Laser scribing exposed: the role of laser-based tools within the solar industry

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ABSTRACT
Laser-based tools have become increasingly visible within R&D labs, pilot production lines, and as the preferred technology used by many turnkey suppliers. As equipment types however, relatively little is known about the differences in the laser-based tools used for solar applications within each of the c-Si and thin-film segments. This paper explains the key components of a laser-based tool, and how they are adapting to meet the demands from next-generation production line equipment required by the solar industry.

Introduction

Historically, the solar industry has been cautious – indeed, somewhat reticent – embracing laser technology within cell manufacturing production lines; using lasers often as a last resort, not as technology enabling. This reticence is matched by widespread ambiguity as to lasers' functionality, capability, and role within the equipment supply chain. Indicative of this uneasiness is a generic label assigned frequently to any tool that just happens to include a laser: the so-called 'laser scriber'. Therefore, it is perhaps no big surprise that speculation permeates throughout the industry as to what a laser scriber really is. Why would manufacturers actually use them? And how do engineers choose the appropriate combination of scribing tool and laser source to work best in a specific production environment?

This article explains what a laser-scribing tool is comprised of, why they are used by solar cell manufacturers, and where they get utilized throughout the value chain. Their prominence within the industry is then highlighted by analyzing market dynamics specific to laser scribers; how big the market is for solar laser scribers, what the trends are, and what the laser scriber of tomorrow will look like.

Case studies are discussed to best illustrate each of these themes. Nomenclature is proposed to describe more clearly the different processes performed by lasers within the solar industry, and how such a classification provides better labels for different types of laser scribers.

