GT Reflectometer: Performance Testing/Error Analysis

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INTRODUCTION

Reflectance spectroscopy is very well-suited for measuring physical parameters of semiconductor wafers, and of surface structures (continuous or patterned) deposited on them as thin films. We have developed a reflectometer (PV-Reflectometer) that can measure physical parameters of wafers, wafer surfaces, and other materials deposited during solar cell fabrication. Concomitantly, PV Reflectometer can also be applied for monitoring various cell fabrication processes. Specifically, this system can monitor the following processes steps:

- Wafer sawing
- Texture etching
- AR coating
- Front metal patterning (area and height of front metallization)
- Back metallization (reflectance of back metallization).

The PV Reflectometer can measure the reflectance spectrum of an entire wafer or cell in a very short time (typically < 100 ms). This spectrum is deconvolved to separate parameters that relate to various parts of the test wafer. Recently, we have built a commercial prototype reflectometer that is being loaned to PV Industry for evaluation and to provide feedback for fine-tuning to specific applications of each industry partner. The PV Reflectometer has been licensed by GT Solar, Inc., Nashua, NH, for commercial production (now called GT Reflectometer). Basic principles and the system configuration of the GT Reflectometer are described in earlier papers [1 –3]. Here we will only briefly describe the system, and focus primarily on discussion of results of our investigations to assess repeatability and error analysis. We undertook this work to establish measurement accuracies of the system and relate them to expected ranges of variations in monitoring various processes.

PRINCIPLES/SYSTEM CONFIGURATION

The approach used in the GT Reflectometer is unique—it uses multiple, wide-angle light sources to illuminate the large-area sample, whereupon the light scattered normal to the sample is collected for analysis. This new approach makes the system quite simple, low-cost, and rapid, and it permits use of high-power sources to enable measurement of "optically averaged" parameter values for large-area solar cells and wafers. However, because only the light reflected in a direction normal to the sample must be collected, this approach demands that all the extraneous light be excluded. Such extraneous light includes non-normal components of the light reflected from the test wafer, as well as the scattered light from parts of the instrument such as the wafer holder and mounting brackets. To accomplish this, the GT Reflectometer uses highly absorbing surfaces and a system of light-trapping baffles, resulting in an extremely high S/N ratio (of about 200). This allows the entire measurement and analysis to be made in less than 100 ms.

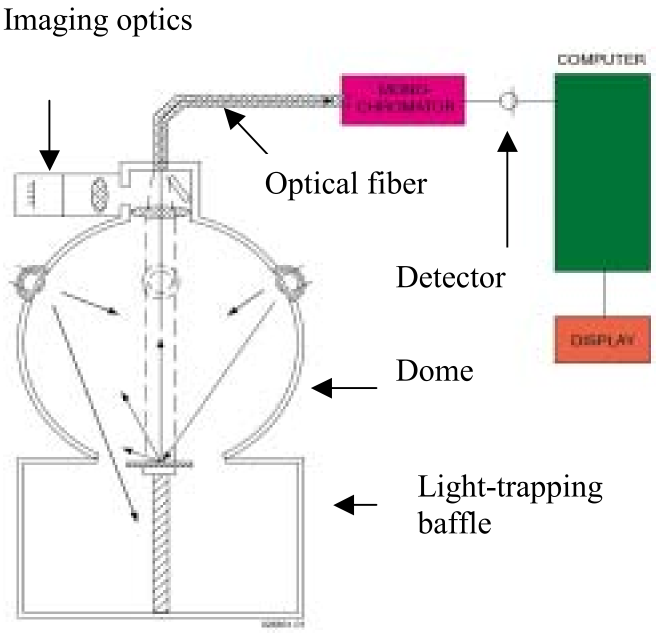

Figure 1. A schematic of the GT Reflectometer showing major parts of the system.

