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Engineering Manufacturing Education: Solar Cell Analysis and Diagnostics Using Scanning and Imaging Techniques

Dr. Michael G Mauk P.E., Drexel University

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

Dr. Richard Chiou, Drexel University (Eng. & Eng. Tech.)

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.

Mr. Carlos Michael Ruiz, Drexel University (Eng. & Eng. Tech.)
Ms. Carol Jeanice Martin
Mr. Smarth H Chadha, Drexel University (Eng. & Eng. Tech.)

Engineering Education: Solar Cell Analysis and Diagnostics Using Scanning and Imaging Techniques

Summary: Solar cells serve as an instructive case study for introducing students to image-based and scanning probe analysis methods useful for photovoltaic, solid-state lighting, displays, and many other thin-film and energy conversion technologies that require large area scale-up for commercialization. We describe the use of CCD (visible) image processing, laser scanning, and infrared thermography of monocrystalline and multicrystalline silicon solar cells to reveal various microstructure features that directly impact solar cell performance. These experiments can be used in materials science, semiconductor devices, quality assurance, and machine vision courses to demonstrate the connections between microstructure and materials functions, particulary as they related to electrical and optical applications.

Introduction

Photovoltaic solar cells are semiconductor-based optoelectronic devices that convert (sun) light energy directly into electric power. Solar cells are now an established and important technology for renewable electricity generation, and are making a substantial and increasing contribution to world energy needs. Global photovoltaic generating capacity increased by 50% from 2015 to 2016, and the cumulative installed capacity now exceeds 300 Gigawatts, enough to supply about 2 percent of the world's total electricity consumption [1]. Based on these trends, photovoltaic science and engineering merit coverage in undergraduate STEM education.

Moreover, photovoltaic solar cells and related supporting science and technology are readily-accessible and effective vehicles for interdisciplinary instruction in optics, semiconductor materials and electronic devices. In addition, thermal imaging of solar cells (in operation) provides convenient demonstrations of the practice and utility of infrared cameras for research, process control, and quality assurance. Here we report student projects to develop solar cell analysis and diagnostics techniques that are instructive introductions to solar cells and their operation.

Improvements in solar cell performance and reductions in manufacturing cost will foster even wider use of solar cells. These aims are served by various methods of solar cell analysis and diagnostics, which informs the design, materials selection, manufacturability, quality, and reliability of solar cells and solar cell-based products. A simple evaluation of solar cells involves measurements of electrical operating characteristics such as photovoltage (open-circuit voltage), photocurrent (short circuit current), current-voltage characteristics include diode or *fill-factor*, output power (efficiency) under uniform illumination with sunlight, light sources that approximate the solar spectrum, Solar cells are an important renewable energy technology and serve as an instructive case study for educational demonstrations and exercises in materials science, thin films and optics, machine vision, quality assurance, manufacturing science, and process control. Most simply, small (~1 cm^2) solar cells can be characterized by point measurements such as open-circuit voltage, photocurrent, efficiency, and spectral response. However, solar cells, including large-area devices (~ 100 cm^2) and modules, can be analyzed in much more detail by scanning and probing the solar cell to map the localized electrical and optical characteristics and performance in two dimensions. Here we describe the adaptation of an inexpensive (~$100) desktop laser engraver and a low-cost CCD camera for 2-D profiling of solar cells based on light-beam induced current, spectral response, surface roughness topography, grain structure and texture, and reflectivity. We also use a thermal camera for imaging hot spots and temperature surface variations in solar cells as a function of electrical current. Thermal imaging can reveal various defects and materials-related inhomogenieties that degrade solar cell performance. These methods give students hands-on, project-based learning activities for developing analytical tools used in research and development, manufacturing, and reliability for diverse industries including electronics, optics, displays, coatings, thin-film technology, solid-state lighting, and catalysts.

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Areal uniformity is critical in large-area devices such as solar cells, solid-state lighting, flat panel displays, imagers, as well as various coatings, thin film structures and solid materials such as filtration media, catalysts, adsorption media, and electrodes. In fact, the successful commercialization of solar cells, new lighting technologies, fuel cells, and batteries may depend on the ability scale-up laboratory prototypes to large-area products in high-yield, low-cost manufacturing processes. Tools based on imaging and two dimensional probing will be very useful for process control, quality assurance, and reliability studies.

Multicrystalline solar cells are particularly interesting due to the intricate grain structures [2-6] which results from the details of the casting process used to solidify silicon ingots from which the silicon wafers are cut. The silicon wafers are processed into solar cells using emitter junction phosphorus diffusion step, screen printing of front and back metal contacts, and coating with an anti-reflection layer.

Image Analysis and Machine Learning for Solar Cells

Image capture, processing, and analysis of solar cells can be quite revealing and informative. A consumer or laboratory-grade CCD camera, or a USB microscope (e.g., Dino-Lite™, ~$100) can be used to capture images of the silicon wafers, completed solar cells, and solar cells in various stages of fabrication. **Figure 1** shows two typical solar cell structures. **Figure 2** shows more detail of grain structure. Grain boundaries are essentially areas of extended defects and are expected to show localized reductions of light-generated current (photoexcited carriers are lost at defects before they can migrate or diffuse to the metal grids and contribute to the external current of the solar cell.)   The severity of such grain boundary losses is highly variable, depended on grain size distribution and relative orientation of neighboring grains, as well as a host of processing conditions.   Therefore, it is informative to characterize the solar cell in view of its grain structure. **Figure 3** shows smaller and more computational manageable (200 x 200 pixel) subimages, corresponding to about 0.5 x 0.5 cm^2 of the solar cell.

