ODTÜ GÜNAM

INTERNSHIP REPORT

A SHORT JOURNEY WITH GÜNAM

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CONTENTS

1. INTRODUCTION TO SOLAR CELLS

The solar cell, also called a photovoltaic cell, is a device that can directly convert light energy into electrical energy through the photovoltaic effect . A solar cell is made up of two layers of silicon that are treated to let electricity flow through them when exposed to sunlight. The silicon that is used to make the solar currently provides a combination of high efficiency, low cost, and long lifetime. One layer is positively charged, while the other is negatively charged. As photons enter the layers, they give up their energy to the atoms in the silicon in the form of electrons. Solar cells are described as being photovoltaic, irrespective of whether the source is sunlight or artificial light. In addition to producing energy, they can be used as photo detectors, i.e., infrared detectors that detect light or other electromagnetic radiation near the visible range or measure light intensity.

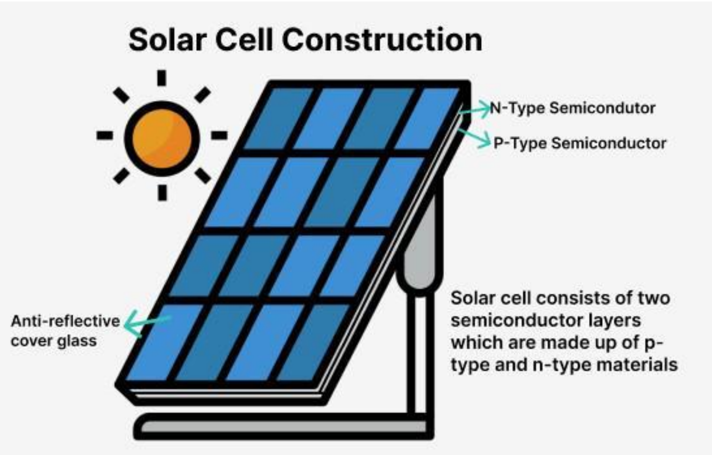

Figure 1 Solar cell construction

When light shines on a photovoltaic (PV) cell – also called a solar cell – that light may be reflected, absorbed, or pass right through the cell. The PV cell is composed of semiconductor material; the "semi" means that it can conduct electricity better than an insulator but not as well as a good conductor like a metal. There are several different semiconductor materials used in PV cells.

When the semiconductor is exposed to light, it absorbs the light's energy and transfers it to negatively charged particles in the material called electrons. This extra energy allows the electrons to flow through the material as an electrical current. This current is extracted through conductive metal contacts – the grid-like lines on a solar cell – and can then be used to power your home and the rest of the electric grid.

The efficiency of a PV cell is simply the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other. The amount of electricity produced from PV cells depends on the characteristics (such as intensity and wavelengths) of the light available and multiple performance attributes of the cell.

An important property of PV semiconductors is the bandgap, which indicates what wavelengths of light the material can absorb and convert to electrical energy. If the semiconductor's bandgap matches the wavelengths of light shining on the PV cell, then that cell can efficiently make use of all the available energy.

2. TYPES OF SOLAR CELL

There are several types of solar cell architectures, each developed to improve efficiency, reduce recombination losses, and enhance light absorption. While traditional silicon-based cells remain dominant in the photovoltaic industry, advanced structures like SHJ, PERC, TOPCon, and IBC offer significant performance advantages. Below is the most prominent solar cell technologies used in modern PV applications, along with their structural features and working principles.

2.1 Silicon Heterojunction Solar Cell

Silicon Heterojunction (SHJ) Solar Cells combine crystalline silicon with amorphous silicon layers to create a high-efficiency structure. This design utilizes intrinsic amorphous silicon for excellent surface passivation, along with doped n-type and p-type amorphous silicon layers for charge collection. SHJ cells are known for their high open-circuit voltage and low recombination losses. They require low-temperature processing and are ideal for applications where high performance and long-term stability are critical.

