Laser-assisted selective emitters and the role of laser doping

Finlay Colville, Coherent, Inc., Santa Clara, California, USA

This paper first appeared in the fifth print edition of *Photovoltaics International* journal.

ABSTRACT

Laser doping is often discussed in relation to silicon photovoltaic cell efficiency enhancement. However, the specific use of lasers for dopant diffusion falls within a broader category of 'Laser-Assisted Selective Emitters.' Understanding the benefits enabled by laser tools here is important not just in explaining what laser doping is, but why laser processing features in most selective emitter concepts.

Introduction

High-efficiency crystalline-silicon (c-Si) concepts command top-priority within research institutes and manufacturers' R&D departments [1]. Ideally, such proposals are accompanied by decreased manufacturing costs (thinner wafers) within 'standardized' process flows. While there are different high-efficiency options (defined by Mason as "technology that, in mass production, gives average performance greater than 17% efficiency" [2]), the most cost-effective involve efficiency-enhancement modification to 'standard' cells. ('Standard' in this case refers to the c-Si cell process that involves applying screen printed front side contacts on top of a PECVD SiN_x layer and a full-area aluminium back-surface-field (BSF) on the rear side.)

Among the new processes, the most eagerly pursued are 'selective emitters.' These feature a heavily-doped contact area underneath the metallized region and a lightly-doped emitter area between front fingers [3]. But even here, different schemes are proposed, each with unique processes and equipment. One equipment type common to most is a laser-based tool, performing selective material modification during emitter 'formation' [4,5,6,7]. Besi-Vetrella et al set the scene: "The laser technique adds the advantage of highly localized steps, meeting the requirements of selective emitter formation" [4], which was substantiated by Abbott: "The application of laser doping to crystalline solar cell fabrication to date has been fairly limited. This is surprising considering the numerous advantages to the technique and the proven ability of laser processes in high-throughput environments... Laser doping is the most underutilized of all laser processes currently used in solar cell fabrication" [8].

Laser doping research began during the 1960s, with application to solar cells gaining prominence in the late '70s and early '80s, generating "spatially localized doping patterns" in "efficient Si solar cells by laser photochemical doping" demonstrated by Deutsch et al [9]. The broader use of lasers to assist selective emitter formation was pioneered at the University of New South Wales (UNSW) during the mid-1980s [10], and through EU-funded programs called 'Low-Therm-Cells' [4] and 'Light-Print-Cells' [11] which featured "the use of spin-on techniques and laser assisted treatments to get selective emitter structures."

This article explains what functions lasers play in assisting selective emitter formation within advanced cell concepts by: classifying the laser/material interactions involved; outlining where laser processing occurs during production; and explaining how to choose optimized laser sources and tools. Emphasis is placed on laser doping, with three processes identified into which current research is assigned.

> "Selective emitters feature a heavily-doped contact area underneath the metallized region and a lightly-doped emitter area between front fingers."

Why selective emitters?

Forming selective emitters confronts inherent limitations of the traditional homogeneous emitter and screen-printed metallization process:

- Front surface metallization, which "requires a heavily diffused emitter to achieve both a sufficiently low contact resistance and adequate lateral conductivity" [12].
- Top surface metal shading losses resulting from linewidth limitations (typically 120-150µm).
- Poor surface passivation [ibid.] "as a result of the large metal/silicon interface area and the lack of a selective emitter to more effectively isolate this high recombination velocity interface from the active regions of the cell."

Many selective emitters are 'hybrid,' in nature; introducing selective emitters while retaining some form (or modified version) of screen-printing. Before discussing selective emitters, here are a few reasons why selective emitters (or high-efficiency cells in general) have not yet featured prominently [2]:

- Screen-printing offers "simplicity and low [investment] cost" [13].
- "Creating a selective emitter simply isn't easy" [14].
- Challenges justifying immediate return-on-investment (ROI) of new cell concepts (especially for 'pure-play' cell makers).
- Availability of standardized (high-throughput) production line equipment for new cell concepts.
- Requires patterning of the doped regions and "a very exact alignment of the front side metallization" over the heavily doped areas [15].
- Historically, strong sector growth put cell manufacturers in a comfortable position; priority was typically afforded to financing capacity of 'standard' lines with efficiencies ~14-16%.

Different types of selective emitters

Firstly, a basic outline is required for each selective emitter type, as well as an indication of where laser processing (including laser doping) is featured. The most common selective emitter types are grouped into five categories (below), linked directly to Table 1, which assigns labels for laser steps as 'Essential,' 'Optional', or 'Extra'.

1. Etch-back
2. (Screen-printed) phosphorous-doped paste
3. Buried contacts
4. Diffusion masking
5. (Single-step) laser doping.

