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Precision Surface Metrology Enables Solar Efficiency Gains

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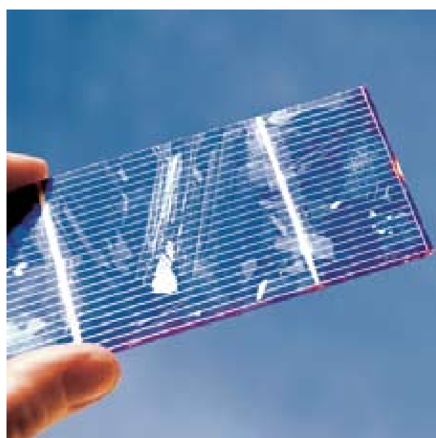


INTRODUCTION

The solar energy industry is experiencing rapid growth due to many factors, including record oil prices and the worldwide desire to reduce greenhouse gas emissions. World energy consumption is expected to double by 2050, and production of solar cells is currently rising at more than 40% annually. As with any industry, the key driver for commercial success is the overall cost to the consumer. For solar cell manufacturers, this key driver is the cost per kilowatt-hour for electricity. This cost will only go down if solar cell material quality and efficiency continue to evolve.

Currently, multiple photovoltaic technologies are competing for share in the growing solar market. Traditional solar cells are made of crystalline silicon, and remain the bulk of worldwide production. Amorphous silicon films, which can produce lighter, more configurable, but generally less efficient cells, are gaining share for production of solar cells. Also, new materials are being used to create solar cells at lower cost (such as CuInGaSe2 or CIGS) and higher efficiency (III/V compounds) than traditional crystalline solar PV cells. Each of these technologies has advantages and disadvantages over the others, but all share the need for precision surface metrology for quality control. The rapid, accurate, and versatile metrology solutions offered by Veeco's stylus and optical profilers are being utilized by many solar cell manufacturers to increase yield and lower the overall production cost of solar cells through quantification, qualification, or monitoring of various process steps.

ROUGHNESS CHARACTERIZATION FOR PROCESS CONTROL

Roughness is one of the critical surface parameters affecting solar cell efficiency. Solar materials that are slightly rough trap more light than perfectly smooth surfaces, thus they achieve greater output in similar light conditions. However, surfaces that are too rough can lose efficiency through excessive scattering and less absorption. On the other hand, glass or plastic encapsulating materials are made as smooth as possible so that a minimum amount of light is absorbed and scattered at the interfaces.

Both Dektak® stylus profilers and Wyko® optical profilers enjoy extensive use in roughness measurement applications. With sub-nanometer vertical resolution and measurement times of no more than a few seconds, Wyko optical profilers are one of the most common area-based tools for quantifying roughness in production

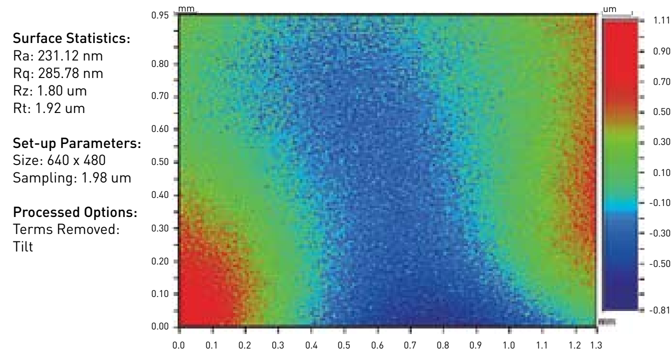
and in quality assurance laboratories. Figure 1 shows characterization of a solar cell, where shape, micro-roughness, and the slope of several scratches present on the surface can all be evaluated with great accuracy from the same measurement.

Stylus profilers are also commonly used in these applications to provide rapid roughness characterization across long traces. With scan lengths up to 200 millimeters, roughness across large regions of surfaces can be obtained, again with sub-nanometer vertical resolution. Single traces can be combined to form large, area-based measurements as well. Figure 2 shows a Dektak scan across a glass substrate, and subsequent analysis through Veeco's Vision® software package, which can analyze both Dektak stylus and Wyko optical measurement results. Sub-nanometer roughness is easily seen over this 1-millimeter trace. Substrate quality can be automatically passed/failed in a database using basic roughness calculations, histogram information of the height, spatial frequency analysis to detect polishing marks, and with many other potential calculations. This flexibility allows the most critical process control parameters to be determined, measured, and reported for quality control and maximum gains in efficiency and yield.

