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Efficiencies of 22% at low cost: the future of mass-produced laser-doped selective emitter solar cells

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ABSTRACT

Laser-doped selective emitter (LDSE) technology, invented and patented by the University of New South Wales (UNSW), is presently generating considerable interest in the photovoltaics industry due to its low cost, high efficiency, and suitability for mass production. The excellent results achieved to date – as high as 19.7% on small area laboratory test devices [1], and 19.0% on industrial large-area 156mm wafers [2] – are attracting a similarly impressive array of commercial partners. Nearly 10 companies are at various stages of implementation of LDSE technology variants into production and pilot production. This paper takes a closer look at the potential for mass production of LDSE-based solar cells.

Introduction

UNSW's LDSE technology continues to attract an impressive array of commercial partners. Part of the LDSE technology's popularity is related to the ease of retrofit of a standard screen print solar cell line. With a few extra tools, a simple selective emitter technology can be realised with a large performance gain. While other selective emitter technologies on the market generally make heavy use of aligned screen-printing techniques, which restrict efficiencies to little more than 18.5% [3] and involve the use of expensive Ag and Al screen printing pastes, UNSW LDSE makes use of self-aligned, rapid plated metallization and inexpensive, low-temperature laser doping and patterning techniques. These techniques:

- Reduce front-side shading losses to as low as 3%
- Allow metal lines to be placed closer together increasing fill factor
- Significantly increase blue response and short circuit current by as much as 10%
- Reduce metal-Si interface area and recombination at these interfaces, thus increasing cell voltage, and
- Involve no optical alignment techniques or associated yield loss.

This improvement in solar cell front-surface design allows efficiency gains of at least 1% absolute over standard screen print solar cells at a reduced product cost. But perhaps the biggest advantage with LDSE technology is the range of opportunities it opens up for improved rear-surface design. In conjunction with effective rear-surface passivation and point contact techniques, efficiencies are expected to increase to 21% and as high as 22% within two years on standard p-type Cz material. This by far eclipses what is possible with screen printing technology, and does not require screen print pastes which can easily account for a third of the conversion cost of screen print solar cells. As a result, large savings are realised in the cost of product.

> "Next-generation LDSE is highly suited to mass production, with significant savings in cost of ownership predicted at the wafer, cell and module level."

The next-generation LDSE solar cells share many high-efficiency features of UNSW's world-record PERL cell structure, having excellent spectral response for both blue and red light and open circuit voltages already easily exceeding 670mV on p-type Cz silicon, well above the values ever demonstrated using screen-printed contacts. Unlike the PERL structure, next-generation LDSE is highly suited to mass production, with significant savings in cost of ownership predicted at the wafer, cell and module level.

UNSW, with its extensive years of research, has compiled a comprehensive portfolio of patents on LDSE that also extends to variants of the LDSE technology.

Single-side LDSE process

A schematic of the standard, single-sided LDSE cell structure is shown in Fig. 1. The structure features front surface metallization formed using rapid light-induced plating, while the rear contact is a standard screen printed Al contact. The selective emitter diffused regions are formed by application of a phosphorus dopant source to a silicon nitride passivated silicon wafer, followed by laser melting of the silicon surface. This

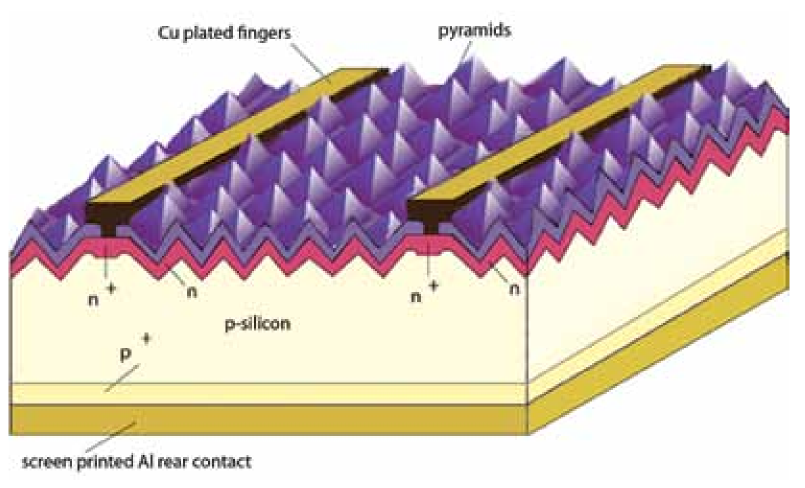

Figure 1. Standard single-sided LDSE solar cell, showing laser-doped selective emitter front surface with plated metallization and screen-printed rear Al BSF.

