Lasers Enable High-Efficiency Processing to Support Solar Roadmap

The fast-growing photovoltaics industry is demanding a host of solutions from equipment suppliers, including improvements in throughput, yield and cost of ownership. Laser applications are playing an increasing role in these efforts.

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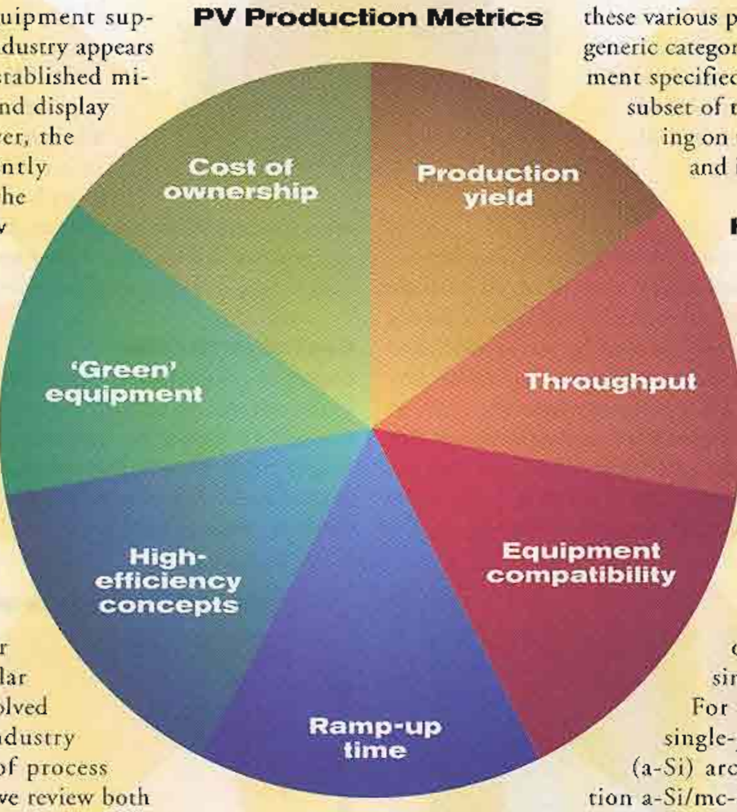
At first glance, equipment supply to the solar industry appears similar to the established microelectronics and display sectors. However, the rapid growth and constantly changing dynamics within the solar industry present a new set of challenges for any equipment supplier looking to become established within the solar supply chain. This is further compounded by the vast number of start-up cell and panel manufacturers, many of which are unknown to established semiconductor equipment suppliers.

Although laser-based tools have been accepted for some time by numerous solar end users, the processes involved are specific to the solar industry with a very different set of process parameters. In this article, we review both existing and emerging laser applications, and see how and why laser processing will play an increasingly enabling role in the solar roadmap. In particular, we look at the new set of challenges placed on suppliers either currently engaged or looking to enter the equipment supply chain.

With a range of solar cell technologies competing with one another for market share, and different approaches being pursued to lower the final module cost per watt ($/W) to the consumer, there can be very different demands placed on equipment suppliers, depending on which type of end user (crystalline silicon or thin film) is engaged. However, we can broadly classify these various production metrics into a few generic categories (Fig. 1). Typically, equipment specified by end users is driven by a subset of these, the exact mix depending on the particular cell technology and its cost-reduction roadmap.



1. Although different solar cell technologies have different demands, they can be broadly classified.

High-efficiency concepts

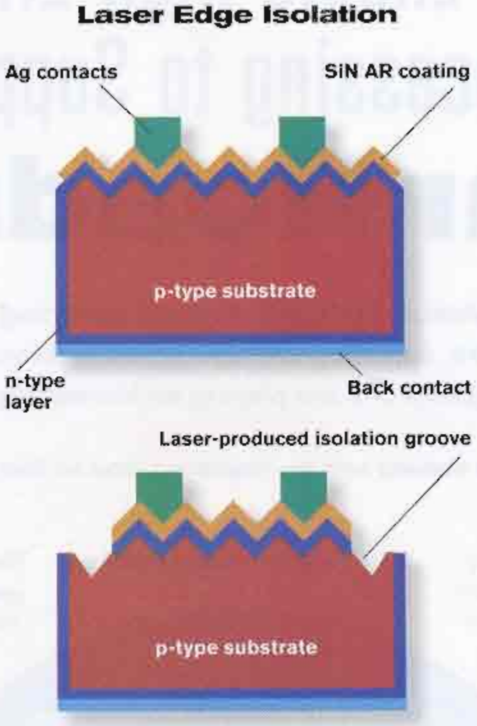
Increasing the efficiency of solar cells and panels is near the top of the wish list of every solar manufacturer worldwide. Most proposed roadmaps spell out an increase of 3-5% for crystalline silicon (c-Si) solar cells to an average value of 18-20% over the next five years. For thin-film solar panels, overall efficiency is lower, but similar increases are expected. For example, changing from a single-junction amorphous-silicon (a-Si) architecture to tandem-junction a-Si/mc-Si (micromorph) structures provides ~4% efficiency gain through increased spectral absorption to give ~10% overall panel efficiency.[1]

