Existing and emerging laser applications within PV manufacturing

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ABSTRACT

Increasing the efficiency and yield of production line processes forms an integral part of PV manufacturers' technology roadmaps. For their next-generation production lines, non-contact processing equipment is considered essential. This prioritizes laser-based processing, already established at several steps in c-Si and thin-film cell manufacturing. This paper summarizes the key issues when using lasers within PV production lines.

Introduction

Laser processing offers a 'non-contact' means of scribing, drilling, and melting specific materials used within production line steps for crystalline-silicon (c-Si) and thin-film manufacturing. Non-contact techniques enable key roadmap drivers in cell and panel manufacturing today to increase yield levels by reducing bulk microcrack formation, and to combine this with high throughput. As explained by Carmen Morilla, Research Technologist at BP Solar, "Lasers will play an important role in future technology especially given the industry trend of using thinner wafers." The transition point in this respect is a wafer thickness of around 160-180µm.

Compared to other technologies (plasma/chemical etching, screen printing, and mechanical cutting), laser processing offers specific advantages such as 'green' equipment types, low cost-of-ownership, and increased micromachining quality. Greater scrutiny is being applied to the environmental aspects of solar production and PV emission life cycle. Viren Rana, Senior Manager at Applied Materials, Inc. Solar Business Group: "Laser processing systems provide green processing in general, not requiring harmful liquids or gases."

The ability of lasers to enable high-efficiency – or 'advanced' – cell concepts is another exciting aspect when applied to solar manufacturing. These concepts are achieved via selective material layer modification (scribing, drilling, or melting) without affecting neighbouring layers or the bulk absorber material. This also avoids the cost and complexity of implementing active depth control. Laser processing can be applied with unique flexibility and selectivity as every material has its own absorption characteristics as a function of wavelength. Thus, choosing the correct laser wavelength permits selective material removal, and also controls the removal rate for a given material. Similarly, varying laser pulse characteristics allows precise control over material removal rates and the size of the heat-affected zone ('HAZ').

Therefore, exploiting laser processing for high-efficiency cell concepts provides a clear route for both technical differentiation and productivity enhancements.

Lasers within the value chain

Whilst niche applications for lasers exist upstream and downstream from cell manufacturing, it is predominantly in the realm of manufacturing that lasers find their ***raison d'être*** within the solar industry. This is true for both c-Si wafer-to-cell and thin-film panel-to-cell processes, despite the different production steps involved.

Today, laser-based tools are introduced directly by cell manufacturers via customized inline and batch integration, or by production line equipment suppliers offering either full or partial turnkey solutions. This results in a wide range of laser-adoption 'maturity' from one solar cell manufacturer to another, symptomatic of the evolving equipment supply-chain. Further, there is a myriad of laser applications presently at the research phase, some of which will soon transition from research to production. Therefore, keeping track of which laser-based processes can add immediate value is often done on a case-by-case basis directly between cell manufacturer and laser equipment supplier. Table 1 summarizes the status of the laser applications within the industry today, separated into c-Si and thin-film.

Applications within c-Si cell production

Laser adoption in c-Si production is most prevalent today with cell manufacturers who are implementing ambitious

	Laser Process	Production Status		
		Widespread Production	Partially Adopted	R&D or Pilot-Line
c-Si	Edge Isolation	✓		
	Laser Grooved Buried Contacts		✓	
	Texturing			✓
	ID Marking		✓	
	Selective Ablation			✓
	Wrap-Through		✓	
	Cutting		✓	
	Dopant Diffusion			✓
	Laser Fired Contacts			✓
	Wafer Inspection			✓
	Defect Repair			✓
	Singulation			✓
	Interconnection			✓
Thin-Film	Patterning	✓		
	Border Deletion		✓	
	Crystallization			✓
	Pulsed Laser Deposition			✓
	Sintering			✓

Table 1. Current status of laser applications within c-Si and thin-film cell and panel manufacturing.

roadmaps to increase efficiency and yield. Applications currently include laser edge isolation, laser grooved buried contacts (LGBC), and emitter wrap-through (EWT).

The most widespread application of lasers is for edge isolation. In this process, lasers scribe an isolation groove on the front surface, typically 10-20µm deep into the underlying p-type Si, to eliminate shunt pathways. This groove is located close to the edges to minimize 'dead' area (as shown in Figures 1a and 2a).

