LASER CONTACT OPENING (LCO) + PLATING AS A SUSTAINABLE SOLUTION FOR TOPCON SOLAR CELLS

The photovoltaic industry is undergoing a major technological shift, driven by growing demand for higher-efficiency solar modules. As a result, manufacturers are moving beyond PERC (Passivated Emitter and Rear Contact) technology in favor of cell architectures offering better performance. Among these, TOPCon (Tunnel Oxide Passivated Contact) has emerged as the leading candidate to dominate crystalline silicon (c-Si) PV manufacturing for the next decade and beyond. According to recent projections, TOPCon is expected to eventually capture up to 60% (ITRPV – International Technology Roadmap of Photovoltaics).

While TOPCon delivers notable performance gains over PERC, including better carrier collection, less energy loss, and higher overall efficiency, it also introduces new challenges, particularly in terms of metallization. Traditional screen-printed silver, a long-time industry standard for forming front- and rear-side solar cell contacts, is becoming increasingly unsustainable. This is because silver is already the second most costly component in a solar cell (after silicon), and TOPCon uses as much as 50% more of it than PERC.

This high level of silver consumption raises concerns around long-term material availability and the economic viability of TOPCon. It increases costs and places additional strain on global silver supply chains, which can in turn induce pricing volatility. Clearly, an alternative is needed.

This is where laser contact opening combined with electrochemical plating (called LCO + Plating) steps in as a compelling solution. Instead of relying on expensive silver pastes, this method employs short-wavelength, ultrashort pulse (USP) lasers to create ultra-precise openings in thin dielectric layers on the front and back surfaces of the cell. These areas of exposed silicon are then copper plated to create high-quality, low-resistance ohmic contacts. Copper, of course, also offers lower material cost, higher conductivity, and better scalability.

Here we explore how MKS Instruments laser and plating technologies support the transition to LCO + Plating.

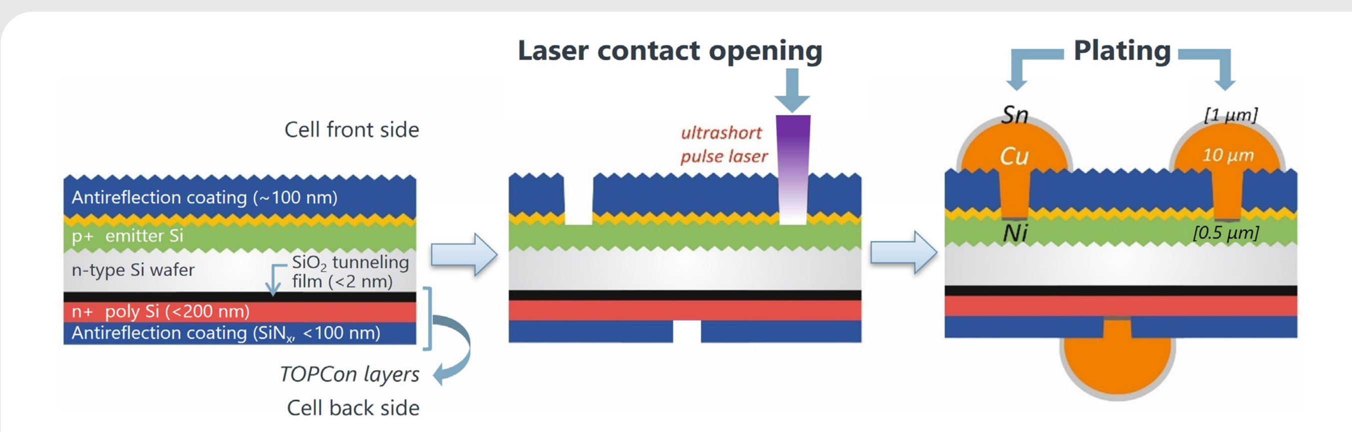

Figure 1. Process flow for LCO + Plating metallization in TOPCon solar cell manufacturing.

The LCO + Plating Advantage

While screen printing has long served as the standard for metallizing silicon solar cells, its limitations are becoming increasingly clear, especially in the context of TOPCon. In particular, silver pastes are both expensive and inherently limited in how finely they can be printed. Wider and taller contact lines means more light shadowing, reduced cell active area, and higher resistive losses, all of which reduce cell efficiency. Additionally, screen printing involves somewhat harsh physical handling – mechanical contact/pressure as well as high-temperature furnace firing – which can be damaging to the thin wafers and delicate TOPCon thin films. These introduce, to varying degrees, a yield/throughput compromise in production.

LCO + Plating directly addresses these limitations. By using a laser to open precisely-defined regions in the passivating dielectric layers, manufacturers can selectively form low resistance contact points, defining exactly where plating will occur. These are then metallized with comparatively lesser amounts of more cost-effective metals (nickel, copper, tin), offering a significant reduction in material cost without sacrificing performance.