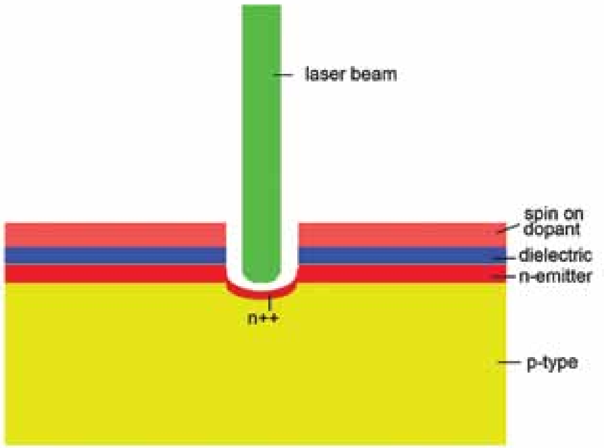

Figure 2. The laser doping process. The dielectric layer is removed while a dopant source is incorporated into the molten silicon, forming a selective emitter and plating mask in one step.

process is depicted in Fig. 2. During melting, the silicon mixes with dopant atoms to create a heavily diffused region on recrystallization. Simultaneously, the silicon nitride passivation layer is ablated where the laser beam is applied, creating openings which can be used as a self-aligned plating mask.

Fig. 3 shows the process steps required for fabrication of an LDSE solar cell. The front end of the process is almost identical to that of a standard screen print solar cell process flow. Incoming silicon wafers are damage etched and textured, followed by light emitter diffusion which can be as light as 200Ω/sq. The profile and sheet resistance of the emitter is non-critical. A PSG removal is followed by an edge isolation procedure which can ideally be done in the same tool using a rear wet etch. Following this, a silicon nitride layer is deposited using PECVD or sputtering techniques.

Whereas a screen printed cell would at this point have its front Ag contacts printed, followed by rear Ag busbars and rear Al BSF printing and cofiring, the LDSE cell requires only rear Ag busbar and rear Al BSF printing and firing. After the rear contact formation, the front surface is laser doped followed by plating and sintering of the front contacts. Due to the similarities between the LDSE process and the screen print solar cell process, it is easy to retrofit an existing screen print line for LDSE, with only a dopant applicator, laser, plating bath and sintering furnace required as additional tools.

The light-induced plating (LIP) process involves a rapid Ni plate and sinter, followed by a rapid Cu plating step and very thin Ag or Sn capping layer to prevent Cu contamination of module encapsulation layers. Unlike older electroless plating methods which were very slow, the Ni LIP process lasts a matter of seconds and the Cu plating step only takes several minutes. The light-induced plating technique developed at UNSW forms very narrow metal lines as little as 20–30µm across. With careful process control, these narrow fingers can be formed as high as 15–20µm and almost semicircular in cross section, with very good adhesion [2,4,5]. With simple optimization of laser doping and plating processes, the peel strength of plated metal lines can be as high as 3N, comparable to that of screen printed cells.

Finally, for the purposes of module fabrication, LDSE cells may have conductive glued or soldered interconnects as desired by the module manufacturer.

Single-side LDSE cost of ownership

UNSW's advanced laser doping and plating techniques reduce front-side shading losses from around 7% to as low as 3%, and allow metal lines to be placed closer together reducing resistive losses in the emitter, increasing fill factor and allowing the emitter to be very lightly diffused. The lightly diffused emitter significantly improves the blue response and short circuit current by as much as 10%. At the same time, the narrow metal lines give a reduced metal-Si interface area and with optimized

	SP	LDSE
Saw Damage Removal & Texturing	✔	✔
Diffusion	✔	✔
PSG Etch/Junction Isolation	✔	✔
PECVD SiNx	✔	✔
Screen Printing and Drying	Front Ag	✖
	Dry	✖
	Rear Ag	Rear Ag
	Dry	Dry
	Rear Al	Rear Al
Belt Furnace for Drying Firing	✔	✔
Dopant Application	✖	✔
Laser Doping	✖	✔
Ni/Cu/Ag Plating	✖	✔
Ni Sinter	✖	✔
Testing	✔	✔

Figure 3. Single-side LDSE process sequence compared to the standard screen print solar cell process sequence. Laser doping and plating are the only extra processing steps, and LDSE does not require printing of the front contacts.