At this time, it is the established c-Si cell manufacturers that are most aggressively pursuing high-efficiency cell concepts as part of their iterative improvements within existing production lines and capacity expansion plans. Laser technology is playing a key role in novel front- and rear-surface stages.[2] For example, in metal wrap through (MWT) devices, the thin metal contact "fingers" are moved to the rear surface. In emitter wrap through (EWT) devices, the power-conveying busbars are moved to the rear surface as well, leaving the front completely free of metal. This is made possible by drilling tiny vias to connect the front surface with rear-surface contacts. With MWT, this requires ~200 holes/wafer. With EWT, up to 20,000 of these vias are required on each wafer. Laser drilling is the only process with the potential to meet the commercial-scale speeds required. Similarly, lasers can be used to create novel elements such as laser-fired contacts (LFCs), which are necessary to support certain advanced thin-wafer products.

To fully meet these diverse processes, equipment suppliers are required to integrate lasers with high average powers (up to tens of watts), with a choice of infrared (IR), visible or ultraviolet (UV) output, nanosecond or picosecond pulse characteristics, and excellent beam quality with M^2 parameters of ~1.1 (M^2 ~1.0 denotes the theoretical perfectly focusable laser beam).

'Green' equipment

Today's equipment supply for solar manufacturing lines is comprised of different competing solutions, some of which use toxic chemicals and produce hazardous waste. For instance, screen printing and wet etching are widely used by well-established manufacturers that acquired existing turnkey production line equipment adapted for solar. They typically chose this route to enable early market entry and fast manufacturing ramp-up. But with solar being a replacement and "renewable" energy type with near-zero carbon emissions, there is a strong drive to use green manufacturing equipment whenever possible.

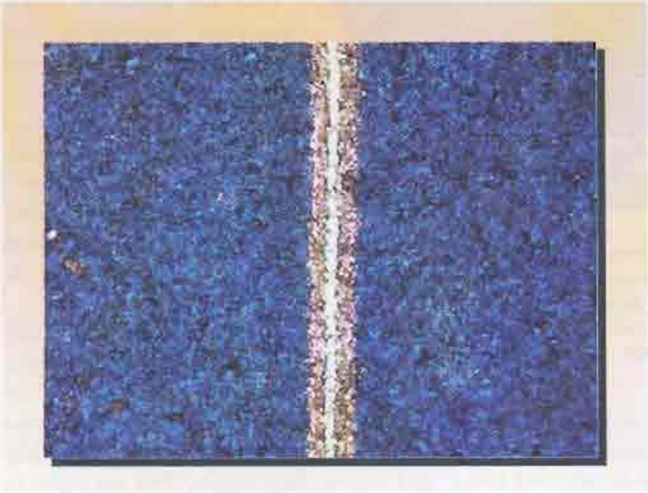


2. In edge isolation of a c-Si solar cell, lasers scribe an isolation groove, typically 10-20 µm deep, to eliminate shunt pathways between the front and rear surfaces.

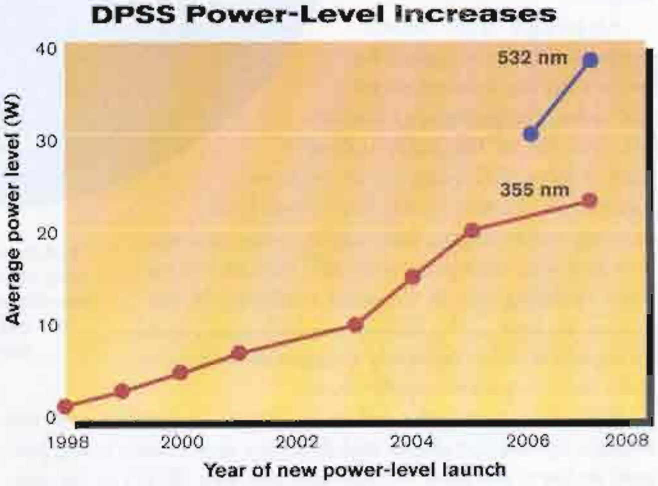
The use of DPSS lasers for edge isolation not only enables greener edge isolation, but also increases yields and improves device efficiency. Specifically, current-generation systems are now relying more heavily on DPSS lasers operating at either visible (532 nm) or UV (355 nm) because of the significantly higher absorption of c-Si at these shorter wavelengths.[4] Silicon absorption is some four to five orders of magnitude stronger at 355 nm compared with IR (1064 nm), allowing highly localized front-surface scribing when using Q-switched UV DPSS lasers (Fig. 3). In addition to shorter penetration depths, UV wavelengths allow narrower grooves to be scribed in a colder process with minimized peripheral thermal damage such as microcracks, which are potentially yield-killing. This enables the grooves to be placed closer to the cell edges, reducing the "dead" area and thereby maximizing the efficiency of the cell.

