

SILICON INK HIGH EFFICIENCY SOLAR CELLS

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ABSTRACT

Innovalight has developed the Cougar™ Process, a method for making a high efficiency solar cell on a Cz-Si wafer with a proprietary Silicon Ink. With the use of an industrial inkjet printer, an n-type ink is deposited on a p-type silicon wafer in order to form a high efficiency selective emitter. The Cougar Process requires only an incremental modification to a conventional front-contact solar cell manufacturing configuration, necessitating only the addition of the inkjet printer system. Consequently, the Cougar Process improves the efficiency of standard screen printed solar cells by about 1% absolute at a manufacturing cost similar to that of a conventional front-contact solar cell. As of the publication date of this paper, a best cell efficiency of 18% has been achieved on a 125mmx125mm pseudo square wafer.

INTRODUCTION

Selective emitter cell architectures have been proposed as the next evolutionary step toward improving the efficiency of standard screen printed Si cells [1-4]. Separating the field region from the metal contact region, a selective emitter configuration allows a lighter emitter doping in the vast majority of the front surface of the solar cell, resulting in both reduced front-surface recombination and enhanced blue response, while confining the heavily doped regions necessary for low contact resistance to relatively small surface areas immediately below the metal contacts. The metal contact region also provides isolation from the field region which tends to enhance higher open circuit voltages.

However, despite the efficiency advantages, a selective emitter configuration has not been widely implemented in industrial solar cell production. A major barrier is the high cost associated with the introduction of additional processing steps necessary for patterning the selective emitter structure onto the solar cell surface. Photolithography is most often used for patterning high efficiency selective emitters. And although this approach is precise and accurate, its low relative throughput and high manufacturing cost put the use of photolithography at substantial economic disadvantage to conventional (although less efficient) alternatives.

Laser patterning, an alternative to photolithography, has been proposed also but not widely accepted. Although capable of producing features sizes comparable to photolithography and requiring fewer manufacturing steps (when compared to lithographic solutions), laser

processing also tends to cause various crystallographic defects on the processed regions which must be properly and carefully removed in order to maintain any performance gain that would otherwise be lost by the laser-induced damage [5-8].

Screen-printed doped diffusion pastes have also been proposed but not used in manufacturing so far. Although capable of forming heavy diffusions for use under metal contacts [9], these pastes also tend to result in uncontrolled contamination between proximately located silicon wafers in a furnace, which may substantially increase recombination in the high efficiency emitter region and thus reduce the overall performance of the cell.

In this paper, the Cougar™ Process, a novel method of forming a high efficiency selective emitter on a p-type Cz-Si (Czochralski) wafer is described. By the deposition of a proprietary doped Silicon Ink in a pattern configuration slightly wider than the subsequently deposited front metal contact grid, a solar cell with both a lightly doped field region and a highly doped metal contact region is formed in a single step, making the Cougar Process one of the most economically competitive solar cell manufacturing methods in the industry.

SILICON INK TECHNOLOGY BACKGROUND

Innovalight has developed a proprietary, low energy, low-cost synthesis approach yielding abundant quantities of high-purity silicon nanoparticles. The silicon nanoparticles are formed through homogeneous nucleation from an inexpensive and abundant silicon precursor. This precursor is largely decoupled from the polysilicon and silicon wafer supply chain and any associated price volatility.

This process converts over 90% of the precursor silicon into nanoparticles in a process that yields mono-dispersed nanocrystals with a size distribution of less than 20%. Consequently, it is possible to create large quantities of high quality nanoparticles with a size that can be controlled down to 2 nm without any sorting or post-processing. This size control capability is essential to formulate stable inks and enables film formation at low processing temperatures. One of the advantages of using silicon nanoparticles is a reduced melting temperature [10] as compared to bulk silicon. This allows the nanoparticles to be cheaply and easily sintered into dense films at temperatures that do not affect the quality of the bulk wafer.

To facilitate solar cell manufacturing Innovalight has developed functional groups that attach to the nanoparticles in solution and protect them from oxidation; the functional groups enable stable Silicon Ink, a type of colloidal dispersion. The functional groups easily detach from the nanoparticles at low temperatures and evaporate from the printed layer together with the ink solvent, leaving a very high-purity silicon film. By incorporating dopant atoms such as Boron (p-type) or Phosphorous (n-type) in the silicon nanoparticles, with highly adjustable dopant concentrations, it is possible to create doped films from the inks.