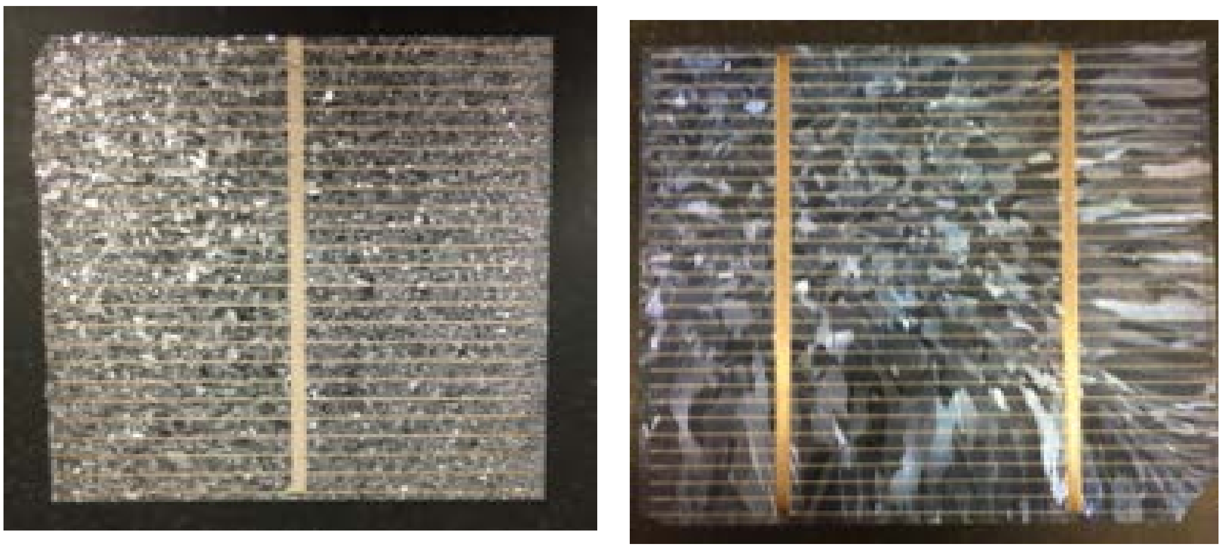

Figure 1 Multi-crystalline silicon solar cells. 10-cm x 10-cm solar cells are made from wafers cut from solidified silicon ingots. (**left**) fine grain pattern, with one busbar and fine grid lines; (**right**) equiaxed and columnar grain structure with fine grid lines and two busbars.

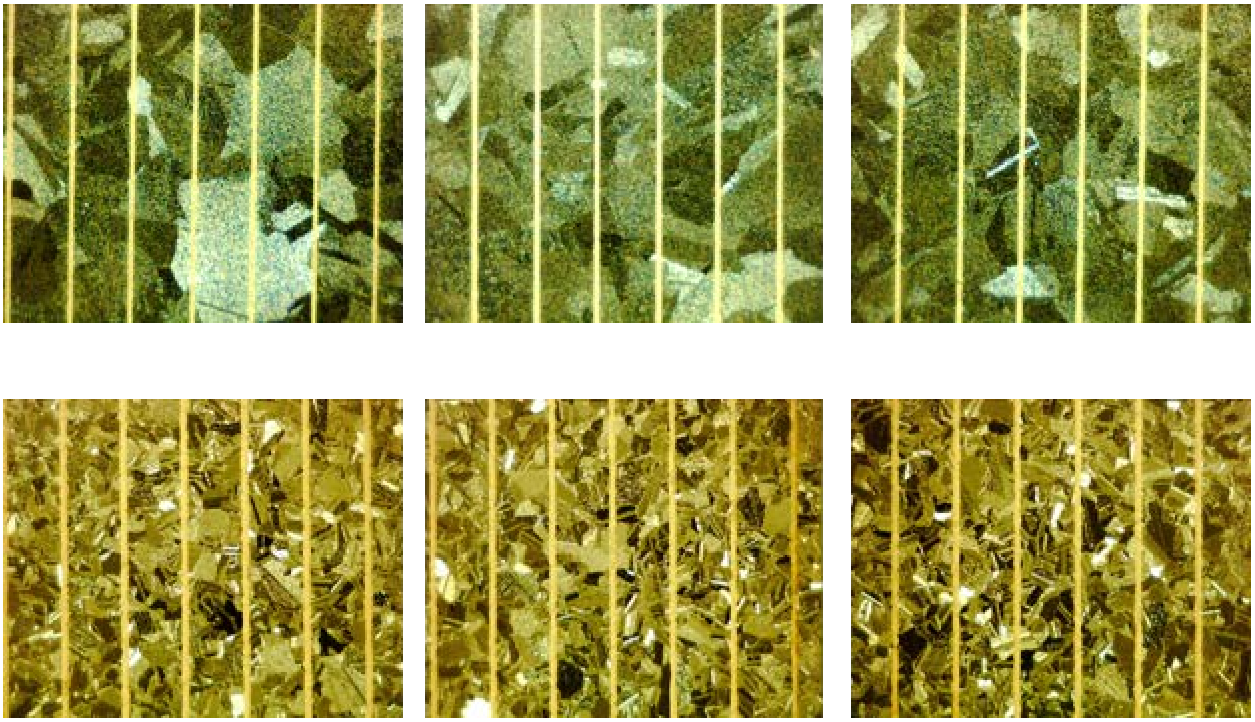

Figure 2: Closer details of grain structures of silicon solar cells showing typical size distributions and texture (orientation distribution).

