THE HOLE STORY

Lasers Take the Wrap

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Crystalline-silicon cell manufacturing is benefiting from laser drilling processes to create conducting pathways from front-to-rear surfaces. Successful implementation, however, is highly dependent on hole quality while maintaining the structural integrity of the wafers moving downstream. Lessons learned from volume production within the semi industry can significantly shorten time-to-market for solar equipment suppliers and cell producers.

BY FINLAY COLVILLE

Laser tools have historically found widespread industrial adoption for applications requiring high quality hole drilling within a wide range of material types. Lasers offer non-contact processing, especially important for brittle or thin material thicknesses. Further, by optimizing key laser parameters (wavelength for absorption, pulse-energy, number of pulses per second, average power, and scanning speed), hole drilling quality can be optimized to a level where alternative drilling methods (e.g., etching) no longer compete. Further, current-generation laser tools typically use turn-key solid-state lasers which operate with high uptime, excellent process reproducibility, and do not require any toxic chemicals or waste management.

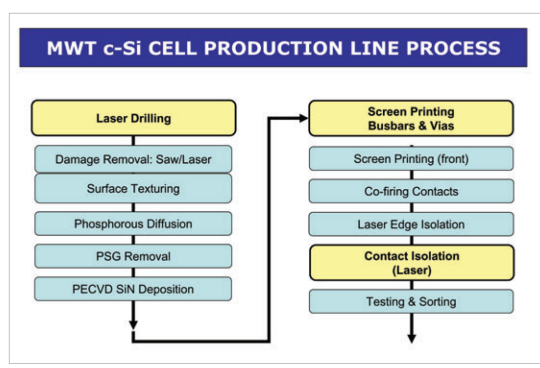

Figure 1. Process flow-chart illustrating typically where laser drilling occurs during c-Si cell manufacturing for Metal Wrap-Through cell concepts[1]. Performed prior to any surface layer deposition steps, laser holes are punched directly through the bare wafers. Only three additional process steps are required compared to standard c-Si cell production (yellow boxes). (Source: Coherent)

The production of standard c-Si cells has largely been based upon screen printed front finger grids with busbars and full Al back-surface-fields. However, these production lines allow only moderate cell efficiencies (14-16%), and utilize tooling which is not matched with current industry drivers to increase either cell efficiency or yield levels when thin sub-180-micron thick wafers become widespread. Alternative cell technologies are broadly termed 'advanced' or 'high-efficiency' concepts. A number of these have been researched over the past few decades, and several c-Si suppliers are already in volume production with specific embodiments. A wide variety of schemes is proposed and summarized within several excellent review articles referenced here[1), 2)]. Among changes compared to standard c-Si cells include the use of high-grade silicon, supplementary doping steps around front-surface fingers (e.g., Selective Emitter concepts, including Laser Grooved Buried Contacts and Dopant Diffusion), or schemes where contacts are located at the rear of the cells: almost all of these use lasers also in some respect[3, 4]. This final class of advanced cell concepts comes under a broad description of "Back-Contact" cell types, an excellent review of these recently undertaken by Van Kerschaver and Beaucarne[5].

Back-Contact cells offer several advantages: overall increase in cell efficiency (decreasing front surface shading or enabling decoupled optimization of passivation layers); simplification of packaging during module formation. There are two basic types of Back-Contact cells: first, creating a fully Interdigitated Back-Contact[6] (IBC) structure with p+ and n+ regions co-planar on the rear surface, also referred to as Back-Junction; second, implementing conductive pathways from the front to rear surfaces. This latter technique is known as "Wrap-Through," and benefits through its relatively simple implementation within existing c-Si cell lines using lower-grade silicon (solar-grade silicon materials have short-diffusion lengths). Wrap-Through concepts represent the one area within c-Si solar production where holes must be drilled through the silicon wafers. Not surprisingly, the use of lasers gets prioritized in all discussions surrounding the optimization for production-ready tooling within the industry for Wrap-Through cells[7, 8]. As explained by Schoonderbeek[8]: "Laser drilling is a key technology for producing EWT [Wrap-Through] cells, because there are no economically feasible alternatives."