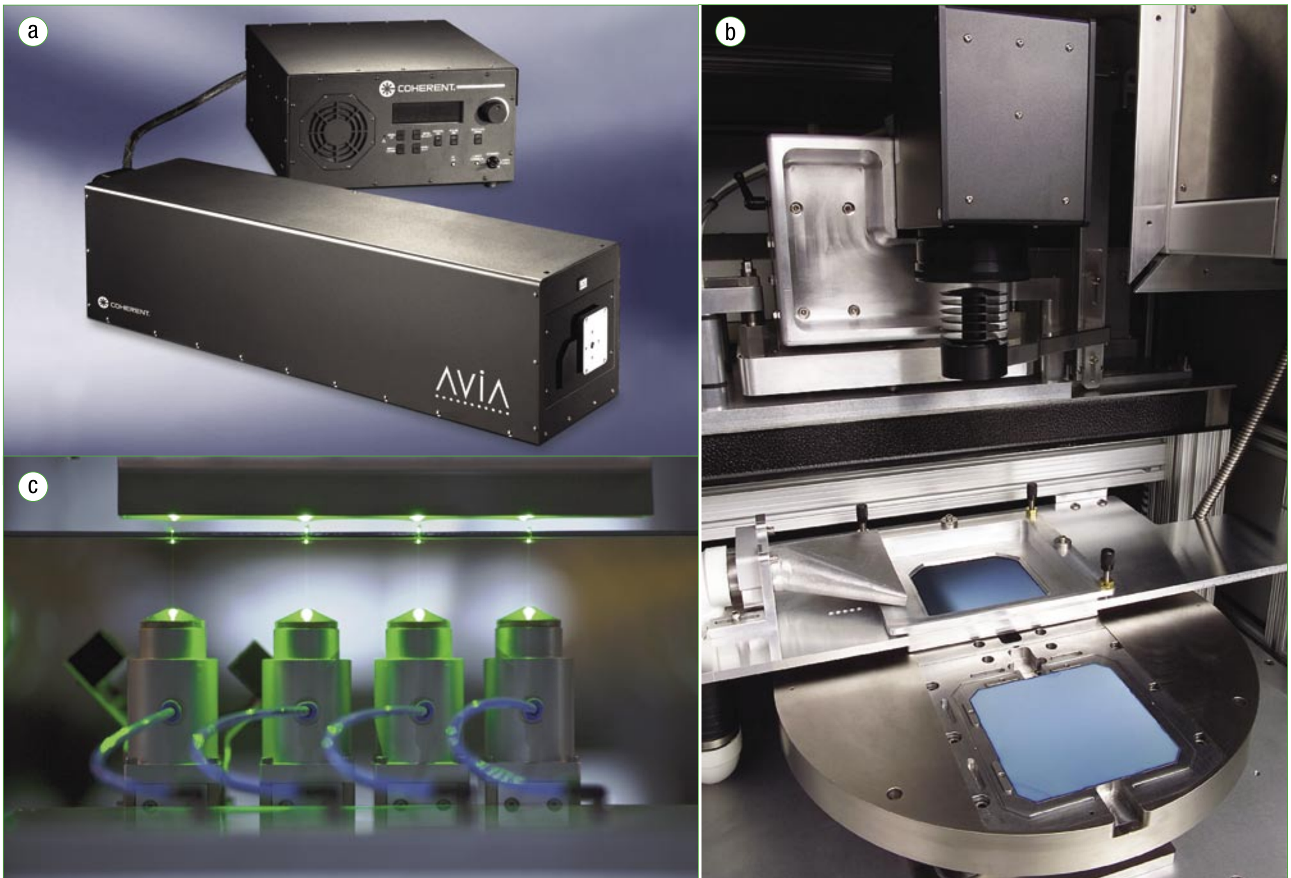

Figure 1. A laser-based tool is typically comprised of a laser source (a), like the Coherent AVIA. (b) shows a c-Si beam-delivery assembly taking the laser beam from source to sample; scanner (black box, top centre), c-Si vacuum chuck and wafer turntable. In thin-film tools, beams can be split for simultaneous patterning (c), courtesy of Oerlikon Solar Ltd., Trübbach, Switzerland.

'Laser scriber' or 'laser-based tool'?

The misleading terminology should first be clarified: 'scribing' simply happens to be one of many different processes that lasers can perform; others commonly used within the solar industry include drilling, melting, cutting and selective ablation. To be consistent with 'non-solar' market segments, and aligned with solar-familiar terms such as plasma-etching tool or screen-printing tool, it is more useful from a top level to refer to any production equipment using a laser source simply as a 'laser-based tool.' Later in the article, a family of laser-based tool names is proposed that encompass all processes enabled by laser-based tools in the solar industry.

Laser-based 'tools' differ from laser 'sources.' And indeed, equipment supply for each of these has historically been different. Laser manufacturers produce laser sources, while tool suppliers make laser-based tools, for which they buy in the most suitable source from a laser manufacturer and then integrate this within a production-ready tool. Of course, some suppliers manufacture both laser and tool. While the laser source is by far the most important line item within the bill of materials of any laser-based tool, there are other key features which influence overall tool performance: beam delivery components to optically couple the laser beam from source to sample; the use of moving (or 'flying') optics or fast scanning mirrors to redirect the laser beam across the target sample; handling and automation of either silicon wafers or thin-film panels into (and out of) the tool workplace.

Figure 2. Examples of some laser-based tools used in cell and panel production lines.

Images courtesy of (2a) M-Solv, Oxford, UK, (2b) InnoLas Systems GmbH, Krailling, Germany, (2c) Schmid Technology GmbH, Schwetzingen, Germany, (2d) Shirai Tech. Inc., Shirai, Japan / Applied Photonics Inc., Arizona, USA.

Figure 1 shows the key components within laser-based tools while Figure 2 includes typical workstations used today within production environments.