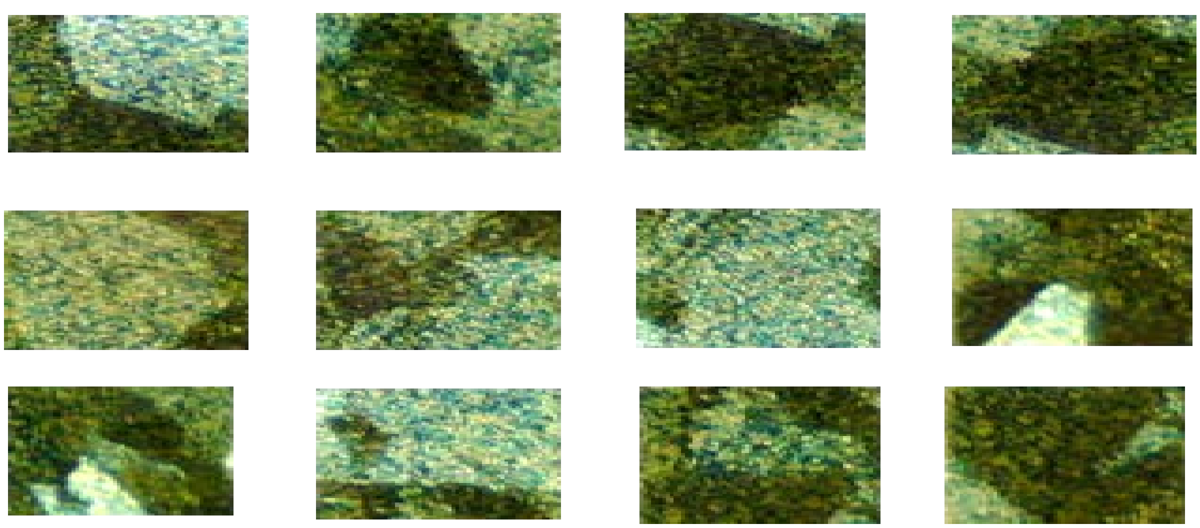

Figure 3: Sample Subimages (200 x 200 pixels)

Images can be processed with MATAB® or ImageJ (freeware) image analysis software. In MATLAB, images are converted to black and white using grey threshold, from which edges (boundaries) of the grains are found using a Canny filter (along with imfill) to connect any broken sections. **Figure 4** shows skeletonization of grains for which analysis can estimate the grain Size and Density. **Figure 5** shows a setup using a red (632.8 nm wavelength) HeNe laser that can illuminate the solar cell with a ~1-mm diameter spot so that the response of small regions of the solar cell can be probed corresponding to the subregions for which image analysis is made. The photocurrents from each subarea are correlated against the number of grains and/or average grain size (**Table 1**).

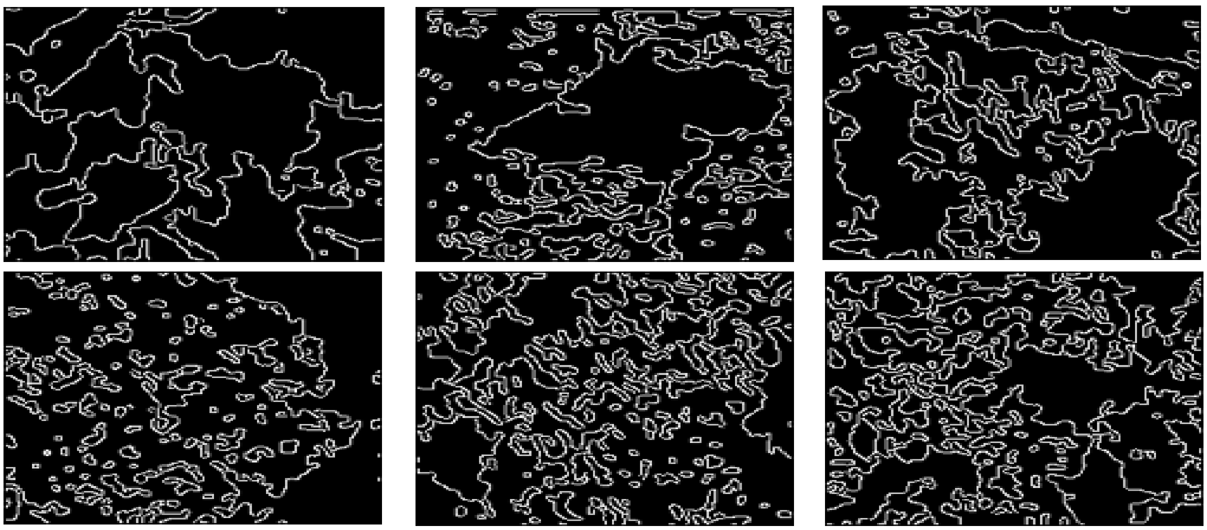

Figure 4: Skeletonization of grains in polycrystalline silicon.

