Laser processing enables high-efficiency silicon-cell concepts

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It is no surprise that approaches that claim to decrease dollar-per-watt ratios invariably grab the headlines within analysts' commentaries on the solar industry. Nearly every roadmap associated with the solar industry can be judged against this 'magic' term: from end-user deployment rates, to comparisons with grid-parity, to the choice of next-generation equipment adopted throughout the supply-chain. Consequently, any new cell concepts or processes that can reduce cost, or increase the efficiency of solar panels, are championed with vigor. This article describes how laser-based tooling offers the possibility of both cost-reduction and efficiency-enhancement when implemented within next-generation advanced crystalline silicon (c-Si) solar cell production lines.

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Laser adoption within the solar industry is associated more with thin-film production lines, than for c-Si cell manufacturing—and for good reasons, too. Lasers sold into thin-film patterning applications have historically dominated the market for lasers-in-solar, accounting for ~70% of an estimated $65M laser-source global revenues during 2008 [1]. This imbalance however, is due largely to the priority afforded to laser-based processes within each of the equipment supply-chains for c-Si and thin-film cells.

Lasers for c-Si production

In thin-film fabs, laser scribing is now widely regarded as an established process at the panel-to-cell isolation and interconnection stages—known as patterning. For c-Si solar cell manufacturing, on the other hand, cells have traditionally been produced in fabs comprised of screen-printing, etching, deposition, and diffusion equipment: lasers have often been perceived here as more of a luxury than a necessity. At least, that largely captures the equipment landscape up until now; with the majority of solar panels made up of c-Si cells manufactured using ~200μm-thick, *p*-type silicon wafers, front-surface screen-printed silver fingers, and full aluminum back-surface-fields. While such standard c-Si cells have been the most cost-effective to produce in volume, the cell efficiency and manufacturing yield levels have considerable scope for improvement. Adding this to the new industry demands on handling and processing much thinner silicon wafers—being implemented to drive down silicon raw material costs—new high-efficiency concepts are anticipated to propagate throughout c-Si cell manufacturing over the next 3–5 years. A recurring theme within many of these concepts is laser-based processing, promoted rigorously today within the leading solar research labs worldwide.

Why laser processing?

To understand best where lasers add value in c-Si cell production, it is important to capture the current bottlenecks within cell manufacturing; and then factor in the additional benefits lasers offer next-generation cell designs.

Increasing the efficiency of standard c-Si cells typically starts with the front and rear contact formation steps, and new processes performed by next-generation equipment types. In fact, this is driven not just by efficiency enhancement: simply reducing the cell thickness to <~180μm impacts on the tooling used. Handling such thin wafers—while at the same time, looking to drive yield levels from ~90% to >95%—immediately promotes the use of equipment that is non-contact by nature. Therefore, performing existing or new steps related to contact formation by optical processing immediately promotes laser-based tooling within the equipment hierarchy of the c-Si roadmap.

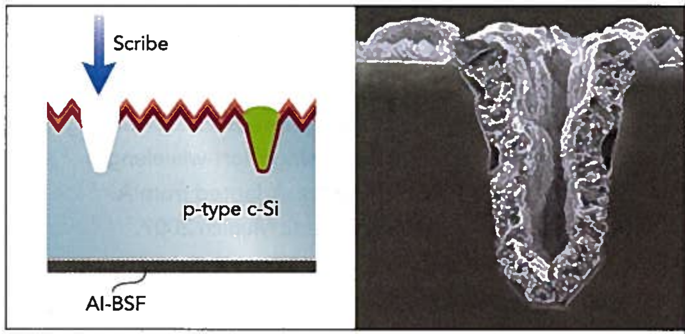


Figure 1. Laser-grooved buried contacts (LGBC) represent (left) the first example of lasers used for high-efficiency enhancement within c-Si cell lines; an image (right) of an LGBC courtesy of BP-Solar.

