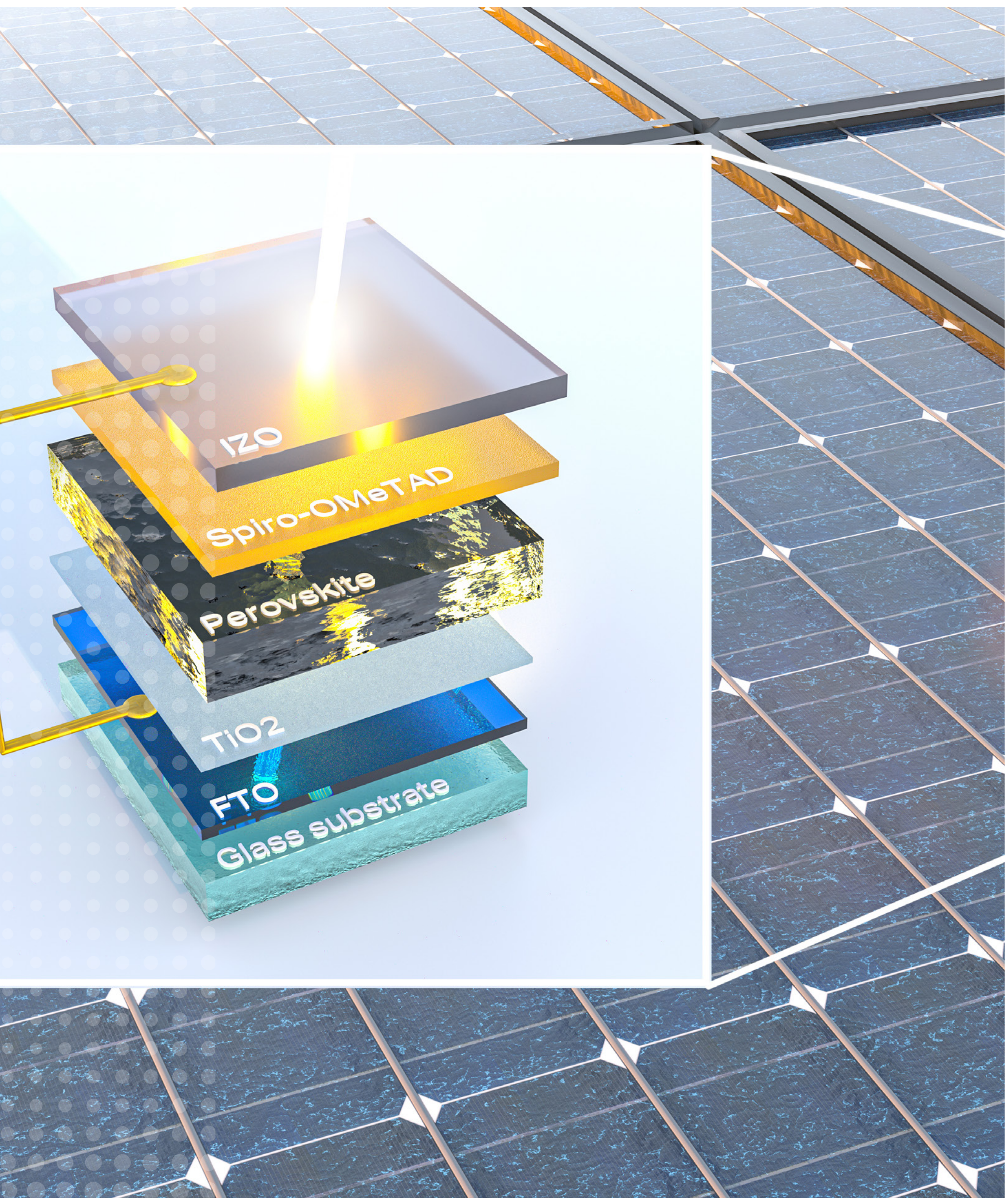
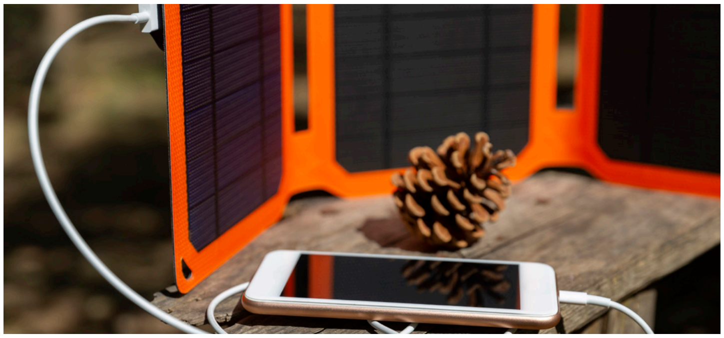
ACCELERATING PEROVSKITE SOLAR CELLS MANUFACTURING