Thus, LCO + Plating delivers narrower metal lines, higher conductivity, lower contact resistance, and a more sustainable metallization strategy. While it also adds complexity in terms of equipment and process control, early results from pilot lines, validated by organizations like Fraunhofer Institute for Solar Energy (Freiberg, Germany), demonstrate that performance can match or exceed traditional screen-printed cells. As a result, as TOPCon adoption accelerates, LCO + Plating is poised to become the new standard for high-efficiency, cost-conscious solar manufacturing.

LCO Process Considerations

The goal of LCO is simple in principle: remove the antireflection and passivation dielectric layers with minimal effect on the underlying silicon and SiO_2 layers. However, achieving this in practice requires a tightly controlled, high-precision process.

Short-wavelength, USP lasers, specifically ultraviolet (UV) picosecond (ps) and femtosecond (fs) lasers, are ideally suited for meeting this need. Combining short pulse widths with the strong absorption of UV light is critical. Since the silicon nitride (SiN_x) antireflection coating transmits a majority of the UV laser light, the interaction (both thermal and optical) in the underlying silicon must be confined to 10's of nm. With this shallow confinement of the absorbed energy, the thin SiN_x layer is ejected by the plasma formation and rapid heating that occurs in the underlying silicon. This controlled, limited spread of energy is essential for maintaining the integrity of the tunnel oxide and poly-Si stack beneath, which is in turn critical for TOPCon cell performance. Figure 2 shows LCO features formed with both ps and fs UV lasers as viewed through an optical microscope.

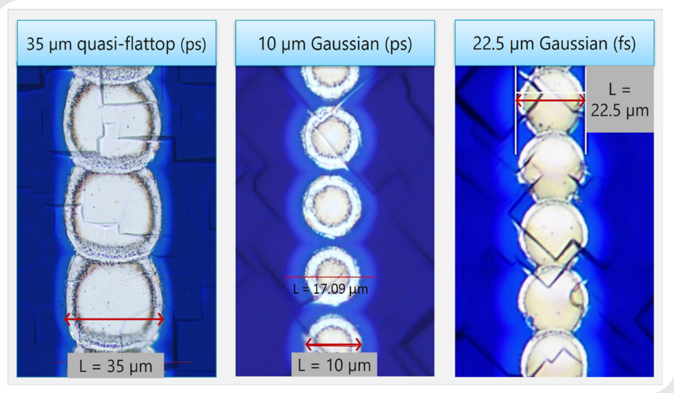

Figure 2. Examples of LCO features processed with ps and fs pulses, along with Gaussian and quasi-flattop intensity distributions.

Laser parameters such as pulse duration, wavelength, spot size, and fluence must be carefully optimized and balanced against process throughput. For most processes, ps lasers offer a strong balance of speed and quality. However, in thin-film applications like TOPCon laser contact opening, fs lasers can sometimes deliver higher throughput and better quality due to their lower ablation threshold and more gentle interaction with layered materials. Beam shaping, such as using a quasi-flattop intensity distribution, can further enhance control over ablation depth and uniformity.

Applications engineers at MKS Instruments have conducted an in-depth study to specifically characterize how different laser process parameters interact during the ablation of TOPCon solar cell materials. The goal of this work was to identify parameter combinations that will reliably achieve:

- Complete removal of the SiN_x anti-reflection layer, which varies in thickness from 70 to 120 nm.
- Uniform ablation across the targeted layers.
- Controlled and minimized thermal impact on the surrounding material.
- Minimal effect on the underlying poly-Si layer (<200 nm).
- No damage to the thin SiO_2 tunneling/passivation layer (1–2 nm thick) beneath the poly-Si.

Figure 3 shows the results from one of the tests performed at MKS Instruments. Using scanning transmission electron microscopy (STEM) it provides a detailed look at how a TOPCon solar cell responds to the laser. In the images here, the region was ablated by three ps laser pulses with slight overlap. Both a top-down view and a cross-sectional image of the same processed area are provided.