The ink formulations have been specifically designed for off-the-shelf industrial inkjet print heads and have demonstrated reliable printing using industrial piezo head technology. Inkjet printing offers many manufacturing advantages for PV solar cells. As a contactless process, it eliminates the use of masks and screens which reduce processing steps, ink usage, ink contamination, and wafer breakage [11-12]. Additionally, inkjet printing also allows, 1) excellent control of film thickness and thickness uniformity, 2) straightforward scalability to large format and high throughput by adding print heads in series and in parallel, and 3) easy transfer from rigid to flexible (or ultra-thin) substrates. Finally, advanced inkjet printing tools provide the ability to form high resolution patterns combined with the flexibility to inkjet print multiple formulations such as n-type and p-type inks in one single processing step. These capabilities provide leverage to advance many PV cell architectures and are applicable to Si wafer as well as thin film technologies.

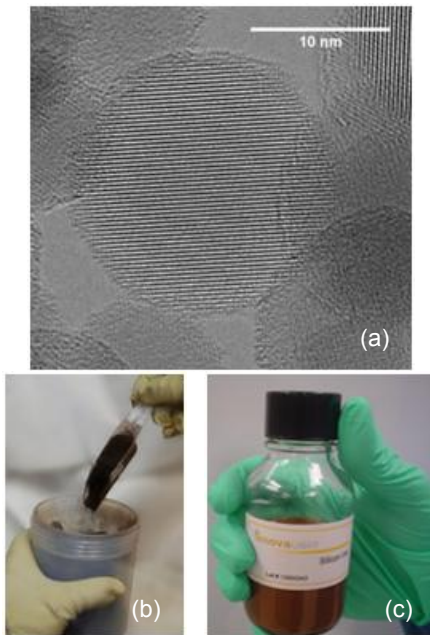


Fig. 1: TEM image of Innovalight's silicon nanoparticles (a), Silicon nanoparticle powder (b), Silicon Ink (c).

CELL FABRICATION PROCESS

The cell fabrication process was completed on industrial scale equipment by using commercially available silicon wafers. P-type Cz-Si pseudo-square (125mmx125mm, 180 μ m thick) wafers with a bulk conductivity of about 2 Ω *cm were used as substrates.

Reference screen-printed solar cells (cf. Fig. 2a) were made by following conventional processing steps. The wafers were first batch cleaned and textured in an alkaline bath to form random pyramids. An n-type emitter was formed by using POCl₃ tube diffusion (MRL Phoenix horizontal tube furnace). The front surface was passivated with silicon nitride by using an inline PECVD system model Roth&Rau SiNA XS and the BSF and front metal grid layers were processed by using a conventional Al and Ag screen printer made by Baccini (single rotary table system plus a "Paternoster" dryer). Finally co-firing was done in a Despatch CF-7210 belt furnace.

To make a Cougar cell an inkjet printing step was introduced to the above process to pattern the emitter on the top surface of Cz-Si p-type wafers (Fig. 2b) by using n-type doped Silicon Ink and an inkjet printer model OTB PixDro LP-50. The inkjet printing step was followed by a thermal step to dry off the solvents, sinter the nanoparticles and form the patterned emitter.

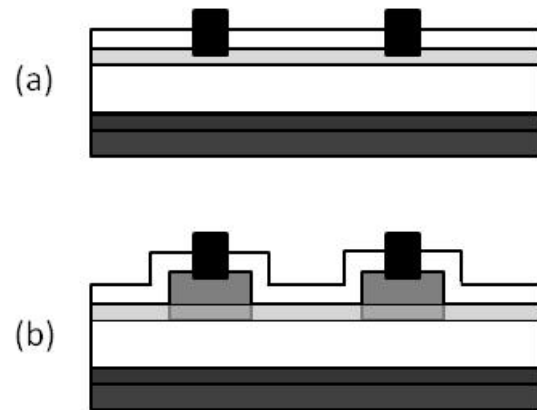


Fig. 2: (a) cross section of reference cell architecture, (b) cross section of Cougar cell architecture using Innovalight Silicon Ink.

The printed silicon pattern gives enough visual contrast to the background of the wafer to allow automatic pattern recognition. An industrial screen printer was used to automatically identify the patterns, align the wafers, and screen-print the Ag grids. By adjusting the properties of the nanoparticle layer and the time/temperature of the thermal step it is possible to achieve a variety of doping profiles. Typically, in a single thermal processing step, a 100-120 Ω / \square n-type field emitter was formed with contact areas having an effective sheet resistance between 10 Ω / \square and 50 Ω / \square . The duration of the thermal process was kept very close to what is used in the industry for standard screen printed emitter formation.

