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Detailed Characterization of AR Coatings on Si Solar Cells: A New Application of GT-FabScan 6000

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Detailed Characterization of AR Coatings on Si Solar Cells:
A New Application of GT-FabScan 6000

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INTRODUCTION

GT-FabScan 6000 (previously known as the Sopori or PV Reflectometer) was developed to measure a variety of solar cell physical parameters in a single measurement. This system rapidly acquires a reflectance spectrum, reflectance (R) vs. wavelength (λ), of the entire wafer or cell, and deconvolves these data to obtain surface roughness, texture quality, AR coating thickness, wafer thickness, front metallization parameters (height and area of metallization), and backside reflectance. Because GT-FabScan 6000 can make measurements very rapidly (typically in < 40 ms) and without physically contacting the wafer, it can be used to monitor various process steps in the commercial production of solar cells. These processes include:

1. Sawing—the sawing process is monitored through (i) measurement of surface roughness and its uniformity and (ii) wafer thickness. The ability of GT-FabScan 6000 to illuminate the wafer from different directions allows it to quantify the sawing irregularities through use of directional reflectance. The thickness measured is the average value of the wafer. This technique of wafer-thickness measurement can also be applied to other substrates that may not have uniform thickness (e.g., ribbons)
2. Texture etching—the texture quality, representing the condition of the texture bath, is monitored by measuring the reflectance of the textured wafers.
3. Antireflection coating thickness—an average value of the AR coating thickness of the entire wafer is measured and compared with a preset value to determine if the process is working as expected.
4. Front metallization—the average area and average height of the metallization is measured.
5. Back contact—the reflectance of the backside is measured to establish the quality of the back contact.

We have developed a new application of GT-FabScan for rapid mapping of AR coatings on Si solar cells. The system generates an image of the AR thickness and presents it in a color format using false colors. This measurement is made in less than 100 ms. The development of this application enables the system to generate thickness maps of the AR coating to determine the repeatability of the deposition system, as well as to ensure that downstream processing can be controlled. These data can also be used to determine the average thickness of the coating. Downstream processing is an important issue in current solar cell technology (as discussed below). This paper describes its importance to the PV industry and discusses the principles and method of this measurement.

NEED FOR MAPPING AR COATING THICKNESS

The primary objective of an AR coating on a solar cell has been to minimize its reflectance and maximize the light-trapping ability to obtain maximum photocurrent for the incident solar spectrum. Typically, the AR coating for a textured Si solar cell should consist of a uniform, 750-Å-thick, dielectric film of refractive index 2 to 2.4. However, the low-cost techniques used for deposition of AR coatings on commercial Si solar cells do not yield very uniform films. It is believed that a good trade-off between the cost and cell performance would favor a "reasonable" variation in the film parameters (thickness, refractive index). Typically, AR coatings used in the PV industry exhibit a variation of ±100 Å in film thickness. It is estimated that this nonuniformity leads to a photocurrent density loss of about 1 mA/cm^2. However, in the current solar cell technology, AR coating deposition and its subsequent processing perform many additional functions. The AR coating is also a buffer to firethrough screenprinted contacts and participates in the hydrogen diffusion for impurity/defect passivation. These functions demand much higher uniformity of the AR coating. In a typical fire-through metallization, a Ag-based contact is screenprinted on the AR coating and is fired by an RTP-like process. In this process, the local temperature acquired by the wafer depends on energy absorbed by that region, which in turn depends on its thickness and reflectance. Thus, a variation in film thickness leads to variation in the reflectance and energy absorbed, resulting in lateral temperature variations during an RTP process. In the hotter regions, the metal can "penetrate" deeper into the junction and cause shunting, whereas in the cooler regions, the metal may not be properly alloyed and cause higher series resistance. Thus, in current solar cell technology, there is a need for the development of a technique for rapid measurement of AR coating thickness and mapping the thickness variations.