The first two methods do not, by necessity, require laser-based equipment. *Etch-back* (1) typically involves performing a single heavily-doped, $POCl_3$

Selective Emitter ‘type’	Essential use of lasers	Optional use of lasers	Extra laser steps possible	Sample references
1. Etch back	None			17, 18, 20
2. (S-P) P-doped paste	None	Ablate openings Scribe grooves		16, 19-21, 23
3. Buried contacts	Scribe grooves		Laser Doping	11, 2-24, 42
4. Diffusion masking	None	Ablate openings	Laser Doping	15
5. (Single-step) Laser Doping	Laser Doping		Scribe grooves Ablate openings	4, 5, 8, 9, 11-13, 13, 24 27, 29, 30, 33-38, 47

Table 1. A variety of laser-based processes (scribing, ablating, and doping) feature in the different selective emitter types. Laser processing can be categorized as ‘Essential,’ ‘Optional,’ or ‘Extra’ depending on the importance within each scheme. Within (3)-(5), options exist for multiple laser processing stages or combining the scribing/doping or ablation/doping within a single laser step.

emitter diffusion step at the front-end with a sheet resistance $< 50\Omega$/Sq, creating an etch ‘barrier’ (or ‘mask’) typically using a screen-printed or photolithography-defined pattern with the same image as the subsequent metalized contact pattern, and then etching-back exposed regions between the emitter locations (grid fingers) for light-doping at $\sim 100\Omega$/Sq. As expected, both plasma [16] and chemical etching [17,18] methods feature prominently. For the *(screen-printed) phosphorous-doped paste method* (2), two variants have been reported [19,20,21]: (i) screen-printing a dopant paste with the same pattern as the metallization, firing the paste and then printing the metallization over the highly doped pattern (requiring alignment of the two patterns); and (ii) adding dopant to the metallization paste to increase the doping density under the metal contact.

> “Diffusion masking – when combined with electroless plating – is a refinement of buried contacts: shallow ‘openings’ compared to deep ‘grooves.’”

For *buried contacts* (3), the default approach uses lasers to form narrow and deep grooves; characteristic of ‘LGBC’ proposed by UNSW [22] and championed by BP-Solar’s 150MW of high-efficiency cells [2]. LGBC scribes inherently define a diffusion/plating mask. The standard method for selective emitter formation in LGBC is a heavy (second) diffusion stage into the grooves – overall ‘double-diffusion,’ while other methods have been proposed. Gee and Hacke [23] suggested combining LGBC with method (2) above, for “simultaneous doping and formation of a metal contact in a buried contact solar cell [by] disposing a self-doping contact material within the groove.” Other versions include “laser enhanced diffusion [doping] within the grooves” [11,24].

Diffusion masking (4) must not be confused with etch-barrier mask formation for front-surface texturing of mc-Si cells [44], which is a front-end process followed by etching and by diffusion. In diffusion masking, laser processing occurs upstream (‘preparatory’), creating selective (dielectric ablated) openings in the SiN_x/SiO_2 AR/passivation coating for subsequent heavy doping and metallization (screen-printed or electroless-plated). In this case, material removal can extend to ablate several microns of the underlying silicon, making this closer to ‘scribing’ than ‘selective-removal.’ The mask-opening step is called dielectric (or selective) ablation (or removal) [7], and is of equal prominence with or without subsequent selective emitter formation. This is also an essential step within most next-generation (‘advanced’) metallization techniques [25].

Following the mask-opening step, an optional damage etch may be required (generally only if non-optimal laser parameters are applied), followed by a second (heavy) phosphorous diffusion. Diffusion masking – when combined with electroless plating – is a refinement of buried contacts: shallow ‘openings’ compared to deep ‘grooves.’ Raabe et al touch on this topic: “this process sequence is utilized in the buried contact cell process [and] also used by the semiconductor-finger concept” [26]. While most diffusion masking schemes require double-diffusion, a single-step process was proposed by Raabe et al, where “a thin mask serves only as a diffusion ‘suppressing’ layer.”

Laser-assisted selective emitters

In each selective emitter, laser/material interaction should be understood before identifying tools for production [7]. Morilla et al reiterate this: “One of the key points in transferring laser processes into production is the selection of the most adequate laser source and processing conditions” [27]. Indeed, selective emitter formation places demanding tolerances on laser tools (a comparison between edge isolation [28] and dielectric ablation [25] provides some guidelines).

To clarify, the term ‘laser doping’ refers to any step where a laser induces heating/melting that results in dopant-diffusion. Laser doping does not ‘form’ a selective emitter per se: it is merely one of several process steps which when put together form a selective emitter. The title of this article borrows from a more appropriate phrase introduced in a paper by Ventura et al in ‘Therm-Cells’ and ‘Print-Cells’; Laser-Assisted Selective Emitter [29]. Table 1 introduces the three relevant laser processes:

- Laser scribing (scribe grooves)
- Laser dielectric ablation (ablate openings)
- Laser dopant diffusion (laser doping).

In laser scribing, ‘deep’ grooves are formed as recessed (buried) locations for front fingers. The most prominent example is LGBC, which remains the flagship of laser-assisted selective emitters today [22]. Scribing removes micron-level depths of material (through dielectric, P-layer, bulk silicon). Laser scribing tool requirements are analogous to laser edge isolation [28].

