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Unlocking laser tools' potential in c-Si cell fabs

August 10, 2009 - Ensuring laser-based tools are accepted as standard equipment during the production of high-efficiency [crystalline silicon \(c-Si\)](#) cells requires better understanding of the process windows involved, qualification of new tooling optimized for specific applications, and a clearly identified supply-chain.

For over 25 years, solar institutes have vigorously championed lasers as an enabling technology to realize next-generation advanced crystalline silicon (c-Si) cells [1-4]. With lasers offering non-contact micro-material processing and selective material removal/modification, the basis for this continued enthusiasm is obvious. And since laser-based equipment has a proven track record within semiconductor fabs, solar tool qualification (with a proactive supply-chain) appears from the outside a done-deal.

Not so! Despite this affirmation, a quick glance at [cell manufacturing equipment](#) used before 2008 shows an alarming dearth of laser-based tools [5]. Indeed, many within the industry are still aware only of lasers being used for a routine (loss-preventative) stage at the back-end of c-Si cell manufacturing: not enabling the headline-grabbing efficiency-enhancement steps [6].

All this changed during the past 12 months. Not however due to any earth-shattering technical breakthrough, but thanks to macro-economic conditions which form the basis of the supply-demand dynamics impacting today on cell manufacturing [7]. Put simply -- this has prioritized technical competitiveness, as evidenced by the numbers of manufacturers actively marketing high-efficiency cell performance from their R&D labs and pilot production lines. This article explains the level to which prevalent supply-demand dynamics can be expected to provide a serviceable market for laser-based tools within c-Si fabs; how the climate until 2008 acted to hinder the adoption of laser-based tooling [8]; and conversely, why the next couple of phases predicted for the growth of the solar industry as a whole outline technical roadmaps which actually favor new tooling and technical advances. Market demand is of course the essential pre-requisite: but successful tool introduction requires other factors to be satisfied. These include: process optimization, laser source and tool qualification, and alignment (with buy-in) throughout the equipment supply chain. **Figure 1** shows a conceptual overview of these four factors. The current status of each will also be reviewed and outstanding challenges highlighted which must be addressed before laser-based tools finally become standard line-items within the bill-of-materials for high-efficiency c-Si cell capex.

3. Contact preparation (finger grooves, through-silicon-vias [20], interdigitated structuring [21]);
4. Contact forming (sintering [22] or firing [23]).

Figure 2 uses this framework now to assign terminology used regularly within the laser industry and in solar research labs. To each of these, some key research and review papers are then cited for further reading. Finally, an overall assessment of the current status applicable to research validation and process qualification is included by some color coding and trend arrows.