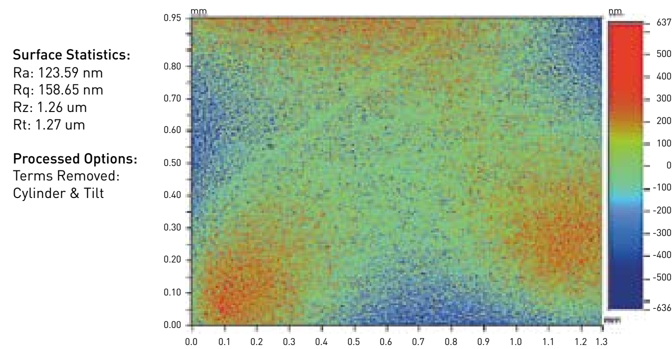
TRACE AND LINE WIDTH MEASUREMENTS

In addition to excellent vertical resolution and fast measurement times, optical and stylus profilers also have data segmenting capabilities for evaluating critical properties on different levels of a sample surface. For solar applications, this is commonly used for trace and line width measurements. The quality of silver or other conductive traces used in solar cell production needs careful control to ensure proper performance of the panels, and that a minimum of area is covered by non-photovoltaic material. In addition, scribe lines, particularly in thin film processes, are later filled

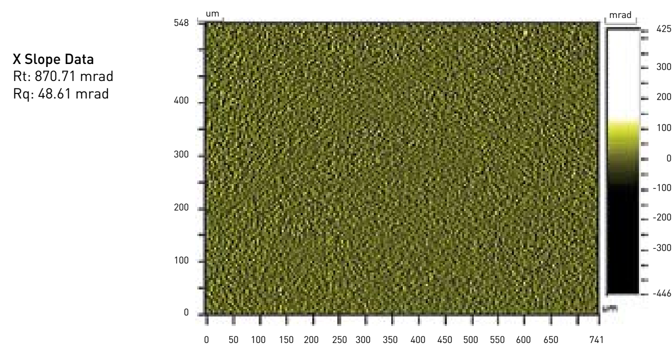
SURFACE DATA



(a)



(b)



(c)

Figure 1. (a) Overall surface roughness and shape, with only tilt removed from the measurement result; (b) The same measurement with the best-fit cylinder also removed, now showing roughness better as well as scratches;. (c) a slope calculation on the scratched region of the same measurement, so that slope of the defects can be accurately calculated.

with expensive conductive inks that connect the various active areas. If the scribe lines are too shallow or deep, the wrong width, or in the wrong places, the panel's performance can be adversely affected. Identifying such defects prior to ink deposition allows material to be scrapped before too much value has been added.

Vision software can automatically calculate line widths, line spacings, depths, volumes, roughnesses within the trace and on the substrate, as well as log all parameters to the database with pass/fail capability for production control. Figure 3 shows a scribe line measurement from a thin-film solar panel, revealing line width, roughness, and depth of the scribed feature. These analyses can be performed on surfaces with one to several hundred critical features within the measurement.

ADVANCED MATERIALS RESEARCH

Optical profilers also are used often to characterize surface properties of materials under varying conditions. The Material Science and Engineering department of the University of Illinois utilize a Veeco optical profiler to characterize grain boundary effects on the growth and optoelectronic efficiency in CIGS bi-crystals. Figure 4 shows a boundary region where differing substrate crystal orientations affected the growth of the CIGS material. By quantifying these and other interactions rapidly and at high resolution, optical profilers help researchers worldwide to improve solar cell performance.

OPTIMIZATION AND CONTROL OF PROCESS EQUIPMENT

Stylus and optical systems are also used for quality control and improvement for the process equipment used in solar manufacturing. Etch and deposition rates can be rapidly calculated across the wafer using the advanced automation capabilities of the Wyko or Dektak profilers. Heights of features are quickly measured at various locations across the substrate. This data allows adjustments to be made both to alignments for better