In addition to 'greener' manufacturing, lasers used for edge isolation can improve yield and efficiency.

Lasers compete with two equipment types for edge isolation. Plasma etching was an early front-runner, but suffers from limited throughput due to batch processing, and from wafer breakage issues due to the necessity to handle – or 'coin-stack' – increasingly thinner wafers. Chemical or wet etching can also be applied and is sometimes the choice of suppliers offering chemical etching at other stages. The high electrical efficiency (single-phase electrical input) and closed-loop water-cooling abilities of lasers make them the only near-ideal 'green' tools for this application.

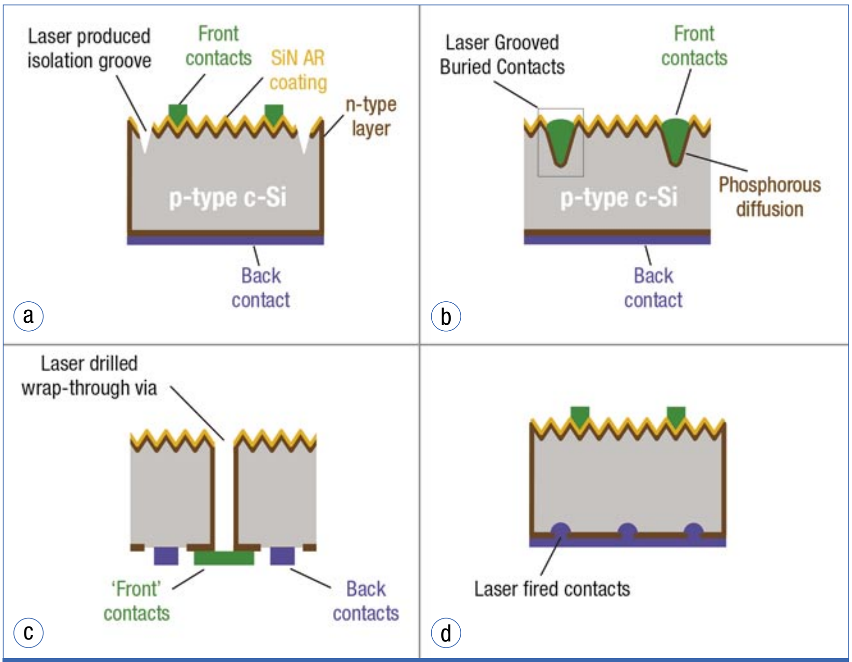

Figure 1. Laser applications include (a) edge isolation, (b) LGBC, (c) EWT, (d) LFC.

In addition to 'greener' manufacturing, lasers used for edge isolation can improve yield and efficiency. This requires optimizing the laser 'type', as evidenced by increased use of visible (532nm) and ultraviolet (355nm) lasers, due to significantly stronger absorption of c-Si at short wavelengths [1]. Silicon absorption is 4-5 orders of magnitude stronger at 355nm, compared to infrared (1064nm), allowing highly-localized front surface scribing (see Figure 3). In addition to shorter penetration depths, UV laser scribing provides higher resolution by virtue of the shorter wavelength. This allows narrower grooves to be scribed in a 'colder' process, with minimized peripheral thermal damage such as microcracking.