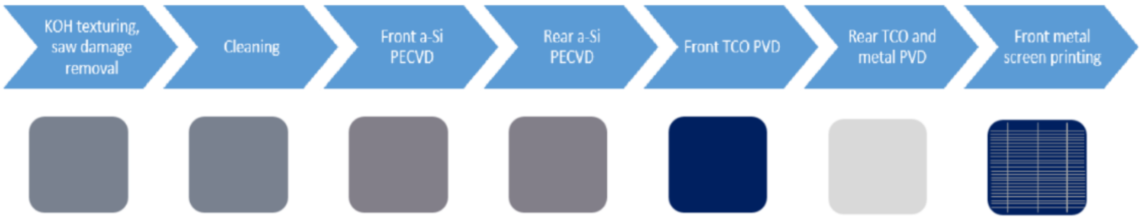

Figure 2 Process steps to manufacture a silicon heterojunction solar cell

The wafers are textured using alkaline wet etching (KOH or NaOH solution) and followed by wet chemical cleaning. The junction is formed using plasma enhanced chemical vapor deposition (PECVD) to grow few nm of intrinsic and doped a-Si: H layers on both sides of the c-Si wafer, forming a p/i/n/i/n stack. Subsequently, the ITO layer is sputtered on both sides of the wafers. In Figure 1 we can see that the TCO thickness at the front and rear is different. The front ITO thickness and oxygen content are optimized to promote a suitable sheet resistance for carriers' lateral transportation, a good transparency to avoid parasitic light absorption, and to enhance light trapping. The rear ITO is optimized for low absorption in the infrared region. The contacts are then screen printed on the front or on both sides of the cell depending on if the aim is to obtain a bifacial solar cell. Finally, the samples are annealed at 200-250 °C for 30-60 min. Figure 2 shows a simplified flowchart of the manufacturing process of SHJ solar cells including photographs of the partly processed wafer after each process step.

2.2 Passivated Emitter Rear Contact (PERC) Solar Cell

PERC SE (Passivated Emitter and Rear Cell – Selective Emitter) solar cells represent an advanced photovoltaic technology that combines two cutting-edge approaches to enhance performance and efficiency. By integrating the PERC (Passivated Emitter and Rear Cell) technology with the Shingled Emitter design, PERC SE cells achieve superior efficiency and reliability. PERC technology reduces electron recombination losses through a passivated emitter and rear layer, while the Shingled Emitter design segments the cell into overlapping strips.

PERC technology enhances efficiency by incorporating a passivated emitter and rear layer, which significantly reduces electron recombination losses. The passivated emitter minimizes surface recombination, ensuring fewer energy losses at contact points, while the rear layer further improves light absorption and energy conversion.

Meanwhile, the Selective Emitter design optimizes performance by cutting the solar cell into overlapping strips that are seamlessly interconnected. This design reduces shading and resistive losses, allowing for better current flow and improved overall efficiency.

P-type PERC solar cells use boron-doped silicon wafers, forming a P-N junction with a negatively charged N-type layer on top. When sunlight hits the cell, it generates electron-hole pairs, which are separated by the electric field at the junction, producing electrical current. P-type cells are cost-effective, widely used, and highly reliable, making them a key foundation for modern photovoltaic technology. With their passivated contact structures and selective emitter architecture, PERC SE solar cells deliver enhanced power output, efficiency, and long-term stability, making them an excellent choice for high-performance solar energy systems.