Some methods for measuring film thickness already exist, but they are either ellipsometery or interference based, and use small-beam spectrometers to measure local reflectance, which is then used to determine local material properties. The small-beam instrumentation is used for two main reasons—to ensure that the measured region is uniform in material properties and that small-beam optics are relatively easy to make. But, for a nonuniform sample, one often uses scanning techniques to map variations in material properties. These techniques of reflectrometery (or spectroscopy) are routinely used in a variety of metrological applications for determination of chemical composition, material identification, and measurement of optical properties of materials. Reflectrometery can also be a powerful tool in photovoltaic (PV) manufacturing to monitor various solar cell fabrication processes. In fact, it is used in a simple, qualitative form (as a visual examination) by process technicians and engineers to check the quality of sawing, texturing, and thickness of AR coating (using color) for QA purposes. But quantitative measurements become quite tedious and time consuming. The main difficulty arises from a need to make measurements across the entire wafer or solar cell. Thus, these methods are not suitable for solar cells, especially those that have textured or rough surfaces. One approach to overcoming this difficulty is to use large-beam optics that will allow the entire cell to be measured at once, eliminating the need for scanning.

PRINCIPLES OF MAPPING AR COATING THICKNESS

The new mapping technique uses the thickness dependence of the local reflectance of the cell/wafer, at a selected wavelength, to determine the corresponding thickness. To understand the principle of this technique, we first consider reflectance of an AR-coated solar cell. Figure 1 shows reflectance spectra (R vs. λ) of a textured and AR-coated wafer for different thicknesses (0.05 to 0.1µm) of AR coating. The coating material is assumed to use SiN:H with a refractive index of 2, and the calculations are made using *PV Optics* optical modeling software. These plots show that for $\lambda > \lambda_0$ (λ_0 = wavelength for minimum reflectance), the reflectance increases as the AR coating thickness (t) decreases. The data of Fig. 1 are plotted in Fig. 2 to

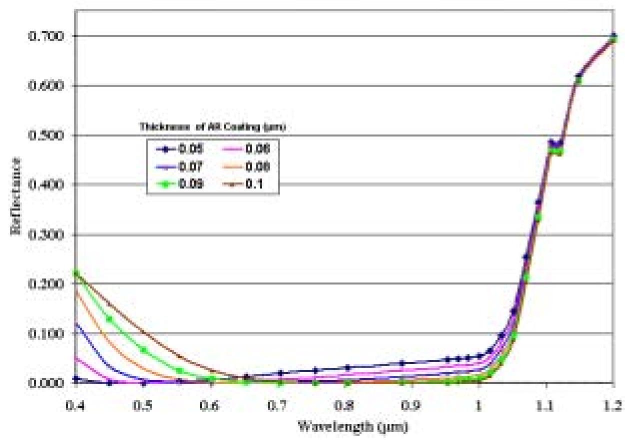

Fig. 1. Calculated reflectance spectra of AR-coated, textured wafers of different AR thicknesses, using *PV Optics.*

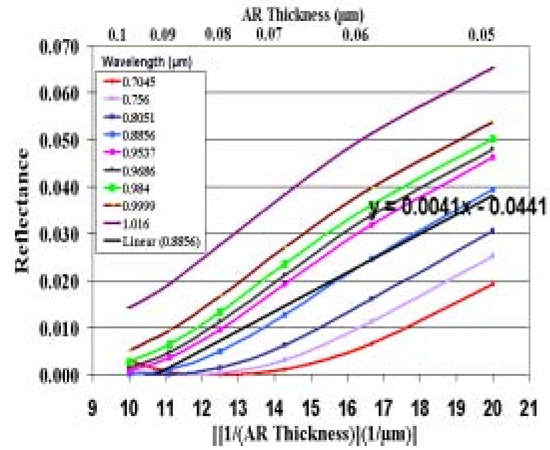

Fig. 2. Plots showing relationship between reflectance and (1/thickness) at different wavelengths for a textured, AR-coated wafer.

show the dependence of R on (1/t) for different wavelengths. It is seen that, for a broad wavelength range, this relationship is nearly linear. In particular, Fig. 2 shows a linear fit for a selected wavelength $\lambda = 0.8$ µm. The important conclusion is that one can assume the local reflectance of an AR-coated wafer is inversely proportional to the film thickness, if the reflectance is measured at a suitable wavelength. This feature can be deployed in a somewhat simple way by suitably illuminating the AR-coated sample and using a camera to image the (1/t)-map, which can then be converted into a t-map. These measurements can be done easily using digital camera systems.