Figure 1 is a schematic of the GT Reflectometer. It consists of a highly absorbing spherical dome, about 12-18 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 controllers 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 an aperture assembly that couples the light reflected from the sample into a diode array spectrometer through an optical fiber. The spectrometer control, data taking/handling, calibration, and system control are done by a computer that generates the reflectance (R) versus wavelength (λ) plot for the test sample. The system operates in a broad spectral range that allows reflections from the front and back sides of the cell to be monitored. The setup shown in Figure 1 includes only the illumination source for measurement of the diffuse reflectance for rough or textured wafers/cells. A slightly different illumination source is used for planar cells.

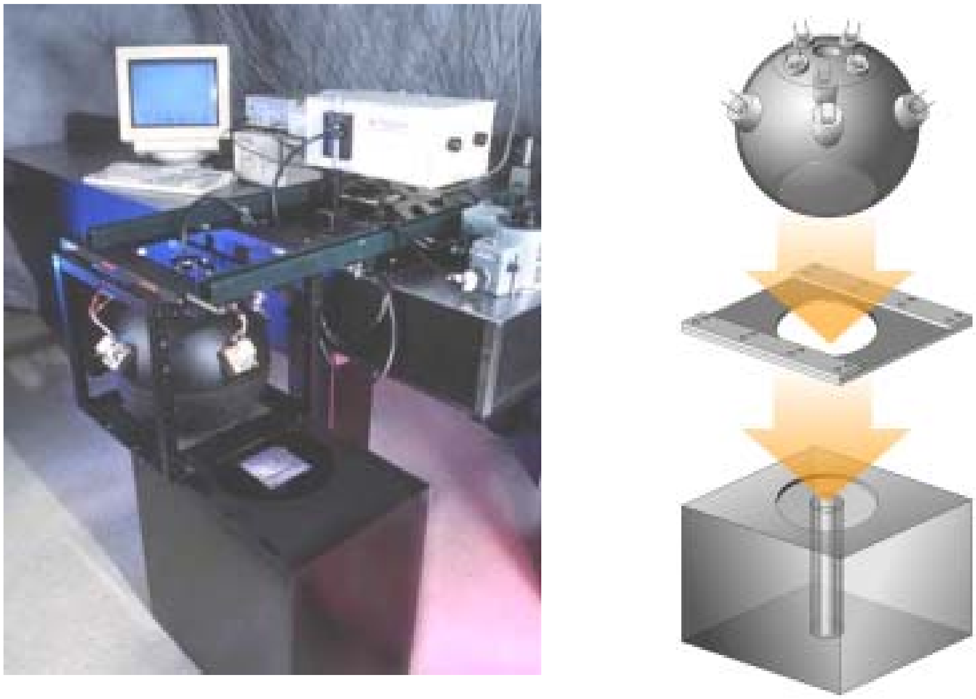

Figure 2. A photograph of a laboratory reflectometer (left) and an exploded schematic showing major optical parts (right).

RECENT IMPROVEMENTS

Recent developmental work involves some newer applications, system improvements to reduce the size, and detailed studies to evaluate measurement accuracy and sensitivities. Because a GT Reflectometer was designed to be a true production monitoring system, capable of very high throughput, we are performing detailed analyses to access the repeatability and reproducibility of the system. Here we will discuss repeatability tests that we have performed, and the corresponding changes incorporated in the system for production compatibility. These studies were carried out to identify and mitigate various mechanisms responsible for variations in the system performance. Some of the mechanisms we have evaluated follow.

1. Stability of the light sources/power sources:

Stability of the illumination is an important parameter in the accuracy of the optical measurements. This is particularly true for the GT Reflectometer because it uses eight lamps that can be connected in several configurations to produce diffuse or specular light sources. These lamps were tested individually for the output and determined to have sufficient stability, with a short-term variation of less than 0.1%. In the past, the lights were powered by AC sources consisting of autotransformers. Figure 3 shows 10 normalized spectra from a reference sample taken 1 min apart. It is seen that the variation is larger for shorter wavelengths, and that the maximum variation in the spectra is about 3%. It is useful to compare variation at a wavelength corresponding to the maximum intensity. This max-power wavelength (MPW) variation, identified by the arrow in the figure, is seen to be 0.8%. Use of a DC power supply greatly reduces the variation in the spectra. Figure 4 shows variation in 10 spectra taken 1 min apart using a TiO_2-painted reference sample. The variation at the MPW is only 0.1%. This is a very low variation for any spectrometer or reflectometer.

