

Laser Systems & Processes within Next Generation Photovoltaic Manufacturing Equipment

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Biography

Dr. Finlay Colville is currently the Director of Marketing: Solar at Coherent, Inc. His academic achievements include a BSc. (Hons) in Physics from University of Glasgow in 1990, followed by a Ph.D in Laser Physics at University of St. Andrews in 1995 and subsequent postdoctoral studies. Between 1995 and 1999, Dr. Colville held various R&D positions at laser companies worldwide. He joined Coherent in 1999 with responsibility for Sales within the UK & Ireland, moving into regional Sales Management from 2003. Since 2006, he has been Director of Marketing with responsibility for the solar market worldwide. Dr Colville has published a range of feature articles in leading solar magazines, and is presently in demand as a speaker on laser applications within the industry at global solar events.

Abstract

Laser sources offer a non-contact means of scribing, ablating, cutting, and melting various materials used in the production steps within both c-Si and Thin-Film solar cells and panels. Understanding how they work, where they add value, and how they can enable next generation solar cell technologies is explained by way of categorizing their role within the solar industry.

Current applications for lasers are outlined, including key processes at the R&D stage, those which are partially adopted within production lines today, and the widespread – or mainstream – applications that lasers satisfy now. The laser / material interactions are classified by type, an exercise which allows direct comparison with similar overviews of laser applications within the microelectronics and flat panel display industries where laser adoption has a higher maturity level.

Complementing the technical overview of laser applications possible for solar cell / panel manufacturing are two other key issues which ultimately frame which processes may finally emerge as candidates within next generation production lines: (i) the market dynamics and roadmaps within the industry driving each of the different crystalline-Silicon (c-Si) and Thin-Film cell architectures; (ii) the performance envelopes of current state-of-the-art industrial-qualified laser sources themselves, and how this is expected to develop in the next few years also.

The contents of these sections form a ‘roadmap’ for lasers in solar. This highlights specific laser systems and processes which are likely to have the strongest impact on next generation manufacturing equipment used within the solar industry.

Introduction

Today, there is a myriad of applications for laser sources and laser-based tools within the solar industry¹. Some of these applications are exclusively at the research stage, and form an integral part of fundamental photovoltaic studies. Some are within R&D activities of solar research institutes or pilot-lines of solar manufacturers, and are in the process of being qualified as suitable or not for industrial usage within 24/7 production lines. And then there are the applications of lasers which are mainstream, or integral parts of production lines currently producing solar cells and panels in volume.

Manufacturing equipment for c-Si and Thin-Film solar cells / panels is known to be ‘technology-specific’, i.e. equipment and processes for each cell type is different. Similarly, laser systems and processes within c-Si and Thin-Film production are different.

Laser tools can perform a range of tasks within the solar industry, from cutting and scribing, to melting and diffusing, to selective ablation and via drilling.

This article starts with generic categorization of the above areas, each important in explaining exactly what role lasers play within the solar industry today:

- Applications (c-Si vs. Thin-Film)
- Production-line adoption status
- Processes (laser / material interactions)

With this information at hand, the remainder of the article takes a look at what role lasers are set to play in next generation equipment used within the solar industry. This is done by looking at trends in the market place, together with the requirements from the market for what is broadly termed ‘next-generation’ equipment. How lasers can enable this requires an up-to-date assessment of currently-available industrial-qualified turn-key laser sources. Therefore, subsequent sections are comprised of the following:

- Market dynamics influencing laser adoption with solar
- Industrial laser types and trends

1. Applications for Lasers in Solar

Laser processes for solar can be divided up into those used either in c-Si or Thin-Film manufacturing². Table 1 lists the most common applications within each cell type. The naming of these is far from standardized within the industry, and some of these routinely come under different headings. For example, ‘Selective Ablation’ on c-Si cells is also known as ‘Dielectric Ablation’, or ‘Contact Openings’, or ‘Thin-Film Removal’, or variations thereof. ‘Border Deletion’ of Thin-Film panels is sometimes called ‘Edge Deletion’ or even the ‘P4’ process. One final point to note is that some of the novel cell architectures themselves have designated labels which themselves include various laser based processes, such as RISE, PERC, or ‘back-contact-cells’.