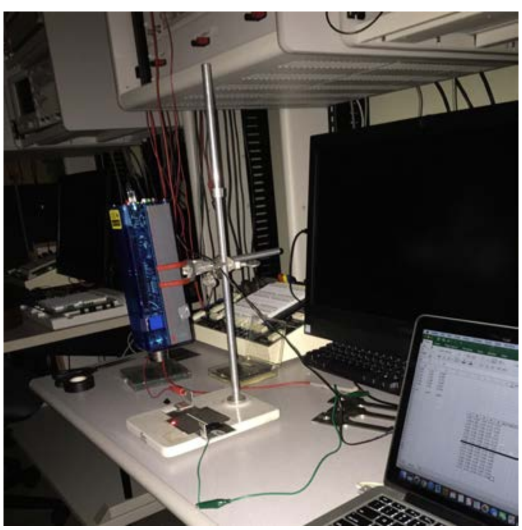

Figure 5: Simple laser (HeNe red) laser system for measuring local photocurrent in silicon solar cell.

Image	**Number of grains**	**Avg grain size (µm)**	**Photo-Current (mA)**
1	336	338	0.112
2	258	347	0.162
3	286	339	0.165
4	230	313	0.157

Table 1: Correlation of measured photocurrent with number of grains and grain size.

There are numerous simple image processing and extensive open-ended projects students can perform to correlate grain texture with solar cell performance.

Laser Scanning of Solar Cells

We constructed a laser scanner for LBIC (light-beam induced current) measurements from a hobby X-Y tabletop engraver (~$100) with two stepper motors that move a laser held in a bracket over the solar cell (Figure **6**). The step size in both directions is 0.125 mm. The laser position (*x*,*y*) is programmed by an Arduino microcontroller, to execute a raster scan. The x-y actuators pause at each step, and a current measurement of the solar cell is made using an Agilent 34401 digital multimeter. The lasers are collimated through a small aperture through a bottom support bracket such that the laser illumination spot is about 1 mm. Three interchangeable 12-volt laser modules are used (Laserland, Inc.): 200-mW 445-nm blue ($90), 300-mW 637-nm red ($45), and 800-mW 940-nm infrared, so that scans can be made at three different wavelengths. Blue light penetrates about 1 micron into the solar cell, while infrared light penetrates completely through the solar cell (~500 microns), creating photocarriers through the bulk of the solar cell. Thus, changing the 'color' of the laser scan can resolve defects by depth in the solar cell.

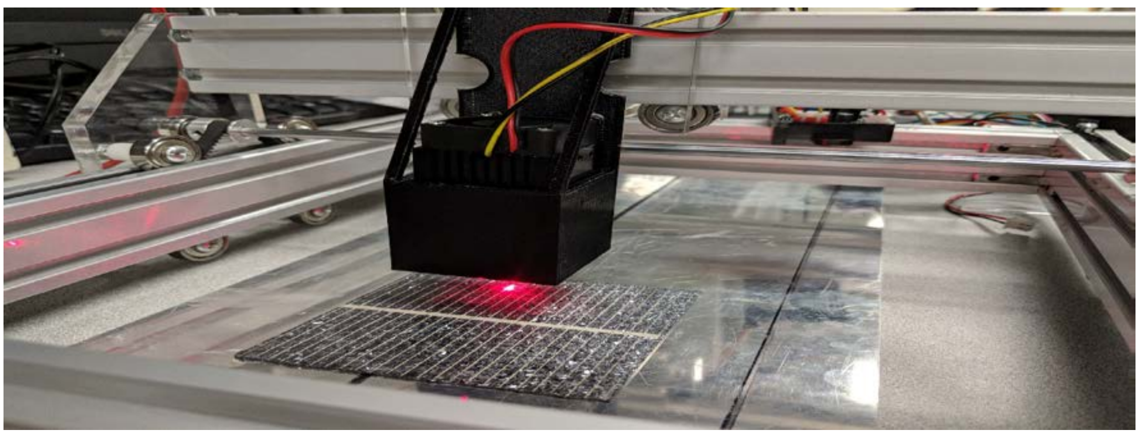

Figure 6: Custom made laser scanner for light-beam induced current (LBIC) measurements of solar cell.

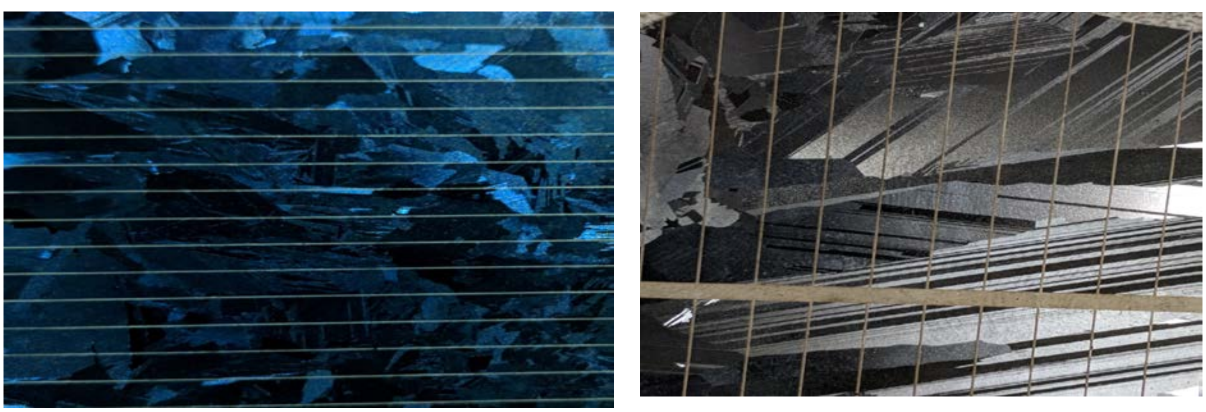

Figure 7: Examples of multicrystalline silicon solar cells used in laser scanning LBIC analysis.