Cost of ownership

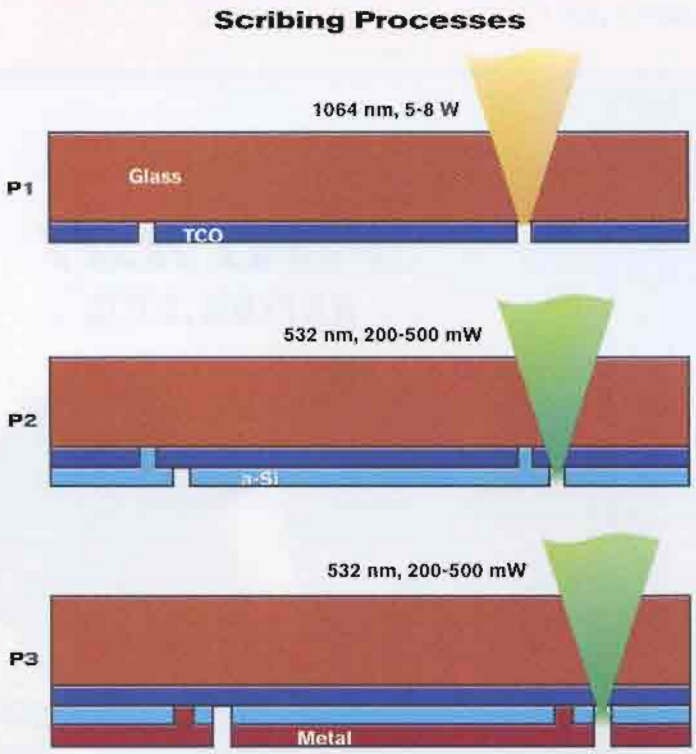
Manufacturing costs for solar cells and panels are constantly under review, as this critically impacts on the $/W passed through to final solar installers. Cost reduction is routinely sought either by reducing raw material costs or through the use of production line equipment with the lowest capital expenditure and running cost.



3. A 355 nm Q-switched DPSS laser scribed grooves ~20 µm wide and ~15 µm deep in a c-Si solar cell. Shorter-wavelength lasers enable highly localized scribing capabilities.



4. Avia Q-switched DPSS lasers have increased their power levels over time to keep pace with increased throughput demands.



5. Patterning is performed using a 1064 nm laser for P1 to remove the TCO, while P2 and P3 rely on the selective absorption of a 532 nm laser.

DPSS lasers provide an ideal solution here, due mainly to their very low operating costs. Further, the solar industry instantly benefits from industrially qualified laser designs already in volume use within semiconductor production lines. These legacy applications have set target levels for uptime, spare-parts availability and on-site service response. The solar industry now stands to gain considerably from this. For example, a high-power laser operating in the UV spectral region with tens of watts output offers fully loaded running costs of typically $3-5/hr when operating at full power, and used 24/7 over five-year periods.

Production yield

Although technically less demanding and involving fewer process steps, solar cell production yields lag that of semiconductor yield levels by a considerable margin for a host of reasons.[5] These include problems resulting from the installation and optimization of new precision equipment tools operating within a high-volume manufacturing environment and from the challenge in maintaining trouble-free operation with reasonable uptime. So historically, within solar, yield optimization has played second fiddle to issues such as long equipment leadtimes and the resulting rush to have equipment installed and producing solar cells to meet market demand. The bottom line: Yield levels <90% are not uncommon within the solar industry, with the leading suppliers now starting to report levels of >95%. But clearly, photovoltaic (PV) manufacturing processes have not evolved and settled to the extent required to produce semiconductor yield levels.

