ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #16254

Machine Vision for Solar Cell Inspection

Dr. Michael G. Mauk, Drexel University

Michael Mauk is Assistant Professor in Drexel University's Engineering Technology program.

Dr. Richard Chiou, Drexel University

Dr. Richard Chiou is Associate Professor within the Engineering Technology Department at Drexel University, Philadelphia, USA. He received his Ph.D. degree in the G.W. Woodruff School of Mechanical Engineering at Georgia Institute of Technology. His educational background is in manufacturing with an emphasis on mechatronics. In addition to his many years of industrial experience, he has taught many different engineering and technology courses at undergraduate and graduate levels. His tremendous research experience in manufacturing includes environmentally conscious manufacturing, Internet based robotics, and Web based quality. In the past years, he has been involved in sustainable manufacturing for maximizing energy and material recovery while minimizing environmental impact.

Ms. Chetana R. Bayas

Machine Vision for Solar Cell Inspection

Introduction

The characteristics of surfaces are important because surface geometry (e.g., smoothness vs roughness) and surface composition determine optical properties (e.g., reflection, absorption), heat and mass transfer rates, contact friction, mechanical strength and susceptibility to fracture from microcracks, amenability to bonding, chemical reactivity and susceptibility to corrosion, and propensity for contamination and effectiveness of cleaning procedures for a particular surface. Further, the surface often reveals information about the underlying material including grain boundaries and defects. As part of a larger project, we are developing a suite of surface characterization methods appropriate for STEM educational purposes. Surface characterization of materials or devices/components in various stages of production is a useful and instructive educational project for engineering students because of its importance to a wide variety of manufacturing processes and technologies, and because it can provide informative case studies in metrology, quality assurance, and process control. Many of the methods involve simple instrumentation, and are suitable for desktop experimentation using cameras, low-cost measuring devices, and easily-obtained samples. The fact that there are multiple techniques of measurement and characterization, and various types of materials and processing methods, suggests comparisons between methods is in order. Thus, one theme of this work is to demonstrate to students the need to select among and assess the various measurement techniques available for a task, and corroborate measurement methods and the information yielded, and apply the optimum measurement effort to a specific application (e.g., quality assurance, reliability studies and failure analysis, in-line process control). For instance, while contact methods such as stylus profilometry and atomic force microscopy (AFM), and sophisticated optical methods such as white light interferometry and spectroscopic ellipsometry, provide very detailed and accurate surface assessment and can serve as a “gold standard”, they may not be appropriate for field measurements and in-line quality control, where a quick, non-contact method is more practical.

Solar cells are a particularly useful and instructive sample type. Machined metals and 3-d printed parts are also interesting subjects of study. Solar cells are, of course, the basis of photovoltaic renewable energy, and so many students have an interest in learning more about this technology, especially as it provides a growing contribution to electricity production in many countries. Solar cells are easily obtained in small lots at low cost (few $ per cell). Solar cells may be of the single-crystal (monocrystalline) type, polycrystalline (multicrystalline) type, microcrystalline, or thin-film. Most are made in silicon or amorphous silicon, but other semiconductors are also used. Solar cells typically are coated with an anti-reflection coating, which can be stripped off to reveal a bare silicon surface by etching. A screen-printed contact grid is also present, but the spacing between contact lines is sufficient wide that it does not interfere with most of the measurements described here. For some of the image-processing based methods, the detection of flaws (broken grid lines, scratches) can be an additional function.

Most of the methods of surface characterization can be broadly categorized as optical *non-contact* methods, and mechanical *contact* methods. Some methods interrogate a small region of the sample, while others integrate information from a large area (~1 cm^2). Some measurements can be performed in a few seconds, with little or no sample adjustment, while others may take much longer. Of particular interest is the use of CCD cameras for non-contact inspection of solar cells for quality assurance and process control, as these methods can be readily integrated into a production mode, e.g., solar cell production in belt furnaces and on conveyer belts. Silicon wafers are processed through various operations: sawing, etching, texturing, diffusion, screen printing, coatings and film deposition, and encapsulation into photovoltaic modules. The solar cell can be inspected at each stage of the manufacturing process. Multicrystalline silicon solar cells have very prominent grain structure which can be readily imaged and analyzed.

We have explored, developed, and compared various surface characterization methods with specific application to machined metal parts, 3D printed plastic parts, and silicon wafers and solar cells in various stages of manufacture. In this paper, we concentrate on machine vision (CCD camera images) of monocrystalline and multicrystalline silicon solar cells as this affords students an opportunity for hands on experience with cameras, image capture and analysis software, and image processing concepts that are important in robotics, automation, and process control. Further, such solar cells are rich in features related to defects, grain structure, manufacturing flaws, thin-film interference, and surface oxidation and other contaminants.

Solar cells are optically and electrically active devices. Applying a voltage (forward bias) to a solar cell creates weak electroluminescence and localized heating at shunts and defects. Detection and imaging of the electroluminescence may need a sensitive camera in the near-infrared. The localized heating can be seen with a thermal camera, and in fact, these has become a standard method for inspecting solar modules in the field. The images are raw data for analysis using image processing and analysis software. Features extracted from the image can be correlated with solar cell performance and other electrical or material characteristics.

This work is also an integral part of our efforts in promoting green manufacturing and sustainability in Engineering Technology programs. Our aims of this work can be summarized as thus:

> Surface roughness and surface cleanliness are important in many manufacturing operations. Surface smoothness/roughness and surface purity/contamination determine the optical characteristics, friction, heat transfer, susceptibility to corrosion, bonding, and appearance of components, as well as their suitability for the clean operations used in the semiconductors, biomedical, food processing industries. Cleaning and surface preparation consume considerable amounts of water, solvents, energy, and time, and generate much waste. Therefore, methods to simplify and improve surface cleaning and surface preparation are crucial for green and sustainable manufacturing. Further, tools for characterizing surfaces are needed to benchmark processes, quantitatively assess the efficiency of cleaning and surface prep, and monitor processes in real-time for better control and efficiency. We are developing a suite of tools for surface characterization including AFM (atomic force microscopy), white light interferometry, laser light scattering, CCD imaging, fluorescence analysis, surface profiling, depth gauge profiling, and other techniques. As specific applications, we can apply these techniques to 3D printed parts, silicon for solar cells, and machined metal surfaces. These techniques have various advantages and disadvantages for particular applications. For example, some methods are non-contact others physically contact the sample. Some probe large areas, others are limited to small areas. Students will gain experience with these techniques, and perform comparative studies to assess the suitability and capability of various techniques for green/sustainable manufacturing operations.

This report on our preliminary work provides an introduction to machine vision projects using solar cells as a means giving students hands-on experience in utilizing image processing for materials and device characterization, quality assurance, failure analysis, and reliability engineering.

