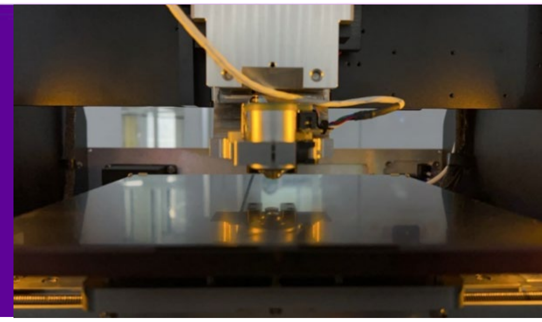
Application Note

KLA INSTRUMENTS

Sheet Resistance Measurement on TOPCon Solar Cells

Filmetrics® R54 Series



Introduction

As countries around the world strive to reduce their carbon footprints and seek sustainable energy resources, the solar energy industry has experienced significant growth. Among the diverse process routes based on crystalline silicon (c-Si), the Tunnel Oxide Passivated contact Solar Cells (TOPCon)[1] stands out because of its high photovoltaic conversion efficiency (PCE) balanced with affordable cost. The highest PCE of industrial TOPCon cells has reached 25.42%[1], which is close to the theoretical limit around 29%[2]. The pursuit of higher PCE poses new challenges in process control as well as monitoring.

Similar to other c-Si solar cell processes, monitoring the doping level is critical in controlling TOPCon process quality, since solar cell performance depends on the careful balance between conductivity, contact resistance and recombination rate, which are all highly manipulated by the doping level. Several test methods such as carrier lifetime measurement and photoluminescence imaging convert microwave or optical signals to carrier density information. However, these indirect testing methods require complex calibration and are easily affected by external interference. In contrast, four-point probe (4PP) sheet resistance (Rs) measurement can provide direct electrical properties like carrier mobility and contact resistance, which makes it an indispensable monitoring term in the TOPCon process.

Since the first four-point probe (4PP) system released in 1984, KLA has been a leader in resistivity measurement innovation, whose Rs measurement systems are widely recognized in the semiconductor industry. The KLA Instruments™ Filmetrics® R54 sheet resistance mapping system is a benchtop Rs system equipped with the latest KLA Rs test probes and measuring circuits. This work introduces the 4PP measurement technique and describes the current TOPCon solar cell process. The Rs data collected from several TOPCon processes demonstrates that the R54 is an excellent solution for TOPCon process monitoring.

[1] JinkoSolar's open data in 2024.6.

4-Point Probe Measurement on Solar Cells

The 4PP technique has maintained popularity for more than 100 years due to its basic simplicity and inherent accuracy. In a four-point probe measurement, electrical current is passed between two pins in contact with a conductive surface while the voltage is measured between two additional pins also in contact with the surface, as shown in Figure 1. The standard measurement configuration at left covers applications where the test area is away from the sample edge. For measurements taken near the sample edge, an extra measurement with the alternate configuration at right may be used as part of the Dual Configuration method. This dual method eliminates the edge effect by adding a calibration coefficient based on the resistance R_A and R_B obtained by the two configurations.

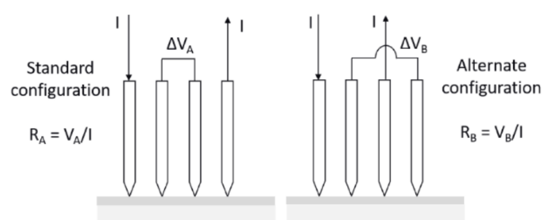


Figure 1. Four-point probe pin schematic for both the standard (left) and alternate (right) linear configurations.

Besides the common 4PP configuration, the R54 is also equipped with several key features that give it significant advantages in testing solar cells, including:

- An opaque measuring chamber (Figure 2, left) eliminates the generation of photocurrent.
- Specially-designed square chuck (Figure 2, right) for holding square-shaped solar samples.
- Compatible with all KLA sheet resistance probes.
- Auto current adjustment according to a target voltage.
- Dynamic correction for edge effects and tip geometry.

Figure 2. The R54 sheet resistance mapping system (left); and the square chuck designed for solar cell applications (right).