Laser dielectric ablation removes (ideally) only the dielectric, while minimizing damage to the underlying P-layer [25]. Most research in this area has been as a prerequisite for (two-step) electroless metallization, but other sophisticated approaches have garnered interest, such as combining dielectric ablation and laser doping within a single step [13,27].

> “Laser dielectric ablation removes (ideally) only the dielectric, while minimizing damage to the underlying P-layer.”

Laser dopant diffusion

Laser dopant diffusion (laser doping) relies upon “lasers’ ability to heat locally a semiconductor surface [which] can be utilized in processes like annealing and dopant incorporation” [5]. When performed as a single step, this is best illustrated by diffusion from ‘residual’ phosphorous-containing material such as the PSG layer, as explained by Carlsson et al: “the P-glass is a possible source for doping atoms” [30], while championed by Besi-Vetrella et al as “laser overdoping of contact regions by writing the grid pattern using a laser" [4]. Using lasers for doping has received widespread acceptance, clarified by Tjahjono et al: "one of the main advantages of using a laser as a means to induce doping is that it only imposes localized heating on the wafer, and sparing the rest of the area from high temperature process" [13]. Morilla et al commented: "laser technology enables the possibility to substitute high temperature furnace driven processes by low thermal budget, locally selective and highly flexible processes offered by lasers" [27]. Doping actually happens during the melting 'phase' of silicon, with "depths varying according to the used wavelength, ranging from 20nm to 1μm" [5].

While laser doping dates back 40 years [31], a succinct (solar-specific) categorisation was provided by Abbott (Chapter 5 in [8]), used as the basis of Fig. 1 (additional inputs from Duley [32]). Within this classification, laser doping within solar research is assigned to one of three laser processing types: (a) 'dry' laser processing with solid films; (b) 'wet' laser processing with liquids; (c) gas-immersed laser processing.

Most initial work (less favoured today) falls within category (c), also known as Gas Immersion Laser Doping (GILD). Here, deposition comes from a gaseous precursor (often flowed over the substrate). Further details can be found within pioneering research conducted in the late-'70s and early-'80s [9,33]. Laser doping via wet laser processing with liquids/chemicals (b) requires a dopant-containing carrier fluid. Early research by Stuck et al in 1981 had the cell immersed within a dopant-contained organic 'bath' and the laser incident from above [34]. A variant reported by Kray et al [35] has the laser beam guided within a chemical acid jet fired at high pressure onto the wafer surface: the dopant contained liquid incident from above but with simultaneous laser scribing of bulk silicon. Similar to GILD, wet laser doping imposes challenges within a production environment; how to achieve fast wafer throughput, having to deal with chemicals remaining on the wafer surface, and incremental operating costs owing to greater process complexity.

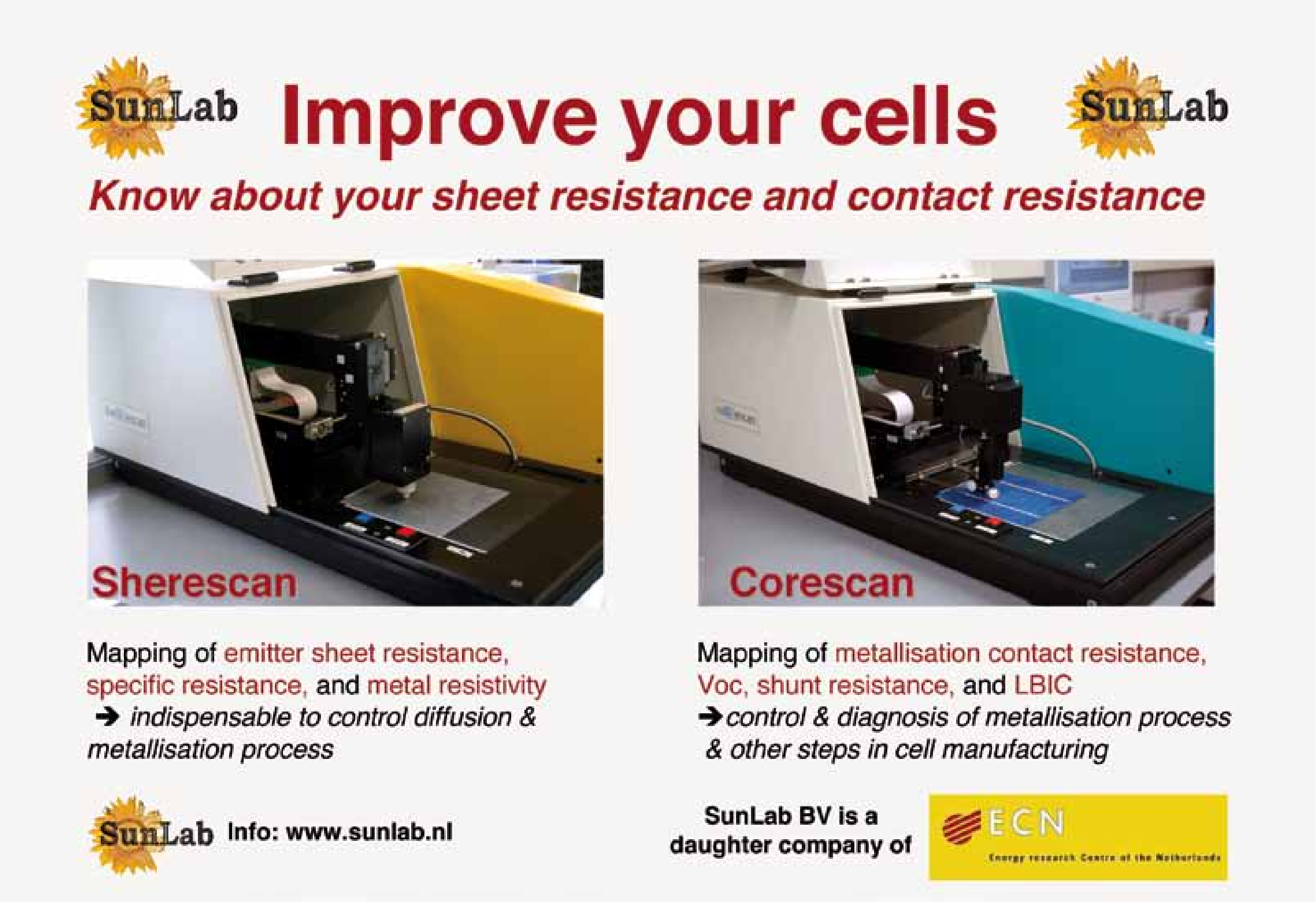
Currently favoured techniques fall under (a) dry laser processing of solid films, and are variants of an established process known as LIMPID (laser-induced melting of predeposited impurity doping) [36]. There are two approaches: (over-) doping of a residual phosphorous-containing layer (e.g. PSG), championed extensively at the University of Stuttgart [30]; or by introducing an extra dopant 'film' or layer (Narayan et al [37], Abbott [8], Guo et al [24], and Horiuchi et al [38]). 'Dry' laser processing with LIMPID is the only laser doping method not requiring extra gases or liquids, a factor that increases considerably the prospects of laser-based tooling entering production for laser doping.