Survey of Surface Characterization Methods

1. **Atomic Force Microscope (AFM).** An AFM scans the surface with a finely-tipped probe generating a signal proportional to height deviations. Educational versions of these instruments (~$15,000) are now available. They scan very small areas of the sample, but give a 2-dimensional profile of the surface at very high resolution (< 10 nm). Although AFM measurements can be tedious, a few representative samples can provide a "gold standard" for comparison of other methods.
2. **White Light Interferometry.** White light interferometry is a non-contact technique for surface height measurement surface profiles ranging between tens of nanometers to several centimeters. These are relatively expensive instruments (~$40,000), but are often available on campuses and can be used for benchmarking samples and calibration of other methods.
3. **Surface profiling with a stylus.** These instruments are moderately priced (~$3000) and are quite commonly used in machine shops. They generate a one-dimensional scan of the surface, and are good for introducing many of the quantitative measures of surface roughness.
4. **Laser light scattering.** These are specialty instruments ($ several thousand dollars) and work by using a detector array to determine the spatial distribution of light scattered from a laser directed at the sample surface. Smooth surfaces reflect specularly; rough surfaces scatter light. The distribution of scattered light can be correlated with roughness.
5. **LED light scattering.** These are low cost instruments (~$300) that measure the diffuse light component of a collimated low-angle incident beam produced by an LED. The diffuse light component is an indicator of surface roughness.
6. **Glossometers.** Glossimeters similar to LED light scattering instruments but use multiple LEDs/detector pairs at three incident angles to assess the

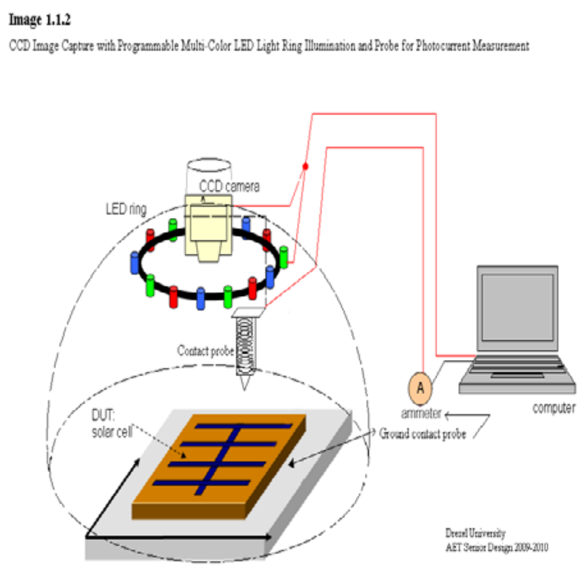
reflection and specular /diffuse components of reflection. These low cost (~$300) instruments are commonly used in the paper, paint, and textile industries.

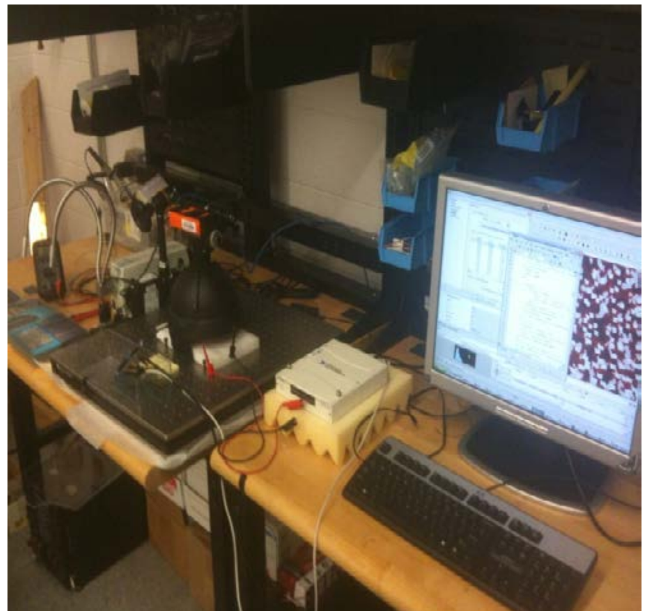
7. **CCD Camera.** CCD cameras can capture images of surfaces and create 2-dimensional matrices of pixel intensities. Pixel intensity histograms can be correlated with surface roughness.
8. **Depth gauge profiling.** Digital depth gauges (~$500) measure the penetration of a probe into surface depressions. Penetration depth can be correlated with surface roughness.
9. **Fluorometry.** Fluorescence dyes sprayed on the surface can be rinsed off. Surfaces with rough features will retain traces of dye, which can be imaged with low-cost handheld USB fluorescent microscopes (~$500). These images can be digitized and quantified.
10. **Thermal infrared images.** Thermal camera images can readily provide a two-dimensional temperature profile (±1 °C). Since the temperature detected is dependent on surface emissivity, the uniformity of the surface geometry can be estimated. Thermal cameras range in price from less than $1000 to $15,000, depending on temperature resolution and image size.
11. **Capillary wetting.** Drops of various liquids (water, alcohol, hexane) on the surface will exhibit a characteristic wetting angle which is a function of surface tensions and is affected by surface roughness and purity. The drop profile and wetting angle can be imaged and quantified with a CCD camera.

Example Case Studies.

We use CCD cameras to characterize the solar cells, sometimes mounted through an optical microscope. A special lighted stage is used to control the angle of illumination and light color (Figure **1**). The images are captured on the CCD camera in standard formats and analyzed with MATLAB or ImageJ (Figured **2** to **4**). Alternatively, the solar cells can be placed in a flat optical scanner to create an image (Figures **5** and **6**). Image processing can be used to quantify micro-structure (Figure **7**).

We have amassed an extensive collection of solar cells and solar cell materials including ingots, wafers, sheets, thin films, as well as solar cells in various stages of fabrication, as well as solar cell modules. Our samples include monocrystalline, polycrystalline, and amorphous silicon solar cells, as well as III-V compound solar cells and various thin-film solar cells, including dye-sensitized nanostructure cells.





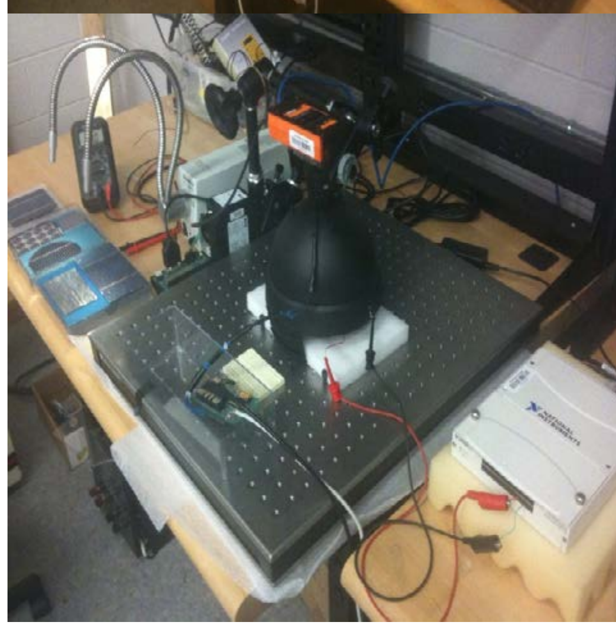


Figure 1: Imaging station for multicolor, variable angle of illumination imaging of solar cells.