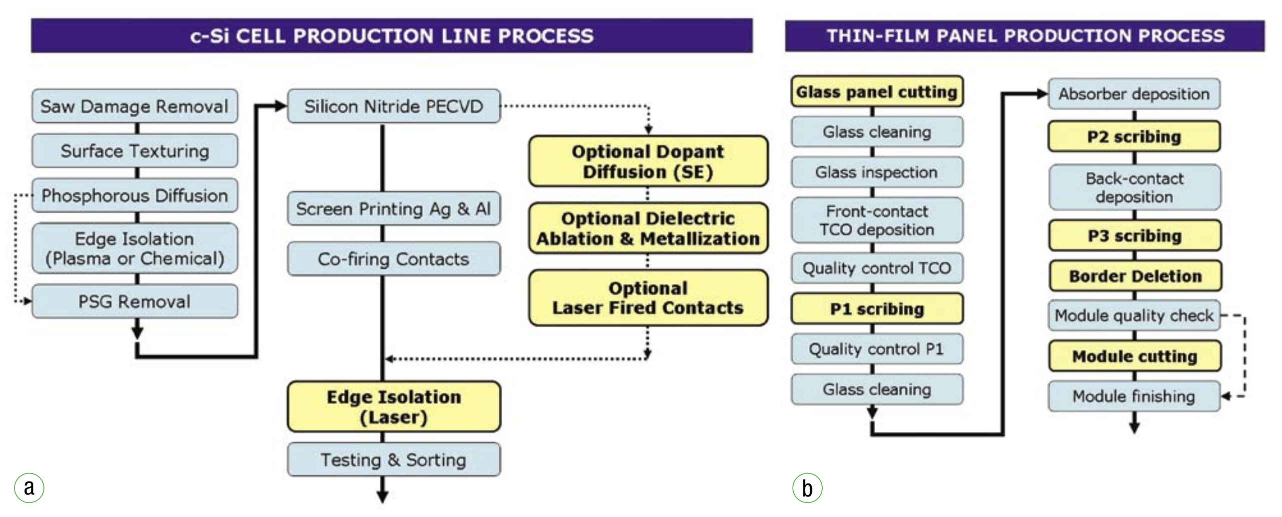

Figure 3. Yellow flow-chart boxes reveal the possible locations of laser-based tools within the value chains for c-Si (a) and thin-film (b). In the c-Si segment, additional laser processes are found upstream (cutting), downstream (module soldering), and during stages specific to back-contact cell designs (e.g. IBC, EWT, or MWT).

Why use laser-based tools?

Understanding why laser-based tools are adopted in production lines is the question most commonly asked by colleagues working at the interface of the solar and laser industries. The reason for this importance is that the tools can be applied to both c-Si and thin-film solar fabs, and also that they bring processes from analogous steps within the microelectronics and flat-panel display sectors. Put simply, laser-based tools enable production steps to be done in a non-contact manner. This results in benefits that are equally applicable to c-Si and thin-film production line users:

- Maximize yield levels in solar fabs. Eliminating any risk of bulk microcrack formation or material strength reduction is of paramount importance both for sub-180μm-thick silicon wafers and large Gen 5 or higher solar glass panels.
- Increase production line throughput. Laser-based tools offer high-speed material processing via automated, inline, horizontal substrate handling.
- Reduce manufacturing costs, best measured by a fully amortized $/wafer analysis, which would factor in capital and operating costs and material process parameters (yield, throughput, utilization rate, etc.) over a typical five-year equipment life-cycle.

- Increase the final panel efficiency. The rationale for implementing laser-based tools diverges here somewhat for c-Si and thin-film production steps. For c-Si cells, the drivers for laser-based tools fall primarily into the category of next-generation, high-efficiency cell concepts; for thin-film panels, the goal is process optimization within simplified production lines.
- Differentiated technology. With so many c-Si manufacturers using etching tools today, those who migrate first to laser-based processes can promote their production lines as 'next-generation'.

While the dual benefits of increased efficiency and reduced cost play directly into the fundamental driver to lower final $/W metrics, ultimately it is the composition of the laser-based tool which determines the return-on-investment to any cell or panel producer. Indeed, this only emphasizes the problem when referring to all laser-based tools as laser scribers, and calls for a much deeper understanding of laser-based tools in general.

Laser-based tools in the value chain

In a recent article by the author [1], the various applications for lasers within the solar industry were reviewed in detail. This included categorizing the processes by segment (c-Si or thin-film) and by their 'production status' (widespread production, partially adopted, or R&D). In this paper, this analysis is moved one rung up the supply-chain ladder, by describing from a top-level where laser-based tools are employed within the value chains for each of c-Si and thin-film production. In Figure 3, the location of laser-based processes is clarified. (The processes shown in Figure 3a include laser-based steps that may be incorporated within a 'standard' c-Si line with discrete front and rear contact formation. Flow diagrams for other cell types, such as back-contact variants, would require individualized representation.) In general, laser-based tools find most widespread application at the wafer-to-cell stage for c-Si production, and at the 'equivalent' panel stage in thin-film manufacturing.

