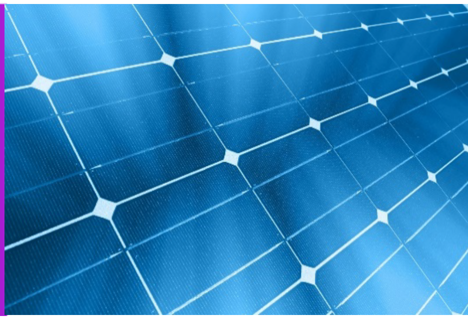
KLA INSTRUMENTS

Solar Cell Metrology Solutions

KLA Instruments™ Zeta™ Optical Profilers



Introduction

Solar energy is widely used as the power source for lighting, heating, pumping, satellites, and small devices such as calculators. Solar cells, mostly made from mono silicon or polysilicon disks, are the basic units that directly convert sunlight into electricity through the photovoltaic effect.

A series of manufacturing processes is required to produce a solar cell from a silicon ingot, including wafer dicing, texturing, acid cleaning, diffusion, etching, anti-reflective coating deposition, laser grooving, contact printing, etc. Figure 1 shows measurement points during the process flow, including diamond wire topography, wafer bow/roughness/roll-off, solar texture characterization, anti-reflective coating thickness and reflectance, and the topography of laser grooves, solar fingers and busbars. Quality control of each process is crucial because small manufacturing errors can adversely affect the overall efficiency of the cells.

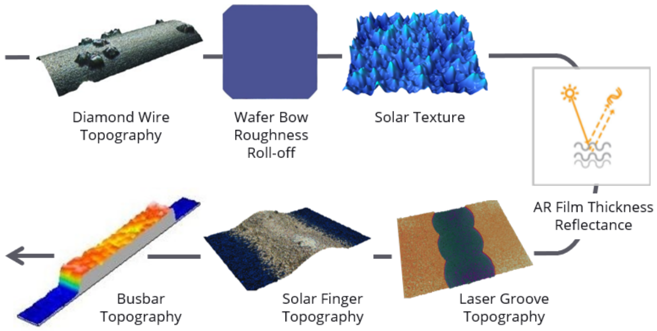


Figure 1. The solar cell manufacturing process flow showing multiple points for process monitoring metrology, including diamond wire topography, wafer bow/roughness/roll-off, solar texture characterization, anti-reflective coating thickness and reflectance, and the topography of laser grooves, solar fingers and busbars.

The Zeta™ 3D optical profiler is widely used throughout the solar cell production process: (i) inspection of the diamond wire used for silicon wafer dicing; (ii) quantification of surface roughness, wafer bow, and roll-off of the sliced silicon wafers; (iii) measurement of the post-texture height, size and pitch of the texture pyramid structure, as well as the surface area ratio using Zeta solar texture recipes; (iv) measurement of the anti-reflectance coating film thickness as well as the absolute reflectance using the Zeta ZFT technique; (v) characterization of the laser grooving for Ag printing; and (vi) measurement of the height, width, area, and volume of the contact printed structures (solar finger and busbar) using Zeta solar finger recipes. This application note focuses primarily on Zeta measurements and analysis of solar texture, laser grooving, solar fingers, and busbars.

The Zeta 3D optical profiler provides 3D imaging and metrology capabilities in a flexible, cost-effective package. The KLA Instruments proprietary ZDot™ technology enables rapid True Color imaging and quantitative analysis of surfaces for off-line product inspection. The Zeta system includes special recipes for solar cell applications that automatically measure step height, width, surface area, feature volume and roughness across multiple sites, making it a reliable and efficient technique for solar cell manufacturing process monitoring and optimization. The Zeta 3D optical profiler's advantages are its non-destructive measurement technique, as compared to a Scanning Electron Microscope (SEM), much higher throughput as compared to an Atomic Force Microscope (AFM), and fully-automatic analysis ability specifically for solar cell applications.