Laser doping can be done as a single-step, or with simultaneous front-surface scribing (SiN_x/dopant-film and bulk 'grooves/pits') or ablation (SiN_x/dopant-film only). For dual processes, a plating-mask, suitable for electroless (or electrolytic) plating, is automatically patterned providing metallization (screen-printing or electroless) self-alignment [39]. It should be noted that laser doping has been confined in this article to (front-surface) emitter formation, but the discussion is equally valid for the base (e.g. PERL/PERT cells [40]) or for boron doping of n type cells [37,38,41].

Laser source and tool selection

Guidelines can be reached on optimized laser tooling for production. Each laser/material interaction is reviewed as a standalone laser-assisted selective emitters process, before 'dual' laser-based processes introduced above are discussed.

For laser scribing, laser source (and tool) selection is provided by way of production qualification by BP-Solar for LGBC [42] and from equipment optimization for laser edge isolation [28]. Collectively, this promotes high-power (10W+), nanosecond pulse-duration,



diode-pumped solid-state (DPSS) lasers at wavelengths in the green (532nm) or UV (355nm) ranges. Fast throughput, aligned with c-Si requirements at 1,500 wafers per hour (or higher), suggests higher average powers (e.g. 2 x 45W green DPSS lasers) within multi-wafer process tooling [43]. Scribing several microns deep (and into the bulk c-Si) has the least stringent tool requirements of the laser-assisted selective emitters discussed, and the widest process windows [44]. Post-process damage etching can be eliminated when scribing 'shallow' grooves by diligent choice of laser parameters (correct wavelength, pulse-width) [45,46]. Nearly all laser tools used for scribing today in production involve dry laser processing coupled with fast galvanometer-mounted scanning mirrors for short process times and high throughput rates.

> "Laser-based dielectric ablation shows excellent promise and increased adoption will clarify final laser source selection, as a stand-alone process or with laser doping."

Dielectric ablation (selective removal of SiN_x or SiO_2 layers without damaging the underlying P-layer) is one of the most exciting applications for lasers in solar; an overview can be found elsewhere [25].

More stringent demands on laser sources (compared to 'scribing') highlight shorter wavelengths (at or below 355nm), possibly shorter pulsewidths (of picosecond duration) and potentially uniform (homogenized, flat-top) beam profiles [ibid.]. The optimum choice of laser source and beam-delivery system may be influenced by the exact film thickness, by the material type (SiN_x or SiO_2), by the level of damage which can be sustained sub-surface, by dopant layer