A PHOTOVOLTAIC BREAKTHROUGH

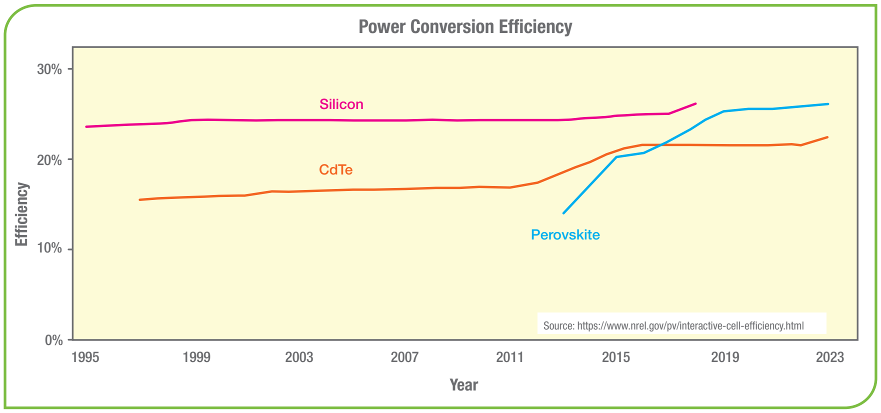
Over the last few decades, there has been a growing demand for clean energy around the world. One form of cleaner energy with an already significant worldwide installed capacity is solar photovoltaic, or PV, technology. We see solar panels around us more and more, on roofs of houses and buildings, at solar farms, and for dedicated applications like lighting, security cameras, appliances and mobile electronics. According to the International Energy Agency, PV contribution covered over 6% of the world's electricity demand in 2022[1]. This contribution is expected to increase substantially over the next several decades.

The first solar panels were based on silicon wafers, and crystalline silicon (c-Si), continues to be the dominant material used in photovoltaics. But ever since the first solar panels were deployed, there has been a continuous quest for higher efficiency and lower cost panels. A second-generation material, cadmium telluride (CdTe), is a thin-film semiconductor that has begun to achieve commercial success. Although not as efficient as silicon, CdTe is lower cost.

A third-generation material, Perovskite, could be a game-changer. It has the potential for both higher efficiency and lower cost compared to c-Si and CdTe. This material can also be used to construct tandem solar cells, which can more efficiently cover a broader absorption spectrum. However, Perovskite is still laboratory-based and has not yet reached full commercial viability. Nevertheless, the growth rate of Perovskite's demonstrated efficiency has been faster than that of silicon and CdTe.

Another major advantage of Perovskite over silicon is that it is easier to manufacture, as it uses a low-cost ink-based process and does not require high-cost factories and equipment. Moreover, Perovskite can be synthesized from common, recyclable chemicals, of which there is a rather abundant supply.

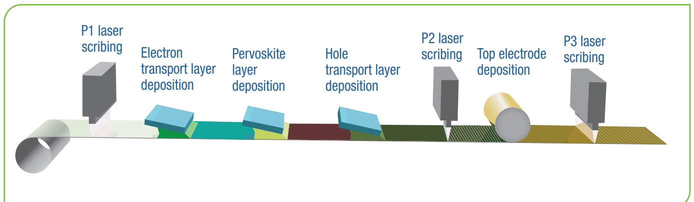
With such possibility to be a breakthrough technology, forecasts indicate that the Perovskite solar cell market size could exhibit a compound annual growth rate (CAGR) of over 30% for the next decade[2].