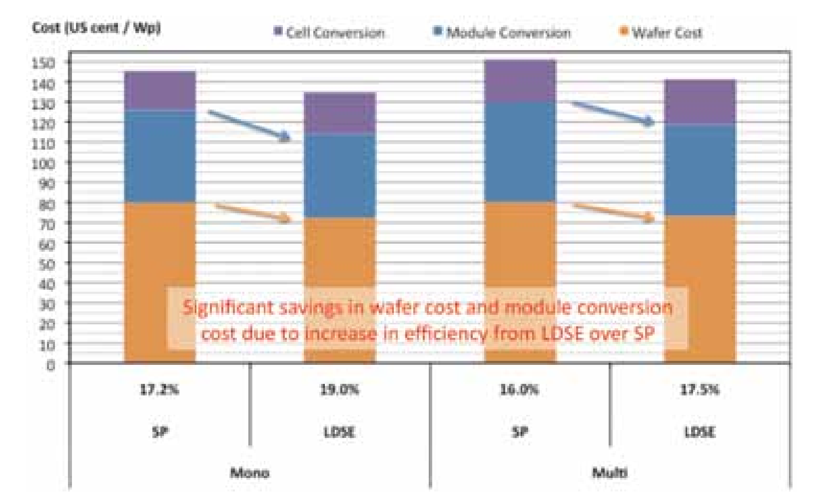

Figure 4. Overall cost of ownership for LDSE solar cells compared to that of standard screen print solar cells. Savings in wafer cost and module conversion due to higher power density are realised.

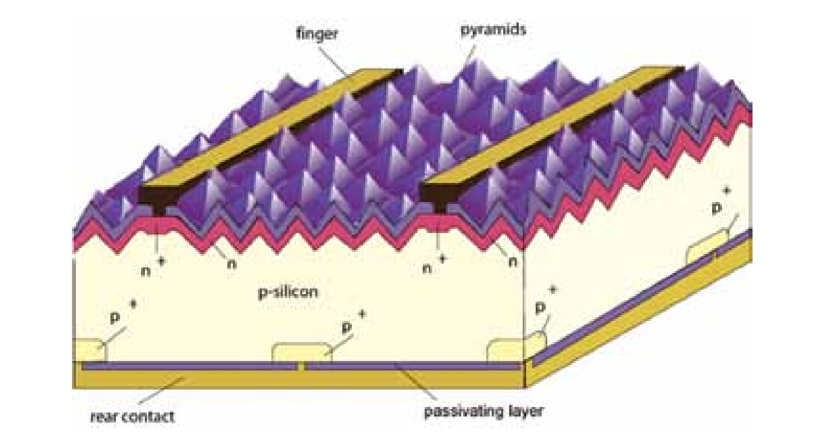

Figure 5. Double-sided LDSE solar cell, showing laser-doped selective emitter front surface and passivated, locally diffused rear surface with point contacts.

heavy laser doping (as low as 5Ω/sq), dark saturation current losses at these interfaces are reduced, increasing cell voltage. The techniques also involve no optical alignment techniques or associated yield loss.

Due to the above high-efficiency features, single-sided LDSE cells reach efficiencies of 19.0% on p-type Cz monocrystalline material and 17.5% on p-type multicrystalline silicon in manufacturing. This compares to around 17.2% on p-type Cz and 16.0% on multicrystalline for industry standard screen printed solar cells. Using these efficiencies, the cost of ownership for LDSE can be compared to that of standard screen print solar cells using commercially available cost of ownership modelling software. The cost of ownership model assumes fabrication on a production line in China running at 2,400 cells per hour with a wafer size of 156 × 156mm, with a yield of 95% and an overall equipment effectiveness of 87%. The model also takes into account production equipment capital cost, building utilities and services (fixed and running cost), labour cost (indirect and direct cost), electrical power, process gasses, DI water and chemicals, metal plating costs (for the LDSE process), and printing paste, screens and screen cleaner (for the screen print process). At around US$0.20/W for both mono- and multicrystalline material, the cell conversion cost for LDSE is similar to that for a standard screen print cell.