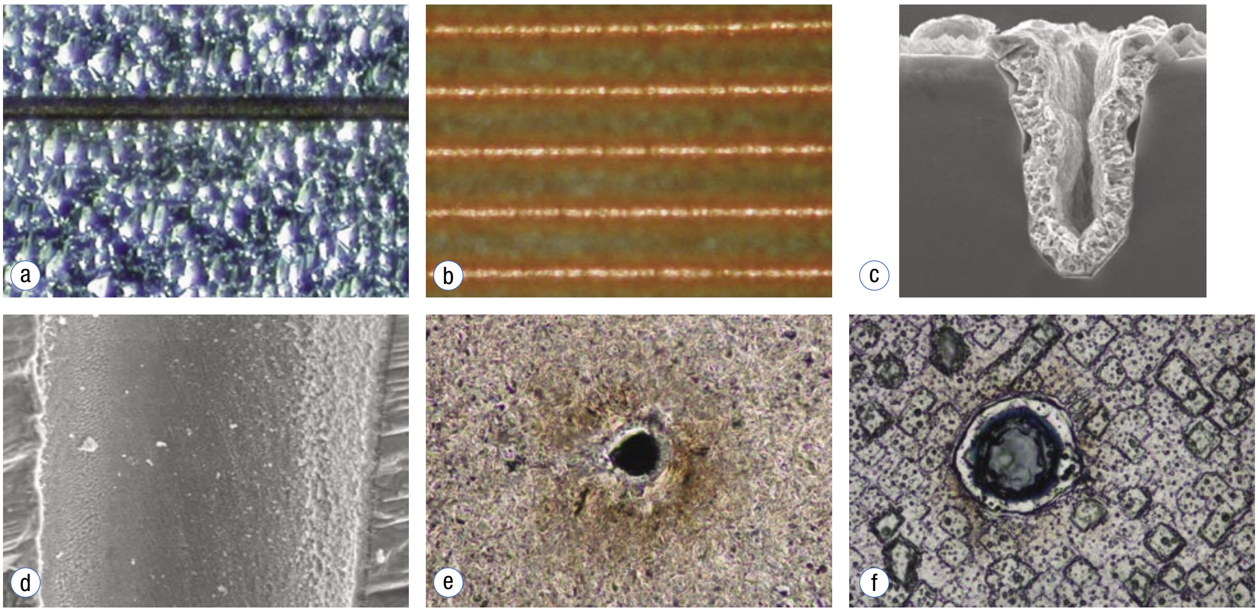

Figure 2. Scribing processes are used in edge isolation (a); LGBC (b, c); EWT employs laser drilling (d, e); LFC is a melting process (f) (image 2c courtesy of BP Solar).

The laser grooved buried contact (LGBC) method was pioneered at the University of New South Wales, Australia in the mid-1980s, and was exploited by a leading cell manufacturer [2]. LGBC is a laser-specific technique and was groundbreaking in both concept and efficiency-enhancement potential. Indeed, LGBC paves the way for other high-efficiency laser-based techniques to move from research lab to production line.

The laser part of LGBC is similar to edge isolation in that it involves scribing trenches at high speed on the front surface, tens of microns wide and deep. However, LGBC is a front-end-of-line manufacturing step, with trenches running in parallel across the front surface every 2-3mm (see Figures 1b, 2b and 2c). Two discrete efficiency-enhancing methods can be implemented. The walls of the trenches are locally (or 'selectively') phosphorous-doped. Contacts are then recessed or buried beneath the front surface where the reduction of 'shadowing,' an undesirable feature of screen-printing, increases cell efficiencies considerably. BP Solar's Carmen Morilla said, "We've been using lasers in high-volume manufacturing of our LGBC technology since 1993. They have proved to be reliable equipment with low maintenance cost and high uptime."

While edge isolation and LGBC exploit front-surface laser scribing, lasers are also ideal for 'drilling' tiny holes through the bulk silicon. Typically, the sidewalls are diffusion-doped with n-type material and metal-plated to create wrapped-through conducting pathways, or vias. One application of through-silicon vias enables 'front-contacts' to be relocated at the rear of the cells, leaving the front surface free of metallization (as in 'back-contact' cells). The most successful laser-based scheme is emitter wrap-through (EWT), where, according to James Gee, CTO at Advent Solar, "improvements in lasers, like DPSS, have enabled new and advanced solar cell designs like wrap-through solar cells". Here, both emitter and base electrodes are relocated at the rear surface, as shown in Figure 1c. Interestingly, 'wrap-through' of c-Si solar wafers has direct analogy to laser-drilled silicon through via interconnects in the manufacturing of integrated circuits; an application where sidewall hole quality and wafer structural 'integrity' are strongly dependent on laser wavelength and pulse width (see Figures 2d and 2e).

The remaining laser/material interaction mechanism within c-Si cell production is 'melting'. There are several high-efficiency techniques proposed that take advantage of laser-induced melting, but the most prominent one is the laser fired contact (LFC) method developed at the Fraunhofer-ISE in Germany [3]. LFC is a rear-surface process, where scanned laser beams 'drive' deposited aluminum through the rear surface passivation layer (typically SiN or SiO_2) several microns deep into the bulk c-Si to create localized Al/Si alloys, as illustrated

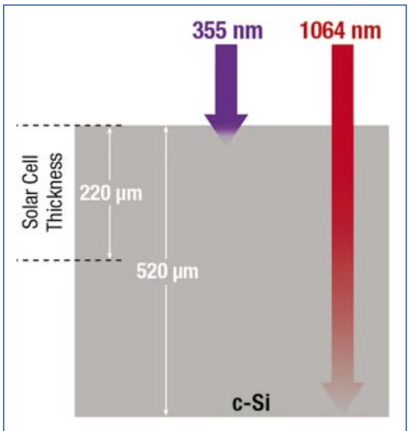

Figure 3. Relative absorption depths in c-Si for incident infrared (1064nm) and UV (355nm) wavelengths [1].