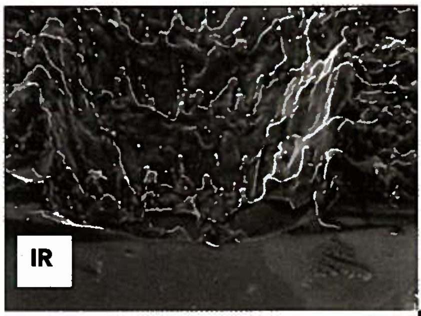
The next key issue for lasers relates to passivation layers on c-Si cells, typically formed by depositing layers or stacks of SiN_x or SiO_x on the wafer surfaces. While passivation layers are not a new feature within c-Si cell production, they assume greater significance when thin wafers are employed; here, the ratio of surface-to-volume is much higher than with 200μm thick wafers. Passivation layers are used to maximize the overall cell efficiency levels: by reducing minority carrier recombination losses at the surfaces, and by increasing the internal reflectivity from the rear surface for the long-wavelength IR portion of the solar spectrum.

However, it is when the above features are brought together in new cell concepts—advanced metallization contact processing on thin wafers with front and rear passivation stacks—as a means of enhancing existing production lines, that laser-based tooling becomes an enabling technology regarded as essential throughout the equipment supply-chain. The following sections address some of these advanced cell concepts—currently in pilotline phase or the subject of extensive research—and what role lasers play within cell manufacturing.

Laser-grooved buried contacts

Any discussion on laser-based efficiency-enhancement processes within c-Si cell production should always start with laser-grooved buried contacts (LGBC); originally proposed by the University of New South Wales, Australia, in 1984 [2], and subsequently licensed by BP-Solar for application within its Saturn production lines [3]. LGBC as an overall process captures so many of the drivers behind currently proposed efficiency-enhancement schemes: locally-doped selective-emitter formation, high-conductivity electroless plated contacts, reduced finger line-width shading, and increased metallization aspect ratios. *Figure 1* illustrates a schematic of the LGBC process, with an SEM image of a laser groove at the front surface, prior to metallization.

As a technique for increasing c-Si cell efficiencies over comparable screen-printing and firing on standard cell types, LGBC is hard to beat, and so this begs the question: why is LGBC not used throughout the industry? (Indeed, this is a question also asked in some of the wrap-through technologies in which lasers drill a plurality of tiny vias from front-to-rear surface, as part of back-contact cell types [4].) The answer involves a range of issues: process reproducibility, extra (fixed) capital and (variable) operating costs, wafer-per-hour throughputs, availability of standardized production line equipment, and the overall efficiency-gain to extra-cost ratio.



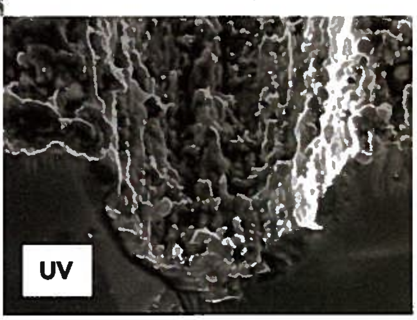


Figure 2. A comparison of scribing grooves (for edge isolation or LGBC) using IR (top) and UV lasers shows less surface redeposit when using the UV laser.

Source: M. Acciarri, Mini PV Conf., Trondheim, 2008.

Surprisingly—analogous to front-surface scribing during laser edge isolation—for a process as important as LGBC, there is limited discussion on the optimum choice of laser type. In fact, reviewing this highlights key issues that impact on the ultimate success of lasers generally in c-Si cell production lines: the relationship between laser wavelength, bulk c-Si damage (laser irradiation causes silicon lattice imperfections that increase the surface recombination rate of photo-generated electron-hole pairs), thermal debris, and sub-surface microcracks; the design of an inline tool to satisfy industry-standard wafer-per-hour throughput rates; and process qualification where the "laser" part forms just one tool within an overall new equipment set. Choosing the correct laser type turns out to be an essential part of any surface scribing process, discussed in more detail below.

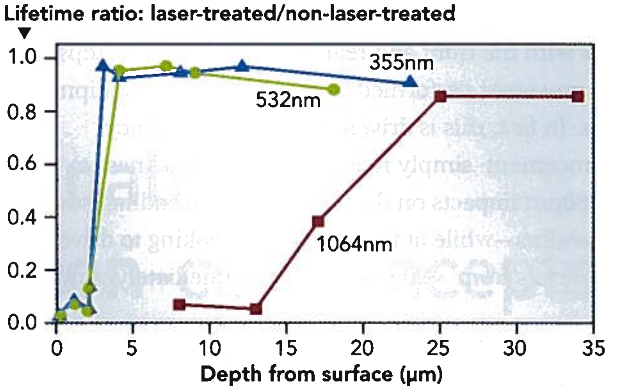


Figure 3. Increased lifetime ratios (decreased laser damage) are obtained when scribing lines using short-wavelength 355nm (UV) or 532nm (green) lasers. Adapted from A. Schoonderbeek et al., *4th WLT Conf.*, Munich 2007.