TOPCon Solar Cell Structure and Process

TOPCon solar cells are crafted from n-doped silicon and contain multiple layer structures on both front and rear sides, as shown in Figure 3. On the front side, the p-type emitter is fabricated on the textured Si surface to facilitate the collection of photo-generating carriers; the emitter layer is covered by a composite passivation layer that reduces the recombination rate; the front surface is then topped with a SiN_x anti-reflective (AR) layer and metal electrodes. On the rear side, the TOPCon solar cell uses a SiO_x/n-poly silicon passivation layer, which favors one type of carrier to tunnel and blocks the other one. This passivation layer reduces the interface recombination rate and raises the open circuit voltage, resulting in improvement of efficiency.

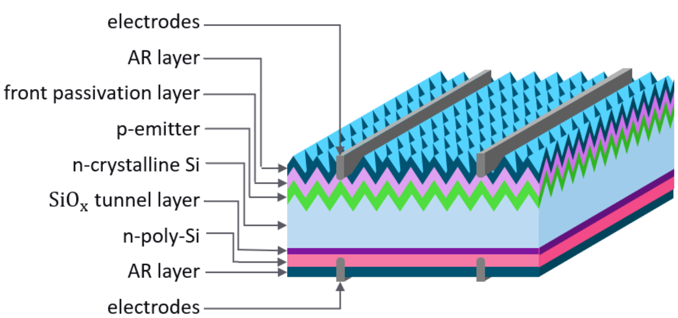


Figure 3. Structure of a TOPCon solar cell.

Figure 4 shows an up-to-date TOPCon process flow. Crystalline n-doped silicon wafers are first alkali-textured to form pyramid structures on the front surface, then a boron emitter is created to construct a p-n junction with the n-doped substrate. A subsequent oxidation process drives in the boron atoms and adjusts the junction depth. The rear surface of the wafer is then etched by hydrofluoric acid and alkali sequentially to obtain a flat Si interface. After cleaning the residue, a thin oxide (SiO_x) tunnel layer is thermally grown on the rear surface, followed by a phosphorus-diffused polycrystalline silicon that serves as the passivation layer. The fabrication of the rear surface passivated contact is finished by an annealing process that heats up the wafer so that the impurities redistribute to a stable state and harmful ions like sodium and potassium are fixed. The remaining steps in the TOPCon process are similar to that in passivated emitter and rear contact (PERC) or other c-Si based solar cell processes: buffered oxide etch (BOE) cleaning removes the oxidation layers and exposes the fresh silicon surface on both sides of the wafer, then the front passivation layer and AR layer are coated sequentially. The process flow is finished with front surface metallization. Laser pulses assist the silver contacts sintering and create a highly doped region to obtain lower contact resistance. This procedure is known as laser-enhanced contact optimization (LECO).

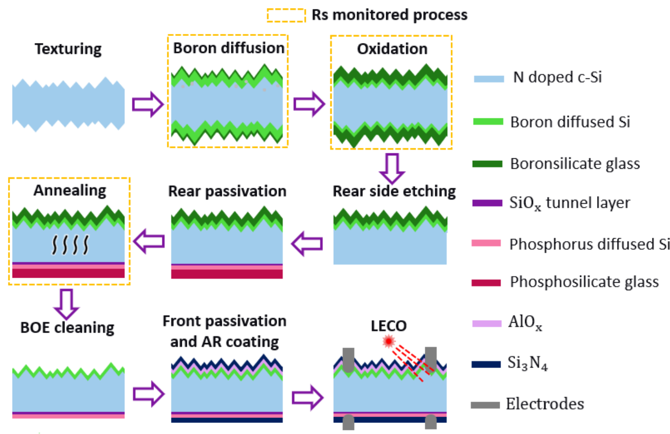


Figure 4. Process flow of TOPCon solar cell.

Rs Monitoring using the Filmetrics R54

In a TOPCon production line, boron diffusion, oxidation and annealing either involve direct doping processes or thermal treatment that can change the doping level of the samples, so precise Rs monitoring is essential. The KLA Instruments Filmetrics R54 sheet resistance mapping system has proven to be fully capable for Rs monitoring in these three processes.

Rs Mapping of TOPCon Solar Cells

Rs mapping is a direct way to provide spatially-resolved information about the uniformity of dopant diffusion. By mapping Rs across the entire wafer, the manufacturers can identify doping level inconsistency, defects, or unexpected wrap coating.

The R54 delivers customizable test patterns within a maximum measurement size of 200mm x 200mm. Figure 5 displays three 225-point Rs maps of a TOPCon cell after boron diffusion, oxidation and annealing processes. The testing probe penetrates the surface oxidation layer for accurate Rs measurement. Rs distribution data for the boron diffusion and oxidation processes is more variable than that of the annealing process due to the more complex doping process of boron compared to phosphorus.