Theory of Operation

The Zeta optical profiler is a fully-integrated microscope-based system that uses ZDot technology to provide 3D imaging and metrology capability. As shown in Figure 2, the Zeta includes two high-intensity white LED light sources. Light from Source 1 passes through the ZDot grid and generates each pixel's contrast peak Z position, while light from Source 2 preserves the sample's True Color information for each pixel. After scanning in the vertical direction, the software combines the Z information with the True Color data to form a 3D True Color image, which can be used to quantify the dimensional roughness and color information all in one plot.

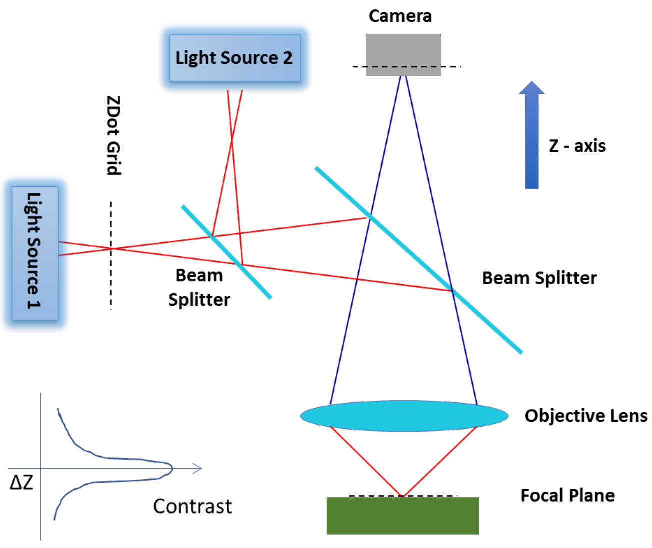


Figure 2. Schematic diagram of ZDot™ technology

The Zeta software has powerful automatic analysis algorithms specifically for solar cell characterization. It can calculate the pyramid size and height in the field of view and display the statistics. It can also automatically measure the solar finger height, width, and volume, and can measure the much wider busbar structures that span multiple fields of view using automatic image stitching.

Solar Texture Analysis

Pyramid structures are etched on the wafer surface to maximize solar cell light absorption by reducing reflectance. These structures can be easily characterized using a custom Zeta recipe that automatically measures, counts, and analyzes the texture, reporting the information shown in Figure 3:

- Histogram of pyramid size
- Histogram of pyramid height
- 2D and 3D True Color images
- Statistics of pyramid size, height, count and surface area ratio

Different algorithms were developed to analyze the different cell textures specific to mono silicon and polysilicon wafers, as shown in Figure 4. For the mono silicon pyramidal texture, the software detects the apex of each pyramid and calculates the height, size, counts, and surface area of the pyramids within the field of view. For the polysilicon pyramids, the software detects the boundary of the textures and performs statistical calculations accordingly.

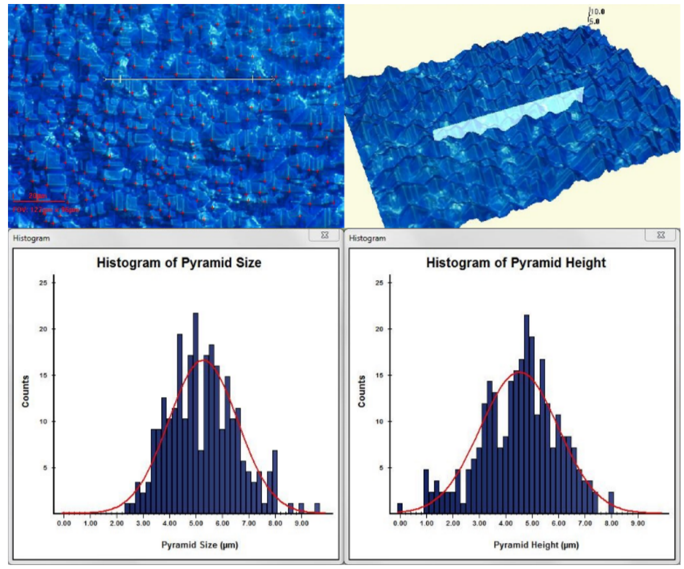


Figure 3. Pyramid analysis window, showing: 2D image with automated pyramid peak location identification and profile location (top left); 3D image of the textured mono silicon (top right); and histograms of pyramid size and height (bottom), where the red curves represent the fit to the data.