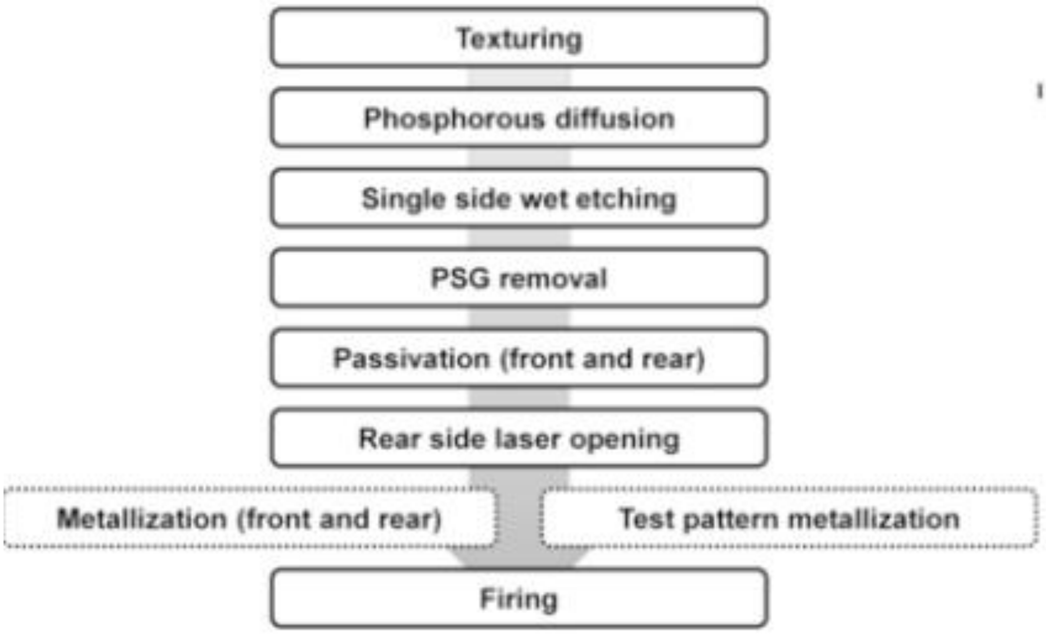

Figure 3 Process steps to manufacture a PERC solar cell

2.3 Tunnel Oxide Passivated Contact (TOPCON) Solar Cell

TOPCon, short for “Tunnel Oxide Passivated Contact,” is an advanced solar cell technology that utilizes an n-type silicon base to enhance efficiency and performance. Unlike traditional p-type silicon solar cells, TOPCon cells employ n-type silicon doping, which offers several advantages. At the core of a TOPCon cell is a sophisticated cell structure designed to minimize electrical losses and improve light absorption. The key components include a thin oxide layer and a polycrystalline silicon layer, which together form a “tunnel oxide passivated contact” on the rear side of the cell. This unique structure facilitates efficient extraction of charge carriers, reducing recombination losses and boosting overall energy conversion efficiency. According to Wikipedia, TOPCon cells can achieve efficiency rates exceeding 25%, significantly higher than conventional solar cell technologies. The n-type silicon base used in TOPCon cells exhibits lower sensitivity to certain impurities, resulting in improved temperature coefficients and slower degradation rates over time. Additionally, the cell structure enables higher bifocality, allowing the modules to generate power from both the front and rear sides, further enhancing energy yield.

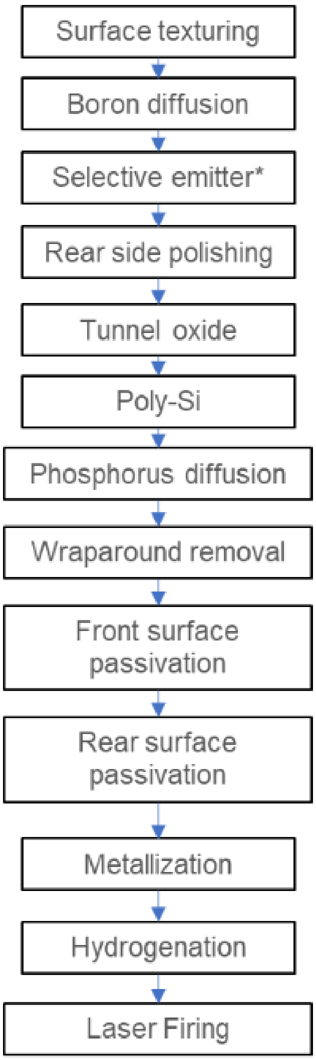

Figure 4 Process steps to manufacture a TOPCON solar cell

2.4 Interdigitated Back Contact (IBC) Solar Cell

The main component featured in most IBC solar cells is a c-Si wafer that acts as the n-type wafer absorber layer, but p-type wafers are also used. Monocrystalline silicon (mono c-Si) is the most common option due to its higher efficiency, but polycrystalline silicon (poly c-Si) can also be used.