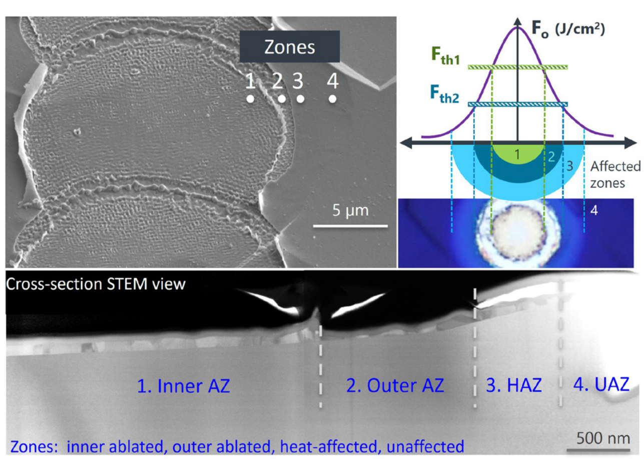

Figure 3. The laser processed area seen here can be divided into four distinct regions; an inner ablative zone (AZ), an outer ablative zone, a heat affected zone (HAZ) and an unaffected zone (UAZ). These are labeled in the image.

It is worth noting that more material is removed from the outer AZ (the trench labeled Zone 2 in the image) as compared to the inner AZ (area labeled Zone 1 in the image), despite the laser spot being more intense nearer to its center. One possible explanation is that the intensity at the laser beam periphery isn't sufficient to initiate non-linear absorption in the overlying layer (SiN_x). As a result, more laser energy passes through that layer at the beam edge than might be expected, causing additional silicon removal. The rapid heating and cooling that occurs with USP irradiation is responsible for forming Zone 3, where some of the p+ polycrystalline Si has been converted into amorphous Si. This will necessitate an additional heating cycle to convert it back to polycrystalline form.

Plating Metallization

Once vias are formed by LCO on a TOPCon solar cell, the next critical step is metal deposition. For high-efficiency, cost-effective metallization, plating is the method of choice. Unlike screen printing, which relies on costly silver pastes, plating uses copper as the primary conductor. Copper offers superior conductivity and dramatically lower material costs.

The standard Cu-based metallization stack for TOPCon typically involves three steps:

1. Nickel (Ni) plating to form the ohmic contact and also act as a diffusion barrier between copper and silicon.
2. Copper (Cu) plating to create the main conductive pathway.
3. Tin (Sn) or silver (Ag) capping to improve corrosion resistance and solderability.

These steps can be implemented using either electrochemical deposition (ECD) or electroless plating. Electroless nickel plating is attractive for sensitive TOPCon structures because it doesn't require electrical contact to initiate deposition and allows for potential double-sided plating. This can reduce handling steps and mechanical stress on fragile wafers.

However, while electroless plating promises greater process simplicity and potential cost savings, it is not yet widely adopted in high-volume production. In contrast, ECD is the more established approach, offering superior process control, more uniform thickness, and higher material purity, albeit with a higher initial capital expense. A focused ion beam (FIB) allows section removal and close inspection of the plated interfaces, as shown in Figure 4 for ECD plating.

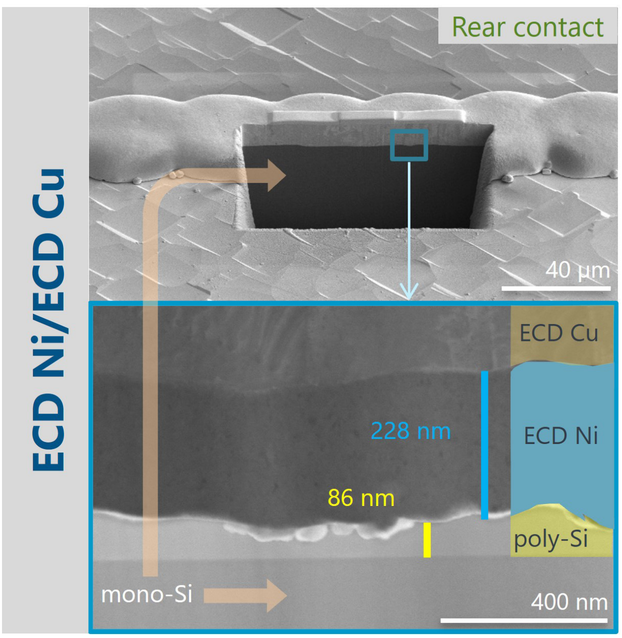

Figure 4. Close inspection of an ECD plated cross-section reveals close and continuous contact between layers.

Whichever metallization method is chosen, process integration is key. The laser-processed openings must be carefully optimized to match the requirements of the plating process, thus ensuring low contact resistance and strong adhesion. Factors of concern include LCO opening size, spot overlap ratio, and residual surface quality, all of which influence plating uniformity, adhesion, and performance.

Cell Performance

What can be realistically expected from an optimized LCO + Plating production process? To find out, TOPCon devices were created using Spectra-Physics laser systems and Atotech plating chemistries; this work was performed in collaboration with Fraunhofer ISE. However, it should be noted that the wafer precursors used in this study were not optimized for LCO and the plating was performed with lab-grade tools.