However, the market adoption for laser-based tools within c-Si and thin-film production reveals an important differentiator between these two segments. In thin-film panel production, laser-based tools represent an established and preferred choice of tooling equipment (see Figure 4 for a glimpse of laser tools running inside an Oerlikon thin-film fab). All thin-film patterning stages (referred to as the P1, P2, and P3 process stages) have identified lasers as the optimum production tooling. The exception to this generalization today are the CIGS P2 and P3 stages where research is ongoing to find the optimum laser process window. In current c-Si production lines, the standard c Si cell architecture (with screen-printed and fired front Ag contacts and a full-Al back-surface-field) can readily be manufactured through use of an off-the-shelf turnkey production line, which – crucially – may not contain a single laser-based step. Therefore, laser-based processes within c-Si production fall broadly into categories of 'advanced' (e.g. most of the back-contact cell types, like IBC, RISE, or EWT/MWT) and 'next-generation' (non-contact electroless plated contacts, thin wafers with rear passivation layers, selective emitter designs with localized doping, or LFC) [2]. A final category summarizes processes where laser-based tools are directly competitive with traditional equipment types such as mechanical cutting, etching, or sand-blasting; this covers c Si Edge Isolation, wafer cutting and cell singulation, and thin-film glass cutting and panel border deletion.

The market for laser-based tools

Each of the issues discussed above contributes towards the size and dynamics of the overall market for laser-based tools, both historically (2000-2008) and forecast (2009-2012). In fact, limited market analysis exists today, reflecting the somewhat peripheral entrance of laser-based tools historically within solar production lines. This is partly because laser sources have been introduced at

Figure 4. Laser-based tools within the solar industry are perhaps best represented by the thin-film patterning tools employed within turnkey Oerlikon thin-film production lines (image courtesy of Oerlikon Solar Ltd., Trübbach, Switzerland).

different tier levels in the supply chains, by laser-based tool suppliers or 'integrators' (most common in the c-Si market segment); by turnkey production line suppliers; and, in some cases, directly by cell and panel producers.

Figure 5 uses data from a recent 'laser-source-only' solar market analysis [3], coupled with typical factors known within the laser industry that relate laser cost to tool cost [4]. Close agreement is seen with a 2008 review article from Gaëtan Rull of Yole Développment [5].

The split illustrates the high priority of lasers within thin-film production lines to date: clearly the inverse of typical 'c Si vs thin-film' growth curves from solar market analysts which track c-Si and thin-film production output (or installed base) by year. While laser-based tool revenues clearly reflect the imbalance in the 'established tooling' status between c-Si and thin-film production lines, there is another prevailing factor that impacts on the market size for laser-based tools within the solar industry: the large disparity between CapEx and production output. Not only are many production lines operating well below stated capacity levels (low utilization), but much of the CapEx has been for pilot lines more focused on understanding processes than for module production to end-users. This issue tends to be more common with emerging cell technologies (e.g. CIGS or Gen. 3 cell types) or early-stage, VC-funded start-ups in North America.

Tool label	c-Si applications	Thin-film applications
Scribing	Edge isolation Defect repair Laser grooved buried contracts ID Marking Texturing (direct) Contact isolution (BC-cell) Interdigitated structuring (BC-cell)	Border deletion ('P4')
Drilling	Emitter wrap-through Metal wrap-through	Transparent BIPV
Doping	Dopant diffusion (SEs)	n/a
Firing	Laser fired contacts	n/a
Cutting	String ribbon cutting EFG cutting Singulation	Sheet glass cutting Panel cutting
Patterning	Dielectric removal Contact openings (BC-cell) Texturing (etch-barrier)	P1, P2, and P3 (a-Si, CdTe, CIGS) ITO removal

Table 1. Categorizing laser-based tools by process type, mapped out against the most common applications for lasers within the solar industry. Glossary: BC (Back-Contact), SE (Selective Emitter), EFG (Edge-Defined Film-Fed Growth), BIPV (Building-Integrated Photovoltaic), ITO (Indium Tin Oxide).