The sheet resistance of the emitter and contact can be independently controlled allowing for a wide variety of contact strengths while maintaining an emitter in the desirable conductivity range. The measured SIMS profile for phosphorous concentration at the wafers front surface for a variety of thermal conditions is shown in Fig. 3. The "Field" trace shows the profile measured in the space between printed fingers where the high resistivity part of the emitter is formed. The profile corresponds to a 100Ω/□ measured sheet resistance. The other three traces show examples of high-doping contact regions (busbar and fingers).

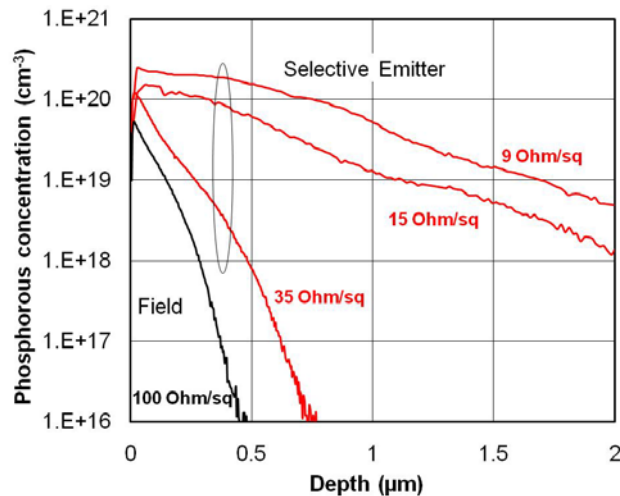


Fig. 3: Example of SIMS data for phosphorous dopant concentration profiles.

CELL RESULTS

The ability of Silicon Inks to form high efficiency solar cells via the Cougar™ Process on 125mmx125mm pseudo square Cz-Si substrates is demonstrated by the efficiencies measured at Innovalight and confirmed by ISE Callab in Freiburg, Germany. Table 1 shows a comparison of Innovalight selective emitter cells with reference standard screen-printed solar cells, both fabricated on Innovalight's 10 MW pilot line. The measurements were performed by a Class A flash sun-simulator (model h.a.l.m. cetisPV-XF2) calibrated by both ISE and NREL. The net result is a power conversion efficiency enhancement of about 1% (absolute).

Table 1

Cell Structure		Voc (mV)	Jsc (mA/cm ²)	FF (%)	Efficiency (%)
Selective Emitter	Best	629	36.5	78.2	18.0*
	Average (20 cells)	627	36.4	78.2	17.9
Reference	Best	618	35.1	77.8	16.9
	Average (10 cells)	617	35.0	77.7	16.8

*Best cell data confirmed by ISE Callab in Freiburg, Germany

Fig. 4: shows an example J-V curve measured on a selective emitter cell. The selective emitter structure yields a higher current and voltage as expected due to a reduction of recombination losses at the top cell interface, which typically affect short wavelength light.

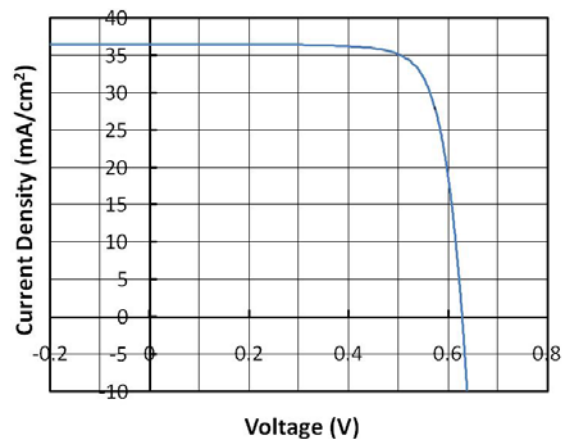


Fig. 4: One-Sun J-V characteristics of the best Innovalight selective emitter solar cell.