Laser selection for c-Si surface scribing

The requirements for laser scribing during the LGBC or edge isolation processes are almost identical (laser scribing can also be used within interdigitated back-contact cell schemes for contact isolation and etch barrier structuring): grooved lines several microns wide and deep on the front surface; minimized sidewall and surface damage; and negligible bulk microcracks. Edge isolation requires a single, continuous groove to be positioned between the edges of the cell and the finger grid. LGBC features a series of equally-spaced parallel grooves for subsequent doping and metallization.

Scribe quality is achieved by optimizing several laser output parameters: short pulse-width below a few 10s of nanoseconds enables clean material ablation; high average powers from 10W upwards for maximum wafer throughput; high-finesse output beams (or in laser terminology, a beam M^2 parameter of < 1.3) to allow focusing with micron-scale resolution; short-wavelength laser output at either 532nm (green) or 355nm (UV) where absorption properties in c-Si are orders of magnitude more favorable in comparison to lower cost 1064nm IR lasers. *Figure 2* illustrates the benefit in using lasers with UV output, for front surface scribing. Perhaps the strongest case for short-wavelength operation in surface scribing such as LGBC or edge isolation is captured in one of the most comprehensive laser-related comparisons in solar cell research to date, undertaken at the LZH and ISFH, both in Germany [5] (*Figure 3*).

Once beam quality and output wavelengths are optimized, the laser's average output power levels then determine the wafer processing time. This is highly application-specific. For example, in a 6" wafer, the distance covered by the laser beam for edge isolation is $\sim$0.6m, which can easily be done with short-wavelength lasers with $\sim$10W average power. This enables a single-laser, single-wafer tool to be used in production. For LGBC, the distance to be scanned is considerably greater (10–20m), requiring much higher laser powers configured with multiple, scanning laser beams. To avoid any compromise to scribe quality, and assessing current state-of-the-art in M$^2 < 1.3$ green/UV lasers, the solution requires 2–4 532nm lasers each with $\sim$50W output power. Appropriate inline tooling would also include multiple scan-heads, wafer chucks, and fully-automated loading/unloading of wafers.

Laser patterning of dielectric layers

The scribing processes discussed above highlight the need to carefully select laser output parameters to ensure that laser-based techniques can indeed flourish within 24/7 production environments. However, the laser steps proposed within the next-generation cells are somewhat more complicated than LGBC or edge isolation, requiring an increased understanding of the laser/material interactions involved, to the extent that laser-type decision-making is more of a make-or-break call in the overall viability of the high-efficiency schemes.

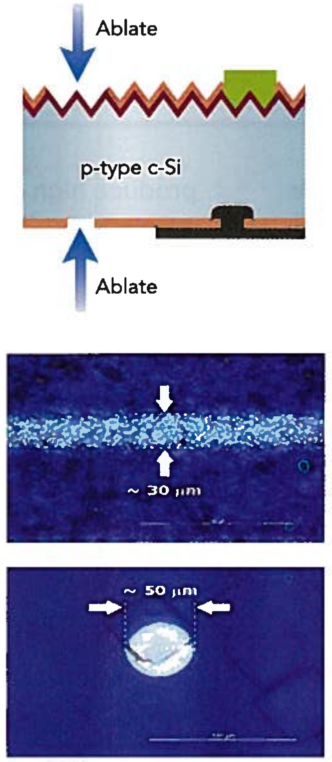


Figure 4. At top, passivation layers are deposited on front or rear surfaces of next-generation cells. The bottom two images show how a picosecond Talisker laser at 355nm selectively removes lines from the front surface, or a matrix of spots from the rear, shown in upper and lower traces, respectively.

Similar to LGBC and edge isolation, the new laser processes involve focusing and scanning laser beams onto wafer surfaces. However, high-efficiency cell types use lasers in a variety of schemes to selectively remove only the passivation layers. The laser/material interaction is termed selective-removal, or in the context of solar cell physics, dielectric ablation. Nomenclature aside, this is the most demanding application to date for lasers in high-efficiency c-Si cell production, however conversely, one with perhaps the greatest scope to drive the solar industry's efficiency and yield roadmaps.

