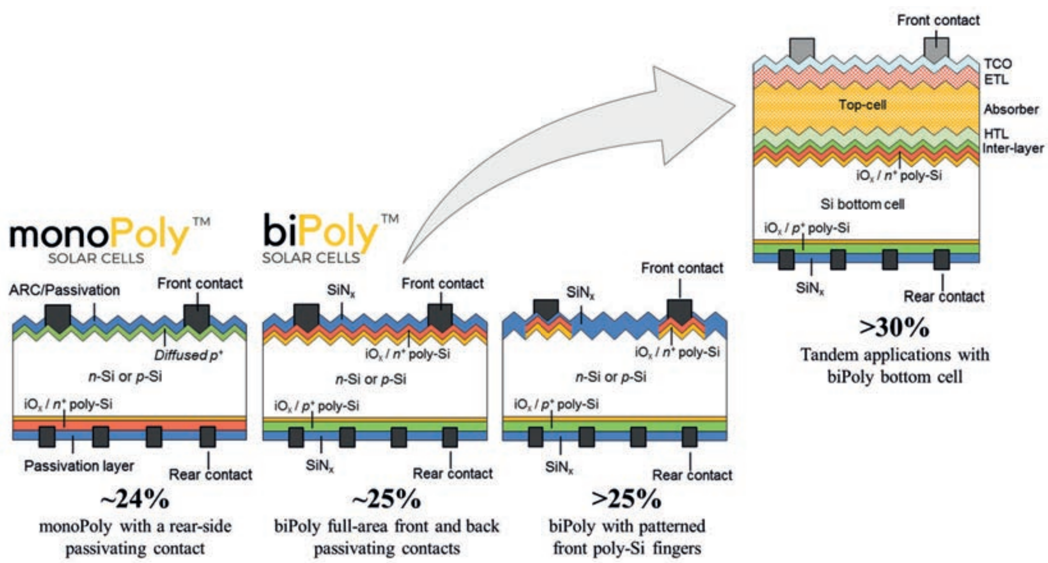

Figure 6. Schematic roadmap depicting the evolution of current PERC cell technology to monoPoly, biPoly and biPoly⁺ as the bottom cell in silicon-based tandem solar cell applications.

Today, PERC technology holds a market share of more than 65% in the PV industry but is limited to cell efficiencies of ~22.5% in production. Integrating rear-side passivating contacts in PERC production lines will offer a boost in cell efficiencies to near 24%, while the addition of front-side passivating contacts will enable efficiencies of above 25% (Fig. 6). Furthermore, these high-V_{oc} devices (potentially up to 740mV with SERIS' biPoly process) serve as an ideal cost-effective bottom cell upgrade for ~100GW of present day PERC lines. This paves the way from mainstream PERC to silicon-based tandem applications for efficiencies exceeding 30% in the PV industry [11,12].

Summary

This paper has presented SERIS' monoPoly™ and biPoly™ cell technologies, for the adoption of rear-side and front-side passivating contacts in the c-Si PV industry. A simple process flow enabled by single-side in situ doped poly-Si layers yields cell efficiencies of close to 24% for the monoPoly technology, while biPoly cell precursors demonstrate iV_{oc} values of up to 730mV, corresponding to an efficiency potential of 25%. These promising results pave the way for the adoption of passivating contacts in retrofitted PERC/PERT production lines today and as silicon bottom

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cells for high-efficiency >30% tandem solar cell applications.

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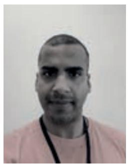

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