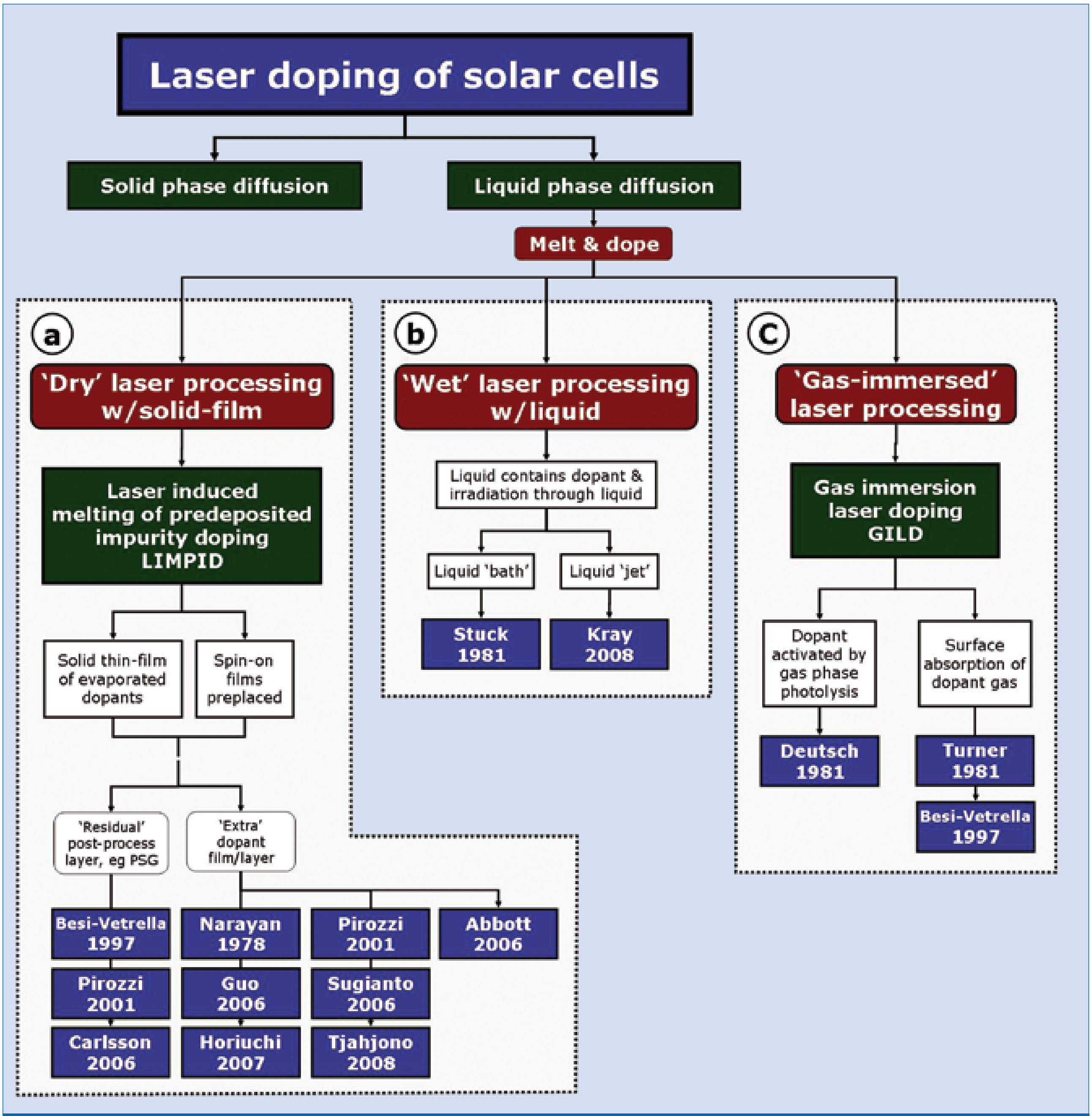


Figure 1. Classification of different schemes using laser doping for selective emitter formation. Abbott stated that solid-phase diffusion "forms extremely narrow junctions (< 0.1μm) for application in the IC industry and [is] not of interest to solar cell fabrication… In liquid-phase diffusion processes the laser energy causes the silicon surface to melt, and dopant atoms [then] enter the silicon in the liquid phase" [8]. Three different types of laser doping are identified, labelled (a), (b), and (c). Most research has focused on (a), 'dry' laser processing with solid films using the LIMPID technique.

concentration levels in fully-processed cells, and when considering tooling throughputs and ROI. However, laser-based dielectric ablation shows excellent promise and increased adoption will clarify final laser source selection, as a stand-alone process or with laser doping.

Laser doping (as a single process step) has been demonstrated with a range of lasers (different pulsewidths, wavelengths, energies, beam-shapes). This serves to illustrate the concept of using a laser to induce diffusion with "the potential of the laser-doping process as a simple selective drive-in process" [30], but most reports have also (not surprisingly) flagged up problems if non-optimal laser parameters are applied [15,47]. Mostly, this simply reflects a limited range of laser types available within any given research lab. Laser doping invariably demands lasers that provide strong localized absorption near the surface (promoting UV wavelengths), whose pulses have relatively low-energy (to avoid material damage) and operate at a fast speed (high repetition rates, or 'quasi' continuous-wave operation). Guidance dates back to 1997, when Besi-Vetrella et al used a laser "adjusted to obtain a fluence necessary to melt silicon, and to furnish a doped, smooth track, about 30 microns wide" [4].