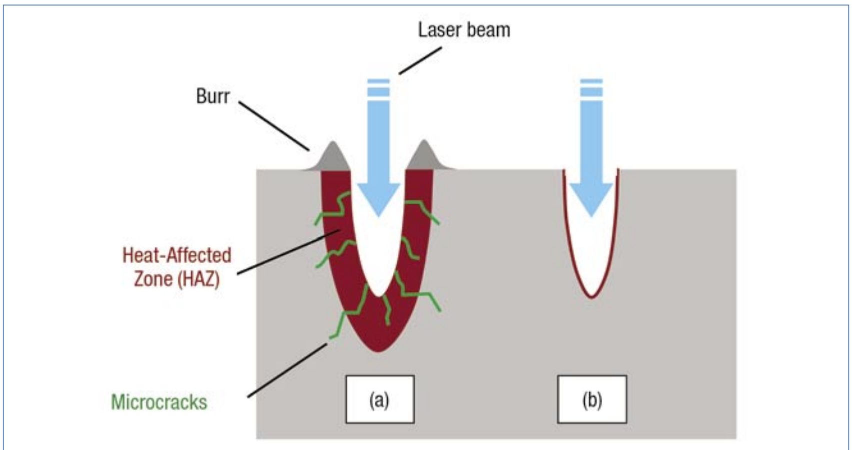

Figure 4. Schematic representation of factors affected by (a) non-optimized and (b) optimized laser selection in c-Si laser applications.

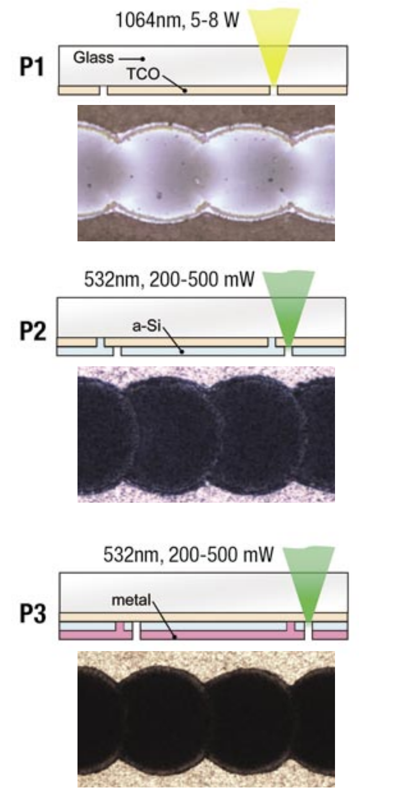

Figure 5. Patterning process for a-Si thin-film production and typical scribe lines for each of the P1, P2, and P3 steps.