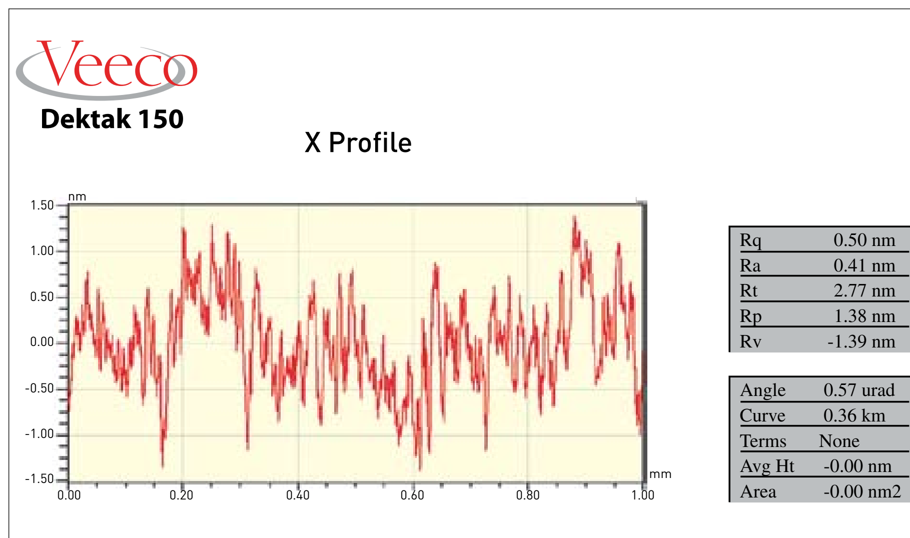


Figure 2. A 1mm stylus scan across a glass substrate shows sub-nanometer roughness through Vision software analysis.

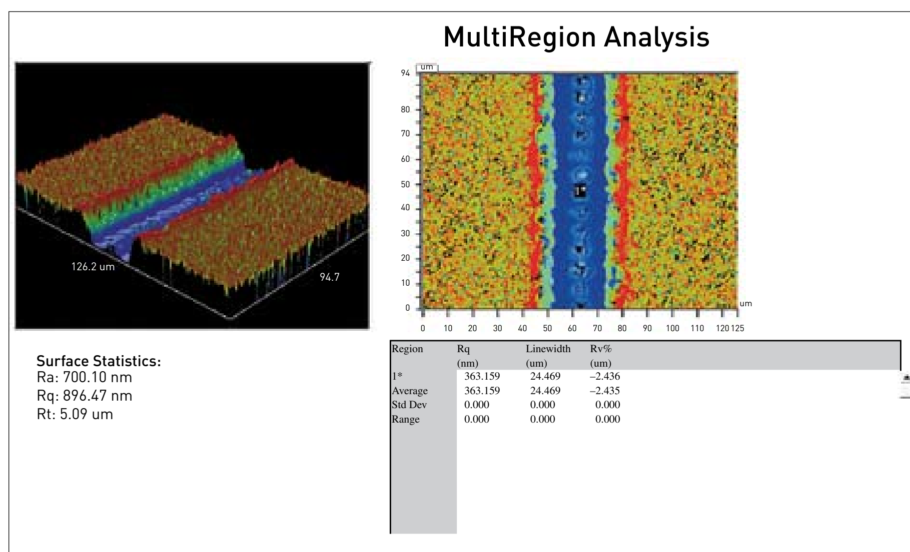


Figure 3. 3D and multiple region display of a scribe line on a thin-film solar panel, showing overall roughness, roughness within the scribed area, line width, and depth of the scribe line.

uniformity, as well as to required processing times to ensure the desired thicknesses are achieved. For instance, Figure 5 shows the variation in height of a stepped feature across an 8-inch wafer during deposition process development. Measurements were taken and analyzed automatically across all positions. The data was then used to improve uniformity and the average height of critical features.

Wyko optical profilers also incorporate a number of features that make them ideally suited for quantitative defect detection and analysis. Volume and/or height thresholds may be set by the user, and the software will automatically identify defects and can report on such features as height, diameter, volume, and X and Y maximum extent. Figure 6 shows a surface measurement of a photovoltaic wafer where the defects are present on the surface. By quantifying them, the system users can determine where in the process they originate and work to optimize the process setup to eliminate them.