The most topical 'dual' laser-process step combines dielectric ablation with laser doping, introduced succinctly by Tjahjono et al: "A particularly effective but simple way of achieving a selective emitter is by using laser doping to selectively remove the anti-reflection coating [dielectric

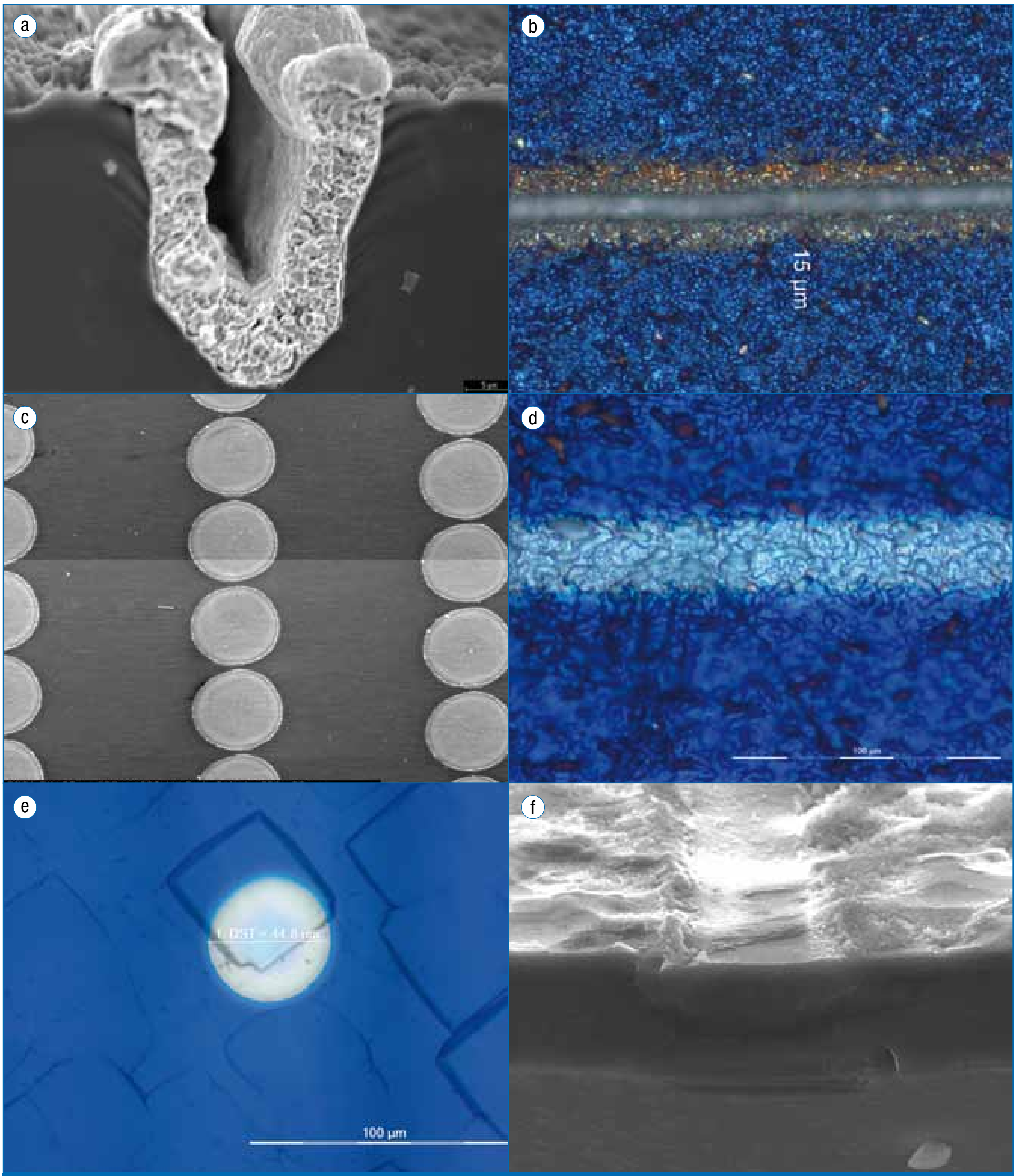


Figure 2. Front surface and cross-sectional images from various laser processes used within laser-assisted selective emitter schemes. Top to bottom, the images show laser scribing, SiN_x removal and SiO_2 removal. Images courtesy of: BP-Solar (a); Coherent, Inc. (b), (d) and (e); NanoGram, Inc. (c) and (f).

Figure 3. Coherent laser sources used for each of the selective emitter formation schemes, all within 'dry laser processing': (a) AVIA (scribing and ablation); (b) Paladin (ablation and dopant diffusion); (c) Talisker (ablation); and (d) LPX (ablation).

ablation] and simultaneously melt the underlying silicon while incorporating dopants into the melted silicon creating a heavily doped region...automatically providing a self-aligned mechanism for plating the metal contacts" [13]. Morilla et al stated: "laser-based ablation and doping are among the processes under development that may help to reduce the complexity and cost of the standard LGBC cell" [27].