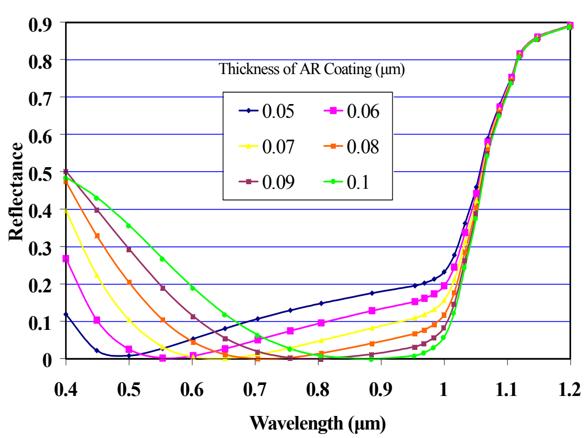

Fig. 3. Calculated reflectance spectra of AR-coated, planar wafers of different AR thicknesses, using *PV Optics.*

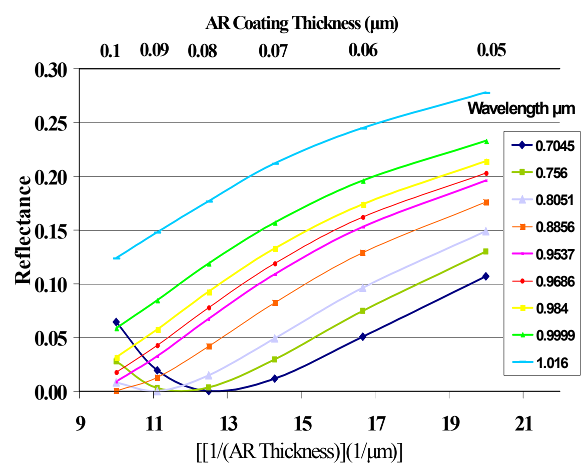

Fig. 4. Plots showing relationship between reflectance and (1/thickness) at different wavelengths for a planar, AR-coated wafer.

Figures 3 and 4 are corresponding calculations for AR-coated planar wafers (such as ribbons). Again, a behavior similar to Figs. 1 and 2 is seen. Hence, this implies a common approach for using local reflectance as a measure of AR-coating thickness (with appropriate calibration for wafers of different surface properties).

MEASUREMENT SYSTEM

Thickness mapping is easily accomplished with the GT-FabScan 6000. For the AR-coating-thickness mapping, the wafer is placed in the reflectometer, where it is illuminated from all sides, and the reflectance normal to the wafer is measured, (see Fig. 5). In the normal operation, the R vs. λ is measured by a diode array spectrometer (DAS). For the present application of film-thickness mapping, the DAS is replaced with a CCD camera fitted with a bandpass filter. This filters out all light intensities that are not directly of interest for the AR coating mapping. The filtered image, in response to the illumination by the optical source of the GT-FabScan 6000, represents a local intensity, which is inversely proportional to the AR-coating thickness. The GT-FabScan 6000's inherent stray-light-eliminating properties prevent the local intensity image from being affected by surrounding "noise," thus allowing the image to be as isolated from disturbances as possible. The intensity image is processed and assigned a false color scheme to identify thickness distribution. Accompanied by the processed image, other statistical data are offered for further AR-coating characterization. Figure 5 shows a schematic of GT-FabScan 6000 with two options —imaging and spectral modes. In the imaging mode, the light reflected normal to the wafer is passed through a bandpass filter and imaged with the camera.