An anti-reflective and passivation layer is placed on one of the two sides of the c-Si wafer, being manufactured with a thin layer of silicon dioxide (SiO_2) placed through a thermal oxidation process. Materials like Silicon Nitride (SiNx) or Boron Nitride (BNx) are also suitable.

For IBC solar cells to relocate frontal contacts at the rear side of the cell, they require interspersed or interdigitated layers of n^+ and p^+ emitters called the diffusion layer. To create it, layers of the n-type wafer are doped with boron through masked diffusion, masked ion-implantation, or laser doping, creating the p-type (p^+) digitation, while the n-type layers stay intact (n^+).

Metal contacts are also placed by laser ablation or wet chemical deposition, using regular metals like silver, nickel, or copper for the contacts of the IBC solar cell.

Figure 5 Process steps to manufacture a IBC solar cell

3. Key Process Steps in the Fabrication of Advanced Solar Cells

Modern high-efficiency solar cells such as PERC, TOPCon, IBC, and Heterojunction (HIT) require a series of precise and carefully controlled fabrication steps. Although the specific sequence and materials may vary depending on the cell architecture, many of the core processes are shared across technologies. Below are some of the fundamental manufacturing steps used in the production of these solar cells, along with their purposes and effects on overall device performance.

3.1 SURFACE TEXTURING

Surface texturing, either in combination with an anti-reflection coating or by itself, can also be used to minimize reflection. Any "roughening" of the surface reduces reflection by increasing the chances of reflected light bouncing back onto the surface, rather than out to the surrounding air. Surface texturing can be accomplished in a few ways. A single crystalline substrate can be textured by etching along the faces of the crystal planes. The crystalline structure of silicon results in a surface made up of pyramids if the surface is appropriately aligned with respect to the internal atoms. One such pyramid is illustrated in the drawing below. An electron microscope photograph of a textured silicon surface is shown in the photograph below. This type of texture is called "random pyramid" texture and is commonly used in industry for single crystalline wafers.

The type of surface texturing used is known as "inverted pyramid" texturing. Using this texturing scheme, the pyramids are etched down into the silicon surface rather than etched pointing upwards from the surface. A photograph of such a textured surface is shown below.