Therefore, Table 1, while a good snapshot of laser applications in solar today, is comprised of applications which are production-step terms (e.g.

Edge Isolation), processes (e.g. Cutting), or generic concepts (e.g. Inspection). In Section 3, this anomaly is addressed.

COHERENT Solid State Lasers for Solar Cell Manufacturing - from the IR to UV		Production Status		
		Widespread Production	Partially Adopted	R&D, Pilot-Line
'Laser-in-Solar' Application				
c-Si	Edge Isolation	✓		
	Laser Grooved Buried Contacts		✓	
	Texturing (Etch Barrier Ablation)			✓
	ID Marking		✓	
	Selective Ablation (Openings)			✓
	Wrap-Through (Emitter, Metal)		✓	
	Cutting		✓	
	Dopant Diffusion (Selective Emitter)			✓
	Laser Fired Contacts			✓
	Wafer Inspection			✓
	Defect Repair			✓
	Singulation (CPV Cutting)			✓
	Interconnection (Module Soldering)		✓	
Thin-Film	Patterning (P1, P2, P3)	✓		
	Border Deletion (or 'P4')		✓	
	Glass Cutting		✓	
	Crystallization			✓
	Pulsed Laser Deposition			✓
	Sintering			✓

Table 1: Laser applications within solar (from Ref. 1)

2. Laser Adoption within Production Lines

The first thing to appreciate is the level to which the above mentioned applications are utilized within current production of c-Si and Thin-Film cells / panels. The ‘Production Status’ part of Table 1 reflects this, showing that only two applications are in widespread production (defined as laser usage that is both 24/7 and spread across a wide range of manufacturers).

Laser Edge Isolation is currently the only mainstream production line process for c-Si cell manufacturing. Even so, lasers compete here with both plasma- and chemical-etching technologies. The choice of laser-vs.-etch has historically been influenced mainly by turn-key production line suppliers and their given preference for one of the three methods when performing the Edge Isolation step.

Other c-Si cell manufacturing applications, such as Laser Grooved Buried Contacts and Wrap-Through, have been implemented for 24/7 production but their adoption remains ‘niche’, not mainstream, on account of the limited number of manufacturers utilizing these process steps.

While lasers certainly find their *raison d'être* at the cell production stage within the c-Si value-chain, listed in Table 1 are a handful of applications both upstream and downstream (silicon cutting, singulation, and interconnection). None of these is a mainstream application today, although isolated tool integrators and c-Si manufacturers do utilize them as key laser-based steps in their production processes.

Within Thin-Film panel production, the big winner for lasers today is at the Patterning stage (sometimes referred to as 'isolation-and-interconnection'). The reasons for this are clear. Lasers are the preferred technology type for selectively removing thin films of materials, without causing any damage to neighboring layers – essential at the Patterning stage. Lasers can scribe high quality lines, with repeatable performance, and fast throughput levels. With Patterning being an essential step for each of the P1, P2, and P3 steps, the market today for lasers (or referred to often within the industry, 'Laser Scribes') within all types of Thin-Film represents the dominant laser use in solar by some margin. Section 4 expands on this, by introducing how market dynamics ultimately play the defining role in laser adoption.

3. Laser / Material Interactions

A useful means of understanding exactly what lasers do within solar manufacturing is to categorize the different laser / material interactions. Such an exercise allows direct comparison with similar classifications done for lasers used within the semiconductor and flat-panel industries, and subsequent use of laser processing knowledge for similar material compositions. Figure 1 (see final page of this article) divides up the applications for lasers in solar into six categories.

To illustrate the benefits of such a classification, one of these applications is discussed now. Wrap-Through is essentially a (through-silicon, via) drilling application, with a subset of performance acceptance criteria including via sidewall quality, reduction of bulk silicon microcracking, and throughput (holes per second). Any side-by-side analysis with lasers-

in-microelectronics would find a direct analogy with laser-based TSV's (or Through Silicon Via's) used for advanced packaging. Laser selection and tooling for TSV's is considerably more developed than for solar Wrap-Through, and a wealth of knowledge is subsequently available to draw upon, as summarized in Ref. 3.

4. Market Dynamics & Laser Adoption

A review of laser applications within solar would be incomplete without a discussion on the solar market itself, and the growth anticipated from the different cell types used. Moreover, it is essential to understand the existing bottlenecks within production lines and where lasers may play an enabling role. Further, the roadmap of each cell type spells out specific technical challenges for next generation tooling, again influencing the adoption of lasers within the industry as a whole.