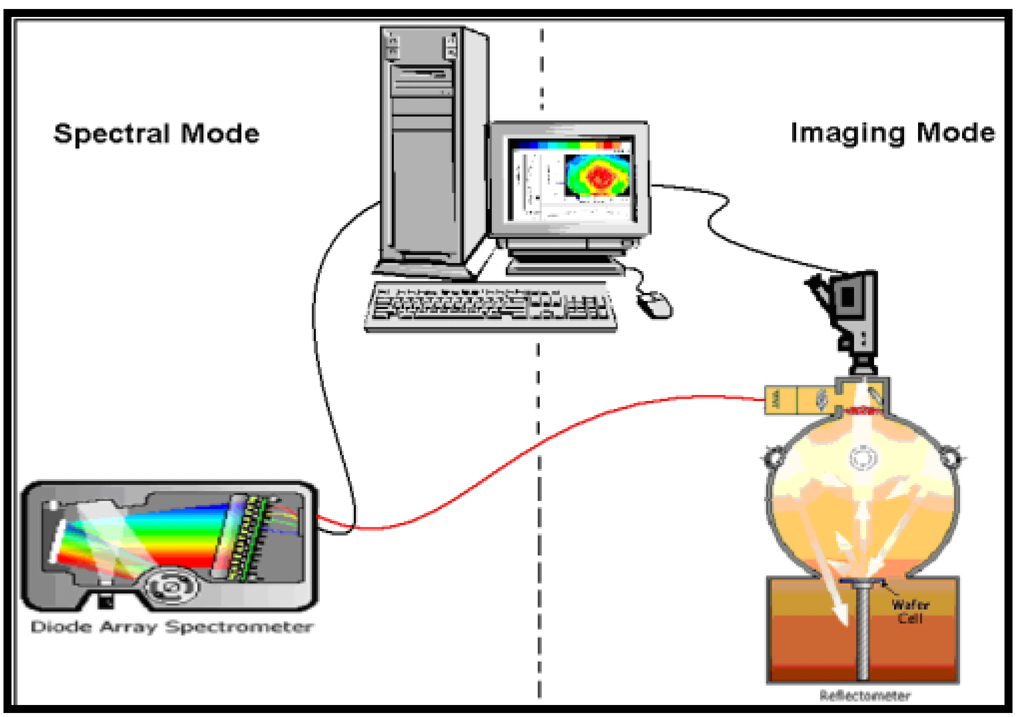

Fig. 5. A schematic of GT-FabScan 6000.

The operating parameters of the camera (contrast, or Gamma, and brightness) and the bandpass filter allow the local intensity of the image of the AR-coated wafer to be inversely proportional to the AR thickness (as described below).

Intensity of the image at any point in the image plane, I (x_i, y_i), and the

$$I(x_i, y_i) = R(x_o, y_o) * T(\lambda) * M$$

where M is the magnification, $T(\lambda)$ is the transmittance of the bandpass filter, and $R(x_o, y_o)$ is the local reflectance of the element (x,y) in the object plane. The bandpass filter is selected to have a linear relationship between the transmission of the filter and film thickness.

RESULTS/DISCUSSION

Figure 6 shows the thickness map of a textured Si wafer (4.5 x 4.5 in), coated with an AR coating of TiO_2 . The film thickness is the largest in the center of the wafer, about 800 Å . The color legend, at the top of figure, identifies the thickness distribution over the wafer. Also shown are the vertical and horizontal line scans of thickness through the center of the wafer (identified by the cursor marker). Figure 7 shows the thickness distribution for a sample that is treated as follows: a layer of a TiO_2 was deposited on a textured Si wafer. The sample was dipped in dil.HF (which reduced the film thickness uniformly) and then slowly pulled out producing, a tapered layer. This figure shows a tapered layer variation along the vertical and horizontal directions of the sample. It is seen that the overall thickness of the dielectric film is etched, and a continuous taper in the film thickness between 236 and 103 Å is generated. The color legend of uniformly distributed colors is shown on the top side of the figure.

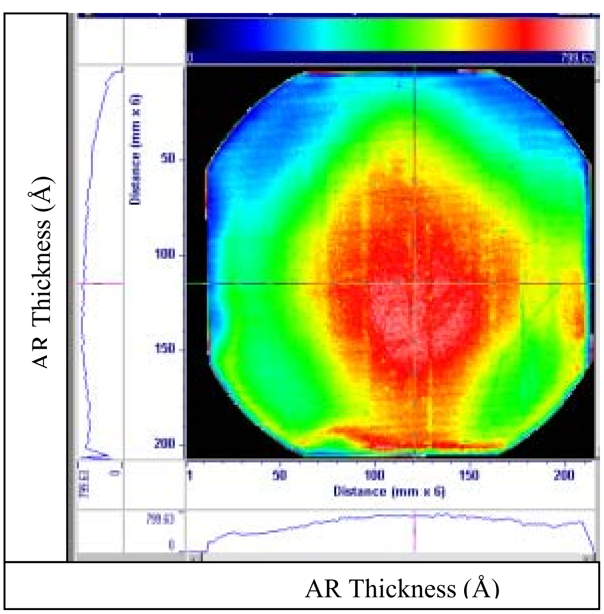

Fig. 6 A map of thickness variation of a 4.5-in x 4.5-in, textured, AR-coated wafer generated in 100 ms by GT-Fab-Scan 6000, using the method described in this paper.