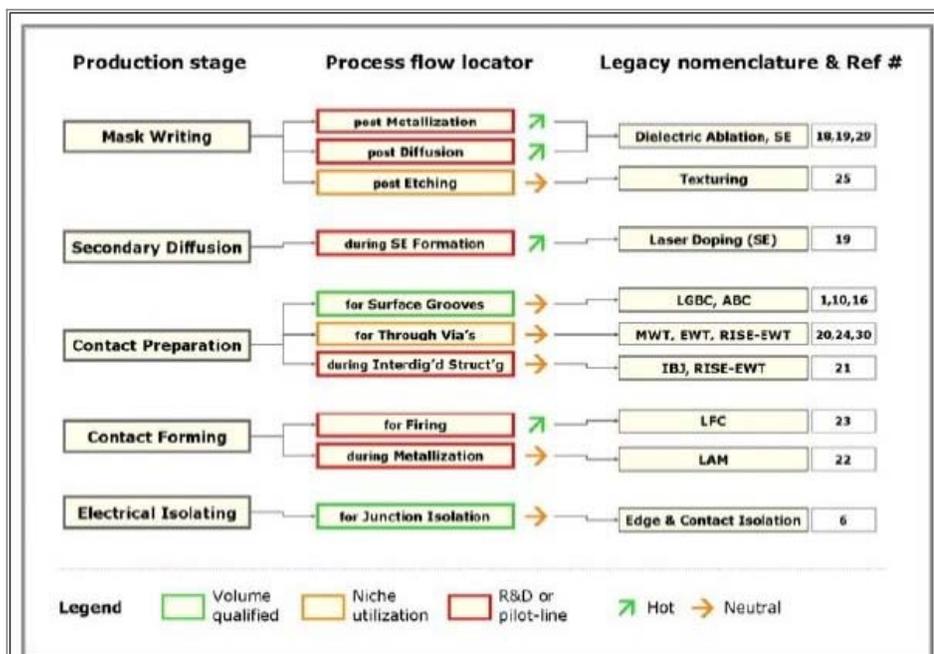


Figure 2. Laser usage within c-Si cell production lines can be understood better by assigning processes to one of five stages, shown down the left-hand column within the template analysis above. The top four are related to high-efficiency cell concepts. The middle column then places the different laser processing options in context, providing the basic rationale for introducing a laser step in the first instance. The box colors show production status; the arrows are for current industry trending. Finally, legacy terms used historically within the laser and solar industries are captured in the right hand column. Some of the most exciting applications see laser processes performing multiple stages simultaneously [19] analogous to the laser part of LGBC [16] which ensured metallization and diffusion masking in addition to surface groove preparation.

The big picture which emerges quickly is that very few (if any) of the processes meet every target deliverable today. (This will be better understood by the end of the article, after discussing the important role of the equipment supply chain here.) Many of the processes are however close to primetime roll-out, and in scanning through the list of Fig. 2, it is a simple exercise to match each to either high-profile new product announcements (e.g. for metal wrap-through [24] or etching for front-surface texturing [25]) or collaborative arrangements which point to imminent commercialization.

The second point here highlights one of the mechanisms promoted eagerly within Europe to take some of the research findings to commercial viability -- local government or EU funded projects such as LOWTHERMCELLS [3], Alpinism [26], CrystalClear [27] and SOLASYS [28]. Alternatively, process qualification today is otherwise being driven in-house by leading cell manufacturers with know-how and intellectual property retained.

Laser source and tool qualification

Identifying suitable laser sources and inline tooling has been ongoing for as long as research itself on laser processing for c-Si efficiency enhancement. To assess the current status here, several issues need to be considered. Firstly, what has been learned from process optimization in the cases where different laser parameters can be compared (laser wavelength used, pulse-energy, average power levels, pulse repetition-rates, beam-profiles and fluence levels at the sample). Tool integration then depends upon the availability of production-ready sources; lasers that have been proven to operate reliably in 24/7 environments as turn-key components. Finally, overall laser-based tools must satisfy economic criteria assigned to new equipment capex introduced to the overall production lines. It turns out that each process step (as depicted in Fig. 2) comes with its own set of acceptance criteria here including: the level of efficiency enhancement from the new cell concept; the process window and dependence on lasers with cutting-edge performance specifications; and the degree to which per-wafer process times dictate the use of multiple laser sources or inline tools to satisfy tact times in production. The purpose of this discussion is not to cover each and every process covered in Fig. 2 (articles cited in the references offer such details), but to summarize the key trends today which impact on laser adoption generally within c-Si production lines.

Process optimization remains high on the agenda of all lasers-in-solar activists, largely due to the process windows at play. Generally, the ability to remove or modify materials is rarely an issue with laser tooling, and a brief tour around any laser exhibition these days will illustrate this by way of eye-catching glossy images of solar cells post processing; leading one to

conclude that such laser micro-materials processing is merely a walk in the park.

What often differentiates c-Si cell processing, however, is sub-surface (either in the passivation layers, the emitter regions, within the bulk substrate, or at the interfaces). Such effects can be evaluated in isolation by various measurement techniques (SIMS, sheet resistance, carrier lifetimes, etc.) and research publications offer key insights here. Higher confidence levels are provided when fully processed cells are characterized for fill-factor, efficiency, etc. And taken to completion, when several thousand wafers (5-in. or 6-in. sized) are statistically analyzed under full production conditions.