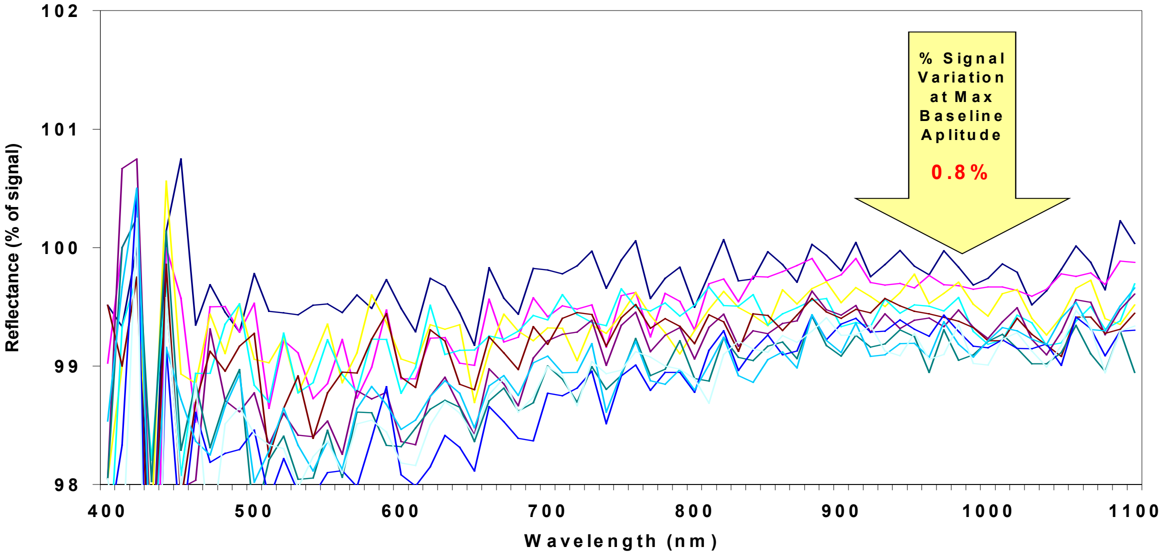

Figure 3. Ten reflectance spectra taken 1 min apart using AC power from low-cost autotransformers. Reference sample: Sprayed TiO_2.