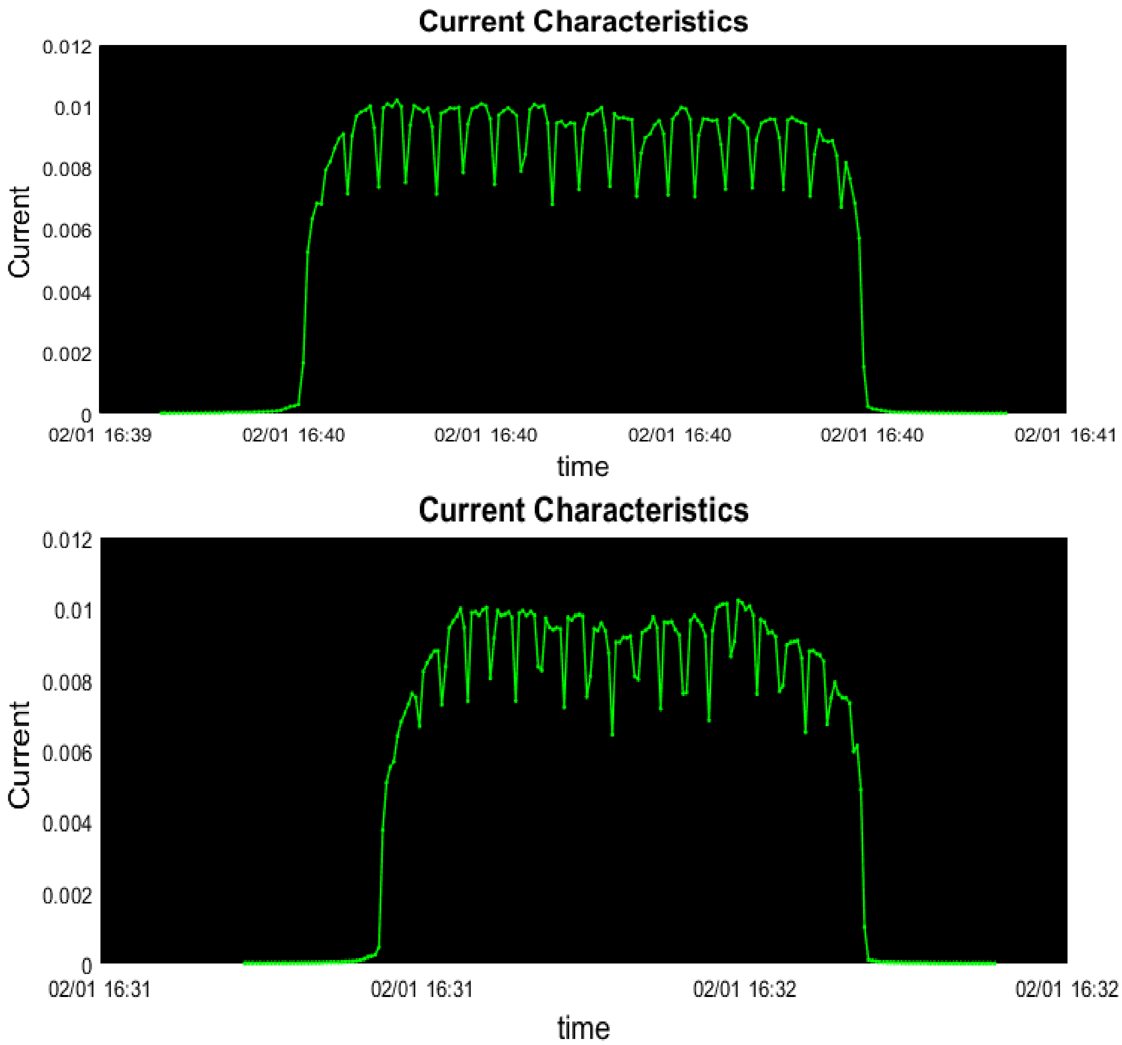

Figure 8: One-dimensional scan showing photocurrent for linear scan across solar cell. Dips are due to grid lines.