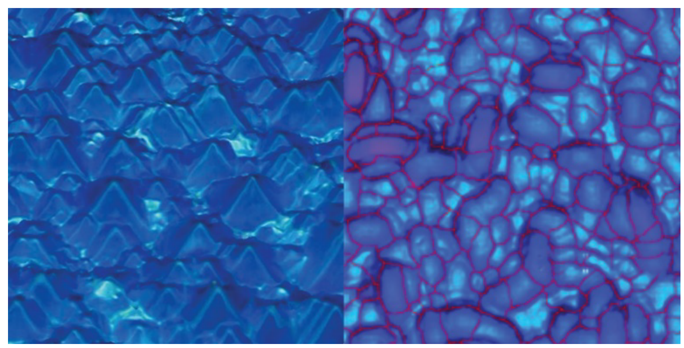


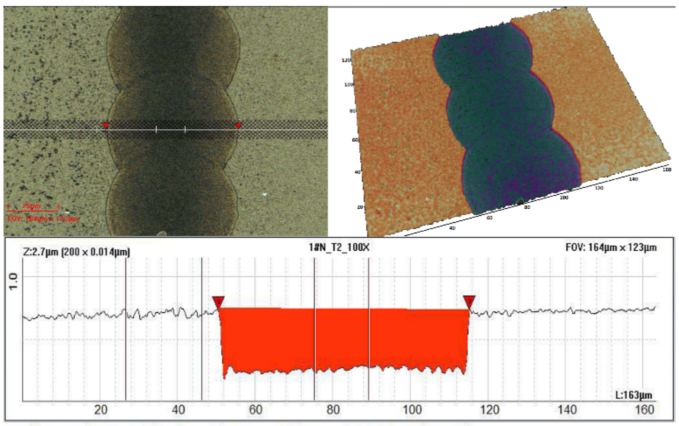
Figure 4. Textures on mono silicon (left) and polysilicon (right). For the polysilicon, the detected boundaries of the structures are highlighted.

Production line metrology usually requires measuring multiple sites to check the uniformity of the product. By defining a Zeta measurement sequence, the measurement and analysis can be automatically repeated for multiple sites across the solar cell.

Laser Groove Metrology

The laser-grooved buried contact is widely used in solar cell production to provide a base structure onto which metal lines are printed. In this process, the grooves are laser scribed through both the anti-reflection layer and the shallow emitter of a textured Si wafer. After the etching process to reduce laser-induced damage, the grooves are printed with Ag metal to make solar fingers.

The Zeta optical profiler can be used to monitor the laser groove process by measuring the width and depth of the laser grooves, as shown in Figure 5. After scanning with the ZDot technique, a 3D image of the laser groove is obtained, and the depth and with of the laser groove can be further calculated from the 2D cross-section. The **Feature Find** recipe function can also be applied to the 3D image to automatically determine the edge of the laser groove and to report the depth and width, making the Zeta optical profiler a fast and non-destructive tool for laser groove metrology.



	Cursor Left		Cursor Right		Cursor L-R			Markers 1-2		
	Avg Ht	Width	Avg Ht	Width	Step	Dist	Angle	Step	Dist	Area
1	0.7054	19.61	0.2628	13.98	-0.4425	45.78	-0.5539	-0.0448	64.72	-30.78

Figure 5. Laser groove analysis: (a) 2D image; (b) 3D image; (c) 2D cross-section analysis results. For the 2D and 3D images, the wide line across the structure defines the area over which the average trench width is calculated.

