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# PV-Reflectometer: a Process Monitoring Tool for Solar Cell Manufacturing

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## ABSTRACT

A new instrument is described for in-line monitoring of various process steps in silicon solar-cell fabrication. This system can rapidly measure a host of parameters that describe the front-surface and the back-surface properties of a wafer/cell. The measured parameters represent values averaged over the entire wafer/cell, making it suitable for monitoring process steps in a solar cell manufacturing facility.

## 1. Introduction

The photovoltaic (PV) industry is strongly interested in developing process monitoring tools to improve manufacturing processes, reduce product cost, and increase the product reliability. In a typical Si solar cell manufacturing facility, the prevalent process-control techniques are similar to those used in the past in the microelectronics industry. While the microelectronics industry has many new and sophisticated characterization-tools, those tools are not suitable for the PV industry. The PV industry needs process-monitoring techniques that can measure an entire large-area device, rapidly at a low-cost, and which are usable on rough and textured surfaces. Here we describe a new non-contact instrument, PV-Reflectometer, designed specifically for PV monitoring and measurement.

## 2. Principles of a PV-Reflectometer

A PV-Reflectometer measures the average reflectance (R) of an entire wafer or cell as a function of wavelength ($\lambda$). The system operates in a broad spectral range that allows separation of the properties related to the front and the back surfaces. This information is used to determine various wafer and cell parameters. To illustrate how the parameters are derived from the reflectance data, Figure 1 shows a sketch of a typical reflectance plot of an antireflection (AR)-coated, textured cell with front and back metallization. In Figure 1:

- $\lambda_0$ (wavelength of minimum reflectance) determines the thickness of the AR coating.
- The value of $R_0$ (reflectance at $\lambda_0$) is used to determine the fraction of metallization. This assumes that, without front metallization, an AR-coated cell would exhibit a reflectance minimum (which is close to a null). Thus, the deviation from the zero implies that the cell is metallized. By calibrating the system, it is possible to relate this value to the fraction of the area covered by the metal.
- $\Delta\lambda$ is the width of the reflectance minimum, which is related to the surface scattering. For a given AR coating, $\Delta\lambda$ increases with an increase in the surface roughness. This parameter is used to calculate the roughness of the surface or the height of the texture (using PV Optics).
- The back-reflectance value can be derived from the reflectance at long wavelength, such as $\lambda$ = 1.2 $\mu$m (using *PV Optics*).

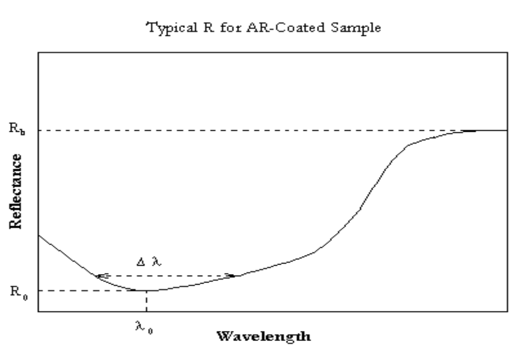


Figure 1. Illustration of parameters used for analysis of the reflectance curve.

Measurement of the reflectance curve of a large-area device is difficult. To overcome the difficulties intrinsic to the conventional methods of making R vs $\lambda$ measurement, PV-Reflectometer uses a new concept based on the reciprocity principle in optics [1]. Figures 2(a) and 2(b) illustrate the reciprocity principle in that the two cases shown are optically equivalent. Figure 2(a) shows that the incident light is normal to the sample, and the reflected (scattered) light is collected through all the angles. Figure 2(b) shows that the light is incident from all the angles and collected normal to the sample. The approach of Figure 2(b) confers many advantages including ease of large-area illumination and simplification of the signal collection—features that can greatly enhance the S/N ratio to render a measurement quickly. The next section will show how this approach is made practical.

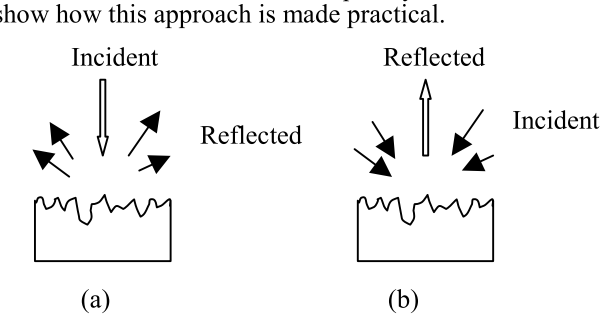


Figure 2. Illustration of the conventional illumination approach (a) and the reciprocal approach (b).

## 3. System configuration

Figure 3 is a schematic of the PV-Reflectometer. It consists of a highly-absorbing spherical dome, about 12 to 18 inches in diameter, with openings at the top and at the bottom. The bottom opening terminates in an optical baffle that houses a platform to support the test wafer. The dome has four sets of diverging lights located on the upper side that illuminate the test wafer. Separate controls balance the intensities of the lights. The entire system is designed to eliminate all possible scattering of the light except by the test wafer. The top-side of the dome has a lens and aperture assembly that couples the light reflected from the sample into a monochromator through an optical fiber. The monochromator drive, data taking/handling, calibration, and system control, are done by a computer that generates the reflectance (R) vs. wavelength (λ) plot for the test sample.