Laser tool selection requires combining lessons learned from standalone dielectric ablation and laser doping processes: short wavelengths for localized absorption; sufficient average powers to activate the heat-generated dopant diffusion; fluence levels to ablate passivation layers while avoiding sub-surface damage downstream; short pulsewidths to reduce heat-affected zones. As explained by Tjahjono et al, "laser conditions were chosen since they provide adequate melting to sufficiently dope the silicon without causing ablation that can potentially result in more recombination sites [damage] and junction shunting" [13]. Morilla et al [27] sums up the issue nicely: "An important challenge is the development of a damage-free ablation process...the reduction or total elimination of damage or laser-induced defects in the silicon material... as expected, induced laser damage is highly dependent on the laser wavelength. V_{oc} drop [damage] was significantly reduced and almost nonexistent when operating the laser at the UV (355nm). A compromise between low damage and effective doping can be found..."

> "Laser tool selection requires combining lessons learned from standalone dielectric ablation and laser doping processes."

Conclusions

Laser-assisted selective emitters represent a class of high-efficiency cells which can be implemented directly within standard lines, as proven by BP-Solar's pioneering LGBC 'Saturn' production [42]. By 2010, selective emitter-based cells may account for 300MW out of 2.3GW of high-efficiency c-Si cells [2]; numbers are expected to grow as high efficiency becomes a necessity, not a luxury, to compete with lower-cost yet lower-efficiency thin-film PV cells. By categorizing the different schemes and material interactions, guidelines for laser source and tool selection can be established, thereby assisting cell and production line manufacturers specifying next-generation tools for high-efficiency cells.

Acknowledgements

Special thanks to **Nigel Mason** (PV Consulting, Ltd., UK) for reviewing this article, correcting some technical aspects, and suggesting various points to enhance the clarity and scope of the final version.

References

[1] Neuhaus, D.H. & Münzer, A. 2007, "Industrial silicon wafer solar cells", Advances in OptoElectronics, ID 24521.

[2] Mason, N. 2009, "High efficiency crystalline silicon PV cell manufacture: status and prospects", *PVSAT-5*, Glyndwr, Wales.

[3] Somberg, H. 1989, "Efficient semicrystalline solar cells using rapid thermal processing for emitter tailoring", *9th EUPVSEC*, Freiburg, Germany.

[4] Besi-Vetrella, U. et al 1997, "Large area, screen printed silicon solar cells with selective emitter made by laser overdoping and RTA spin-on glasses", *IEEE 26th PVSC*, Anaheim, CA, USA.

[5] Pirozzi, L. et al 1997, "Innovative applications of laser technology in photovoltaics", *Proc. SPIE Conf. on Laser Applications in Microelectronic & Optoelectronic Manufacturing II*, San Jose, CA, USA.

[6] King, D. et al 1990, "Development of a multi-purpose, pulsed-laser system for solar cell processing applications", *21st IEEE PVSC*, Orlando, FL, USA.

[7] Colville, F. 2009, "Laser scribing exposed: the role of laser-based tools in the solar industry", *Photovoltaics International*, Ed. 3, p.105.

[8] Abbott, M. 2006, "Advanced laser processing and photoluminescence characterisation of high efficiency silicon solar cells", Ph.D Thesis, University of New South Wales, Australia.

[9] Deutsch, T. et al 1981, "Efficient Si solar cells by laser photochemical doping", *Appl. Phys. Lett.*, Vol. 38, p.144.

[10] Green, M. 1995, *Silicon solar cells: Advanced principles and practice*, Center for Photovoltaic Devices and Systems, Sydney, Australia.

[11] Pirozzi, L. et al 2001, "Selective emitters in buried contact silicon solar cells: some low-cost solutions", *Solar Energy Materials & Solar Cells*, Vol. 65.

[12] Mai, L. et al 2006, "New emitter design and metal contact for screen-printed solar cell front surfaces", *4th IEEE World Conf. on Photovoltaic Energy Conversion*, Hawaii, USA.

[13] Tjahjono, B. et al 2008, "High efficiency solar cell structures through the use of laser doping", *23rd EUPVSEC*, Valencia, Spain.

[14] Hirshman, W. 2008, "Banking on selective research", *Photon International*, Ed. 3, p.91.

[15] Book, F. et al 2008, "Two diffusion step selective emitter: comparison of mask opening by laser or etching paste", *23rd EUPVSEC*, Valencia, Spain.

[16] Ruby, D. et al 1997, "Recent progress on the self-aligned, selective-emitter silicon solar cell", *26th IEEE PVSC*, Anaheim, CA, USA.

[17] Mouhomb, A. et al 2003, "Selective emitters for screen printed multicrystalline silicon solar cells", *Rev. Energ. Ren.*, ICPWE, p.83.

[18] Dastghaib-Shirazi, A. et al 2008, "Selective emitter for industrial solar cell production: a wet chemical approach using a single side diffusion process", *23rd EUPVSEC*, Valencia, Spain.

[19] Meier, D. et al 2000, "Self-doping contacts to silicon using silver coated with a dopant source", *28th IEEE PVSC*, Anchorage, AL, USA.

[20] Horzel, J. et al 1997, "Novel method to form selective emitters in one diffusion step without etching or masking", *14th EUPVSEC*, Barcelona, Spain.