Solar Finger Characterization

Solar fingers are used for conducting the electrical energy generated in the texture region to the busbars, which in turn conduct the energy to the edge of the wafer to reach external circuits. Solar fingers are commonly made of costly silver, and the geometry should be optimized to ensure good conductivity as well as low cost by minimizing the amount of Ag used. Accurate measurement of the Ag lines by the Zeta 3D optical profiler enables that optimization to be achieved.

3D imaging of a metallic surface on the nitride-textured background is not easy. Solar fingers have very high reflectivity, while the adjoining nitride regions have extremely low (< 5%) reflectivity. Imaging such a surface in a single scan requires the optical metrology system to have a large dynamic range. Zeta's high dynamic range (HDR) imaging system enables precision 3D profiling of the highly-reflective metal fingers on the very dark (non-reflective) textured surfaces, as shown in Figure 6. After the scan, the appropriate light level is determined for each pixel to form the final image. Critical parameters such as line width, height and volume are automatically calculated based on this high-quality 3D image.

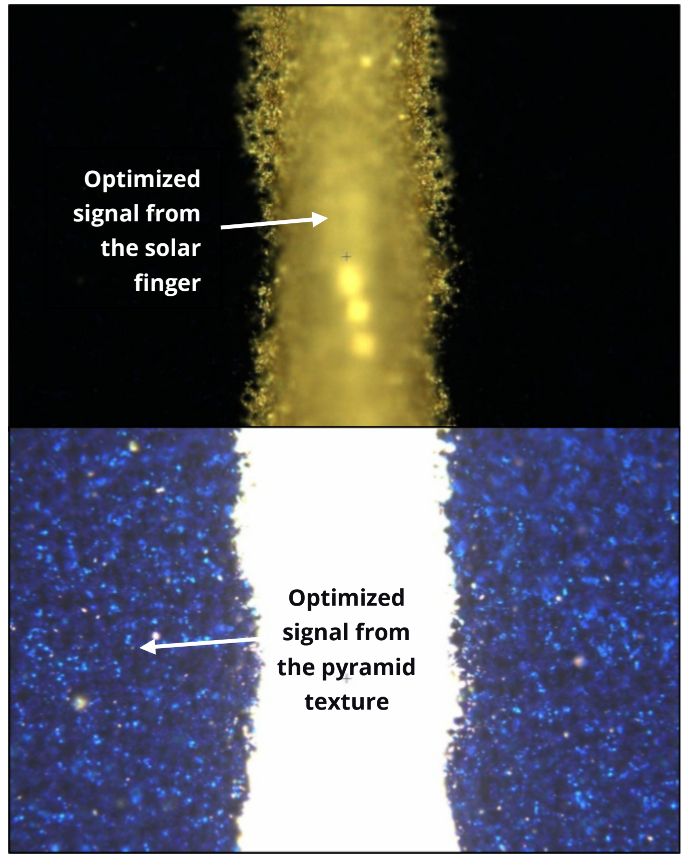
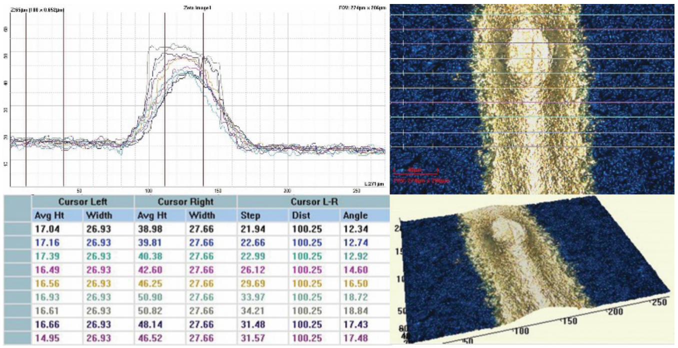


Figure 6. HDR imaging: low-intensity light is applied to generate effective signal from the high-reflectance solar finger (top); high-intensity light is applied to generate effective signal from the low-reflectance pyramid structure (bottom).