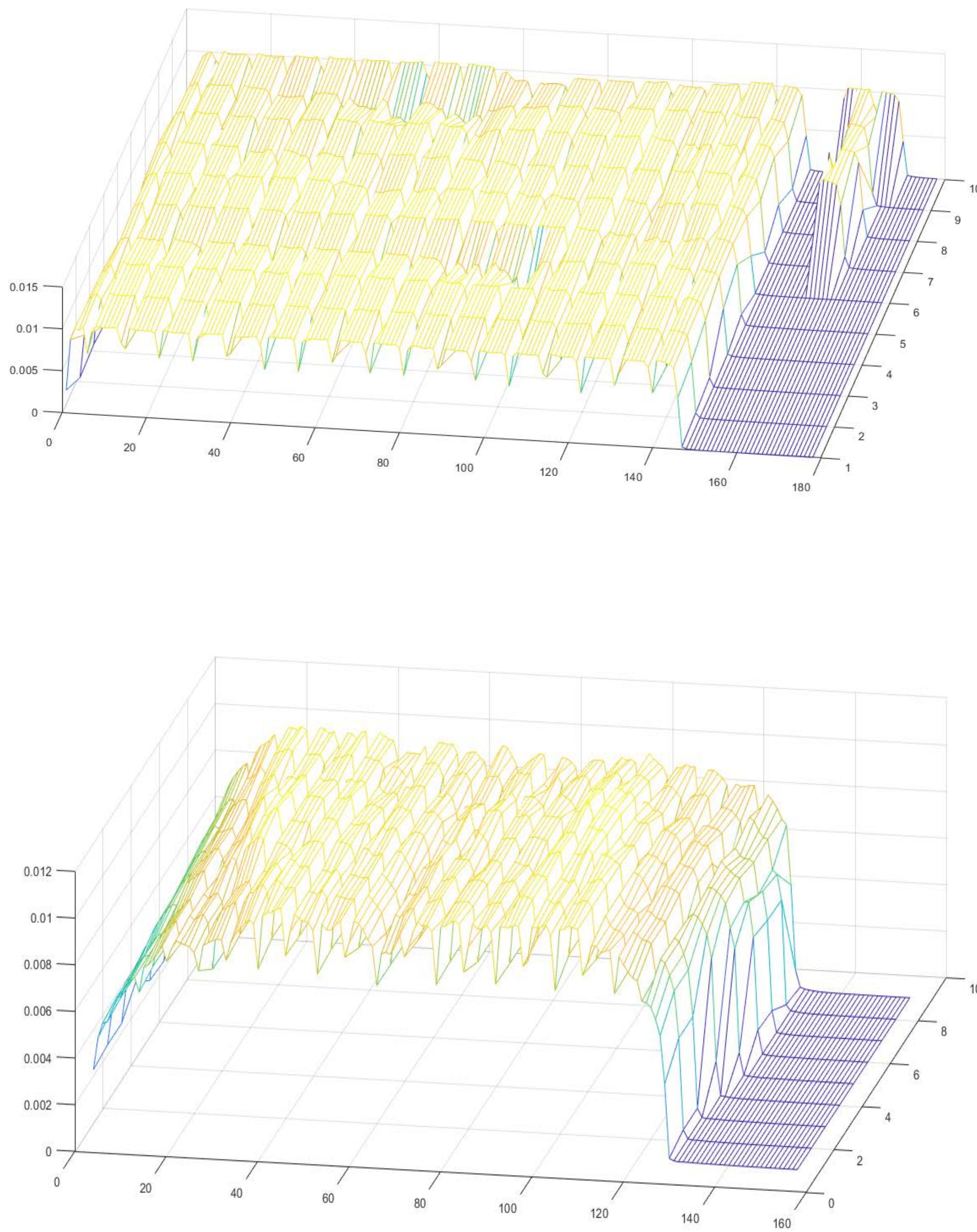

Figure 9: Examples of current as a function of *x*,*y* position for solar cells from red light laser scanning. Single scans make a composite 3-dimensional plot.

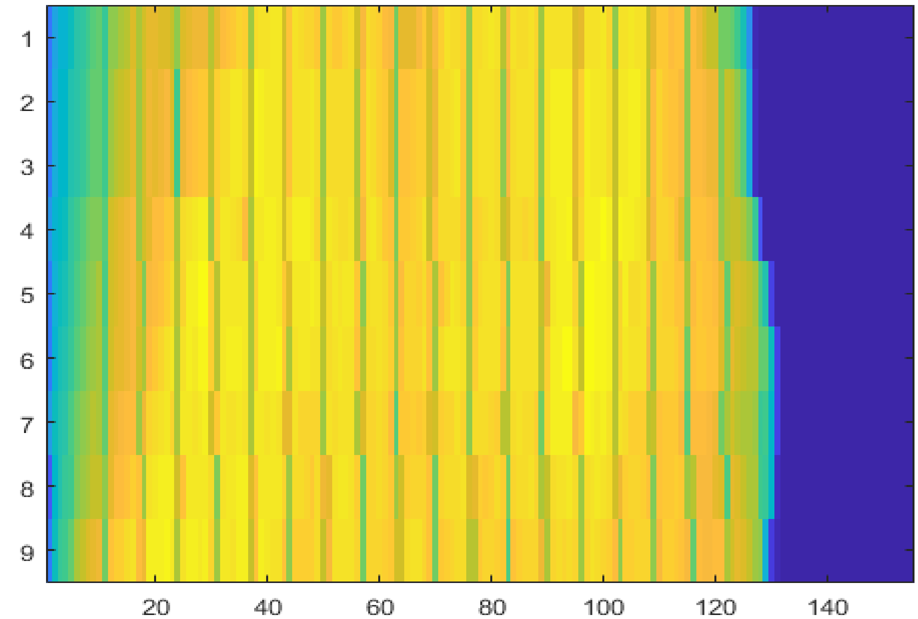

Figure 10: Colored rendered light-beam (red laser) induced current map of solar cell.