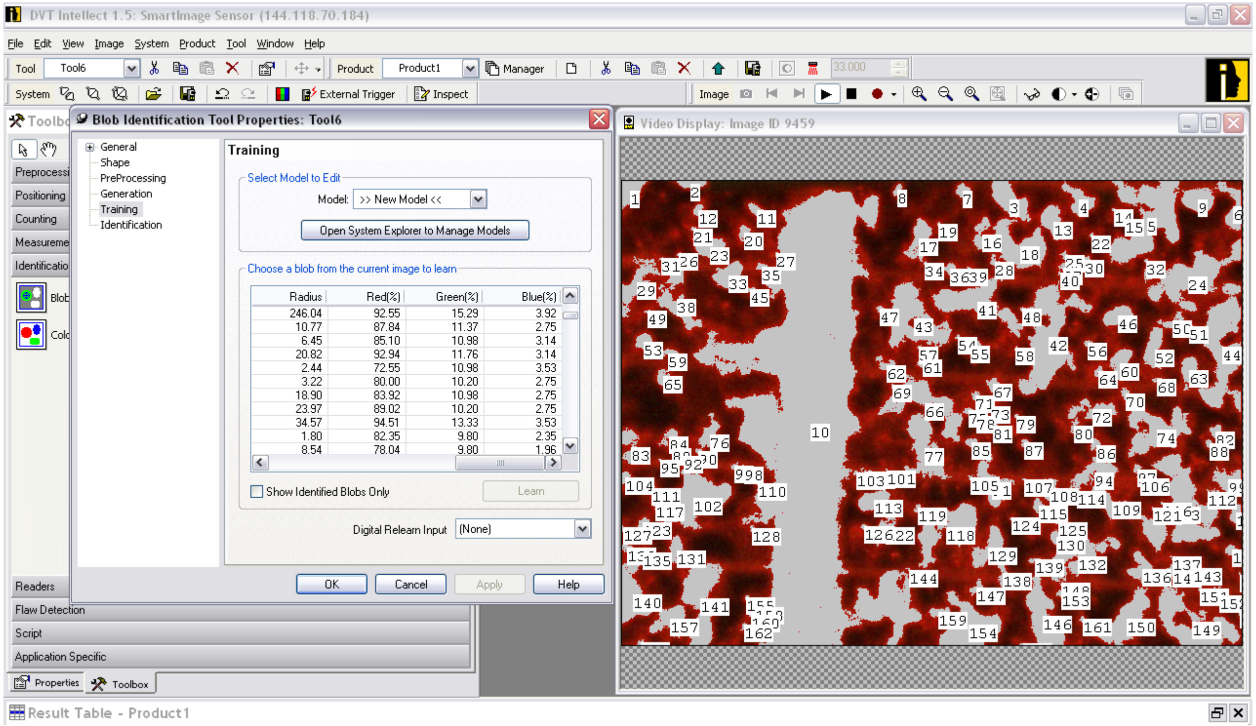


Figure 2: Characterization of grain size distribution can also be performed by various image processing utilities available in MATLAB and ImageJ software.

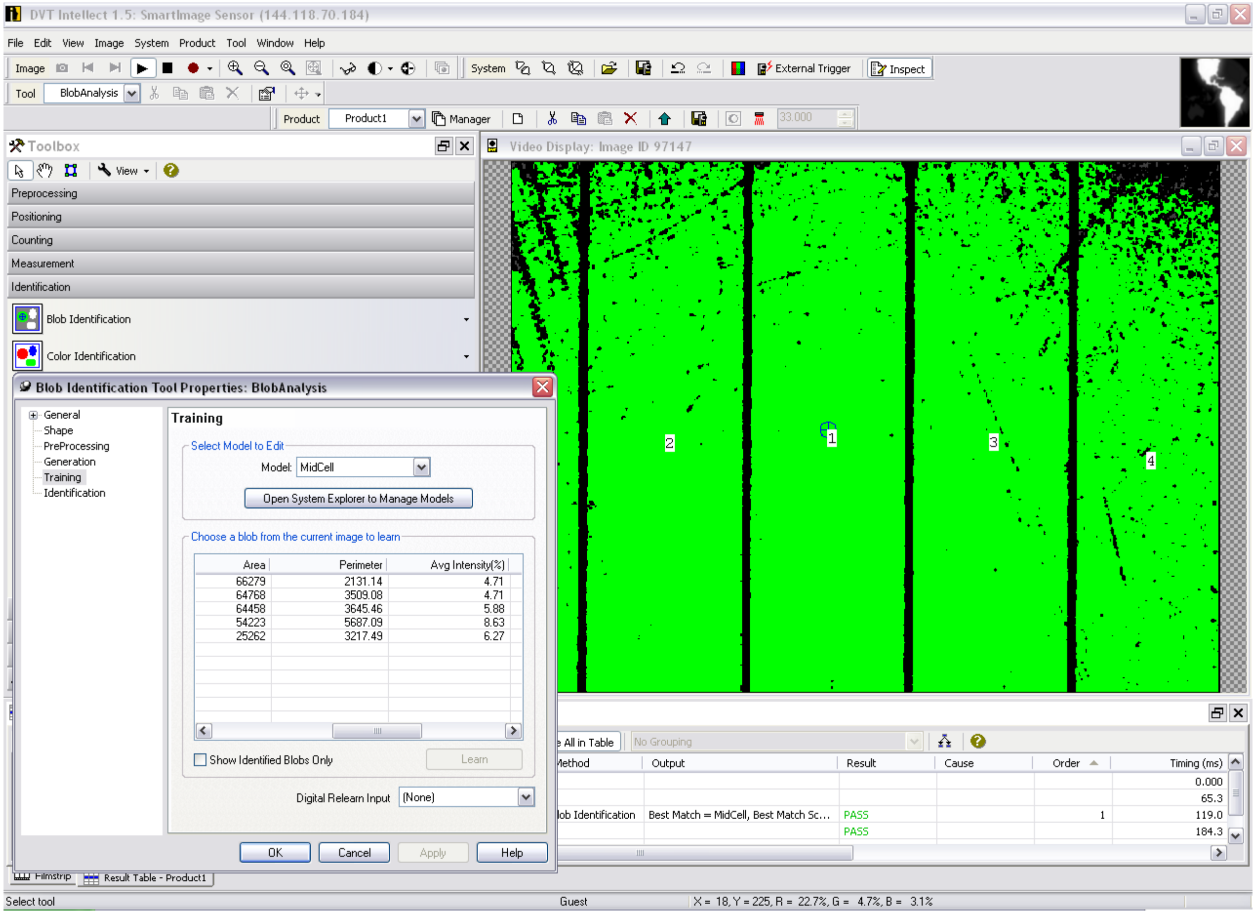


Figure 3: Many statistics of features revealed by imaging can be used as metrics for quality control and correlation with solar cell performance.

