Chapter 14
Image Processing for Solar Cell Analysis, Diagnostics and Quality Assurance Inspection

Michael G. Mauk
Drexel University, USA

ABSTRACT

Image capturing, processing, and analysis have numerous uses in solar cell research, device and process development and characterization, process control, and quality assurance and inspection. Solar cell image processing is expanding due to the increasing performance (resolution, sensitivity, spectral range) and low-cost of commercial CCD and infrared cameras. Methods and applications are discussed, with primary focus on monocrystalline and polycrystalline silicon solar cells using visible and infrared (thermography) wavelengths. The most prominent applications relate to mapping of minority carrier lifetime, shunts, and defects in solar cell wafers, in various stages of the manufacturing process. Other applications include measurements of surface texture and reflectivity, surface cleanliness, integrity of metallization lines, uniformity of coatings, and crystallographic texture and grain size. Image processing offers the capability to assess large-areas (> 100 cm^2) with a non-contact, fast (~ 1 second), and modest cost. The challenge is to quantify and interpret the image data in order to better inform device design, process engineering, and quality control. Many promising solar cell technologies fail in the transition from laboratory to factory due to issues related to scale-up in area and manufacturing throughput. Image analysis provides an effective method to assess areal uniformity, device-to-device reproducibility, and defect densities. More integration of image analysis from research devices to field testing of modules will continue as the photovoltaics industry matures.

INTRODUCTION

This chapter reviews image processing technology and methods in their application to research, engineering development, and production of photovoltaic solar cells. Image processing can be utilized for device and process diagnostics and materials analysis; as well as for inspection and quality assurance. Most of the foregoing discussion focuses on monocrystalline or multicrystalline silicon solar cells. Such silicon-based solar cells make up about 90% of the world solar cell

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market, and the features and fabrication methods of silicon solar cells readily lend themselves to useful and informative image processing analysis. We will emphasize aspects of image processing with digital photography /machine vision, specifically—analysis of CCD images captured from solar cells in various stages of processing. Many of these techniques are applicable at virtually all phases of solar cell manufacture, including steps preceding the formation of a *p-n* junction, as well as those preceding application of metal contacts and anti-reflection coatings. More in-depth evaluation is possible with samples that have junctions and metallization contacts, such that the working solar cell can be energized with an externally applied electrical voltage. The resulting infrared thermal emission and electroluminescence can be imaged to provide a two-dimensional map of solar cell characteristics and defects. Images of infrared transmission though the solar cell are also revealing, as the infrared absorption is proportional to the number of free carriers. If free carriers are generated by supra-bandgap excitation, they will quickly reach a steady state concentration where the generation rate is matched by the recombination rate. As such, the density of free carriers is an indicator of the recombination rates, and an infrared transmission image is a map of the variation of minority carrier recombination. Thermography, the temperature mapping of the energized solar cell via thermal infrared emission, is also an important diagnostics tool. Infrared cameras can detect small temperature changes (< 0.1 °C), and image areas of localized heating in solar cells as caused by shunts, for example. Lock-in thermography techniques, using pulsed thermal excitation, for example, flash lamps or modulated lasers or electrical, synchronized with multiple image capture, have increased sensitivities by factors of 100 to 1000.

Imaging techniques can be used to assess surface cleanliness, scratches, reflectivity, surface texture, uniformity of anti-reflection coatings, minority carrier recombination lifetime, localized shunting, and flaws in metallization. Many of these imaging techniques are relatively fast (~1 second), and can be done in-line for real-time process control and quality assurance on the factory floor. More detailed solar cell image analysis methods are realized with scanning/probing techniques, such that small sub-areas of the solar cell are individually probed to show the spatial variation of defects and other areal inhomogenieties. It is important to compare and correlate image processing methods with more established scanning and probing methods since the interpretation and analysis of images is complicated, material- and process-specific, and test conditions (bias, light intensity, minority carrier injection level) may not correspond to actual operating conditions of the solar cell. The solar cell can be scanned by physical contact with a moving mechanical probe that impinges the solar cell, or more commonly, the solar cell can scanned with a collimated energy source such as a laser or electron beam. Probably the most common and useful of these techniques measures the solar cell current when raster scanned with a laser or focused light beam, in which case it possible to ascertain highly localized features of the solar cell. This LBIC (light beam induced current) analysis is time consuming and generally not appropriate for in-line inspection. The information derived from light-beam induced current measurements may serve as a benchmark with which methods of simpler or faster solar cell imaging can be compared and assessed.

BACKGROUND

Solar cells are, by practical necessity, large-area devices relative to other semiconductor components. Silicon solar cell areas are typically in the order of 100 cm^2, and commercial thin-film solar cell modules have areas of hundreds of square centimeters. This may be compared with semiconductor components such as photodiodes and light-emitting diodes (LEDs), where the area of