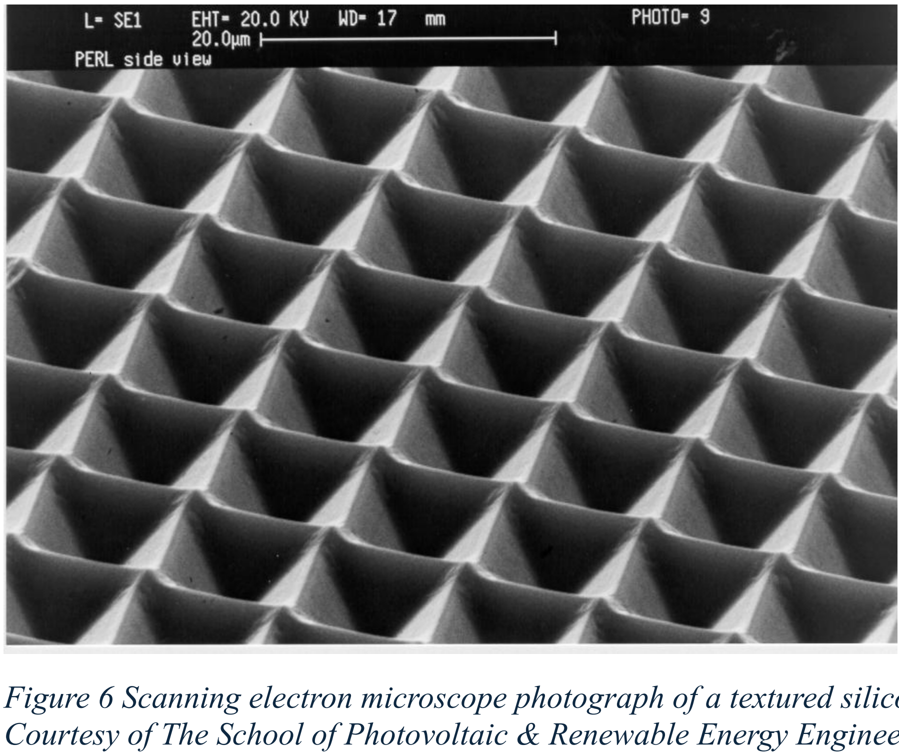

Figure 6 Scanning electron microscope photograph of a textured silicon surface. Image Courtesy of The School of Photovoltaic & Renewable Energy Engineering, University of New South Wales.

Figure 7 Surface texturing process using alkaline solution at ODTÜ GÜNAM.

Surface texturing process observed during my internship at ODTÜ GÜNAM. In this photo, one of the engineers (Rena) is preparing the silicon wafers for the alkaline texturing step, which creates pyramid-like surface structures to enhance light trapping.

3.2 DOPING

Doping is a crucial step in the fabrication of solar cells, as it defines the electrical properties of the semiconductor by introducing controlled amounts of impurities. In silicon solar cells, this process is used to form p-n junctions by introducing donor atoms (such as phosphorus for n-type) or acceptor atoms (such as boron for p-type) into the silicon wafer. The doping process can be carried out through thermal diffusion or ion implantation, depending on the desired junction profile and cell design.

In high-efficiency technologies like TOPCon or SHJ, the doping profile must be precisely optimized to minimize recombination losses and ensure efficient carrier collection. For example, in TOPCon cells, phosphorus diffusion is used to create the front emitter, while the rear side features a passivated contact formed by tunneling oxide and heavily doped polycrystalline silicon. The uniformity, depth, and concentration of dopants are critical parameters that directly influence the open-circuit voltage (Voc), fill factor (FF), and overall cell performance.

During my internship, I observed how phosphorus and boron diffusion recipes were adjusted to achieve higher voltages and lower surface recombination.

Figure 8 Wafer loading before boron diffusion in the quartz tube furnace at ODTÜ GÜNAM.

In this step, boron diffusion was performed to form the p-type region of the solar cell. The wafers were placed in quartz carriers and processed in a high-temperature furnace under controlled atmospheric conditions.

3.3 PASSIVATION

Passivation is a key process in solar cell fabrication that reduces the number of surface defects and minimizes carrier recombination at the silicon interfaces. These surface states can trap charge carriers (electrons and holes), leading to a loss in efficiency. To prevent this, a thin dielectric layer is deposited on the wafer surface to "passivate" the dangling bonds and electrically stabilize the material.

Common passivation materials include silicon nitride (SiNx), aluminum oxide (Al_2O_3), and intrinsic amorphous silicon (i-a-Si:H), depending on the cell type. For example, in PERC cells, Al_2O_3 is typically applied to the rear side for excellent field-effect passivation, followed by a silicon nitride capping layer. In SHJ cells, intrinsic amorphous silicon is used to passivate the crystalline silicon surface before depositing doped layers.

Effective passivation improves open-circuit voltage (Voc), increases carrier lifetime, and significantly boosts overall cell performance. The quality of the passivation is often evaluated through lifetime measurements or photoluminescence imaging.

Plasma Enhanced Chemical Vapor Deposition (PECVD)

PECVD is a widely used technique for depositing thin dielectric films—such as silicon nitride (SiNx) or intrinsic amorphous silicon (i-a-Si:H)—at relatively low temperatures. This process uses plasma to enhance chemical reactions between gas-phase precursors, enabling uniform and conformal coating on the wafer surface.

In solar cell production, PECVD is commonly used for depositing:

SiNx as an anti-reflection and passivation layer in PERC cells,

i-a-Si:H as a passivation layer in SHJ cells,

Or multilayer stacks combining Al_2O_3/SiNx depending on the application.