The split between the production outputs of c-Si and Thin-Film (and 'Gen 3 cell types) based solar panels to satisfy short- and long-term end-user demand forms the subject of many detailed market analyses, available from a wide range of sources. The most recent summary in *Photon International* provides an up-to-date reference point here⁴, a key takeaway being the continued dominance of c-Si panels at the 90% level out to 2012. This emphasizes the importance of the c-Si cell 'roadmap' and incremental improvements in cell efficiency and yield while transitioning to equipment suitable for processing sub-180-micron thick wafers¹. Consequently, laser applications within c-Si production and next-generation equipment which feeds into the c-Si roadmap are projected to only increase in significance and market-adoption levels.

When reviewing market dynamics within the Thin-Film segment, several different factors come into play. The first is that production output does not tell the whole story. Aside from a few players already in volume production, the majority of Thin-Film manufacturers are in 'ramp-up' or capital expenditure (CapEx) mode. Understanding Thin-Film growth therefore requires detailed knowledge of *Capacity* (not *Production*) expansions (or CapEx) and the transition timelines from R&D / pilot-line

qualification to mass production. Each of the three Thin-Film types requires a separate analysis to project forward the role of laser based processes.

Laser adoption within a:Si Thin-Film Patterning has historically been one of the most established markets for lasers in solar, with the Patterning steps for P1-P3 well understood⁵. There are two market drivers here that impact most on laser sources. First, the transition from small panel sizes (solar Gen. 4 or Gen. 5) to Gen. 8.5 (or larger) places increased scrutiny on the beam handling and delivery to perform longer scribe lines at high speed. Second, the upgrade from single-junction a:Si to tandem-junctions (in particular a:Si/ μ c-Si configurations) represents an additional requalification phase. With turn-key a:Si production-line suppliers aggressively driving capacity with strong year-on-year growth, laser usage for a:Si Patterning is rapidly becoming a market segment with its own unique set of technical and market drivers.

When looking at laser Patterning for CIS/CIGS panels, both technical and market dynamics are at large once again. The technical challenge relates to finding a laser solution to the P2 and P3 steps, done today with mechanical 'needles'. The market pull (specifically the 'pilot-to-mass' production transition point) is perhaps influencing laser adoption more, as explained very clearly in a recent *Photovoltaic International* feature⁶.

Lasers used for CdTe Thin-Film Patterning have, by comparison, a more prescriptive recipe. By virtue of the (much smaller) number of companies producing CdTe panels, and the maturity of equipment used within these production tools, lasers are as close to a standardized part as anywhere else within the overall lasers-in-solar space.

As expected, the level of market interest has a direct influence on how much fundamental research is undertaken within research labs, how much R&D expenditure is assigned by leading cell manufacturers, and to what degree leading laser equipment suppliers are engaged directly. This highlights another important factor impacting successful laser adoption: resource

availability at the qualification stage. Here there are three resource types which all contribute in getting the ideal mix: (i) access to a wide range of laser sources with different wavelengths, pulse-widths, repetition-rates, and power levels; (ii) laser processing (or machining) expertise and knowledge on how to transport laser beams, modify beam profiles from laser output to sample including various scanning options on the market today; (iii) solar cell characterization post laser processing, as a means to predict final cell performance in a production environment.

5. Trends in Industrial Laser Sources

Understanding the current state-of-the-art in turn-key industry-qualified laser sources is important in assessing which laser applications can be implemented within turn-key 24/7 solar production lines. Equally, what to expect from lasers in the next 3-5 years provides a similar assessment of which laser-based processes can be used for next-generation production line tooling. This is possibly most relevant for c-Si cell production, due to the many different steps where lasers may add value. (Coupled with the anticipated 90% contribution of c-Si to worldwide cell production out to 2012⁶, starting here may also be prudent!)

The laser 'models' used within the solar industry are found to be restricted to a few generic laser types. First, due mainly to the absorption characteristics of the materials comprising c-Si cells (c-Si and dielectric layers), the laser sources used for applications in c-Si manufacturing typically have output wavelengths in the near-infra-red (IR), visible, and ultra-violet (UV) spectral regions. Further, the laser / material interactions outlined in Section 3 generally require lasers operating in the pulsed regime where the instantaneous pulse, or *peak*, power is used for processing.