Wrap-Through Cell Types

Two different Wrap-Through cell types have received considerable attention; Metal Wrap-Through (MWT)[9] and Emitter Wrap-Through (EWT)[10]. The main purpose of this article is to examine each of these from a laser-processing perspective, and bring knowledge from other market segments over to solar. First, however, it is important to outline briefly the differences in the Wrap-Through approaches.

In MWT*, the standard front-contact

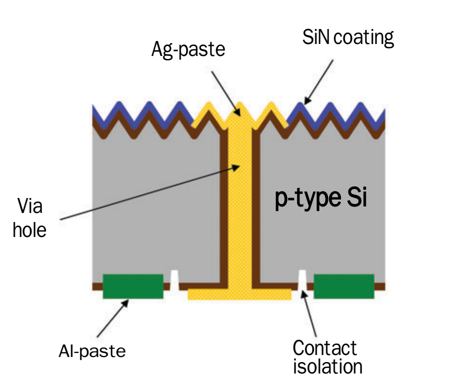

Figure 2. Schematic representation of the Metal Wrap-Through (MWT) process after final BEOL cell steps have been performed. (Adapted from Kubera[12].) (Source: Coherent)

Characteristic	Metal Wrap-Thru'	Emitter Wrap-Thru'
Via holes per wafer	~100 - 200	~15,000 (5" wafer) ~25,000 (6" wafer)
Hole diameter (mm)	~80 - 200 mm	~30 - 100 mm

Table 1. Key parameter ranges for laser processing of via holes in each of MWT and EWT. While holes are typically smaller for EWT, the number of vias to be drilled per wafer is considerably higher. The requirement to process wafers in ~ 2 seconds, therefore, makes MWT much easier to realize in production than EWT. (Source: Coherent)

'finger' grid remains on the front surface. As described by Van Kerschaver and Beaucarne[5]: "These cells are characterized by the presence of a metal grid on the front surface in combination with the presence of interconnection pads for both polarities on the rear surface. The front metal grid is connected to the corresponding pads either around the edge of the wafer or through holes or slots made in the substrate."

Figure 1. shows a typical process flow for MWT solar cells[11]. Figure 2. illustrates where laser via drilling occurs[12]. In EWT+, both the fingers and the busbars are wrapped through to the rear surface along doped conductive channels, creating an appearance similar to Back-Junction cells (EWT cells retain p+ and n+ regions at opposite sides of the cell).

Laser hole drilling, however, is significantly different for each of EWT and MWT cell types, and this has profound implications when optimizing laser-based tools to provide the level of quality and throughput essential for commercial tooling introduction. Table 1. summarizes the key differences in laser processing parameters for each of MWT and EWT. One factor not immediately captured in such a table—but ultimately the determining factor in using lasers for Wrap-Through—is quality. Indeed, the finish quality takes precedence over all other considerations. This includes sidewall quality of the holes, microcracks emanating from the holes within the bulk silicon, debris generated, and the mechanical strength of the wafers before and after laser processing. Achieving high-quality within a wide process-window is the ideal solution, rather than induced crystal damage mitigation via any subsequent etching steps.

Within Table 1., the holes-per-second parameter is a direct consequence of the throughput rates required in production to provide cost-effective processing while ensuring the laser-step does not become a bottleneck within the overall production line. Clement states[11], "Usually, three rows of 17-24 holes with a diameter of approx. 100 μm are processed [for MWT on 5" wafers]." While the efficiency increase from most advanced cell concepts can tolerate additional tools per new process step (and even parallel wafer processing), the starting point is always to introduce low-cost tooling. In the case of laser-based tools, this generally translates to single laser sources/tools within c-Si cell lines at the 20-30 MW capacity level today.