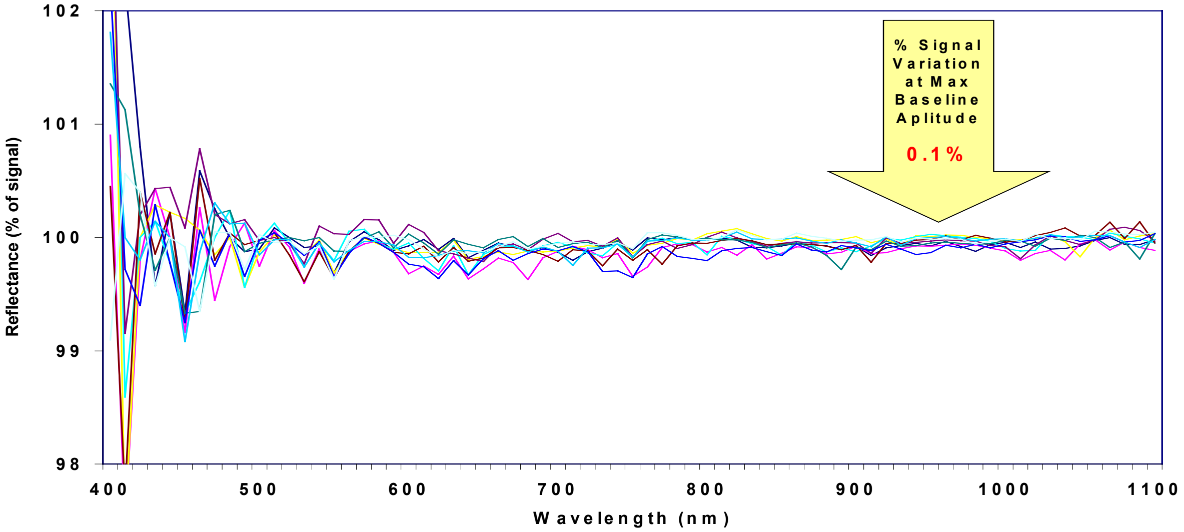

Figure 4. Ten reflectance spectra taken one minute apart using DC power supplies. Reference sample: Sprayed TiO_2

2. Stability of the reference: We have also evaluated three different reference samples. They consisted of a thick white paper, a Teflon sheet, and a TiO_2-rich paint. All reference samples had a matte finish. Figure 5 shows 10 spectra taken 1 min apart using a Teflon reference. The MPW variation is 0.3%. Figure 6 shows 10 normalized spectra taken with a white paper reference, which show MPW variation of 0.4%. These figures should be compared with Figure 4, which shows similar spectra for the new TiO_2-painted reference (with MPW variation of 0.1%). It is thus clear that our special paint (and its processing) produces a high-quality reference.

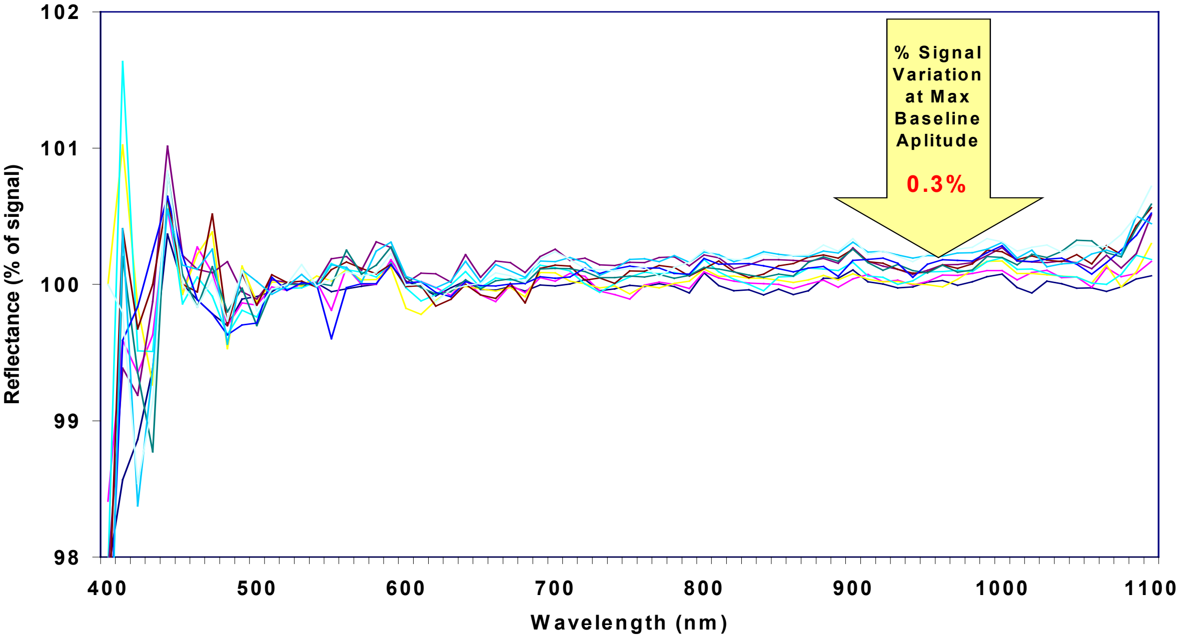

Figure 5. Ten normalized spectra taken with Teflon reference (DC power).