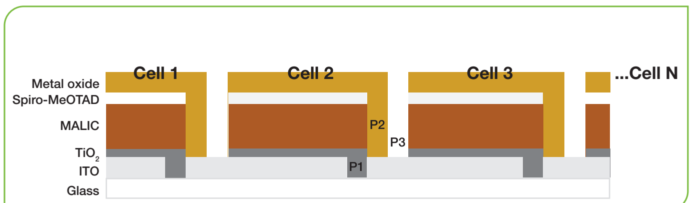
[1] https://iea-pvps.org/wp-content/uploads/2023/04/IEA_PVPS_Snapshot_2023.pdf
[2] https://www.precedenceresearch.com/perovskite-solar-cell-market

PV Perovskite Manufacturing Challenges

Perovskite solar cell manufacturing is a roll-to-roll process. Part of the process involves removing very narrow portions of thin-film layers of material in a multi-film stack without delamination or debris. This is commonly referred to as "patterning" or "scribing," which is done to achieve monolithic serial interconnections with adjacent cells. Traditional mechanical scribing methods, such as with a blade, and wet chemical etching methods have limitations and may cause undesired problems. Thankfully, a superior solution for Perovskite solar cell manufacturing is available: lasers. Here are some of the reasons why.



Perovskite solar cell roll-to-roll processing with laser/mechanical scribing



Schematic of laser-based Perovskite cell patterning and selective layer material removal to construct finished cell and achieve monolithic serial interconnection with adjacent cells

To begin with, lasers are very high precision devices that can perform accurately and repeatably on the order of microns. This helps increase manufacturing yields. By contrast, traditional mechanical tools cannot reliably perform on nearly the same scale. In addition to their high precision, lasers offer more variable and intricate patterns for scribing compared to mechanical tools, which may enable more complex, and possibly more efficient, Perovskite solar cell designs.

Another distinct advantage that lasers have over mechanical processes is the quality of their results. Lasers produce fewer burrs than mechanical scribes and cuts do, and there is less thermal damage to the surrounding areas. This further results in higher manufacturing yields, as less of the material is wasted. Additionally, this can also lead to better quality and reliability of the product in the field, as fewer of these issues will end up in the final assembly.

Laser scribing is a contact-free operation with no tool wear. Thus, replacement downtime is exceedingly infrequent by comparison to mechanical methods.

Wet chemical etching is often used for thin film removal. However, a particular concern with this method is that the waste management required presents extra complications and costs. Lasers, on the other hand, can be thought of as a more "green" technology which does not produce environmental waste. Moreover, it is difficult to control the depth and width of chemically etched lines, resulting in lower yields than laser scribing.

Taken all together, MKS believes that incorporating lasers into Perovskite solar cell manufacturing will help to accelerate their commercial viability.

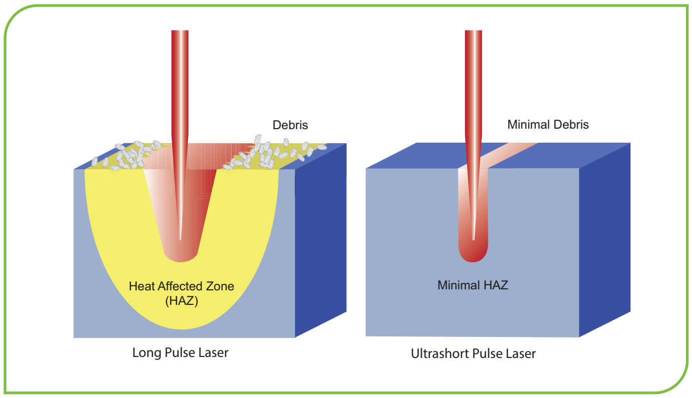
The MKS Advantage for PV Perovskite Manufacturing

MKS understands the challenges faced in designing and building Perovskite solar cells. We've turned this knowledge into unique product features that provide an advantage when used in Perovskite solar cell manufacturing.