Therefore, projecting laser-based tool revenues beyond 2008 is subject to a variety of 'wildcards,' including the transition point from pilot- to production-line status for many CIGS and Gen. 3 cell suppliers; the ability, and timing, of a-Si production line suppliers to ramp up capacity or transition from single-junction absorbers to tandem junctions (in particular a-Si/μc-Si micromorph); the implementation of thin silicon wafers prompting the market entrance of next-generation c-Si concepts; and of course macroeconomic factors influencing short-term CapEx spend at the cell and panel stages.

In summary, the forecast to 2012 highlights several key points:

- Continued strong growth for laser-based tools within the solar industry
- Onset of cyclic trends due to either CapEx delays caused by global macroeconomic factors, or a shift in emphasis on ramping up production output on newly installed lines. (A recent article from Paula Mints at Navigant Consulting captures this succinctly [6].)
- Increased proportion of revenues from c-Si laser-based tools from next-generation c-Si concepts (and possibly aided by a decrease in the average selling price for thin-film laser-based tools).

Trends impacting next-generation tools

If laser-based tools are really to become widely adopted within the solar industry, their functionality must evolve in alignment with the technology roadmaps spelled out by both c-Si and thin-film manufacturers for next-generation equipment. Each of these manufacturing methods is discussed separately in the following section.

Since laser-based tools are already workhorses within thin-film production fabs, changes to tools here are more thin-film-solar-generic than laser-processing-specific. Reducing equipment capital costs within existing fabs may drive advanced optical designs, enabling the use of lower-power (and by consequence, lower-cost) laser sources. Increased panel sizes and fab line capacities beyond ~50MW may require lasers that operate with higher repetition rates (greater than 100kHz) to allow the patterning steps to be done in shorter time periods. Optimizing laser output parameters (most typical being the use of shorter laser wavelengths and pulse-widths) should improve the scribe quality of certain selective ablation processes for P1, P2 and P3 patterning, or when using different TCO layers. The other applications for lasers in thin-film (border deletion, or P4, and glass cutting) represent areas where laser-based tools must show a direct return-on-investment (improvements in yield, quality, and cost-of-ownership) compared to traditional equipment options.