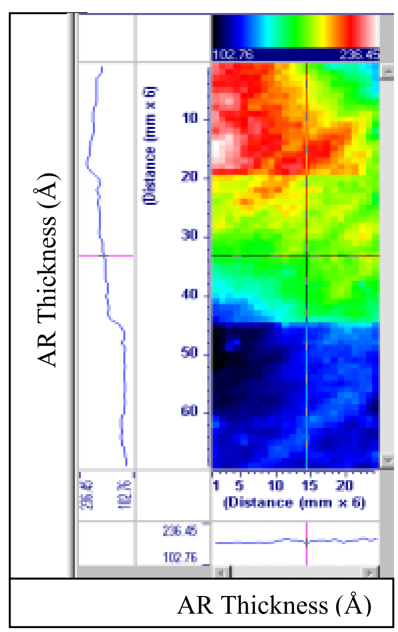

Fig. 7. A map of thickness variation of the taper-etched film on a textured Si wafer.

CONCLUSION

A new technique for rapid mapping of AR-coating thickness has been developed. The rapid-mapping capability makes the instrument well suited for online process monitoring and valuable to ensuring a good process control and enhancing reliability. The advantages of this technique are that it is very rapid—maps the entire wafer in one measurement in less than 100 ms; the measurement is insensitive to the nature of the wafer surface (works on planar, rough, and textured wafers); because a digital image is obtained, a variety statistical parameters can be quickly identified; and that the system is capable of online process monitoring. Use of this technique is expected to be very valuable in optimizing hydrogen passivation and the fire-through metallization process. In particular, current method(s) of AR-coating deposition need to be evaluated for non-uniformities in the coating thickness and its effects on cell performance. For example, Fig. 8 shows a map of AR thickness on a wafer that was in the same batch for AR-coating deposition as the wafer in Fig. 6. As seen, the general distribution pattern of both wafers is the same, but details of thickness profile are considerably different. It may no longer be sufficient to relate AR-coating effects simply to the loss in photocurrent. It is expected that large variations in the AR-coating thickness can be detrimental to achieving high cell performance in fire-though contact processing.

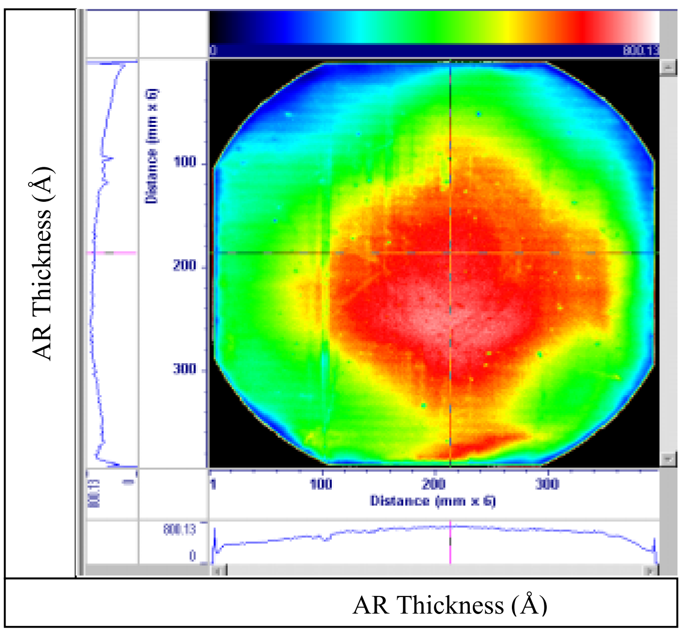

Fig. 8. A thickness map of a 4.5-in x 4.5-in, textured, AR coated wafer from the same batch as the wafer shown in Fig. 6.

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