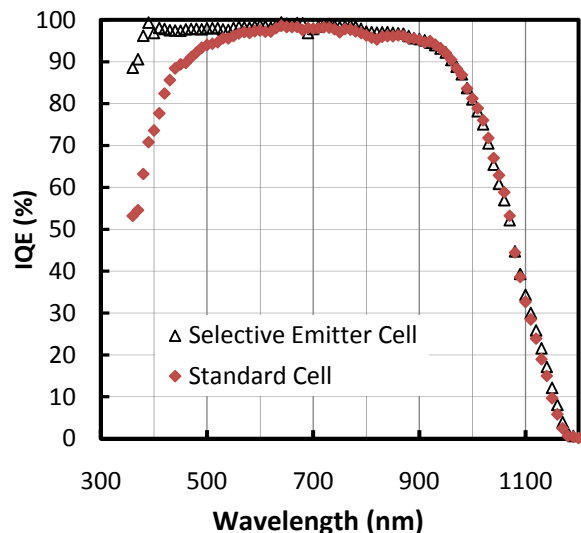


Fig. 5: Internal Quantum Efficiency (IQE) for standard and the selective emitter cells.

One important aspect of using a new material to fabricate crystalline silicon solar cells is to assess its impact on recombination in the silicon wafer. Additionally the successful use of a high resistivity emitter in the field between fingers requires optimization of the dopant profile and dielectric surface passivation to achieve low recombination. We have used photocarrier injection level dependent lifetime curves measured on control samples processed simultaneously with our devices to monitor and optimize the recombination of our process.

Control samples are processed with double sided emitter, double sided nitride deposition and contact firing. The injection level dependent lifetime curves are measured

using a photo conductance bridge from Sinton Consulting [13]. The bulk lifetime and emitter saturation current density (J_0) are extracted from the curves by fitting the high injection region as described in the Sinton manual [14].

The compatibility of the silicon ink with high lifetime processing and low recombination emitters is demonstrated by the results shown in Fig. 6. The results were collected from the control samples run in twelve batches processed recently at Innovalight. The comparison in each plot is shown for two different front surface preparations, (left) low resistivity emitter only and (right) ink pattern.

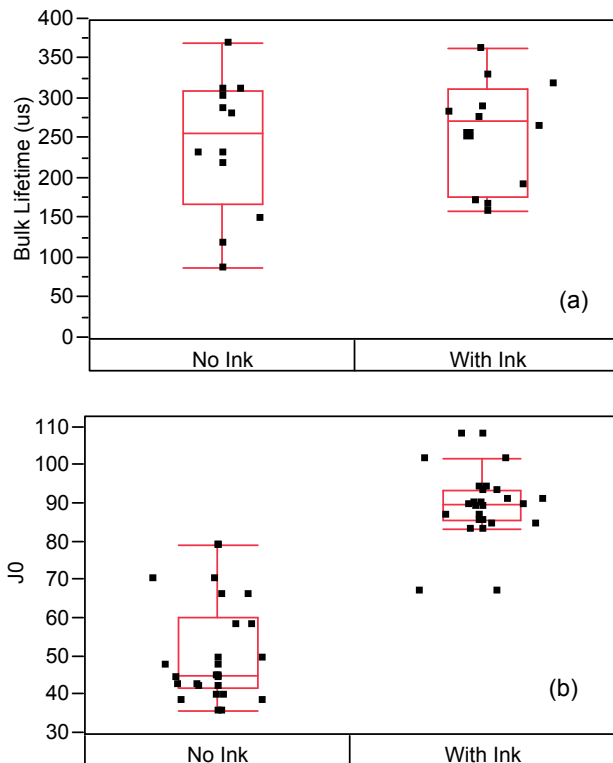


Fig. 6: Extracted (a) bulk lifetime and (b) emitter saturation current values for samples processed without ink, or with ink pattern on front side.

As a simplification the samples are assumed to be perfectly symmetric and as such the number shown for J_0 is divided by 2 to show the J_0 of the emitter in the final device. In actuality the J_0 of the side with the heavily doped ink regions is expected to be slightly higher.

The consistently high bulk lifetime demonstrates that the Silicon Ink does not introduce any significant contamination into the substrates. Furthermore the low values of the emitter saturation current density demonstrate the quality of the high efficiency emitter being formed under this process. It should be noted that more accurate extraction of the J_0 would be possible using differently doped substrates.

SUMMARY AND OUTLOOK

Innovalight has demonstrated the formation of an 18% selective emitter device using Silicon Ink with an inkjet printing system along with the same tools and materials used to produce conventional screen-printed cells having uniform emitters. Verified on industrial scale equipment using commercially available silicon wafers, Innovalight's Cougar Process is one of the most economically competitive solar cell manufacturing methods in the industry today.

Innovalight is further exploring the use of Silicon Ink and inkjet technology to enhance the efficiency of multicrystalline cells, as well as to offer an economically viable path to manufacture advanced cell architectures such as back-contact patterned ultra thin cells.

ACKNOWLEDGEMENTS

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