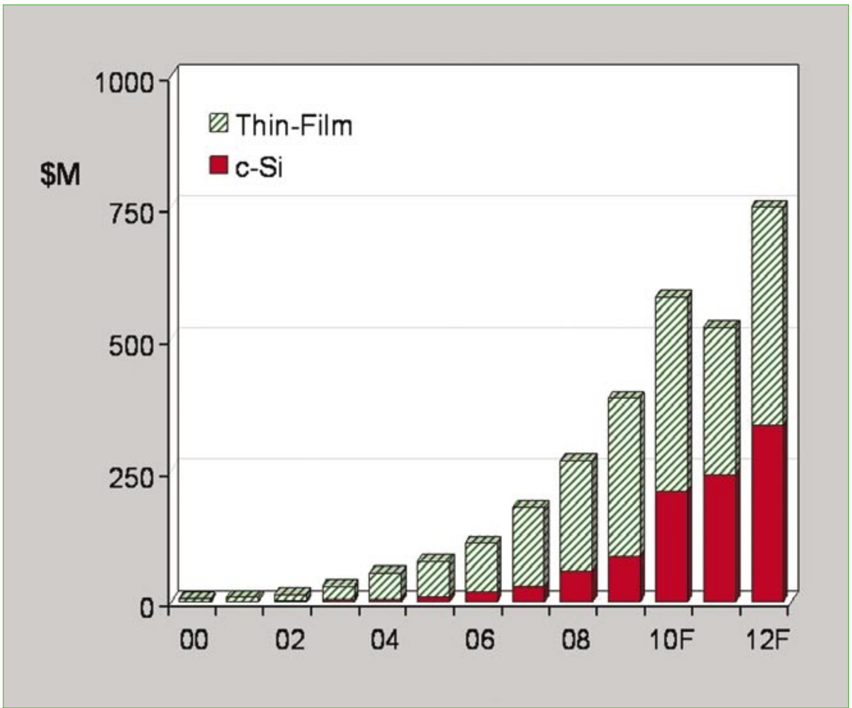

Figure 5. Annual total available market (TAM) for laser-based tools (inclusive of laser sources) within the solar industry, split into c-Si and thin-film segments over the time period 2000 (shown as '00') to 2012 ('12F'). The bias towards thin-film tools is a reflection of lasers' essential role within all thin-film production lines at the three patterning stages.

The c-Si roadmap drivers have a fundamentally different impact on laser-based tools, due partly to the fact that alternative technologies dominate the equipment landscape today. To start with, laser sources must be carefully chosen to reduce bulk c-Si material damage, placing extreme scrutiny on laser source selection. This prioritizes new industrial-grade laser sources operating with short wavelengths (for increased, more localized absorption within c-Si or surface dielectrics, and reduced microcrack formation) and short pulses below the nanosecond-level from picosecond lasers (to reduce the thermal diffusion length, or heat-affected zone around any laser material removal).

In addition to laser source selection, inline tools must process sufficient numbers of wafers per hour to allow possible retrofitting within existing production lines (or as part of any new process step where lasers are required). This latter point highlights another difference between next-generation laser-based tools in c-Si and thin-film. Novel c-Si cell concepts generally require several new process steps, compared to traditional c-Si cell manufacturing. Therefore, the value-added proposition of the laser-based tool is embedded within the overall return-on-investment for the new process steps collectively. For example, moving from a screen-printed full-Al-BSF cell to a rear-passivated, laser-ablated metallized cell must take into account the overall benefit in yield and efficiency specifically when ultra-thin wafers are employed. A similar comparative analysis was performed when Laser Grooved Buried Contact cell production lines were first implemented [7].

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Classifying laser-based tools

We return now to the nomenclature for laser-based equipment within the solar industry, and propose terminology that allows better understanding of the different laser tools used. The easiest way to categorize tooling is by reference to the laser/material process (or interaction) performed. Often, different applications that are based upon the same laser/material interaction share similar criteria when optimizing the laser source and beam delivery or handling. One example that comes to mind here is laser Edge Isolation and Laser Grooved Buried Contacts: the differences in laser-based tooling being the laser power level required and the number of lasers per machine for production line wafer-per-hour throughput rates.

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Once again, it is necessary to differentiate between laser-based tools used in c-Si and thin-film applications. In this scenario, not only is laser source selection application-specific, but the entire beam-delivery and substrate handling could not be more different. For some highly specialized applications (such as dopant diffusion or laser fired contacts), I have taken the liberty of using the application name as a good fit for the laser-based tool itself.

As laser-based tools become increasingly accepted within the solar industry, it will be more intuitive to review specific laser sources and tools that are application-specific and fall under each of the categories shown in Table 1. Furthermore, the relative market size for tools sold into each application will provide a clear metric to assess how well accepted each laser-based application has become within the solar industry.

Summary

Groundbreaking research in laser-based processes is widely known from extensive work undertaken initially at the University of New South Wales dating back to the mid 1980s, and during the past decade from European-led activities at the Fraunhofer-ISE, the ISFH in Hameln, FZ-Jülich, the Laser Zentrum Hannover, HMI-Berlin, Universität Stuttgart, and the ECN and IMEC in Benelux. Laser-based tools configured to enable many of these proposed schemes have either become standardized tooling within production lines, or are poised to form part of next-generation production lines within the solar industry. Understanding what is important within a laser-based tool is essential to ensure process optimization and comparison to alternative technologies already accepted within the supply chain. Providing terminology that captures the laser process and application will assist production engineers to engage with the laser tool supply chain when evaluating optimum lasers and tool suppliers.

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