Revisiting Semi TSV's with Lasers

In contrast to many of the other applications for lasers within c-Si solar cell production (e.g. Edge Isolation, Dielectric Removal, Laser Doping, Laser Fired Contacts) Wrap-Through is the one area where the laser industry has most experience strictly from a laser-processing-in-silicon perspective. The analogy, however, is not within the solar industry, but microelectronics (semiconductor) and the use of lasers for drilling holes (vias) within semi-grade silicon wafers in an application known as Through-Silicon-Via's, or TSV's. Gee captures this theme in the context of EWT cells[13], "The first-generation c-Si PV technology took advantage of the semi processing capabilities of the electronics industry, the next-generation c-Si technology will take advantage of concepts and processes from the packaging portion

* A similar cell structure called the 'PUM' cell has been proposed by ECN, Belgium. Some reviews also discuss a variant called Metal Wrap Around, or MWA.
+ A similar process called EpiWT has also been proposed by the Fraunhofer-ISE.

Characteristic	Preferred Value
Wavelength (nm)	< 400 nm
Pulsewidth (ns)	< 80 ns
Average power (W)	> 15 W
Repetition rate (Hz)	> 5,000
Pulse energy (mJ)	> 100

Figure 3. SEM image of optimized semi-grade TSV drilling using a nanosecond laser operating at 355 nm (left-side): image courtesy Joe Callaghan, Xsil, Ltd. Data to the right shows ideal laser-based specifications for commercial tooling for TSV, from Albelo[16]. (State-of-the-art semi TSV tools can drill ~ 500 holes/second with 80㎛ diameter / 120㎛ depth.) (Source: Coherent)

of the electronics industry."

Laser micromachining within the semiconductor industry can be divided into two main areas: dicing/scribing/cutting and via drilling. The maturity of via-drilling in the packaging industry to provide compact interconnects in 3D stacking applications, and the years of process development and knowledge accumulated from high-uptime laser-based tools, provides some key takeaways for solar Wrap-Through optimization. Moreover, simply by examining these in isolation of solar Wrap-Through highlights potentially important issues which influence whether MWT or EWT can be enabled by industrial-grade and qualified laser-based equipment used for semi industry TSV tooling today. Takeaways include:

- Hole quality is significantly improved through the use of short-wavelength laser sources[16]. While a number of factors come into play within overall laser tools, in like-for-like systems, the highest quality has been achieved when using lasers with output wavelengths in the UV at 355 nm. Rodin[15] said, "Recent advances in the process development of blind, micron sized vias drilled in Si by UV DPSS lasers exhibit a clean top and an excellent sidewall quality along with a negligible heat affected zone. With UV, surface roughness figures of ~ 0.12㎛ from White Light Interferometry were measured for vias."
- There are significant advantages to process-quality when using either a 532 nm (green-laser) or a 355 nm (UV-laser), both compared to the use of (lower-cost) infra-red lasers (which typically operate around 1,060 - 1,070 nm).
- Semi TSV's using laser-based tools today use Q-Switched lasers operating with nanosecond pulse duration and repetition rates (pulses per second) in the tens of kHz.
- Via processing quality can, in principle, be improved by moving to shorter pulsewidths (from so-called 'picosecond' lasers), due to reduced thermal diffusion lengths, or heat-affected-zones (HAZ's). However, optimized nanosecond lasers have proved highly successful within semi TSV's, largely implying that a move to shorter pulsewidth picosecond lasers is not essential. Further, nanosecond lasers' 'Production Maturity' over industrial-grade picosecond lasers, have lower CAPEX costs, and offer production-ready power levels for high-throughput operation.
- State-of-the-art semi TSV production line tools have been able to achieve high-quality hole drilling with maximum throughputs of a few thousand holes-per-second. While exact via thicknesses and depths can differ from the solar Wrap-Through numbers shown in Table 1, an upper limit in the range of 2,000-2,500 holes-per-second for 10-50㎛ diameter holes[15] and 200-300 holes-per-second for 100-200㎛ diameter holes does provide a good starting point when cross-referencing semi- to solar- via drilling parameters.