The Zeta solar finger recipe automatically measures and analyzes the solar finger: the solar cell surface is first detected via auto-focus, the solar finger is then located using pattern matching, the solar finger is then centered in the field of view, followed by 3D data collection using the HDR method, as shown in Figure 7. Finally, the recipe automatically calculates the individual and statistical average of the height and width of multiple cross sections, returning the following parameters:

- Average height of the solar finger
- Average width of the solar finger
- Area of the solar finger
- Volume of the solar finger

The Zeta recipe pattern match is an advanced function to ensure fully-automatic measurements. The operator doesn't need to manually move the solar finger into the field of view; instead, the system searches the vicinity for the solar finger based on a pre-defined pattern, and, when located and automatically centered, measures and analyzes the solar finger.

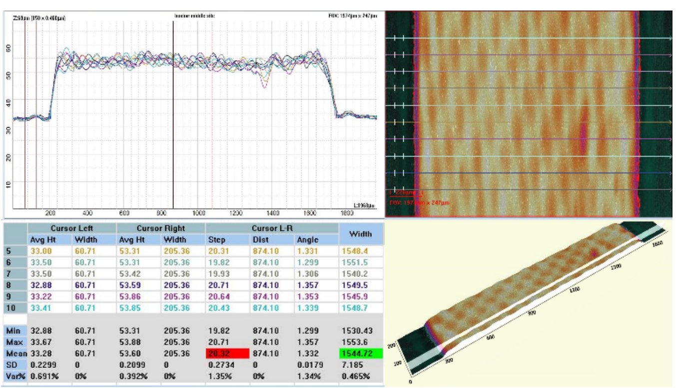


	Cursor Left		Cursor Right		Cursor L-R		
	Avg Ht	Width	Avg Ht	Width	Step	Dist	Angle
	17.04	26.93	38.98	27.66	21.94	100.25	12.34
	17.16	26.93	39.81	27.66	22.66	100.25	12.74
	17.39	26.93	40.38	27.66	22.99	100.25	12.92
	16.49	26.93	42.60	27.66	26.12	100.25	14.60
	16.56	26.93	46.25	27.66	29.69	100.25	16.50
	16.93	26.93	50.90	27.66	33.97	100.25	18.72
	16.61	26.93	50.82	27.66	34.21	100.25	18.84
	16.66	26.93	48.14	27.66	31.48	100.25	17.43
	14.95	26.93	46.52	27.66	31.57	100.25	17.48

Figure 7. Solar finger analysis: 2D cross-section profiles (top left), 2D image with cross-section locations (top right), 2D cross-section results (bottom left), and 3D image (bottom right).

Solar Busbar Characterization

In contrast to the solar finger, which is usually < 100µm wide, the solar busbar is a much larger structure; typically 1500µm wide. The Zeta optical profiler utilizes automatic image stitching technology to measure the entire busbar. The width and height are calculated automatically, as shown in Figure 8, and the results can be automatically saved as *.txt or *.csv files.



	Cursor Left		Cursor Right		Cursor L-R			Width
	Avg Ht	Width	Avg Ht	Width	Step	Dist	Angle	
5	33.00	60.71	53.31	205.36	20.31	874.10	1.331	1548.4
6	33.50	60.71	53.31	205.36	19.82	874.10	1.299	1551.5
7	33.50	60.71	53.42	205.36	19.93	874.10	1.306	1540.2
8	32.88	60.71	53.59	205.36	20.71	874.10	1.357	1549.5
9	33.22	60.71	53.86	205.36	20.64	874.10	1.353	1545.9
10	33.41	60.71	53.85	205.36	20.43	874.10	1.339	1548.7
Min	32.88	60.71	53.31	205.36	19.82	874.10	1.299	1530.43
Max	33.67	60.71	53.88	205.36	20.71	874.10	1.357	1553.6
Mean	33.28	60.71	53.60	205.36	20.32	874.10	1.332	1544.72
SD	0.2299	0	0.2099	0	0.2734	0	0.0179	7.185
Var%	0.691%	0%	0.392%	0%	1.35%	0%	1.34%	0.465%