To arrive at the correct laser-type, it is necessary to review the properties of the passivation layers, key to concepts related to advanced non-contact finger metallization, or as part of the passivated-emitter and rear cell (PERC), the passivated-emitter and rear locally diffused (PERL) or interdigitated back-contact cell types. Passivation layers—either single SiN$_x$ or SiN$_x$/SiO$_x$ stacks—are typically 100nm thick or less, and show little absorption for incident laser wavelengths $> \sim$250nm. Coupled with stringent demands for negligible damage to the bulk silicon material below the passivation layers, two different laser types now emerge as candidates to fulfill the process requirements.

The first (and preferred) laser option is to use ultra-short pulse-width lasers, where the time duration of the pulses is in the picosecond regime [6] (1 picosecond $= 10^{-12}$ seconds) or shorter (femtosecond lasers). These lasers offer the minimum heat-affected-zone and thermal-induced surface damage, due mainly to their short diffusion depth in c-Si. As a result, they provide a much cleaner form of selective dielectric layer removal, compared to nanosecond lasers (confirmed, for example, by measurements of the underlying phosphorous emitter dopant profile before and after laser ablation [6]). Pulses with this short time duration also enable material ablation via what's known as multi-photon absorption; here, a material with appreciable absorption only below, for example $\sim$250nm, can use a laser wavelength of $\sim$500nm through a two-photon absorption process. It is only during the past couple of years, however, that industrial-grade picosecond lasers have become available to meet the process demands. (Most of the R&D done in solar research labs for dielectric removal had used nanosecond pulse-duration lasers between 355nm and 1064nm.) *Figure 4* illustrates dielectric removal using high-energy picosecond lasers operating at 355nm.

An alternative route is to use laser sources with short-pulse, high-power output at wavelengths < 250nm where SiN$_x$ and SiO$_x$ start to show measurable levels of absorption. In fact, ablation of micron-resolution patterns on SiN$_x$ with 248nm, nanosecond-pulses from an excimer laser source has been qualified for a few years—for a different application to form a barrier for front-surface etching of poly-c-Si cells with improved light trapping.

Excimer lasers have a strong track-record within laser-based industrial tools, and are unique laser types when deep-UV processing is essential. In contrast to scanning low-M^2 laser outputs from diode-pumped solid-state (DPSS) lasers across the wafer to form lines or a matrix of holes, excimer lasers are typically used in conjunction with masks and line-beam generators to yield the desired surface pattern. In addition to their wavelength options < 250nm, excimer lasers deliver high average power levels of hundreds-of-Watts output; a factor that allows fast throughput with sub-second wafer processing times. Research activity is ongoing here, and the relative merits of excimer vs. picosecond lasers for dielectric ablation should be evaluated fully within the next six months.

Conclusion

The success of laser-based processes within next-generation high-efficiency c-Si cell concepts depends strongly on the correct choice of laser type. Advances in the past few years regarding industrial-grade short-pulse and short-wavelength lasers suggest that optimum laser sources are now available for the most demanding laser-based processes including dielectric removal of passivation layers on the front and back surfaces of c-Si cells. ●

Acknowledgment

Talisker is a trademark of Coherent Inc.

References

1. F. Colville, "Lasers in the solar industry: market size, growth rates, & trends," Lasers & Photonics Marketplace Seminar, San Jose, 2009.
2. M. Green et al., "Improvements in silicon solar cell efficiency," Proc. of 18th IEEE PVSC, p. 39, Las Vegas, 1985.
3. N. Mason et al., "The Technology and Performance of the Latest Generation Buried Contact Solar Cell Manufactured in BP Solar's Tres Cantos Facility," Proc. of 19th European PVSEC, Paris, 2004.
4. P. Hacke et al., "Current status of technologies for industrial emitter wrap-through solar cells," Proc. of 21st European PVSEC, p. 761, Dresden, 2006.
5. P. Engelhart et al., "Laser processing for back-contacted silicon solar cells," ICALEO Paper M703, Scottsdale, 2006.
6. V. Rana et al., "Investigation into selective removal of silicon nitride using laser for crystalline silicon solar cells," Proc. of 23rd European PVSEC, Valencia, 2008.

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