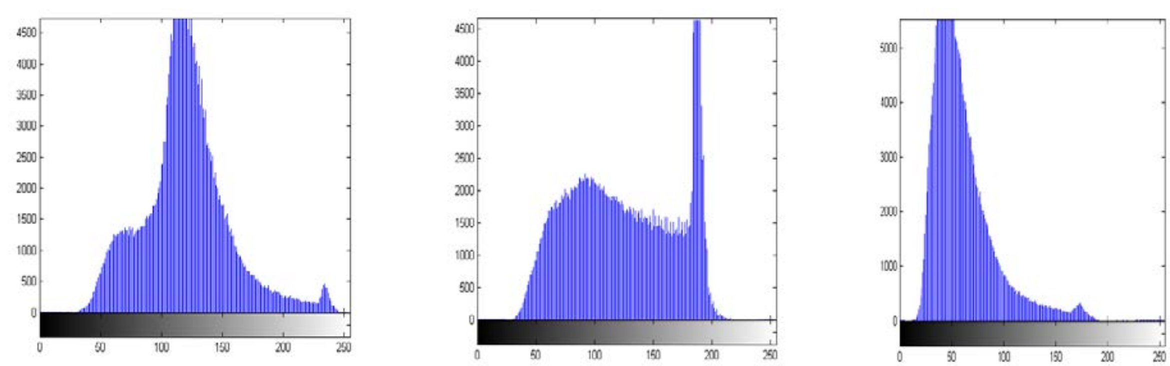


Figure 4: Histograms of pixel intensity distribution is a simple analysis for analysis of solar cells.

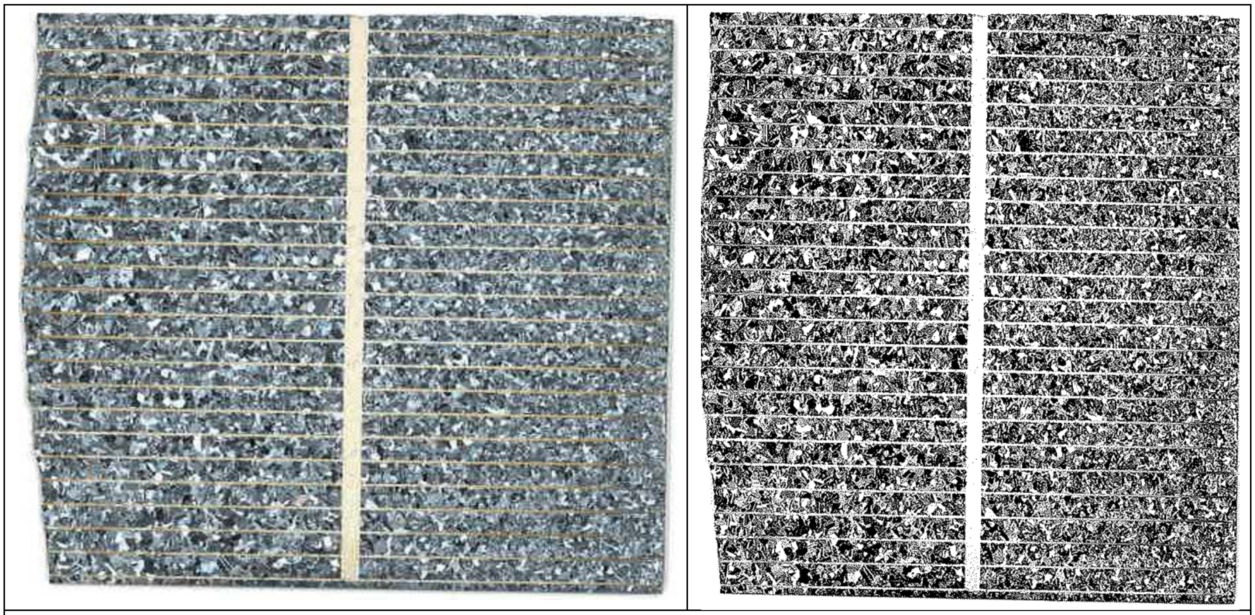


Figure 5: Scanned polycrystalline solar cell.

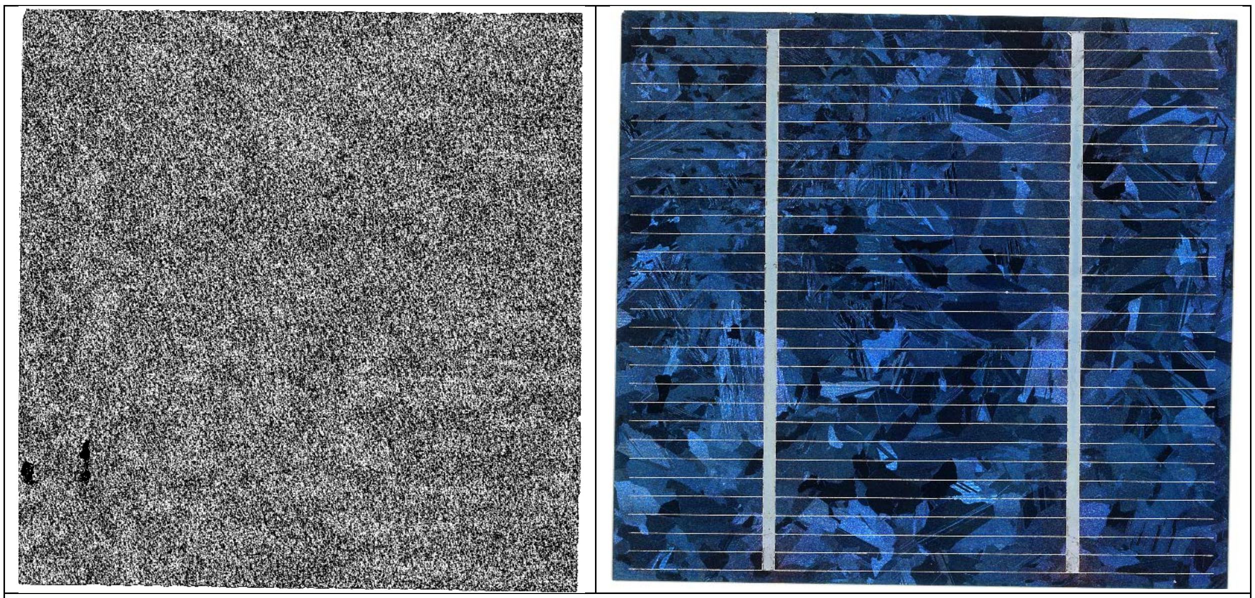


Figure 6: Scanned multicrystalline silicon wafer and solar cell made from similar.