These criteria elevate Diode-Pumped Solid-State (DPSS) lasers as the most suitable laser types within the solar industry as a whole, but especially within c-Si manufacturing; in particular pulsed DPSS lasers, operating with output pulses of nano- or pico-second pulse duration, and wavelengths at 1064, 532, or

355 nm. This section focuses on commercial state-of-the-art performance here, and projects trends in the laser roadmap for this technology over the next 3-5 years.

Note – in addition to pulsed DPSS lasers – fiber and Excimer lasers are used within the solar industry at various R&D / production stages. Fiber lasers are an attractive option for infra-red laser operation at 1064 nm. Excimer lasers are the only industrial laser type with high-energies at wavelengths in the deep-UV, e.g. 193 and 248 nm, and have a demonstrated track-record within the flat panel industry. However, neither fiber nor Excimer lasers can provide the range of IR / visible / UV wavelengths or short-pulse operation at the sub-ns level required for a number of next-generation laser / solar tools.

Pulsed DPSS lasers provide further benefits for solar cell manufacturing: solid-state design with long-lived components lasting tens of thousands of hours; turn-key operation ideal for system integration; requirement only for low-current single-phase electrical inputs; no external gas or water usage. In many respects, pulsed DPSS lasers represent a near-ideal tool for solar cell manufacturing, and their implementation within so many solar research labs, pilot-lines, and volume manufacturing sites is by no means a coincidence.

The roadmap for pulsed DPSS lasers displays two trends of high significance for c-Si manufacturing: increasing the average power levels at short-wavelengths of 532 and 355 nm; industrial turn-key availability of short-pulse (sub-ns) lasers at 1064 / 532 / 355 nm. For most applications, it is a further requirement that the output beams from these lasers are of a very high quality to allow focusing these beams to micron-level spot sizes. The laser specification here is referred to as the M²-squared factor (a beam ‘finesse’ factor). M² parameters are typically required at less than 1.3 (where a value of ‘1’ is the theoretical limit).

Average power levels from short-wavelength pulsed ns DPSS lasers have increased year-on-year, driven primarily by the requirement for faster production throughput (or processing speed) from laser based tools. Figure 2 shows

powers from the AVIA™ laser, the most commonly used UV DPSS laser within solar.

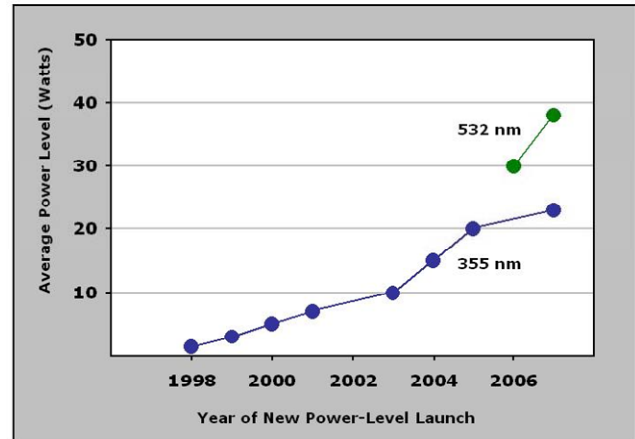


Figure 2: Incremental power increases from a state-of-the-art visible / UV DPSS laser (Coherent AVIA™)

Lasers with pulse-widths shorter than a nanosecond (sub-ns) generally provide ideal sources for very high quality micromachining applications. They enable applications in which the longer pulse duration of a ns laser may cause excess material damage or surface melting. One critical application within c-Si manufacturing is for dielectric layer removal / contact-opening / patterning. High-energy pico-second lasers represent a new technology type on the pulsed DPSS laser roadmap. They offer high peak powers, and decreased thermal diffusion depth $L_d(Si)$ within c-Si (Fig. 3). Combining UV operation with ps pulse-widths currently represents one of most exciting features of lasers for next-generation equipment for c-Si cells.