The plasma environment allows for lower process temperatures compared to traditional CVD, which is especially important for temperature-sensitive cell architecture. Parameters such as gas flow rate, RF power, chamber pressure, and substrate temperature are carefully optimized to ensure high-quality film deposition with excellent passivation properties.

A sole precursor is activated to increase or reduce unusual growth effects on the surface of a substrate when gaseous molecular precursors are placed into the plasma. This process of plasma assisted fabrication for nanomaterials is known as plasma-enhanced chemical vapor deposition (PECVD). In this area, the latent consumption of metal catalyst nanoparticles is also effective. It is also called radio frequency (RF) plasma technique.

Figure 9 PECVD system at GÜNAM

ATOMIC LAYER DEPOSITION (ALD)

Atomic layer deposition (ALD) is a thin-film deposition technique based on the sequential use of a gas-phase chemical process; it is a subclass of chemical vapor deposition. Most ALD reactions use two chemicals called precursors (also called "reactants"). These precursors react with the surface of a material one at a time in a sequential, self-limiting, manner. A thin film is slowly deposited through repeated exposure to separate precursors. ALD is a key process in fabricating semiconductor devices, and part of the set of tools for synthesizing nanomaterials.

The capacity of atomic layer deposition (ALD) to produce thin films that are both uniform and conformal, including dispersed particles ranging from individual atoms to sub-nanometer clusters, has garnered significant interest among researchers in the field of materials science. Atomic Layer Deposition is a mechanical synthesis technique employed to produce catalytic materials. This approach operates in a bottom-up manner, wherein gas-phase deposition occurs within an environment of ultra-high vacuum conditions. ALD is a sequential process that involves several steps. Initially, the initial reactan precursor is introduced into the chemical reaction chamber. Subsequently, the reaction chamber undergoes a purging process to eliminate any surplus reactant. The second precursor of the reactant is put into the chamber, followed by another purging step is carried out to regulate the size and morphology of the material being deposited.

Figure 10 ALD process at GÜNAM

3.4 METALIZATION

Metallization is an important part of silicon wafer processing. It refers to the metal sheets that electrically interconnect the different structures in the device manufactured on the silicon wafer. The most common material used for metallization is thin-film aluminum. It's also considered to be the third major ingredient for IC fabrication. The metallization process enables the formation of electrical contacts on the solar cell to extract and conduct the generated current. The choice of metallization technique significantly influences the cell's resistance, fill factor, and overall efficiency. Below are the main methods used in industry and research environments:

Figure 11 Paste printing step of the metallization process performed via screen printing.

1. **Evaporation of Metal (PVD)**

Metal evaporation is a Physical Vapor Deposition (PVD) technique that involves:

Heating a metal (such as Ag, Al, Ti) until it vaporizes.

Transferring metal atoms into a high-vacuum environment toward the wafer surface.

Allowing those atoms to condense and form a uniform metal film.

There are several heating methods for metal evaporation:

Thermal evaporation (resistive heating)

Electron-beam (e-beam) evaporation

Laser-induced evaporation

This method ensures precise control over metal thickness and purity and is commonly used in high-efficiency cells like IBC and HIT, especially for back contacts.

Not suitable for mass production due to its high cost, complex equipment, and low throughput.

2. **Alternative Printings**

Alternative printing methods are developed to overcome the limitations of screen printing and reduce metal paste usage. These include:

Parallel Dispensing: A contactless method where metal paste is dispensed through a nozzle, achieving homogeneous lines without mesh marks.

Rotary Printing: Uses a rotary screen with higher line speed (up to 160 m/min) and better pattern control; ideal for mass production.

Laser Transfer Printing (LTP): Transfers metal from a donor layer to the substrate using a focused laser beam. Enables high-resolution, contactless, and structured metallization. Suitable for metals in solid, liquid, or paste forms.

These techniques are especially attractive for fine-line printing, reducing shading losses and improving the aesthetics and efficiency of the cell.