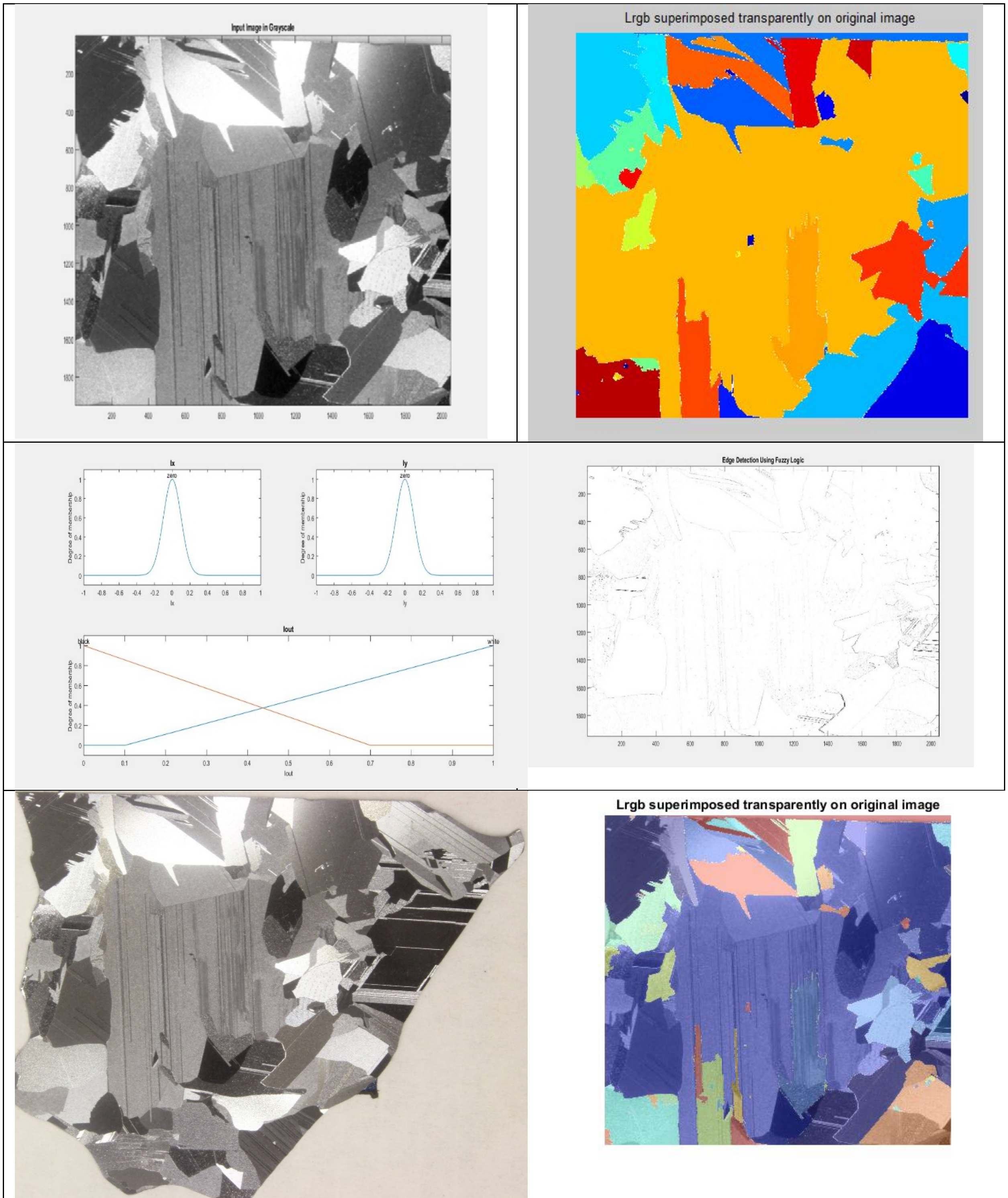


Figure 7: Image processing operations (filtering, edge detection) on solar cell images to characterize solar cells (size distributions, aspect ratios, and texture (preferred orientation.)

.

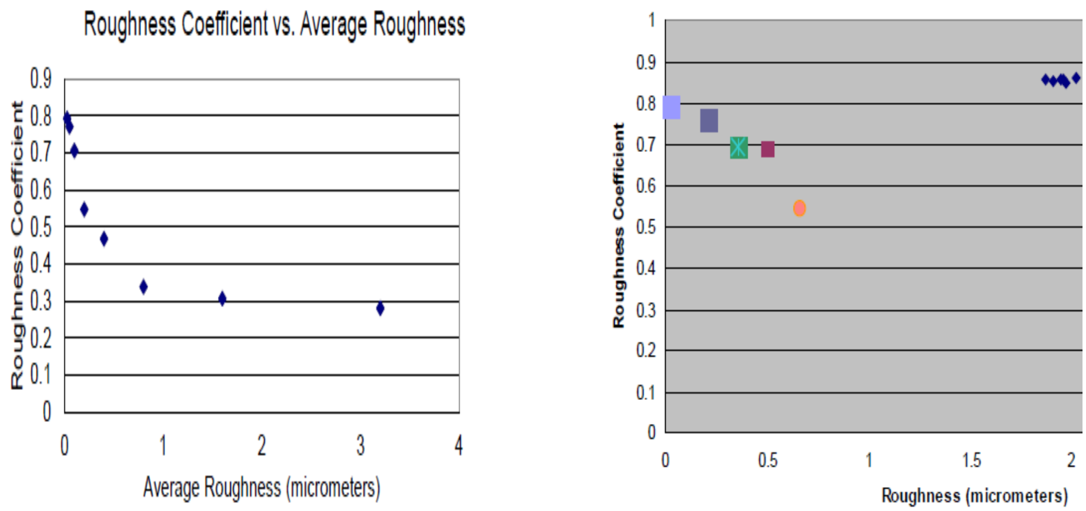


Figure 8: Relative variance or standard deviation of pixel intensity was correlated to surface roughness measured by surface profiling. Thus, image analysis in some instances can provide a useful non-contact method of surface roughness estimation.