Figure 8. Solar busbar analysis: 2D cross-section profiles (top left), 2D image with cross-section locations (top right), 2D cross-section results (bottom left), and 3D image comprising automatically-stitched images (bottom right).

Other Solar-Related Applications

The Zeta optical profiler is a general metrology tool that can also be used to characterize silicon wafers during the initial steps of solar cell processing. The roughness of the silicon wafers can be measured with ZDot mode and Phase Shifting Interferometry (PSI) mode to calculate both 2D and 3D roughness of unpolished silicon wafers. Figure 9 shows a top-down image of an unpolished silicon wafer where the rectangle defines the area for surface roughness calculation. Figure 10 shows the measurement of bow across a silicon wafer.

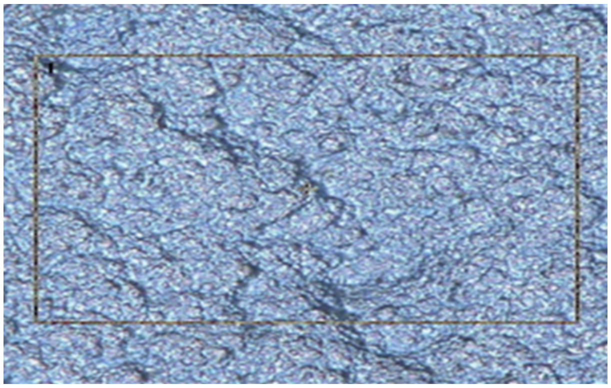


Figure 9. Image of an unpolished silicon wafer for areal roughness analysis. The user-specified rectangle defines the area used for calculation.

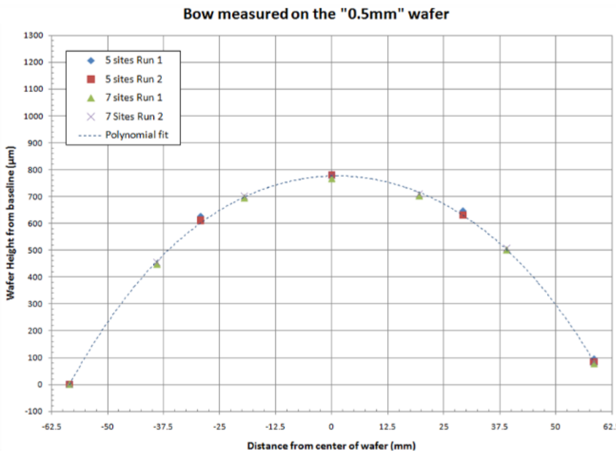


Figure 10. The 2D wafer bow measurement result quantifies the height variation across a silicon wafer.

Conclusions

The Zeta optical profiler is a flexible and accurate tool for non-destructive and high-throughput measurement of solar cells. With ZDot technology, HDR capability and specialized algorithms and recipes, the Zeta optical profiler can perform an automatic and comprehensive characterization of solar cell texture, laser grooves, solar fingers, and solar busbars. The Zeta systems include solar industry-specific recipes to quantify the key geometrical features of the solar cell, allowing process engineers to optimize their fabrication processes and quality control engineers to monitor the results to produce the most cost-effective and high-performing solar cells.

KLA SUPPORT

Maintaining system productivity is an integral part of KLA's yield optimization solution. Efforts in this area include system maintenance, global supply chain management, cost reduction and obsolescence mitigation, system relocation, performance and productivity enhancements, and certified tool resale.

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