Thermal Imaging of Solar Cells

We forward-biased (1 to 3 volts) the solar cells with dc power supply, resulting in current levels of 1 to 10A and made thermal images using a FLIR 320 infrared camera (**Figure 11**). The main idea is that many types of defects are shunting with high current and localized heating and elevated temperature. **Figure 12** shows some of the thermal images from solar cells. These images are correlated with laser scans and CCD images.

Figure 11: Thermal imaging with a FLIR infrared camera.

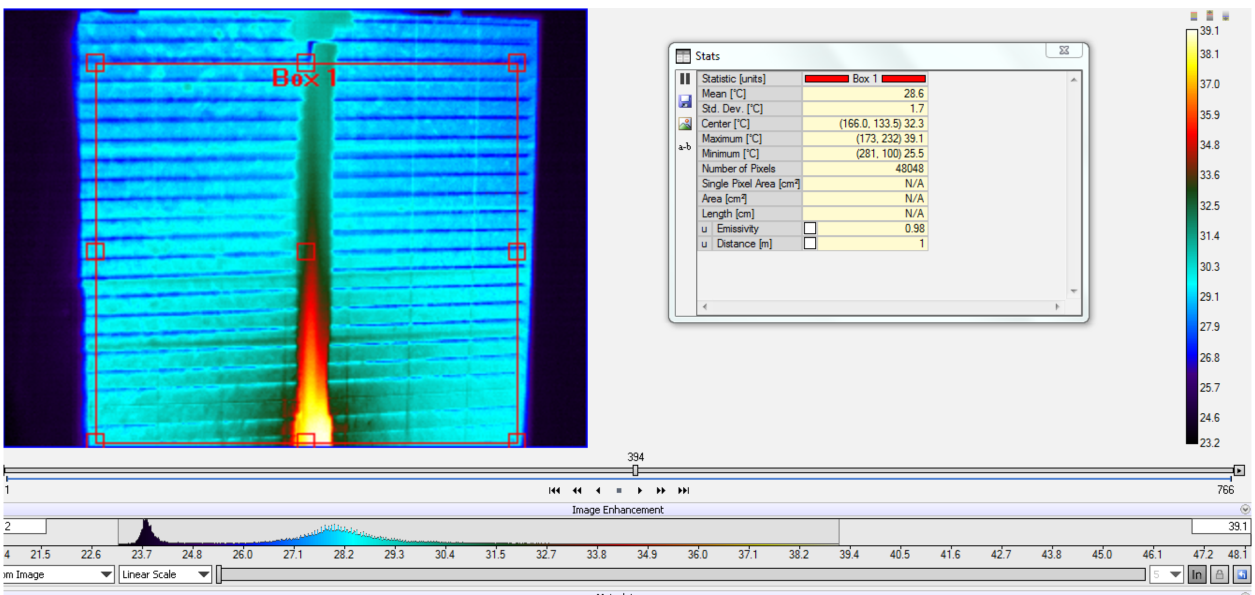

Figure 12a. Thermal image of solar cell under forward bias.

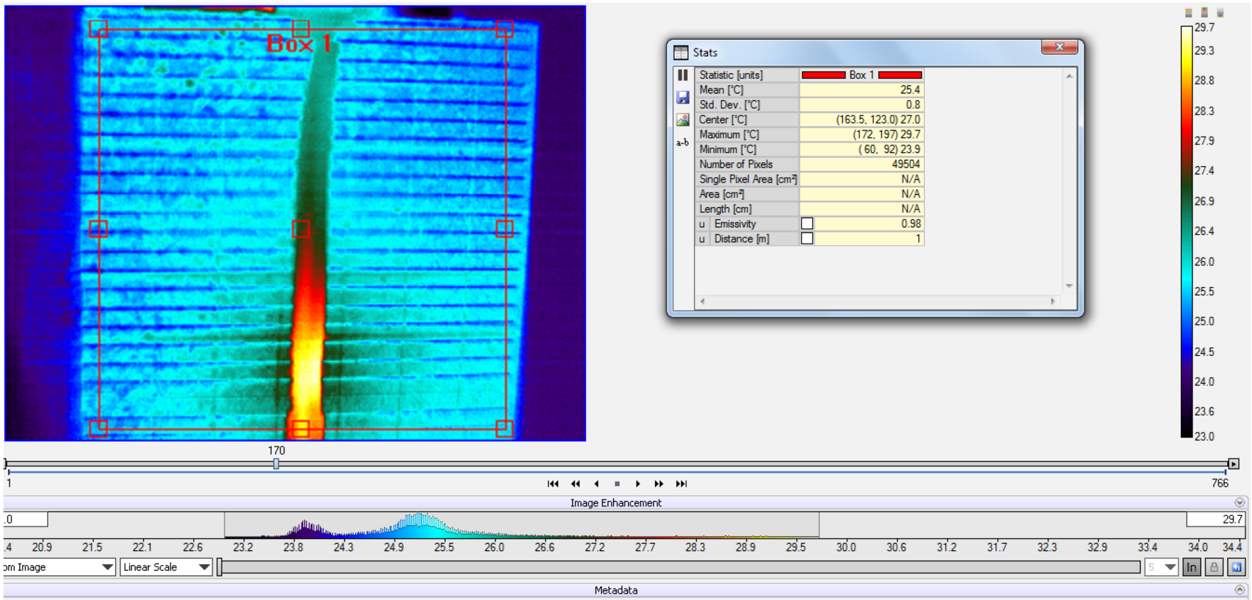

Figure 12b. Thermal imaging of solar cells (cont).