Ultrashort Pulse Lasers

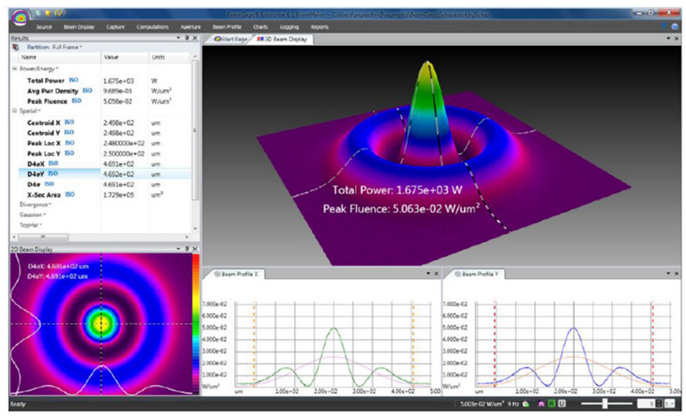
One of the challenges for laser materials processing is removing only the desired material, usually through localized heating, while at the same time minimizing the extent of the heat-affected zone (HAZ) to any of the remaining material. Since patterns created on Perovskite solar cells can be just several microns wide in order to minimize "dead areas" and thereby increase "fill factors" to maximize efficiency per unit area, the HAZ must be kept as close to zero as possible.

Ultrashort pulse widths in the picosecond through femtosecond range—which are available with Spectra-Physics® IceFyre® and IceFyre FS lasers, respectively—can be advantageous to achieving higher quality results, as they yield intense peak powers that result in nonlinear absorption at the sample for instantaneous material vaporization, very minimal heat transfer into the material, and a negligible HAZ. The result is a fast, high-precision, high-quality operation which leads to higher throughput and fewer part failures. Additionally, the laser's stability is vital—especially with regard to energy, wavelength, pulse width and pulse rate—to ensure precise and accurate control of depth when continuously scribing thin films in a production environment.



The impact of laser pulse width on machining quality for a long pulse laser (left) versus an ultrashort pulse laser (right).

For such a delicate operation as Perovskite solar cell manufacturing, a perfect laser beam should be desired from the start to ensure the highest quality and to minimize material scrap. Therefore, it is crucial to monitor the laser beam frequently with first rate metrology instruments—like Ophir® power sensors, power meters and beam profilers—that can operate at the laser's wavelength while handling its maximum output power level. Furthermore, this monitoring must be accomplished rapidly to ensure high throughput.



Beam profiling graphical user interface

Choice of Laser Wavelengths

The laser wavelength chosen will have a dramatic effect on the quality of the operation, as materials absorb different wavelengths in particular ways. This is especially important with Perovskite solar cells that are constructed of layers of various materials in a multi-film stack, with each layer's thickness on the order of microns or less. The table below summarizes the types of materials that are commonly present in Perovskite solar cells and the preferred laser wavelength to use for patterning. MKS' Spectra-Physics lasers are available for all wavelengths shown.

Beam Analysis

Even with the advantages that lasers have over traditional tools, laser systems can still degrade over time. Some causes of degradation include thermal effects on a laser system's internal components, debris, vapors and spatter on the protective glass and vibrations or shock. These issues could affect laser performance in a number of ways. First, output power may be reduced, causing the laser to be less efficient. Another problem that may be caused is a change in the focus or other profile of the beam, which may lead to an ablation to be off target, not deep enough, low quality or possibly damaging to another part of the material.

Solar Cell Layer	Example Materials	Preferred Laser Wavelength
Light absorbing active layer	Perovskite	UV or Green
Hole-transport layer	Spiro-MeOTAD, NiO_x	UV or Green
Electron-transport layer	TiO_2, ZnO	UV or Green
Top electrode / back contact	Ag, Pt, Au	UV or Green
Coatings from glass surface	Indium tin oxide (ITO), fluorine-doped tin oxide (FTO)	IR

MKS Products for Perovskite Solar Cell Manufacturing

MKS offers many products that are broadly utilized for Perovskite solar cell manufacturing.