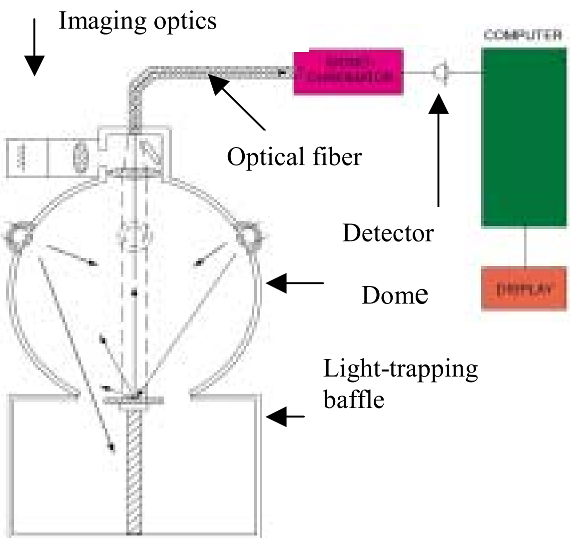


Figure 3. A schematic of the PV-Reflectometer.

## 4. Results

Figure 4 shows reflectance curves of three sets of samples, each having four wafers, taken at various stages of commercial Si solar cell fabrication—after sawing and pre-etch cleaning, after texture etching, and after AR coating. It is important to note that the reflectance values are in arbitrary units (AU), representing a scale that is much higher than the absolute scale. For comparison, the absolute reflectance of a typical textured mc-Si wafer is about 20%, and the minimum reflectance of an AR coated mc-Si wafer is <1%. Because of a high S/N ratio in a PV-Reflectometer, it is possible to rapidly scan the monochromator, and to achieve a good accuracy in measuring small shifts in the reflectance curve.

Figure 4 carries information, as outlined in the earlier section, which is automatically calculated by the computer. A detailed discussion is beyond the scope of this short paper. However, one can easily draw the following inferences:

- The measured thicknesses of the AR coating ($TiO_2$) ranges from 794 to 858 Å.
- There is very little variation in the sawn and cleaned samples. This is clearly expected if the sawing process is well controlled. We have found that in situations where sawing problems occur, the reflectance curve is typically shifted to higher values.
- The textured samples exhibit two interesting features. First, the average reflectance of the textured wafers is higher than the sawn wafers. This is because while texturing mc-Si wafers can reduce the reflectance of some grains, the reflectance of grains that have (111) orientation actually increases. Second, texturing introduces significant variation in the reflectance. This arises from the fact that the composition of the texturing bath changes continually as the etching proceeds, leading to variations in the texture quality within a batch as well as from batch to batch.
- The reflectance after AR coating is rather insensitive to variations in the texture, but is more controlled by the thickness of the AR coating (and its refractive index). This is rather fortunate because it greatly relaxes the degree of control needed for texturing bath.

Another unique feature of the PV-Reflectometer is its ability to measure both the fractional area and the thickness of the front metal contact. This is accomplished by making R VS λ measurements with two different illumination conditions. Details of this will be given in a forthcoming publication [2]. While a PV-Reflectometer can provide a variety of information for researchers, it provides powerful means of process monitoring and control on production lines.

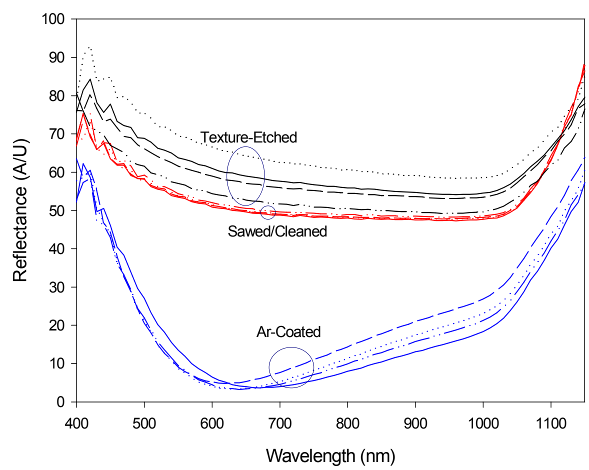


Figure 4. Reflectometer results on three groups of commercial PV-Si wafers (4.5 in. x 4.5 in.) at different stages of solar cell processing.

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[1] B. L. Sopori, "Principle of a new reflectometer for measuring dielectric film thickness on substrates of arbitrary characteristics," *Rev. Sci. Instrum*. **59(5)**, 725,1988.
[2] B. L. Sopori, W. Chen, Y. Zhang, and J. Madjdpour, 'Silicon Solar Cell Process Monitoring by a PV-Reflectometer," to be published.