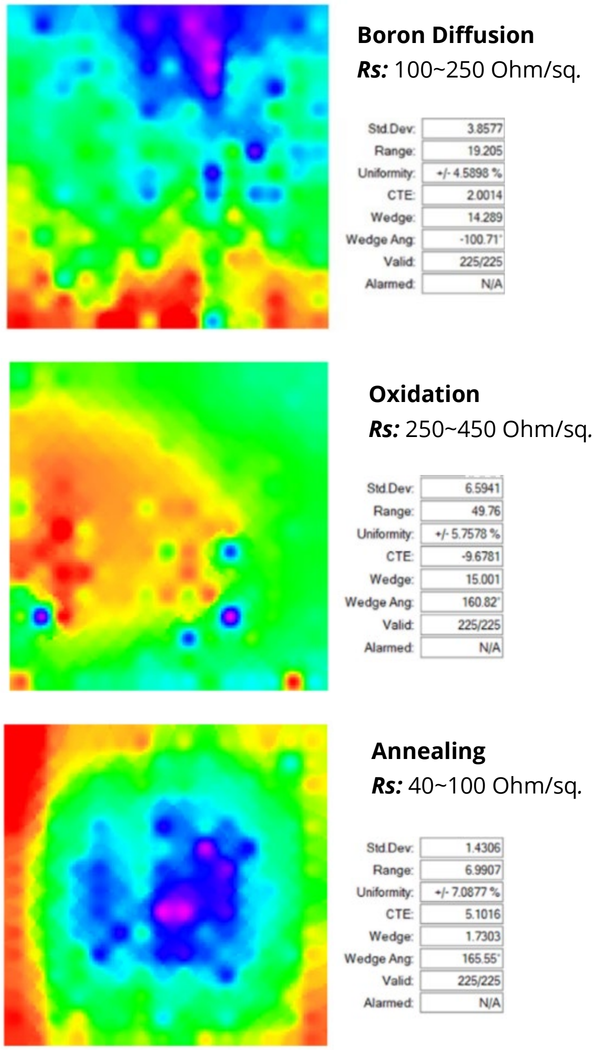


Figure 5. 225-point sheet resistance maps of boron diffusion (top), oxidation (center) and annealing (bottom) processes.

The R54 software interface displays statistical results once the Rs mapping has completed. Rs mean value and uniformity are the two most important values in process control. The uniformity is defined as (max Rs – min Rs)/(2*mean Rs), which is the common definition adopted by the solar industry.

Reliability of Rs Measurements

Most TOPCon production lines included integrated in-line Rs monitoring tools, which require a highly accurate and stable off-line Rs golden tool to ensure precise calibration and matching of all in-line Rs monitors. The Filmetrics R54 is one of the most competitive Rs golden tools for the solar industry, and whose Rs test reliability has been confirmed by testing repeatability and long-term stability.

To assess Rs measurement repeatability, a comprehensive evaluation was conducted using 10 wafers measured for each process. Each wafer was mapped 10 times to calculate the wafer average Rs, with the repeatability indicated by the standard deviation of wafer average Rs values (refer to the zoom-in view of Figure 5.a). As shown in Figure 5, the repeatability values on boron diffusion wafers (Figure 5.a) are below 0.5% of the average Rs. As for oxidation(Figure 5.b) and annealing wafers(Figure 5.c), the repeatability are all below 0.3% of the average Rs. Both values are far below the monitor threshold of the processes.