Again, other factors have limited progress in this area until recently. With the exception possibly of work done at the Laser Zentrum Hannover [21], Exitech, Ltd. for their Alpinism [26] contributions, and the CiS Research Institute [29], much of the published research has been carried out with a limited range of laser sources on-site. Over time, several of the solar research institutes have bolstered their laser labs with extra laser sources. But it remains a fact that the majority of laser processing on c-Si cells has been done with non-optimal laser sources. Now, much of this is actually due to the timing of work done during the 1980s and '90s, when ideal laser sources were simply not available commercially as turn-key tools. And with no end-user economic motivation for the equipment supply-chain to participate strongly, evaluation was typically biased towards research rather than production. The net result today is that process optimization remains work-in-progress, with many of the leading c-Si cell manufacturers having taken leading roles in establishing production ready criteria.

Largely as a consequence, laser-based tools with production ready sources and optimized process capability also have some way to go. Until recently, the lure of laser edge isolation (as the only widely visible laser-based process in c-Si production lines) has at least been useful in acclimatizing some c-Si end-users with laser technology [6]. A similar case can be made with the emitter- and metal-wrap-through (EWT [30], MWT [24]) and laser grooved buried contact (LGBC) [16] processes too, albeit with lower volume of units commissioned.

The requirement however for increased tooling options for high-efficiency cell concepts down through the equipment supply chain cannot be overlooked. In this respect, there is little doubt that new variants will emerge here in the next 12 months now that tangible rewards are on offer. Both from the existing equipment supply chain (inline laser-based tool suppliers and turn-key c-Si line players) and new entrants, possibly finally making the transition from laser-based semi or display optimized solutions to the silicon solar equipment segment. The realization of high-efficiency cells though is critically dependent on these options coming to fruition.

Lastly, laser-based tooling return-on-investment (ROI) has to be prioritized far more than to date; and understood with clarity throughout the supply-chain. While directly linking the addition of a single laser-based process with an overall cell efficiency increase is outwith the scope of the laser tooling community -- however well the marketing is pitched! -- it should be a given that the cost-per-wafer (fixed and variable costs) of any laser-based tool is calculated correctly, taking into account production environment criteria. This calculation obviously includes making sure that the correct laser source is integrated within the tool and having the laser parameters and beam-delivery optical arrangement matched to the process being fulfilled.

More crucially perhaps is the process time per wafer and how this compares to production environments envisaged for next-generation high-efficiency cells. So, while laser tool suppliers have their own to-do list in terms of per-wafer costs for the different processes shown in Fig. 2, the overall assessment on ROI viability definitely needs better engagement and understanding throughout the supply-chain, involving in particular automation suppliers, turn-key line manufacturers and (during pilot-line build) with strong inputs from cell producers themselves.

Repositioning the equipment supply-chain

Since this seems to be the recurring theme of the article, let's look at how the equipment supply-chain has evolved historically, and see if this sheds some light on where things stand today. Some perspective can be obtained quickly by reviewing the type of equipment used for the majority of standard c-Si cells produced to date: diffusion furnaces, deposition tools, wet and dry etching equipment, metallization tools, and screen-printers.

Production lines traditionally have been readily configured using off-the-shelf components or via single vendors supplying complete lines where their specific technology has been supplemented with the required processes added at the front- or back-end. Laser technology largely fell out the comfort-zones of many, or amounted to an R&D effort able to accommodate requests for laser tooling if requested for junction isolation. It's fair to say thought that, during the industry's initial-growth phase, this proved a highly successful strategy.