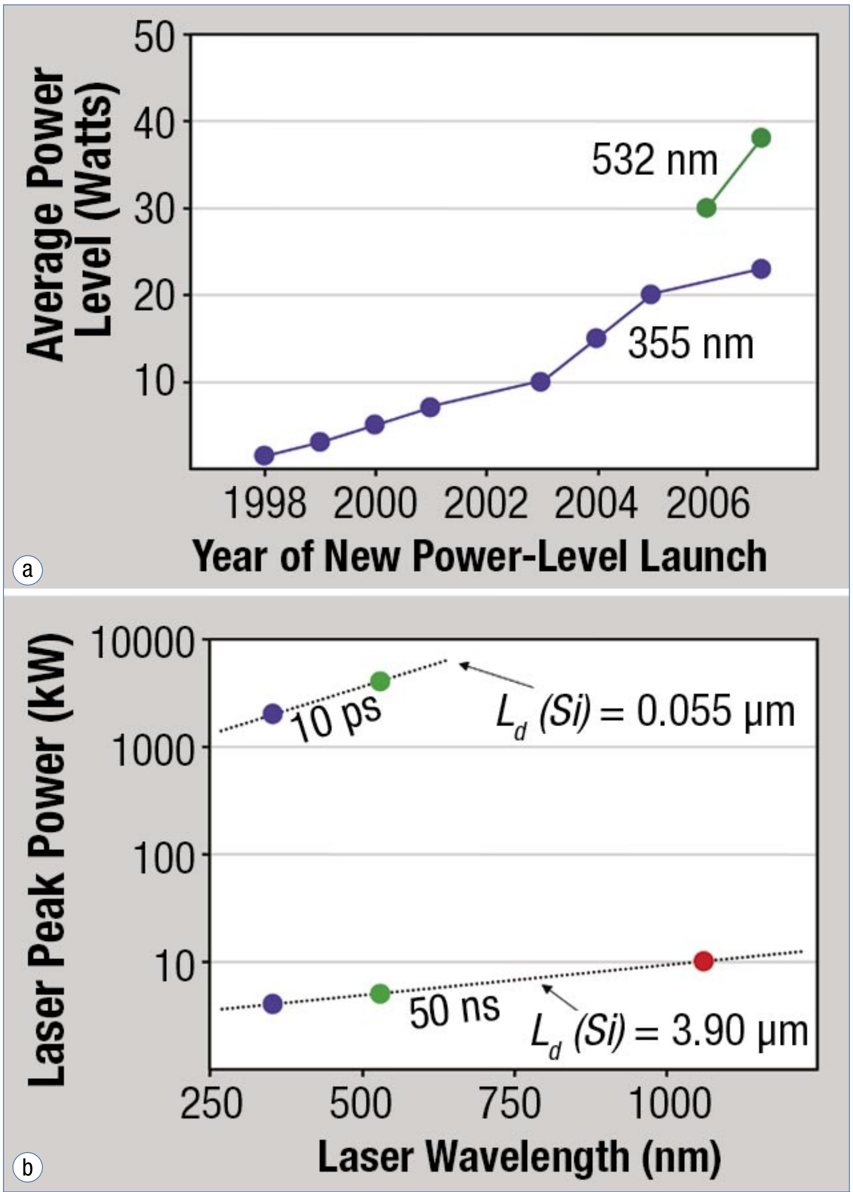

Figure 6. (a) Maximum power levels from state-of-the-art, short-wavelength, nanosecond AVIA lasers.
(b) Peak-power and thermal diffusion depth in silicon (L_d) of a high-energy picosecond Talisker laser (upper data), compared to high-power 50ns platforms (lower data).

in Figures 1d and 2f. The LFC technique is readily compatible at the back-end-of-line in today's c-Si production lines. The most pronounced efficiency and yield benefits are anticipated for sub-180µm-thick wafers, where existing high-temperature and contact-based processes can increase the risk of wafer warping and breakage.

Optimizing lasers for c-Si manufacturing

Scribing, ablating, drilling, and melting applications typically require lasers operating in a non-continuous or pulsed mode where the instantaneous (or peak) power is above the processing threshold.

The most common and lowest cost pulsed lasers deliver pulse-widths of a few tens of nanoseconds at an output wavelength in the infrared range at around 1064nm. For some applications, these lasers are fit-for-purpose and no further optimization is required. However, to enable the full benefits of most laser processing on c-Si wafers, it is essential to optimize laser parameters. Indeed, most applications in c-Si production work best with pulsed lasers offering different wavelengths and pulse-widths from these 20-50ns/1064nm platforms. Crucially, any higher capital equipment cost for more dedicated laser types is easily justified by significant efficiency and yield paybacks to manufacturers. In fact, laser adoption within the solar industry is aligned with this progression; 'proof-of-principle' research or first pilot-line tooling using legacy short-pulse nanosecond lasers at 1064nm, followed by optimization of the laser parameters to maximize efficiencies and yield levels in production. The rationale for this transition is explained by reviewing the materials used within c-Si solar cells, and the effects of the laser/material interactions.