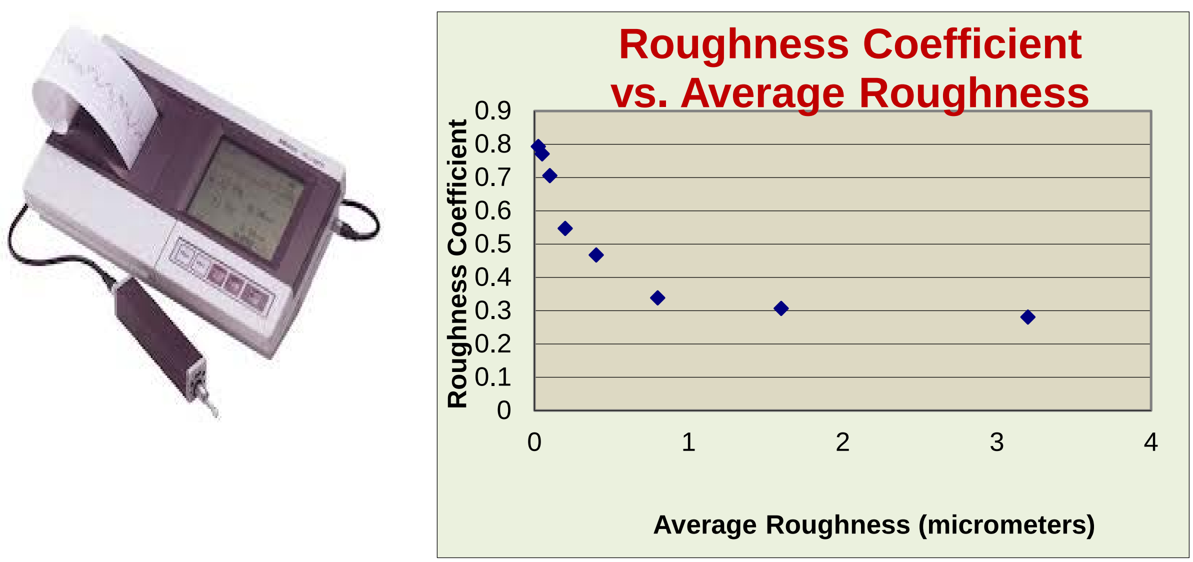


Figure 10: Stylus surface profiler and comparison of roughness measurements between laser scattering and stylus profilometer.

Laser Reflectometry for Surface Characterization

The reflection of an incident laser beam can be used to characterize the surfaces of solar cells. This data, as well as surface profiling with a stylus profilometer, can be used to validate the measurements and roughness estimates made by the CCD camera. A robotic scanner was used to move the laser surface roughness measurement device over the surface of the solar cell (**Figures 9** and **10**).

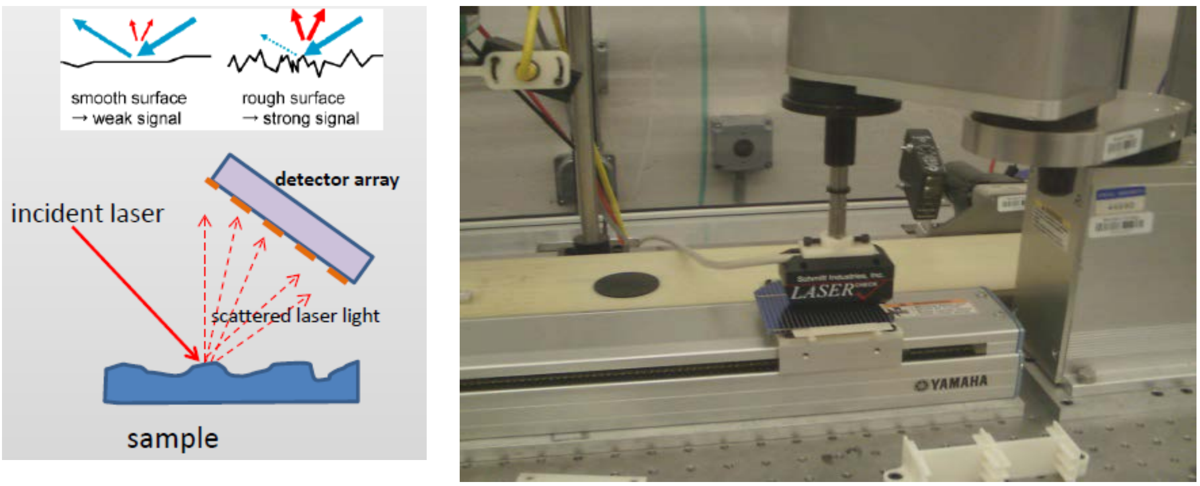


Figure 9: Laser reflectometry for surface roughness.

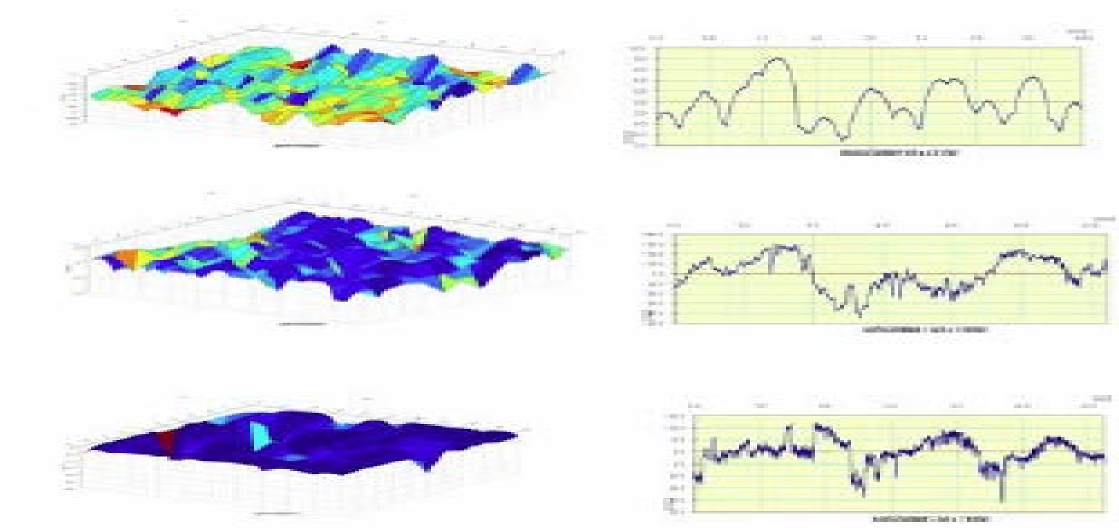


Figure 10: Scanning Laser Surface reflectance measurements over solar cell.

The image capture station was next adapted to a conveyer built system, where solar cells or wafers were conveyed under the camera to detect flaws (Figures **11** and **12**). A robot arm with a suction cup can pick up solar cells whenever image analysis indicates some anomaly or flaw. Solar cells can be sorted into bins based on criteria indicated by image analysis.