Picosecond Laser

The Spectra-Physics IceFyre ps laser sets a new standard for ps micromachining and can provide the ultimate solution for Perovskite solar cell patterning. With up to 50 W of UV, green and IR output power and typical ultrashort pulse widths of less than 15 ps, IceFyre can ablate quickly with negligible HAZ. Moreover, IceFyre's unique design exploits fiber laser flexibility and Spectra-Physics' exclusive power amplifier capability to enable *TimeShift*™ programmable burst-mode technology for the fastest and highest quality processing. Based on Spectra-Physics' *It's in the Box*™ design, the laser and controller are integrated into a single, compact package, and IceFyre is manufactured to provide 24/7 industrial reliability.

- Up to >50 W power
- Typical pulse widths <15 ps
- UV, green and IR wavelengths
- Proprietary *TimeShift* burst-mode technology for unprecedented pulse control

Femtosecond Laser

Spectra-Physics' IceFyre FS laser is an extraordinary leap forward in 24/7 industrial micromachining, delivering industry-leading performance, versatility and reliability. It is ideal for high throughput, highest quality micromachining of critical materials, including those used in Perovskite solar cells. Featuring up to 50 W of UV power or up to 200 W of IR power with typical ultrashort pulse widths of less than 500 fs, IceFyre FS delivers the highest quality laser patterning and minimizes HAZ even more than ps lasers can. IceFyre FS also includes our proprietary *TimeShift* programmable burst-mode technology for the most versatile pulse control. Based on Spectra-Physics' *It's in the Box*™ design, the laser and controller are integrated into a single, compact package, and IceFyre FS is manufactured to provide 24/7 industrial reliability.

- Up to >200 W (IR) and >50 W (UV) power
- Typical pulse widths <500 fs
- Single shot to 50 MHz repetition rate range
- Proprietary *TimeShift* burst-mode technology for unprecedented pulse control

High-Power UV Nanosecond Laser

If processing speed is a priority, the new Spectra-Physics Talon® Ace™ high-power ns UV laser should be considered. Delivering an industry-leading >100 Watts of UV power, this laser offers the lowest cost-per-Watt and cost of ownership in its class. Like the IceFyre series, Talon Ace also includes our proprietary *TimeShift* programmable burst-mode technology for the most versatile pulse control. Pulse widths from <2 ns to >50 ns can be created at a constant repetition rate or conversely, the user can maintain constant pulse width with varying repetition rate from single shot to 5 MHz. This leads to more efficient material removal or modification with small HAZ. Designed to provide 24/7 industrial reliability, the laser and controller are integrated into a single, compact package.

- Up to >100 W UV power
- Programmable pulse widths from <2 ns to >50 ns
- Single shot to 5 MHz repetition rate range
- Proprietary *TimeShift* burst-mode technology for unprecedented pulse control

DPSS Q-Switched Lasers

Another laser that offers fast processing performance is the Spectra-Physics Talon diode-pumped solid state (DPSS) Q-switched laser series. Producing up to 45 W of UV or 70 W of green wavelength output power with ns range pulse widths, Talon is well suited for patterning all materials in a Perovskite solar cell stack (except for coatings from the glass surface). All Talon lasers feature our proprietary *E-Pulse*™ technology, which holds pulse energy and pulse width constant over wide repetition rate ranges to ensure outstanding process control. Based on Spectra-Physics' *It's in the Box* design, the laser and controller are integrated into a single, compact package, and the rugged industrial design can provide the performance necessary for a 24/7 precision manufacturing tool.