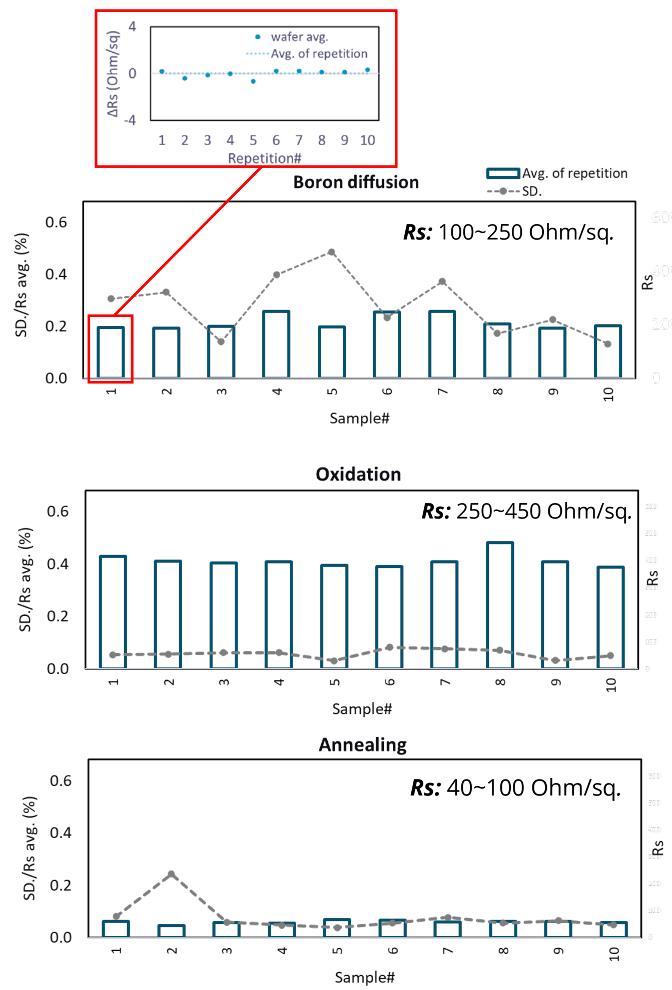


Figure 6. Repeatability of measured sheet resistance on ten wafers for boron diffusion (top), oxidation (center), and annealing (bottom). The inset in the top graph shows the Rs variation for a 10x measurement.

For the demonstration of long-term stability, Rs monitoring of the three different processes was conducted for a four-week period. The Rs values were tested once every two weeks, and the results are shown in Figure 7. For the five samples selected from each of the three processes, the Rs variation over the four-week period measured < 1% of the wafer average, indicating stable long-term performance within the expected range of the samples' natural Rs fluctuation. The repeatability and long-term variation data are summarized in Table 1.

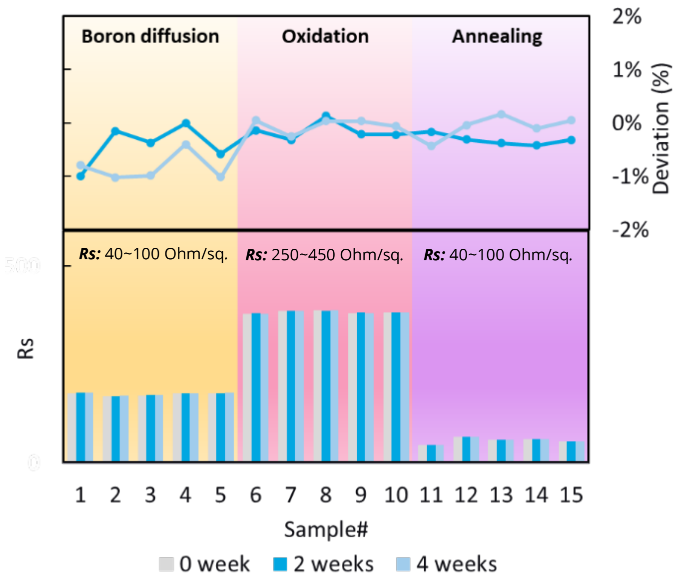


Figure 7. Long-term stability of Rs on five samples of each of the three processes, measured over a four-week period.

Table 1. Repeatability and long-term variation in different processes

Process	Repeatability	Long-term variation
Boron diffusion	0.3%	1.0%
Oxidation	0.1%	0.2%
Annealing	0.1%	0.1%

Conclusion

Because TOPCon technology is extending the boundaries of c-Si photovoltaic efficiency, precise sheet resistance monitoring is crucial for high quality process control. The KLA Instruments™ Filmetrics® R54 system provides comprehensive sheet resistance mapping with outstanding repeatability and long-term stability. With the solar cell chuck, the R54 is fully capable of TOPCon solar cell sheet resistance measurement with performance validated for actual production processes.

References

[1] F. Feldmann, M. Bivour, C. Reichel, M. Hermle, and S. W. Glunz, "Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics," *Solar Energy Materials and Solar Cells*, vol. 120, pp. 270–274, Jan. 2014.

[2] A. Richter, M. Hermle, and S. W. Glunz, "Reassessment of the Limiting Efficiency for Crystalline Silicon Solar Cells," *IEEE J. Photovoltaics*, vol. 3, no. 4, pp. 1184–1191, Oct. 2013.

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