However, due to the high efficiency and therefore higher energy density of the LDSE technology, significantly lower wafer and module conversion costs result in a lower cost of ownership for the LDSE technology (around US$1.35/W on mono, US$1.40/W on multi) compared to screen print technology (around US$1.45/W on mono and US$1.50/W on multi). This lower cost of ownership is depicted in Fig. 4, with further savings to be expected in balance of systems and installation costs for the LDSE technology.

"Single-sided LDSE cells reach efficiencies of 19.0% on p-type Cz monocrystalline material and 17.5% on p-type multicrystalline silicon in manufacturing."

LDSE technology is an attractive option compared to many other selective emitter solar cell designs on the market, as it does not require the use of optical alignment techniques, and due to the lack of high temperature processing it is also suitable for multicrystalline material.

The single-sided LDSE cell provides a

	SP	LDSE	D-LDSE
Saw Damage Removal & Texturing	✔	✔	✔
Diffusion	✔	✔	✔
PSG Etch/Junction Isolation	✔	✔	✔
PECVD SiNx	✔	✔	✔
Screen Printing and Drying	Front Ag	✖	✖
	Dry	✖	✖
	Rear Ag	Rear Ag	✖
	Dry	Dry	✖
	Rear Al	Rear Al	✖
Belt Furnace for Drying Firing	✔	✔	✖
Dopant Application	✖	✔	✔
Laser Doping	✖	✔	Front & Back
Ni/Cu/Ag Plating	✖	✔	✔
Ni Sinter	✖	✔	✔
Rear Surface Metallization	✖	✖	✔
Testing	✔	✔	✔

Figure 6. D-LDSE process sequence compared to the single-side LDSE and standard screen print solar cell process sequences. The D-LDSE cell requires no screen printing at all, eliminating expensive screen print paste usage.

competitive edge to screen printed solar cell technology, but with the new LDSE technology appearing to further enhance these cost and performance advantages. Test devices indicate that the new LDSE with passivated rear surface has the potential to reach efficiencies as high as 22% on standard p-type CZ wafers, with corresponding open circuit voltages above 700mV, values far exceeding those achievable by screen printing technology. This should lead to even greater savings in cell conversion cost in addition to wafer and module conversion cost.

Double-side LDSE process

A schematic of the double-sided LDSE (D-LDSE) cell structure is shown in Fig. 5. The structure features many of the high-efficiency features found in UNSW's world-record PERL cell, with several new rear-surface technologies enabling a high-quality rear passivation, local selective diffusions and self-aligned point contacts. In addition to the improved rear, the structure features the usual high-quality LDSE textured front surface incorporating narrow self-aligned plated metal lines.

Fig. 6 shows the process steps required for fabrication of a D-LDSE solar cell. The process is similar to single-sided LDSE fabrication, the main differences being the application of a passivating layer to the rear surface which is laser doped along with the front surface. The rear surface is then metallized using a range of industrial techniques that do not involve screen printing. In this way, screen print tools and expensive print pastes can be completely eliminated for this cell design.

Double-side LDSE cost of ownership

In addition to the usual high-quality LDSE front surface, the high-efficiency features present at the double-sided LDSE rear surface increase efficiency above 20%. A high-quality rear passivating layer, point contacts giving a smaller metal-semiconductor interfacial area, along with heavy diffusion at the point contacts, all contribute to dramatically lower dark saturation current losses at the rear surface and allow open circuit voltages to approach 700mV (pilot production voltages already easily exceeding 670mV have been achieved), even on p-type Cz material, far exceeding what was previously thought possible for this material. The improved rear surface also enables an improved red response, further increasing short circuit current, while several effective industrial metallization schemes ensure minimal additional resistive losses. As for the single-sided LDSE process, the processing techniques are all industrially feasible and require no optical alignment techniques or associated yield loss.

Where the screen printed rear surface limits single-sided LDSE cells to around 19% on p-type Cz monocrystalline material and 17.5% on p-type multicrystalline silicon, D-LDSE cells appear capable of comfortably exceeding 21% on Cz and 19% on multicrystalline material. This is again compared to around 17.2% on p-type Cz and 16.0% on multicrystalline for industry standard screen printed solar cells. Using these efficiencies, the cost of ownership for D-LDSE can be compared to that of standard screen print solar cells using commercially available cost of ownership modelling software. It is again assumed that fabrication is on a production line in China, with 2,400 cells per hour, a wafer size of 156 × 156mm, a yield of 95% and an overall equipment effectiveness of 87%.