Laser Tooling for MWT Production

A quick comparison between the demands for EWT processing speed, and the upper limits used today for semi TSV drilling, highlights a clear discrepancy. Indeed, this was summarized by Van Kerschaver and Beaucarne very succinctly in 2006: "To date no solution has been found to have sufficiency fast drilling of the vias [for EWT]. A typical via spacing of 1 mm would require almost 25,000 holes in a 156 mm² substrate. Even with laser systems capable of drilling holes in silicon in a single pulse++ with a repetition rate greater than 1 kHz, the throughput of modern production lines (1,000 cells/hr) cannot be reached." And by Schoonderbeek[8]: "Typical demands for EWT solar cells are 15,000 laser drilled via holes with a 80㎛ diameter [5″ wafers]." Of course, some caveats come into play on these statements. First, a key driver to date with EWT has been the requirement for high throughput levels from single-laser based tools[8]. This certainly places extreme demand on lasers, and has process requirements well above those reached by any tool used today in semi TSV production. However, number of tools per production step in advanced solar cell production ultimately comes down to the efficiency or yield gain and the overall Return-on-Investment (ROI). There are many cases in advanced c-Si production schemes where several laser-tool workstations (various combinations of multiple-laser-based tools, multiple scanner / workplaces, dual lane tooling) are being considered and still provide a positive ROI to cell producers. Further, new laser sources are constantly being developed with higher powers to allow faster production throughputs.

Today, within solar Wrap-Through, it is clear that MWT does appear to be more widely pursued than EWT, and while there are many issues which affect this, it is certainly true that quality and throughput are strong factors when comparing the process demands with the tools qualified by semi tool makers in the past few years. As Glunz points out[2]: "Due to the high lateral conductivity of the metal grid a relatively low number of vias is needed [for MWT]." Therefore, the remainder of this article will address production requirements for MWT.

- What does an optimized laser tool look like?
- What type of laser source is used?
- What are typical throughput rates?

And most importantly, once quality is optimized, what are fully-amortized production-tool costs per wafer using typical industry-standard inputs.

There are several key components of a laser-based tool for MWT. These include the laser source, the beam-delivery system including scanning 'head', wafer handling, and automation. While each of these has a strong impact on overall production line performance, the selection of laser source is certainly the most important for an application as quality-sensitive as solar Wrap-Through. Figures 3. and 4. show via holes drilled within similar applications studies using nanosecond lasers operating at differ-

++ Hole drilling typically prefers multiple pulses to average out any shot-to-shot variations in energy and beam profile. The use of multiple low-energy pulses is preferable to single high-energy pulses.

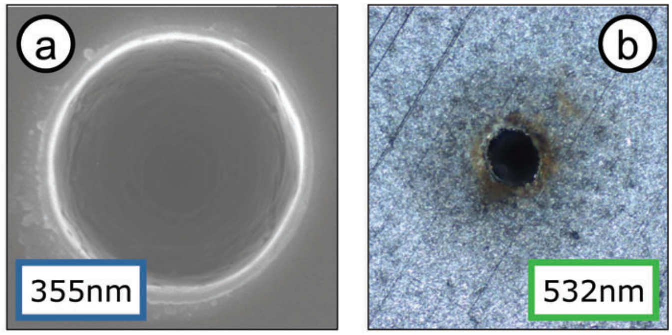

Figure 4. Silicon via-drilled entrance holes of the order 50-100μm diameter, using 'nanosecond' lasers operating in the UV (4a), and (4b) from an AVIA-532-30 green laser at 80 kHz with a scanner speed of 800 mm/s. (Image 4a courtesy of Joe Callaghan, Xsil, Ltd.) (Source: Coherent)