Moving from this scenario to one where complete production lines are offered with laser tooling, capable for example of performing dopant diffusion or front-surface mask writing for electroless plating, requires a new approach. For their part, several of the turn-key equipment suppliers in Europe are starting to make announcement to this effect, again motivated by EU-funded activity and close working relationships with local cell manufacturers. While this provides confidence, it's clear that further participation is needed between the various tiers of the supply-chain (turn-key line providers, sub-component laser-based tool manufacturers and laser source suppliers). The collective inputs will form a key deliverable necessary for laser-based steps to become mainstream processes for high-efficiency cell production in the long-term [17].

Conclusion

Considering each of the adoption criteria shown in Fig. 1 together allows an estimate to be made of the serviceable market for laser-based tools within c-Si production lines. This forecast is shown in **Figure 3**. Overlaid on this graph is the incremental capacity expected to be added for high-efficiency cell concepts, showing a clear correlation between laser-tool adoption in c-Si manufacturing and high-efficiency concepts. Various caveats have to be considered in the mix here, with risk still associated with each of the topics discussed in this article.

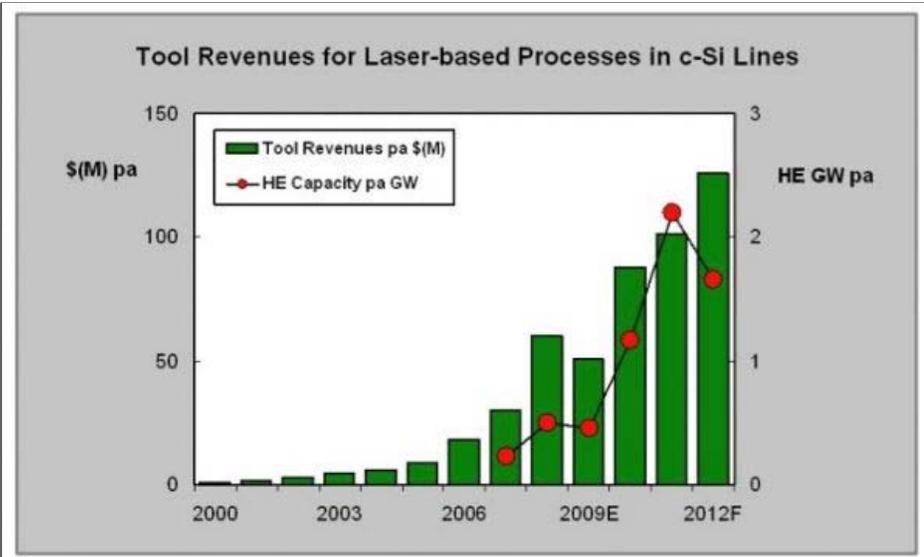


Figure 3. Comparison of separate bottom-up analyses for incremental laser-based tool revenues within c-Si fabs (bars) and high-efficiency cell capacity or capex added annually between 2007 and 2012 (lines). Tool revenues are projected to grow significantly from 2010, with the dip in 2009 due to (i) the pause in capacity from market oversupply, and (ii) an increase in wet-etching tools used for junction isolation. Similar revenue projections have been presented during the past 12 months [31-33]. (E) estimate; (F) forecast.

Other wildcards exist too, no more so perhaps than the ability of alternative technologies to perform at lower cost tasks today considered to be laser owned. Validation that things are coming together in favor of laser-based tools will be evident however as marketing efforts take off and an increased number of laser tools occupy the pages of trade magazines or the aisles at the solar specific equipment trade-shows.

In the final part of this lasers-in-solar Photovoltaics World trilogy, the author will describe the three leading candidates for laser-based processes expected to form part of high-efficiency cell lines in the coming years.

Finlay Colville received his BSc in physics at the U. of Glasgow in 1990 and PhD in laser physics at the U. of St. Andrews in 1995, and is director of marketing for solar at Coherent Inc., 5100 Patrick Henry Drive, Santa Clara, CA 95054 USA; ph +44-7802-238-775; email Finlay.Colville@coherent.com; www.Coherent.com/Solar.

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