3. **Screen Printing**

Screen printing is the most widely used method in industrial solar cell production. It involves:

Applying silver (Ag) paste to the front side of the cell to form fingers and busbars.

Applying aluminum (Al) paste to the rear side for the back contact (and BSF formation in PERC).

Using a screen mesh and squeegee to transfer the paste pattern onto the wafer.

After printing:

The wafer is dried to remove solvents,

Then passed through a firing furnace, where metal-silicon contact is formed by sintering.

Screen printing is reliable, low-cost, and suitable for mass production — especially in PERC, Al-BSF, and bifacial cell types.

4. **Plating**

Plating involves electrochemical deposition of metals, often used in plated PERC, TOPCon, and advanced selective emitter cells.

Process:

First, the passivation layer is opened using laser ablation (Laser Contact Opening - LCO).

Then, nickel (Ni) is deposited as a seed layer for adhesion and barrier function.

Copper (Cu) is plated over Ni for conductivity. Optionally, a silver (Ag) capping layer is added for corrosion resistance.

This method is gaining popularity for next-generation, high-efficiency cells due to its superior electrical characteristics and cost advantages over time. As solar cell architectures evolve, metallization techniques are being optimized to reduce resistive losses, improve contact quality, and minimize material usage while maintaining compatibility with large-scale production.

5. Laser Contact Opening (LCO)

Laser Contact Opening (LCO) is a laser-based technique used to selectively remove dielectric passivation layers—such as silicon nitride (SiNx) or aluminum oxide (Al_2O_3)—from specific regions of the solar cell surface. This step is essential for creating openings where the metal contacts can directly interface with the silicon wafer during the metallization process.

How it works:

A pulsed laser beam (typically in the nanosecond or picosecond range) is focused on the wafer surface. The laser locally ablates the dielectric layer without significantly damaging the underlying silicon. Openings are formed with high precision, allowing for selective metal deposition via plating or printing.

Where it's used:

In PERC cells: LCO is applied to the rear side to open the Al_2O_3/SiNx stack before aluminum contact formation. In plated PERC, TOPCon, and IBC structures: LCO allows for selective Ni/Cu/Ag plating only where needed. In selective emitter technologies: LCO may also define doped and non-doped zones.

During my internship, I had the chance to observe LCO performed using UV laser systems. The process was optimized to achieve clean contact openings on the rear side of PERC cells before aluminum metallization.

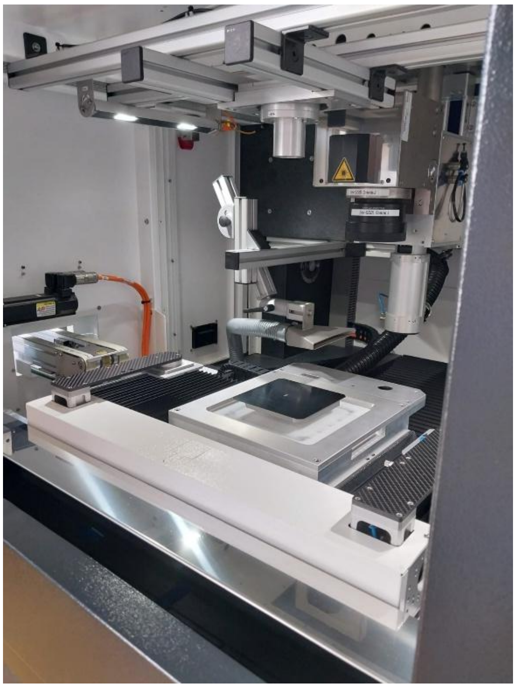

Figure 12 Laser Contact Opening (LCO) system used to remove rear-side passivation layers before metallization

4. Firing and Electrical Measurements

Firing

Firing is the thermal process used to sinter the metal pastes (typically silver and aluminum) that were applied during the screen-printing step, forming ohmic contacts between the metal and the silicon surface. It is the final process in solar cell fabrication before testing and packaging and plays a crucial role in determining the electrical performance of the cell.