Fig. 7 compares the cell conversion cost of D-LDSE cells compared to standard screen print cells. Where the single-sided LDSE cell conversion cost was close to that of standard screen print solar cells, with cost advantages coming at the wafer and module levels, the D-LDSE cell should cost less than US$0.14/W on mono material (compared to around US$0.19/W for the screen print cell) and about US$0.15/W on multi material (compared to around US$0.21/W). These significant savings are due mainly to the elimination of the screen print process and expensive screen print pastes, along with the large increase in power output per unit area for this cell technology.

Fig. 8 shows the overall cost of ownership for double-sided LDSE technology at the module level. The very high energy density of the double-sided LDSE technology results in further savings in wafer and module conversion costs, giving a significantly lower cost of ownership (US$1.17/W on mono and US$1.23/W on multi) to standard screen print technology (US$1.45/W on mono and US$1.51/W on multi) and other screen printed selective emitter technology on the market today. Further savings are to be expected in balance of systems and installation costs for the D-LDSE technology.

The single-sided LDSE cell provides a competitive edge to standard screen print solar cell technology. The most exciting aspect, however, is that the new LDSE technology with passivated rear surface, capable of efficiencies as high as 22%, leads to even greater cost savings in cell conversion costs in addition to wafer and module conversion cost.

Finally, the D-LDSE technology is an attractive option compared to other high-efficiency solar cell designs on the market, as it does not require the use of expensive float-zone feedstock, transparent conducting oxides (TCOs) or photolithographic patterning of contacts. Again, unlike other high-efficiency technologies, it is also suitable for multicrystalline material.

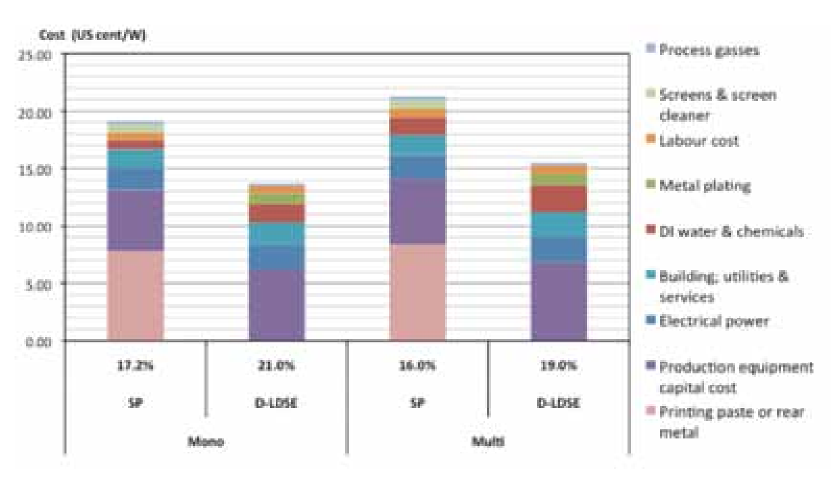

Figure 7. Cell conversion cost of ownership for D-LDSE solar cells compared to that of standard screen print solar cells. Significant savings are realised due to much higher efficiencies and elimination of screen print processes and metal pastes.

Overcoming LDSE challenges

As with any new technology, there have been hurdles to overcome in order to ensure the technology can gain widespread acceptance. At UNSW, many years have already been spent on evaluating and overcoming the challenges associated with LDSE technology. As previously mentioned, many of the process steps are identical to those required for standard screen print cells, the only new processes being the laser doping and plating steps. The remaining challenges associated with LDSE are generally ones that need to be addressed through selection of appropriate equipment and corresponding optimization of these processes. By using an approved continuous wave laser to perform the laser doping, most of the reported surface damage normally caused by nanosecond q-switched lasers can be avoided. UNSW has evaluated several lasers over the years and gives all collaborators an approved list of lasers (and other processing tools) that will work.