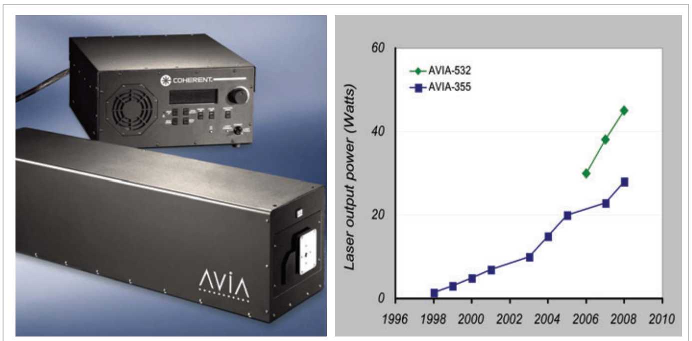

Figure 5. The AVIA™ DPSS laser from Coherent (left), with more than 10 years proven qualification within silicon-based microelectronics manufacturing, and now used for the production of Wrap-Through solar cell concepts. The graph to the right shows powers aligned with increasing MWT line capacities. (Source: Coherent)

ent wavelengths. Often, the default route for laser applications within c-Si solar processes has been to start with nanosecond solid-state lasers operating in the infra-red (the fundamental of diode-pumped solid-state, or DPSS lasers, or fiber lasers). The rationale is a simple one—lowest cost for the laser source. However, two factors often result in a change of laser wavelength. First, when quality needs to be optimized to reduce bulk c-Si damage, shorter wavelengths at 532 and 355 nm show strong benefits (as evidenced in almost all other laser based applications within c-Si production such as Edge Isolation, Dopant Diffusion, Selective Ablation); secondly, ROI is based upon the overall tool cost, and a significant contribution is taken up from non-laser-source items on the tool bill-of-materials. To provide necessary quality for MWT, moving to either 532 or 355 nm has been an outcome of many comparative studies, with the additional observation that the best quality is achieved from 355 nm sources. Again, consistent with semi TSV conclusions, the shift from IR wavelengths to either green or UV, appears to be a recurring theme for optimized MWT tooling.

The next key parameter to consider is the laser power. Again, while tool set-up and handling has a large impact on the wafer-per-hour throughput, correct laser power selection often takes precedence when specifying overall tool throughput. Factoring in handling times, scanner speeds, optical losses from source to workplace, and hole process demands (Table 1.) for MWT, laser average powers in the range 20-30 W are typically required for equipment tooling used today in c-Si production lines+++. A comparison to the power levels from industrial-grade nanosecond laser sources operating at 532 or 355 nm, already used successfully within semi TSV production, shows that MWT can indeed be performed with the required quality and throughput today. Figure 5. illustrates how semi TSV production throughput demands have resulted in year-on-year average power increases from qualified lasers such as the Coherent AVIA™. Indeed, a quick glance at the power available by year reveals how timely solar Wrap-Through implementation is today for commercial tooling. And that there is headroom from industrial-grade sources to allow multiple wafer processing from single laser sources for increased throughput, aligned with higher c-Si fab capacity rates up to 50 MW, or for single laser tools to potentially feed into multiple lanes downstream within a GW-type fab plant.

Conclusions

Laser-based tools are readily available today with industrial-grade 532 or 355 nm lasers for MWT production line integration. Process qualification (by[16] "judicious choice of [laser] wavelength and power") from years of research and production within semi TSV provides excellent comfort to c-Si producers seeking to minimize risk during implementation of a new tool set for advanced cell types such as MWT. Headroom on the average power levels of nanosecond green / UV lasers such as the AVIA™ indicate roadmap alignment for higher throughput tooling in larger fab capacity lines. Developments in laser sources with either higher powers (> 100 W nanosecond lasers in the UV / green) or shorter pulsewidths (picosecond lasers) may provide new options for EWT concepts or for further quality improvements within any Wrap-Through process being considered within the solar industry as a whole. PV

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+++Laser average powers are highly dependent on the wafer thickness. Numbers presented here are for today's cell thicknesses in the 180-200μm range, still somewhat deeper than for standard TSV drilling tools.