- Up to >45 W (UV) and >70 W (green) power
- Typical pulse widths <25 ns, <35 ns or <43 ns
- 0-500 kHz or 0-700 kHz repetition rate
- Proprietary *E-Pulse* technology for superb process control

Compact DPSS Q-Switched Lasers

For systems with space constraints, the Spectra-Physics Explorer® One™ compact DPSS Q-switched ns lasers are ideal. Output power of the UV models starts at 60 mW and for green wavelengths starts at 2 W, which is adequate for many Perovskite solar cell patterning applications. If more power is required, there are also Explorer One versions which deliver up to 6 W for UV and 5 W for green. Based on Spectra-Physics' *It's in the Box* design, this is the most compact laser in its class, weighing only a few kg, and can perform reliably for years with uninterrupted use.

- Output power from 60 mW to 6 W
- Pulse widths <5, 10, 12 or 15 ns
- UV and green wavelengths
- Most compact laser in its class

Laser Thermal Power Sensors

MKS offers a comprehensive portfolio of Ophir laser thermal power sensors, several of which are capable of measuring the optical output power of short- and ultrashort-pulsed lasers such as IceFyre and IceFyre FS. These sensors have a very high damage threshold to withstand the high optical peak power delivered by each pulse. Ophir sensors and meters meet the ISO/IEC 17025 standard for calibrated devices, and many can be customized and embedded into laser systems.

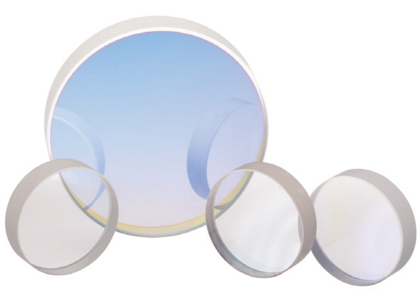
- Spectral ranges from UV to mid-IR
- Power ranges up to a few hundred Watts
- Can be customized and embedded into laser systems
- Response times of a few seconds or less
- Various cooling methods

Beam Profiling Cameras

An effective way to analyze beam profile is with a camera-based system. Ophir beam profiling cameras allow real-time viewing and measuring of a laser's structure in high resolution. Camera-based systems can also measure cross-sectional intensity of the laser and provide a complete 2-dimensional view of the laser mode.

- Spectral ranges from UV to mid-IR
- High-resolution, real-time viewing
- Highest accuracy measurements
- User-friendly application software with extensive analytical features included

High-Energy Laser Optics



Dozens of Newport™ standard catalog optics are designed to operate with high-energy lasers such as those used in Perovskite solar cell manufacturing. Mirrors, lenses, beam splitter cubes and waveplates are readily available in various sizes and shapes whose substrate materials and coatings are optimized for UV, green and IR wavelengths. These high-performing optics can withstand high laser fluences to enable many solutions for Perovskite solar cell manufacturing.

- LIDT of up to 45 Joules per cm^2
- Optics for UV, green and IR wavelengths
- Ultrafast-optimized optics selection guide
- Mirrors, lenses, beam splitters, waveplates

Solar Cell Testing

In order to know exactly how solar cells perform and how they compare to other solar cells, they must be tested. MKS offers Oriel® solar simulators and PV measurement systems, long recognized as leading products in the industry. For laboratories exploring the effects of solar radiation, Oriel solar simulators provide the closest spectral match to solar radiation, including Class AAA models for the most demanding applications. Complete PV I-V test stations that are compatible with Oriel solar simulators are also available for reliable, accurate measurements of a variety of PV cell configurations. Additionally, MKS provides complete, turn-key Oriel quantum efficiency measurement systems which can simultaneously measure EQE and IQE on virtually any photon-to-charge converting device.

- Class AAA, ABA, ABB and UV arc lamp solar simulators
- Class AAA and ABA LED solar simulators
- PV I-V testing systems for solar cell efficiency measurements
- Complete, turn-key quantum efficiency measurement solutions

WHY MKS?

CRITICAL TECHNOLOGIES

World-class technology and development capabilities for leading-edge processes

PROVEN PARTNER

Recognized leader delivering innovative, reliable solutions for our customers' most complex problems

OPERATIONAL EXCELLENCE

Consistent execution across all aspects of our business

COMPREHENSIVE PORTFOLIO

Largest breadth of product and service solutions for the markets we serve

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