Laser optimization criteria for c-Si applications can be divided into two categories. The first is generic to most equipment tools used within cell production today. This includes increasing the throughput to greater than 3,000 wafers per hour, decreasing the per-wafer cost component attributed to capital equipment, and enabling inline automation. Laser tools are optimized for these parameters by increasing the average power and scanning speeds, by using turnkey Diode-Pumped Solid-State (DPSS) lasers, and by providing handling interfaces compatible with neighbouring production line stages, respectively. The second category is unique to laser processing. Optimizing laser-specific parameters provides the key differentiator between a laser-based process being competitive with existing contact-based technologies and the process being significantly improved with enhanced cell characteristics. The two laser parameters that most require optimization are the wavelength and pulse-width. Figure 4 highlights detrimental effects that result when using non-optimized parameters. For c-Si processing, the most problematic defects are the damaged regions immediately surrounding any scribed grooves or drilled/ablated holes (HAZ), and microcracks emanating from grooves and holes. Depending on the application within Table 1, reducing these effects can often be achieved through (i) wavelength optimization, in particular shorter wavelengths at 532 or 355nm; (ii) shorter pulse-widths (picosecond pulse-durations) which decrease the laser energy's thermal diffusion depth; or (iii) a combination of both.

Applications within thin-film panel production

Laser adoption within thin-film production differs from c-Si, both in the more limited range of efficiency-enhancing techniques and the increased level of laser maturity. Laser use within thin-film PV dates back to when the first thin-film production techniques were developed [4]. This is because lasers were quickly recognized to be the preferred and enabling technology available (compared to photolithography or mechanical scribing), due to depth selectivity, edge quality, process repeatability and high throughput.

Lasers represent the preferred equipment type mainly due to the precision and quality when selectively ablating thin layers of material.

Within thin-film production, pulsed DPSS lasers are used to generate discrete cell isolation and interconnection strips by scribing up to a few hundred thin lines on each of the three material layers deposited during manufacturing [5]. These scribing processes, referred to as P1, P2 and P3, are collectively called 'patterning' and are fundamental to so-called 'monolithic integration' for thin-film panels. Lasers represent the preferred equipment type mainly due to the precision and quality when selectively ablating thin layers of material, without any damage near the scribe lines or within overlying or underlying layers.

The principles of thin-film patterning are similar for the three common material groups (a-Si, CdTe, CIGS). Laser adoption scales with the installed capacities associated with each type, with 'single-junction' amorphous-Silicon (a-Si) laser tools having the highest level of maturity. Figure 5 illustrates the patterning processes specific to a-Si production, with magnified views of the three scribe lines.

Key issues for laser processing in thin-film

While lasers are established tools for patterning, process improvements are ongoing. These include increasing production line capacities and throughputs and improving the cut integrity of the scribing process. Capacity throughput increases are not satisfied simply by increasing average powers, which requires the ability to scan beams over increasingly larger panel sizes with high scribe uniformity across different material layers (smooth edges, no recast debris, minimized HAZ). However, the speed of optical scanning technology is limited, necessitating the use of multiple laser beams configured in parallel to cover up to a few hundred meters of scribing with a processing (TAKT) time of a few minutes. A more critical requirement is pulse repetition frequency (PRF), or how 'fast' the laser pulses. With target scan rates in excess of 2m/s, the PRF needs to be high (≥ 100kHz) to achieve a desired 'scalloped' profile, while optimizing parameters such as wavelength, pulse-width and pulse-to-pulse repeatability.

Next-generation lasers and characterization

Historically, the microelectronics and flat panel display industries have fashioned the specifications of industrial-qualified lasers. However, increased adoption by the solar industry has resulted in lasers being optimized for solar manufacturing, such as new ultra-short-pulse picosecond lasers. With pulse-energies and PRFs analogous to existing nanosecond lasers, lasers such as the Coherent Talisker offer wavelength flexibility from infrared to UV. Figure 6 captures the dual benefits of increased peak power and minimized thermal diffusion depth in c-Si. With very low cost-of-ownership, the key issue, again, is that cell efficiency and yield enhancements far outweigh any increase in capital equipment cost for higher specification/performance laser sources.

Another requirement for increased laser adoption is to perform detailed wafer characterization, as outlined by Applied Materials' Viren Rana, both "during process development to ensure that there is no material damage or unwanted effects, or during production, to check on microcracks, etc." This includes undertaking techniques such as carrier-lifetime measurements, X-ray diffraction, I-V curve analysis, and breakage tests. The differences can be subtle, often only surfacing in statistics generated after thousands of wafers are processed in a production environment. Understanding these to a greater extent will improve the selection of optimized lasers for each application.

As the solar industry evolves with increasing laser-enabled manufacturing process steps, more solar-specific laser tools will be developed for next-generation forward-compatible production tools. At this point, laser processing will move from bearing the status of competitive to that of an 'accepted,' incumbent technology.

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