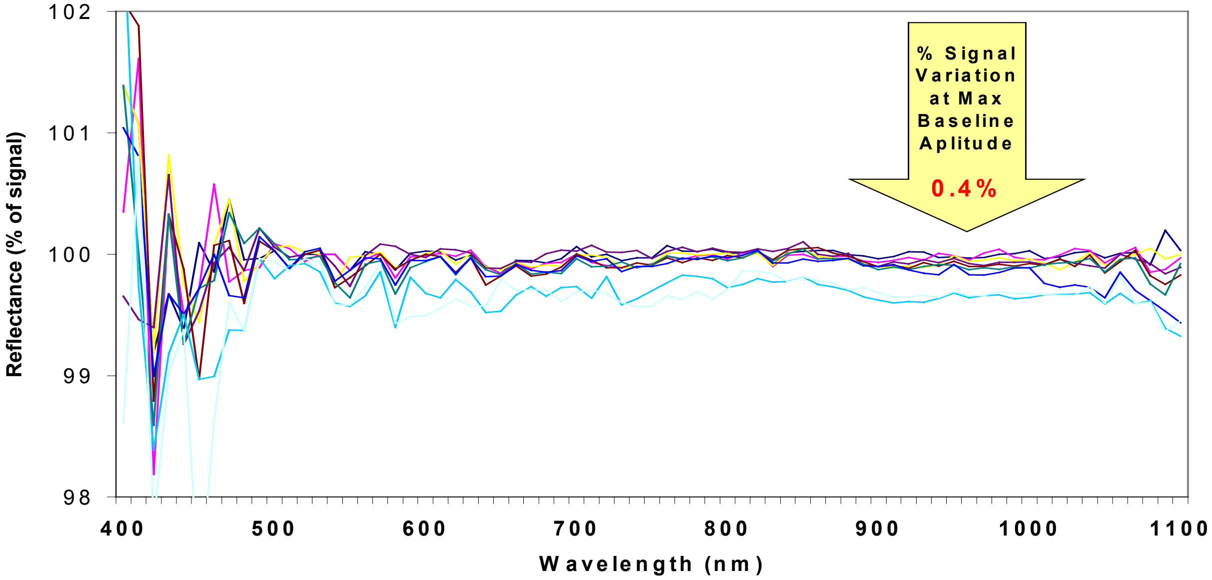

Figure 6. Ten normalized spectra taken with white paper reference (DC power).

3. Positioning of the test device within the reflectometer: GT Reflectometer is designed to have a relaxed sensitivity to positioning of the test. This feature helps in maintaining a high-throughput capability so that the wafers can be brought into the measurement chamber at a high speed. We have studied the sensitivity to lateral and vertical positioning of the wafer.

4. Duration of the test-wafer in the reflectometer: Figure 7 shows ten normalized spectra taken over a 1-hour period with the lights on for the entire test period. The resulting MPW variation is 0.3%.

5. System noise: The ultimate system noise is associated with the detector/amplifier combination. Because the light intensity is quite low in a short wavelength region, this noise is highest, in a range of 0.4-0.5 µm. Beyond 0.5 µm wavelength, the noise is considerably less than 0.1%