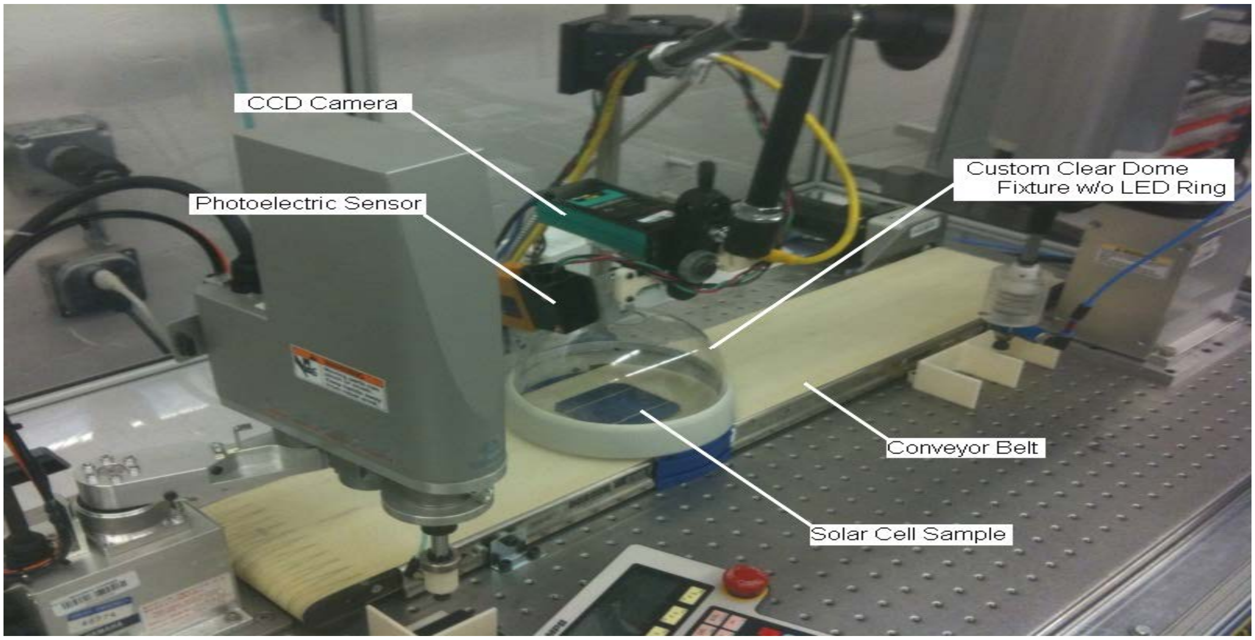


Figure 11: Incorporation of image capture on a conveyer belt system.

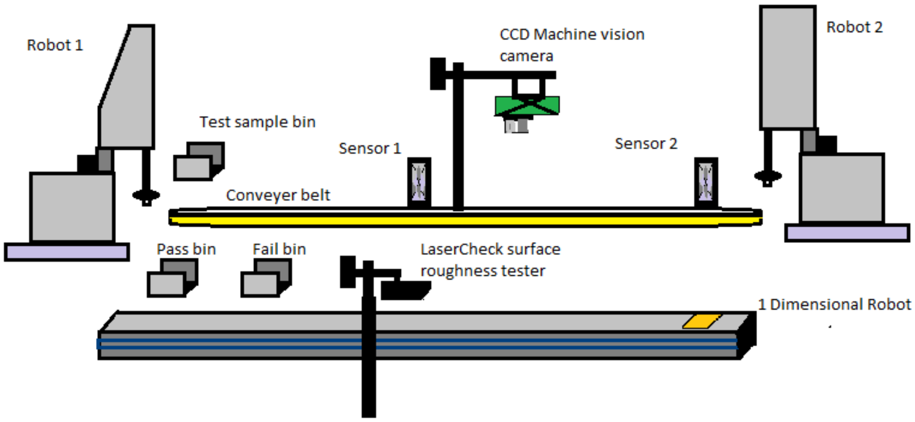


Figure 12: Schematic of conveyer belt solar cell imaging system.

Laser Scanning (Light-Beam Induced Current Imaging)

Light-beam induced current (LBIC) measurements are a useful diagnostic for analysis of solar cells. A light beam is scanned over the surface of the solar cell, and the photogenerated solar cell current is measured at each light beam position (*x,y*) on the front surface of the solar cell. A map of current generation versus position is thus produced. This localized solar cell current is a good indicator of defective regions (which produce reduced or no current) and general areal variation of material quality. Also, in multicrystalline solar cells, the grain boundaries are generally areas of diminished photocurrent generation and the reduction in solar cell performance due to grain boundaries can be assessed. Some types of grain boundaries are more detrimental to performance than others (often due to coupling with impurity effects as impurities tend to agglomerate at grain boundaries), and further, many solar cell manufacturing processes utilize grain boundary passivation techniques to varying degrees of effectiveness.

Conventional LBIC systems are relatively expensive and complicated. We implemented a simpler system by using a robotic arm to move a laser pointer in order scan the solar cell with a beam of collimated or focused beam of light (**Figure 13**). Simultaneously, an ammeter measures the solar cell current. Red, green, and blue lasers and comparison of their data can be used for more detailed analysis. The penetration of light into the solar cell depends on wavelength: blue light excites photocarriers near the top surface, and red light throughout the volume of the solar cell. Some scans of solar current vs. position of the laser are shown in **Figure 14**. As a senior design project, students designed and fabricated a low-cost laser scanner (**Figure 15**) using parts from a compact optical CD player and G-code software for CNC. Recently, very inexpensive (~ $100) laser scanner engravers are commercially available which may be adaptable to this application.