FILM THICKNESS

The thickness of varying substrate layers, both transparent and opaque, needs proper characterization, particularly for CIGS devices. The contact method utilized by stylus profilers provides very rapid and accurate film thickness measurements where there is a boundary, readily identifying the film-to-substrate distance. With its very low contact forces, Dektak profilers are able to do this without damage, even on soft polymers. More importantly, as a contact technique, the stylus profiler is insensitive to the material property differences that can create offsets in optical techniques if the materials are too thin or have differing absorption. Figure 7 shows the measurement of a 2-micron step to verify the deposition process. Here, small amounts of contamination can be seen as spikes in the dataset, in addition to a report of the overall step height. Since this information is obtainable in only a

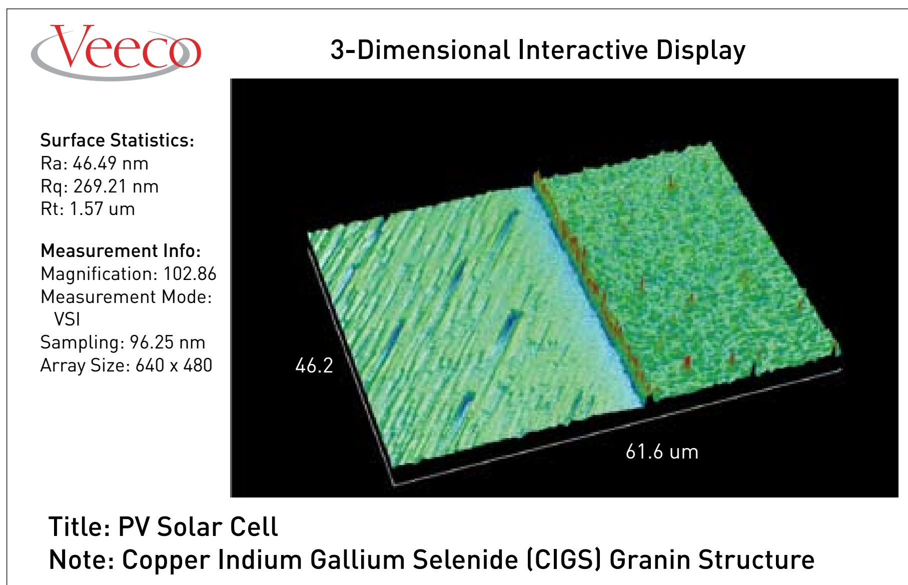


Figure 4. CIGS boundary region as measured by an optical profiler shows different grains structures on either side of the boundary. Data courtesy A. Hall/A. Rockett, Dept. of Materials Science & Engineering, University of Illinois.

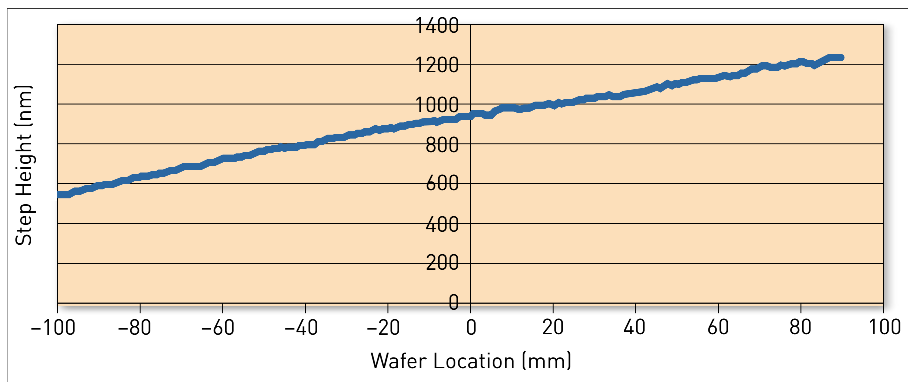


Figure 5. Height variation of a stepped feature across an 8-inch wafer.

few seconds, it becomes practical to perform frequent checks on the process quality.

Due to their respective capabilities stylus and optical profilers often are commonly employed in tandem for film thickness control. For example, Wyko optical profilers complement Dektak stylus measurements for film characterization in several key ways. Transparent film greater than about 2-microns in thickness can be measured across the entire sample surface. The optical system delivers faster area-based measurements, but if height offsets from the optical properties are present, the Dektak can be used to quickly calibrate the film. Then Veeco's SureVision™ analysis software can automatically apply the offsets to future optical measurements. Additionally, the Wyko profilers can provide information on the surface roughness and defects for the top and bottom surfaces of the films separately, so that the conformal properties of the film can be analyzed. Thus, the two systems work well together to ensure both film thickness and surface qualities are adequately characterized to improve and maintain peak performance.