Under these conditions, we achieved cell efficiencies of up to 23.3%, with open-circuit voltages (VOC) around 693 mV and fill factors exceeding 82%. This efficiency matches well with the screen printed metallization result (24%), which the wafers were actually designed for.

Testing by other groups – which optimized the wafer precursor, laser process, and chemistry together – reached efficiency levels of 26.7%. This value is near the upper bound considered practical for manufacturable TOPCon cells.

Conclusion

TOPCon is positioned to lead silicon PV manufacturing for the next decade, but its long-term success hinges on moving beyond silver-based screen printing. LCO + Plating offers a scalable and sustainable alternative. In particular, the combination of Spectra Physics lasers and Atotech plating chemistry has demonstrated the ability to create metallized TOPCon cells that support both high-efficiency performance and manufacturability. The process can be scaled using multiple high-speed processing heads in parallel to meet throughput at levels of up to 35,000 wafers/hour. This makes LCO + Plating a viable path forward for commercial production of TOPCon solar cells.

PRODUCT

IceFyre® Industrial Picosecond Lasers

The IceFyre UV50 is the highest performing UV ps laser on the market, providing >50 W of UV output power at 1.25 MHz (>40 µJ) with 100's µJ pulse energies in burst mode, and pulse widths of 10 ps. The IceFyre UV50 sets new standards in power and repetition rates from single shot to 10 MHz. The IceFyre UV30 offers >30 W of typical UV output power with pulse energy >60 µJ (greater pulse energies in burst mode) and delivers exceptional performance from single shot to 3 MHz. The IceFyre IR50 provides >50 W of IR output power at 400 kHz single pulse and delivers exceptional performance from single shot to 10 MHz.

IceFyre laser's unique design exploits fiber laser flexibility and exclusive power amplifier capability to enable TimeShift™ ps programmable burst-mode technology for the highest versatility in the industry. A standard set of waveforms is provided with each laser; an optional TimeShift ps GUI is available for creating custom waveforms. The laser design enables true pulse-on-demand (POD) and position synchronized output (PSO) triggering with the lowest timing jitter in its class for high quality processing at high scan speeds, e.g. when using a polygon scanner.

	IceFyre UV50	IceFyre UV30	IceFyre GR50	IceFyre IR50
Wavelength	355 nm		532 nm	1064 nm
Power	>50 W @ 1250 kHZ	>30 W typical @ 500 kHz >25 W @ 800 kHz >20 W typical @ 1 MHz	>50 W @ 500 kHZ	>50 W @ 400 kHZ
Maximum Pulse Energy, typical (greater pulse energy per burst possible with TimeShift ps)	>40 µJ @ 1250 kHz	>60 µJ typical @ 500 kHz >31 µJ @ 800 kHz >20 µJ typical @ 1 MHz	>100 µJ @ 500 kHz	>200 µJ @ 200 kHz
Repetition Rate Range	Single shot to 10 MHz			
Pulse Width, FWHM	<12 ps (10 ps typical)		<15 ps (13 typical)	
TimeShift ps	yes			
Pulse-to-Pulse Energy Stability	<2.0%, 1 σ			<1.5%, 1 σ
Power Stability	<1%, 1 σ, over 8 hours			

MKS Atotech

Electroplating contact fingers on solar cells enhances cell efficiency while significantly reducing material cost. The plated Ni / Cu / Sn contacts outperform conventional screen-printed contacts.

Nickel plating: A thin nickel seed layer acts as an interface, establishing the ohmic contact with silicon. Nimate® PV (electrolytic) or EXPT PV EN 4 (electroless) serve as seed layers and/or diffusion barriers.

Copper plating: Provides highly conductive copper fingers with excellent electrical behavior. The low-stress, ductile composition also withstands mechanical impact. The Cupracid® PV family is tailored for operation in current densities ranging from 2 to 25 ASD.

Tin plating: Ensures solderability for a reliable cell connection and protects copper from any environmental impact. Stannacid® PV is the standard tin process, while Niveostan® PV 20 offers a high-speed tin process.

	Ni Plating		Cu Plating		Sn Plating	
	EXPT PV EN 4	Nimate PV	Cupracid PV 70	Cupracid PV 5-2	Niveostan PV 20	Stannacid PV
Application	Pd activation-free electroless Ni process	ECD nickel sulfamate process	Copper process for medium-speed application	Copper process for high-speed application	High speed tin process	Standard sulfuric based tin process
Properties	1 - 6% P content	High Ni purity	• Low internal stress • High aspect ration		• Fluoroborate and lead-free electrolyte	• Outstanding throwing power
Plating Speed	0.1 - 0.3 nm/min	0.5 - 5 ASD	5 - 10 ASD	10 - 50 ASD	5 - 40 ASD	1.2 - 3 ASD

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