The firing process is typically performed in a belt furnace with multiple heating zones, where the wafers are exposed to temperatures ranging between 750–900 °C for a very short time (few seconds). This short, high-temperature exposure activates the metal paste, drives the contact formation reactions, and burns off organic binders from the paste.

Figure 13 Industrial fast-firing at oven tool

After the firing process, solar cells undergo electrical testing and characterization to evaluate their performance and quality. Several advanced tools and techniques are used to measure parameters such as efficiency, open-circuit voltage (Voc), short-circuit current (Isc), fill factor (FF), and series/shunt resistance. These tests help verify the effectiveness of each fabrication step and identify any defects or performance losses before module integration.

At ODTÜ GÜNAM, I had the chance to work with tools such as IV testers, photoluminescence imaging systems, and lifetime measurement setups for solar cell characterization.

Figure 14 Sinton SunsVoc tool

Minority carrier lifetime is a key indicator of solar cell quality, as it reflects how long charge carriers can exist before recombining. The Sinton to evaluate the effective lifetime, implied open-circuit voltage (Voc), and recombination behavior of silicon wafers. Measurements can be made at different injection levels, helping determine both bulk and surface recombination effects. This tool is especially useful in characterizing passivation layers applied after diffusion or PECVD processes.

Figure 15 The PLI system is used to detect defects in silicon wafers or solar cells.

Photoluminescence Imaging (PLI) is a powerful, contactless technique used to assess the internal quality of silicon wafers and solar cells by visualizing carrier recombination behavior. The SEMILAB PLI-1001 system captures spatial variations in photoluminescence emitted from the sample after laser excitation.

When the silicon wafer is illuminated by a laser, electron-hole pairs are generated. The subsequent radiative recombination leads to light emission (photoluminescence), which is captured by a sensitive camera. The intensity and distribution of the emitted light provide valuable information about:

Minority carrier lifetime variations

Surface and bulk recombination defects

Crystalline defects

Process-induced non-uniformities (e.g., poor passivation, contamination, etc.) This tool is particularly useful for early defect detection and process monitoring without needing full device processing.

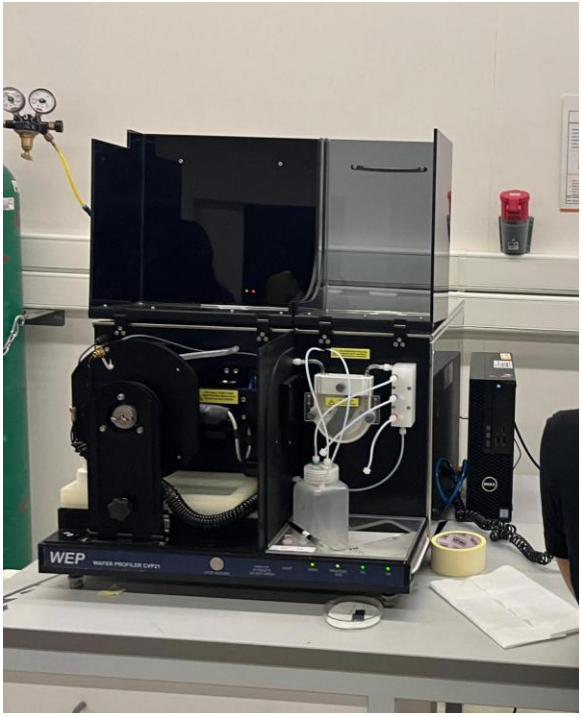

Figure 16 Wafer profiler system for surface flatness and film thickness measurements

The WEP CVP21 Wafer Profiler is used to measure the surface profile, film thickness uniformity, and overall flatness of silicon wafers. It plays an important role in quality control and post-deposition inspection steps of solar cell manufacturing. Using non-contact optical and mechanical sensors, the system can detect: Layer thickness variations after deposition (e.g., SiNx, Al_2O_3) Warpage and bowing of the wafer, Surface defects or irregularities, Edge exclusion and step height differences. Precise surface profiling ensures that layers are uniform and conformal, which directly impacts the optical and electrical performance of the solar cell.

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