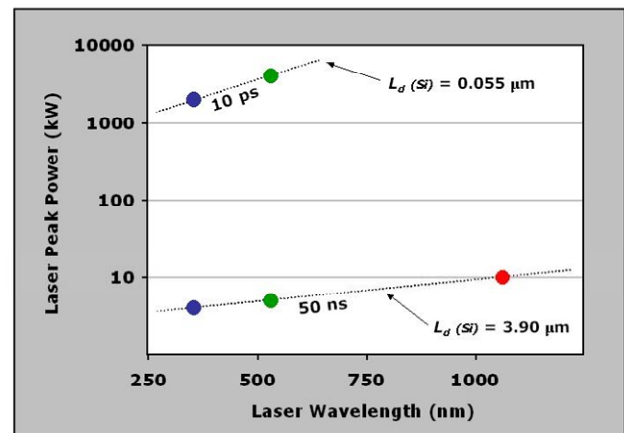


Figure 3: Peak-powers and thermal diffusion depth of a Talisker™ laser, compared to 50-ns platforms.

Conclusions

Laser processing plays an enabling role within many different applications of c-Si and Thin-Film R&D and production. Understanding the trends is performed by categorizing the applications and the laser / material interactions. Applying market dynamics with laser roadmap trends themselves provides a route to predicting the role that lasers are poised to play in next-generation tooling within the solar industry.

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Acknowledgments

The author wishes to acknowledge Corey Dunskey, Stephen Lee, Colin Moorhouse, and Jan Brune for applications activities within Coherent, and Carmen Morilla and Richard Russell (BP-Solar), Viren Rana (Applied Materials), and Andreas Grohe (Fraunhofer-ISE) for enlightening discussions relating to the use of lasers within solar cell production.

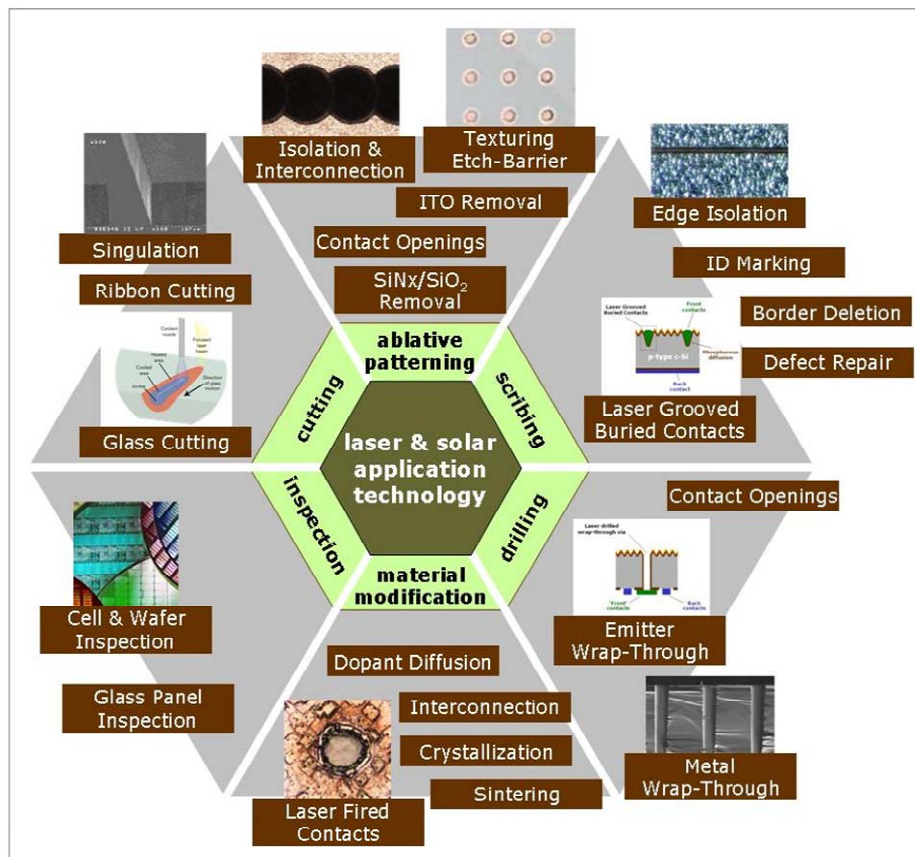


Figure 1: Classification of the different laser applications in solar by laser / material interaction process