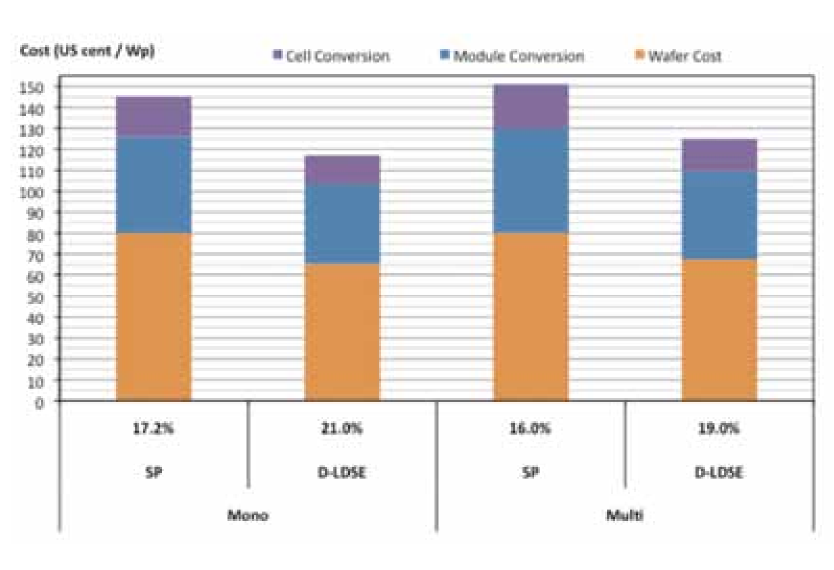

Figure 8. Overall cost of ownership for LDSE solar cells compared to that of standard screen print solar cells, showing very significant savings in wafer and module conversion costs.

The laser doping speed also needs to be optimized to allow a continuous laser-doped line. This ensures that the plating is of good quality and shunt paths through the emitter are avoided. It appears that the optimal speed is easily fast enough to allow very short cycle times and high throughput for mass production. Likewise, plating and sintering conditions need to be optimized to ensure good adhesion, prevent shunting and create an effective barrier against copper contamination. Fortunately, it again turns out that optimum temperatures are low and plating times short, leading to compatibility with mass production.

> "By using an approved continuous wave laser to perform the laser doping, most of the reported surface damage normally caused by nanosecond q-switched lasers can be avoided."

At UNSW, questions about plating reliability and adhesion are often received. With good process control and optimization of laser doping and plating processes, the peel strength of plated metal lines should be as high as 3N, comparable to that of screen printed cells. Furthermore, with process optimization, these narrow fingers can be formed as high as 20μm and almost semicircular in cross section, with very high throughput. LDSE modules have also been through the usual rigorous durability tests performed for all industry modules, with favourable results.

Conclusion

UNSW's laser-doped selective emitter technology is highly suited to industrial fabrication and has several advantages over traditional screen print solar cell technologies, both conventional homogeneous and selective emitter. Single-side LDSE variants are in pilot production at several different companies and are achieving efficiencies as high as 19.0% on p-type Cz and 17.5% on p-type multicrystalline silicon. High-efficiency features of single-sided LDSE technology include 30μm-wide, self-aligned, rapid plated metal fingers with heavily doped selective regions under the fingers and lightly doped emitter. These features improve J_{sc} by as much as 10% (through significantly reduced shading loss and improved blue response) and improve open circuit voltages (through reduced recombination under the front contacts).

The next generation of double-sided LDSE solar cells will also feature rear point contacts with heavy selective diffusions, along with effective rear-surface passivation. D-LDSE will thus contain many of the high-efficiency attributes of UNSW's world record-holding PERL technology. Through the improved open circuit voltage this allows even on Cz or multicrystalline material, efficiencies are expected to exceed 21% on p-type Cz and 19% on p-type multi by 2012, while also being suited to mass manufacture. While cell conversion cost for single-sided LDSE is similar to that of conventional screen print solar cells, its increased efficiency results in cost savings at the wafer and module level and an overall decrease in cost of ownership.

For D-LDSE however, the cost of ownership is significantly lower than that of standard screen printed solar cells at the wafer, cell and module level. This is due to its superior efficiency and elimination of expensive screen print pastes and processes. LDSE solar cells have, after optimization, also proven to be reliable and durable under normal rigorous industry testing regimes. LDSE's superior cost of ownership, ease of manufacture, self-aligned low temperature processing, suitability to low-cost silicon and thin wafers, reliability and ease of adaptation to existing screen print solar cell lines are set to ensure it remains the technology of choice for savvy solar cell manufacturers. It is likely to take its place as the favoured alternative to supersede screen printed solar cells as the low-cost, high-efficiency solar cell technology of the future.

Disclaimer

LDSE technology is protected by a portfolio of patents owned by UNSW. For information on licensing or collaborative research opportunities, please contact the author (matte@unsw.edu.au) or Neil Simpson of NewSouth Innovations (n.simpson@nsinnovations.com.au).

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