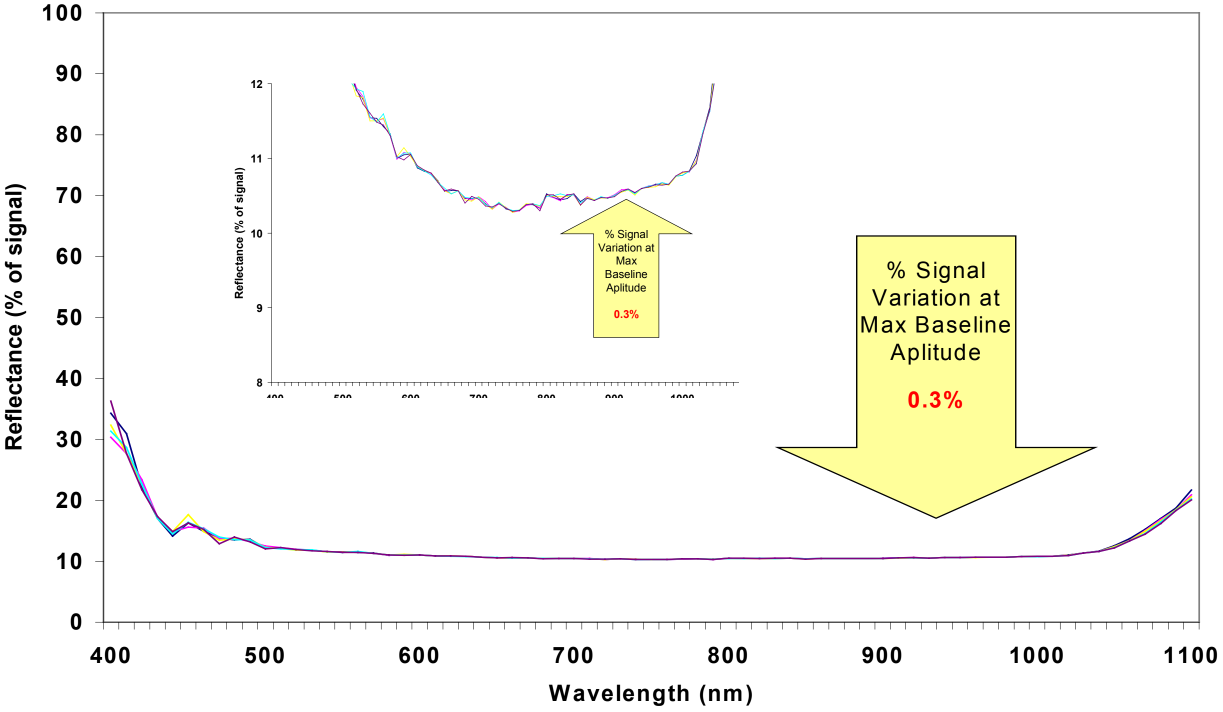

Figure 7. Variation in the spectra textured Si Wafer taken over a one-hour (DC power).

SUMMARY

We have carried out a performance/noise analysis of the GT Reflectometer. The results are summarized in Table 1. The dominant sources of noise were determined to be the lamp power supply and reference standard. A stabilized DC power supply and a new reference standard (using spray on TiO_2-rich paint) have been incorporated in the new GT Reflectometer. These changes have improved the measurement accuracy to 0.1%.

Table 1. Summary of the Test Results

Test	Results (MPWV)
Stability of the light sources/power sources	Lamp stability :very high Power supply: AC ---- (0.8%- -short term) DC ---- (0.1%--short term , o.3 long term)
Stability of the reference Sample *(with DC power)*	White paper -- 0.4% Teflon -- 0.3% TiO2 -- 0.1%
Positioning of the test device within the refelectometer *(note: these measurement correspond to AC power supply)*	Sensitivity to lateral location: < 2.5 within 5 mm Height sensitivity <2.5 % within 10mm
Duration of the test wafer in the reflectometer	Long term -- 0.3% Short term -- 0.1%
System noise	The ultimate system noise is associated with the detector/amplifier combination. A typical S/N system is about 200

REFERENCES

[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] Bhushan Sopori, Yi Zhang, Wei Chen, and Jamal Madjdpour, “Silicon solar cell process monitoring by PV Reflectometer,” *IEEE PVSC, Anchorage, AK, Sept. 2000.*

[3] Bhushan Sopori, U. S. Patent No. 6,275,295.