CONCLUSION

The various technologies used for solar cell manufacturing are advancing rapidly as researchers and corporations work to improve efficiency and drive costs lower. Accurate surface metrology of key features is a critical part of this process. Both Wyko optical profilers and Dektak stylus profilers, which enable rapid surface and thickness metrology to sub-nanometer resolution, complement one another to provide the data necessary to improve solar cell development and production. Roughness, step heights, trace widths, scribe widths, film thickness, and defect detection all assist manufacturing lines. Meanwhile, researchers can study material effects, environmental attack and fatigue as well as perform sophisticated characterization of the effect changes in the process equipment can have on the end products.

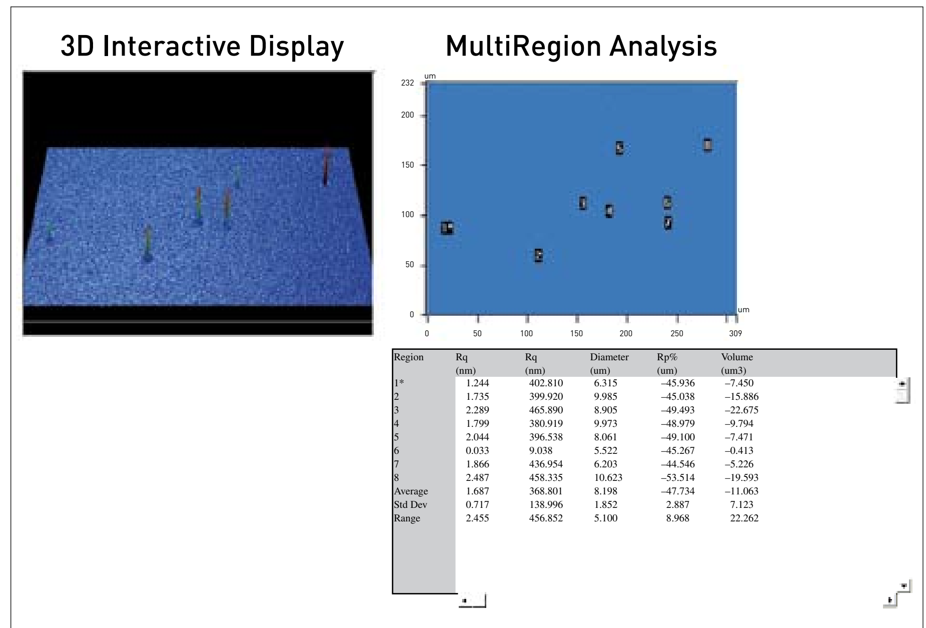


Figure 6. Defect detection and quantification on a photovoltaic wafer.

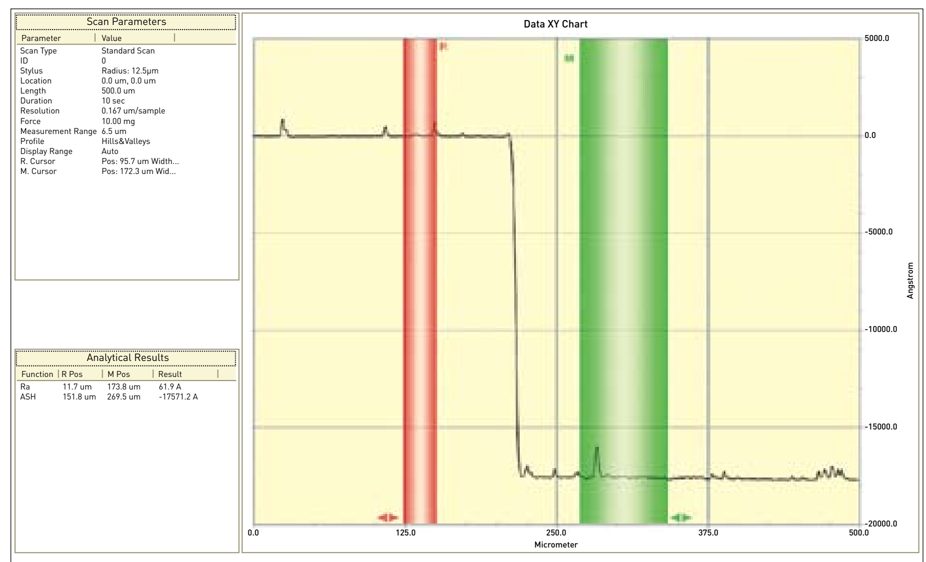


Figure 7. A 2μm step is characterized to verify the deposition process, revealing small amounts of contamination, seen as spikes in the dataset.

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