[21] Hilali, M. et al 2004, "A review and understanding of screen-printed contacts and selective-emitter formation", *14th Workshop on Crystalline Silicon Solar Cells and Modules*, NREL, CO, USA.

[22] Wenham, S. & Green, M. 1985, "Buried contact solar cells", Australian Patent 570309.

[23] Gee, J. & Hacke, P. 2005, "Buried-contact solar cells with self-doping contacts", US Patent 0172998.

[24] Guo, J.H. et al 2006, "Laser-formed electrodes for solar cells", International Patent 005116.

[25] Colville, F. 2009, "Selective criteria: lasers go short for dielectric ablation of silicon solar cells", *Solar: PV Management Magazine*, Ed. 2.

[26] Raabe, B. et al 2005, "Monocrystalline silicon – future cell concepts", *20th EUPVSEC*, Barcelona, Spain.

[27] Morilla, C. et al 2008, "Laser induced ablation and doping processes on high efficiency silicon solar cells", *23rd EUPVSEC*, Valencia, Spain.

[28] Colville, F. 2009, "Lasers scribing tools edge in front", *Global Solar Technology*, March/April edition.

[29] Ventura, L. et al 1996, "Influence of baking conditions of doped spin-on glass source on the formation of laser assisted selective emitters", *25th IEEE PVSC*, WA, USA.

[30] Carlsson, C. et al 2006, "Laser doping for selective silicon solar cell emitter", *21st EUPVSEC*, Dresden, Germany. See also http://www.esolarenergynews.com/2009/05/solar-cell-efficiency-record-set-at.html.

[31] Fairfield, J. & Schwuttke, G. 1968, "Silicon diodes made by laser irradiation", *Solid State Electronics*, Ed. 11.

[32] Duley, W. 1996, *UV lasers: effects & applications in materials science*, Chapter 8, Cambridge University Press, Cambridge.

[33] Turner, G. et al 1981, "Solar cells made by laser-induced diffusion directly from phosphine gas", *Appl. Phys. Lett.*, Vol. 39.

[34] Stuck, R. et al 1981, "Laser-induced diffusion by irradiation of silicon dipped into an organic solution of the dopant", *Appl. Phys. Lett.*, Vol. 39.

[35] Kray, D. et al 2008, "Laser chemical processing – a versatile tool for microstructuring applications", *Appl. Phys. A*, Vol. 93.

[36] Sameshima, T. & Usui, S. 1987, "Analysis of dopant diffusion in molten silicon induced by a pulsed excimer laser", *Jap. Journal of Appl. Phys.*, Vol. 26.

[37] Narayan, J. et al 1978, "p-n junction formation in boron-deposited silicon by laser-induced diffusion", *Appl. Phys. Lett.*, Vol. 33.

[38] Horiuchi, K. et al 2007, "Profile controlled laser doping for n-type silicon solar cells", *22nd EUPVSEC*, Milan, Italy.

[39] Wenham, S. & Green, M. 2002 "Self-aligning method for forming a selective emitter and metallization in a solar cell", US Patent 6429037.

[40] Zhao, J. et al 1999, "24.5% efficiency silicon PERT cells on MCZ substrates and 24.7% efficiency PERL cells on FZ substrates", *Prog. Photovolt: Res. Appl.*, Vol. 7.

[41] Lo, V. et al 1996, "Excimer laser assisted doping of boron into silicon", *Semiconductor Science Technology*, Ed. 11.

[42] Mason, N. et al 2004, "The technology and performance of the latest generation buried contact solar cell manufactured in BP Solar's Tres Cantos facility", *19th EUPVSEC*, Paris, France.

[43] Colville, F. 2009, "Into the groove: how buried contacts brought lasers to life in solar", *InterPV*, June edition.

[44] Engelhart, P. et al 2006, "Laser processing for back-contacted silicon solar cells", *ICALEO LMC*, Paper M703, Scottsdale, AZ, USA.

[45] Knorz, A. et al 2009, "Selective laser ablation of SiN_x layers on textured surfaces for low temperature front side metallization", *Prog. Photovolt: Res. Appl.*, Vol. 17, p. 127.

[46] Rana, V. et al 2008, "Investigations into selective removal of silicon nitride using laser for crystalline silicon solar cells", *23rd EUPVSEC*, Valencia, Spain.

[47] Sugianto, A. et al 2007, "Impact of laser induced defects on the performance of solar cells using localised laser doped regions beneath the metal contacts", *22nd EUPVSEC*, Milan, Italy.

About the Author

Dr. Finlay Colville is Director of Solar Marketing at Coherent, Inc. He holds a B.Sc. in physics from the University of Glasgow and a Ph.D. in laser physics from the University of St. Andrews. Since joining Coherent in 1999, he has held a range of sales and marketing positions worldwide, concentrating on laser applications within the solar industry for the past three years.

Enquiries

Coherent, Inc.
Patrick Henry Drive
Santa Clara
California 95054
USA

Tel: + 44 7802 238 775
Email: finlay.colville@coherent.com
Website: www.coherent.com/solar