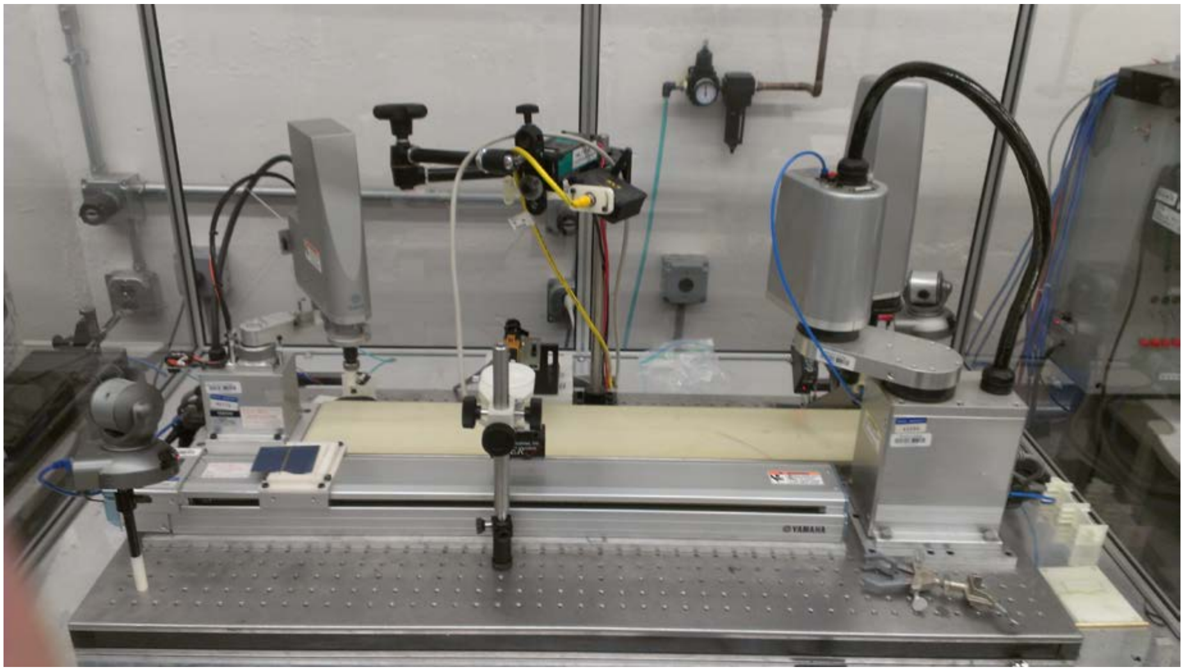


Figure 13: Robotic arm manipulating laser pointer for LBIC measurements that map localized solar cell photocurrent to position on the surface of the solar cell.

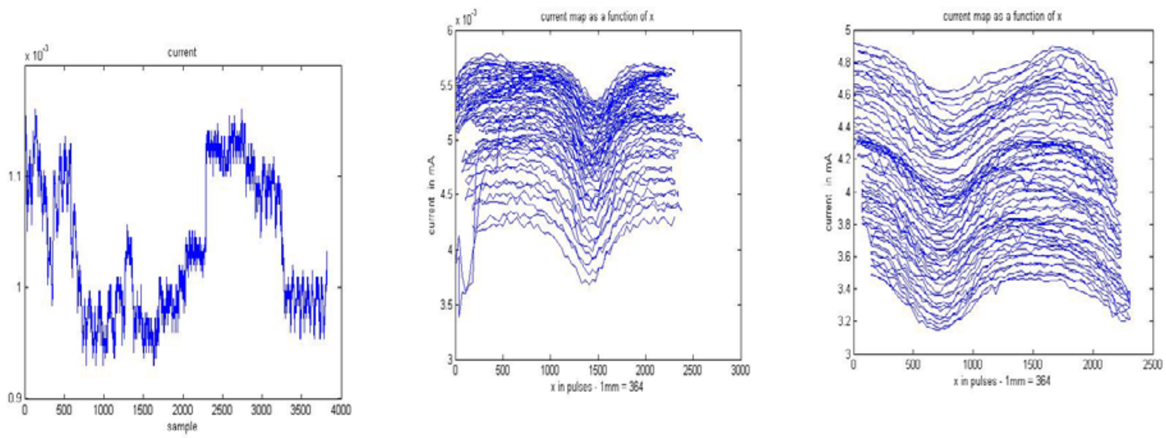


Figure 14: One-dimensional scans of solar cell (LBIC vs. position).

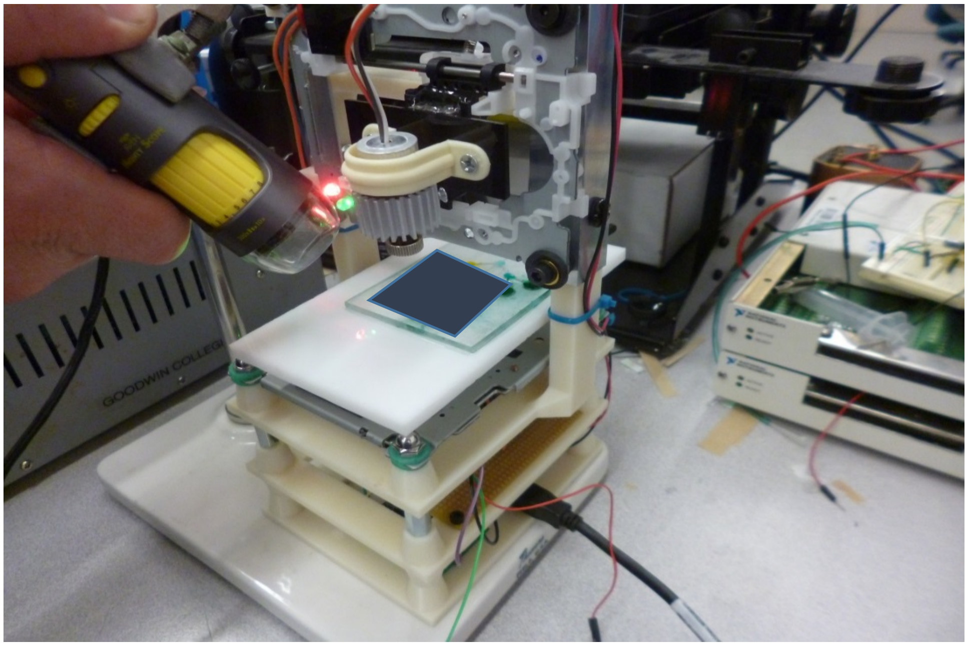


Figure 15: Laser scanner of solar cells.

Conclusion and Discussion

Solar cells and solar cell materials (e.g., multicrystalline silicon wafers) provide excellent vehicles for teaching image capture, processing, and analysis for materials and device characterization and quality control. Solar cells images, captured by simple CCD cameras with LED lighting, are rich in data that students can harvest using basic image analysis techniques provided by software such as MATLAB or ImageJ. These experiments are low in cost, and can be easily disseminated and supported by web-based resources. They are part of a larger effort whereby surface analysis tools for characterizing reflection, roughness, and cleanliness, are used as educational laboratories and projects in green manufacturing, image analysis, and quality assurance.

References

1. J. HAUNSCHILD, M. GLATTHAAR, M. DEMANT, J. NIEVENDICK, M. MOTZKO, S. REIN, and E.R. WEBER, “Quality control of as-cut multicrystalline silicon wafers using photoluminescence imaging for solar cell production” *Solar Energy Materials and Solar Cells* **94, 12** 2007-2012 (2010).
2. MICHAEL G. MAUK, “Image Processing for Solar Cell Analysis, Diagnostics and Quality Assurance Inspection” Ch **14** in *Handbook of Research on Solar Energy Systems and Technologies*, SOHAIL ANWAR, HARRY EFSTATHIADIS, and SALAHUDDIN QAZI, eds. (IGI Global Publishers, Hershey, Pennsylvania, 2012) pp. 338-375.
3. T. TRUPKE and W. MCMILLAn, “Photovoltaics: Photoluminescence imaging speeds solar cell inspection Laser Focus World 12, 6 (Dec 2010).
4. E.C. QUINTANA, M.A. QUINTANA, K.D. ROLFE, K.R. THOMPSON, and P. HACKE, “Exploring diagnostic capabilities for application to new photovoltaic technologies” Proc. 2009 34th IEEE Photovoltaic Specialists Conf. 002031-6