There is also another development that is poised to impact yields and, hence, production equipment selection over the next 3-5 years: the move to thinner and larger wafers. With thicknesses soon to go below 200 μm, wafers will be mechanically weaker than ever before. Put simply, any contact technology used with these brittle wafers will carry the risk of further lowering yield levels in production. Therefore, the non-contact nature of laser processing offers significant inherent advantages, both to reduce wafer breakages and minimize the effects of microcracking, currently one of the main contributors to nonconforming product output.

Throughput

Historically, manufacturing cost reductions in the PV industry, achieved by growing plant capacities and thereby decreasing costs through economies of scale, are similar to those observed in the microelectronics industry. Over the past decade, a 20% reduction in module cost has been achieved with each doubling of worldwide manufacturing output. To put this in perspective, a state-of-the-art c-Si cell production line today can have an hourly throughput exceeding 3000 wph. Manufacturing sites generally have a handful of parallel production lines with a total annual capacity up to several hundreds of megawatts, a number expected to soon rise to the landmark gigawatt-level plant size. Scaling cost reductions are similarly projected as thin-film panel sizes increase from Gen 5 to Gen 8 or bigger.

What does this mean for suppliers of laser-based process equipment? For many c-Si laser processes, production line throughput scales almost directly with average laser power level. Therefore, a key driver here is increasing the average power levels from pulsed DPSS lasers while maintaining characteristics that determine

6. Prisma lasers use a high pulse repetition frequency (PRF) to achieve the desired scalloped profile in scribing. The scan rate is >2 m/sec.

Key Five-Year Roadmap Trends for c-Si Cell Production

	Current 'typical'	Five-year trend
Cell efficiency	14-18%	Increase by 2-3%
Wafer size	125 or 156 mm	Move to 210 mm
Wafer thickness	200-220 µm	Transition to sub-200 µm
'Green' production equipment	Varies per production line	Cleaner production tools
Yield levels	~90%	Increase to >95%

process yields and operating costs. These include beam quality, product lifetime and pulse-to-pulse stability levels. Figure 4 shows how the power of Q-switched 355 and 532 nm DPSS lasers have evolved to keep pace with increased throughput demands.

Within thin-film panel production, DPSS lasers are routinely used to generate discrete cell isolation and interconnection strips by scribing up to a few hundred thin lines on each of the three layers deposited during the panel production stage. These scribing processes, often referred to as P1, P2 and P3, are collectively called laser patterning (Fig. 5). Here, capacity throughput increases cannot be satisfied merely by increasing average laser power; rather, they also require the ability to scan over large panels with high scribing uniformity across the different material layers.[6]

The limiting speed of optical scanning technology means that multiple laser beams must be used in parallel, so average power requirements are fairly modest. A much more critical requirement is pulse repetition frequency (PRF). With a target scan rate of 2 m/sec for large panels, the PRF has to be very high (up to 100 kHz or higher) to achieve the desired scalloped profile (Fig. 6) while retaining key characteristics, such as short pulse widths and excellent pulse-to-pulse repeatability.

Equipment compatibility, ramp-up time

Solar cell and panel end users today have the option of purchasing either complete turnkey production lines available from a few suppliers worldwide or configuring various modular turnkey inline tools to form a complete production line that can be highly customized for their brand of solar cells. This decision has a strong bearing on the types and available suppliers of equipment used, including those of lasers. In addition, the rate of solar growth in the past few years, coupled with the number of new players entering the market, has placed extreme demands on the suppliers of the full-line turnkey manufacturing systems that were initially favored by solar manufacturers. As a result, long delivery times and slow production ramp-ups have sometimes been reported.

Looking forward, it is important to understand that laser-based systems are next-generation enabling tools that are forward-compatible as the solar industry evolves. In contrast, tools based on modified etching or screen-printing equipment types are already reaching the end of the road for some applications. This is certainly true for processing thin wafers, where several contact-based processes are right on the edge of current capabilities and, therefore, poorly aligned with roadmap objectives to move below 180 μm in thickness.[7] And while emerging laser processes hold promise as upcoming enablers of the industry's cost and performance roadmaps, the lasers themselves are not new. Indeed, microelectronics-qualified lasers are already produced in high volume with short leadtimes and supported by existing worldwide service and support networks.

Summary

Final selection of laser equipment for PV manufacturing lines requires a specific match of equipment to specific processes' demands, as outlined in this article. The Table summarizes the key five-year roadmap changes of the solar industry, of most relevance to laser-based equipment suppliers. As the supply chain expands to meet these demands, it is anticipated that laser processing in solar will move from the status of a competing technology to that of accepted, incumbent technology, and will be a key factor in how quickly the roadmap is achieved and the solar industry as a whole continues to grow. **SI**

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