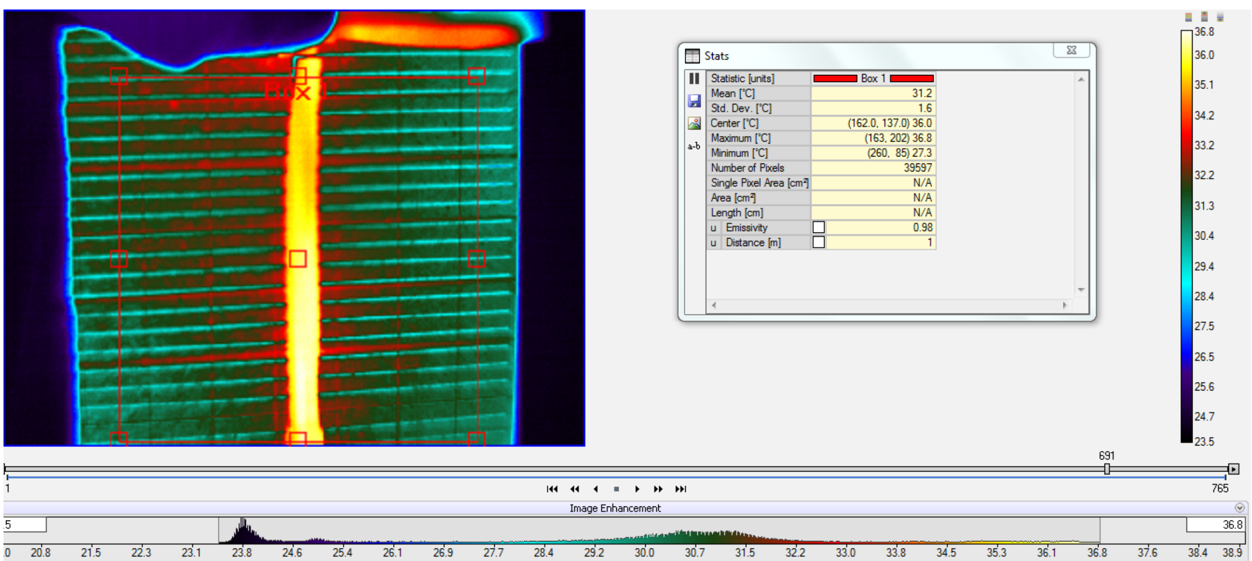

Figure 12c. Thermal imaging of solar cells (cont).

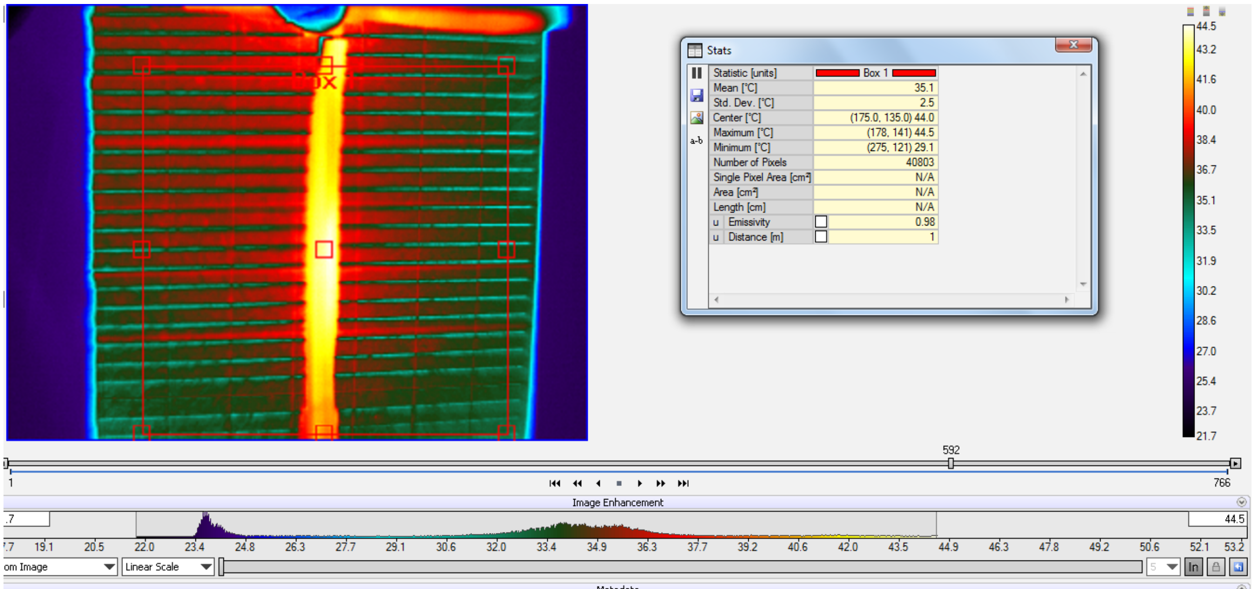

Figure 12d. Thermal imaging of solar cells (cont).

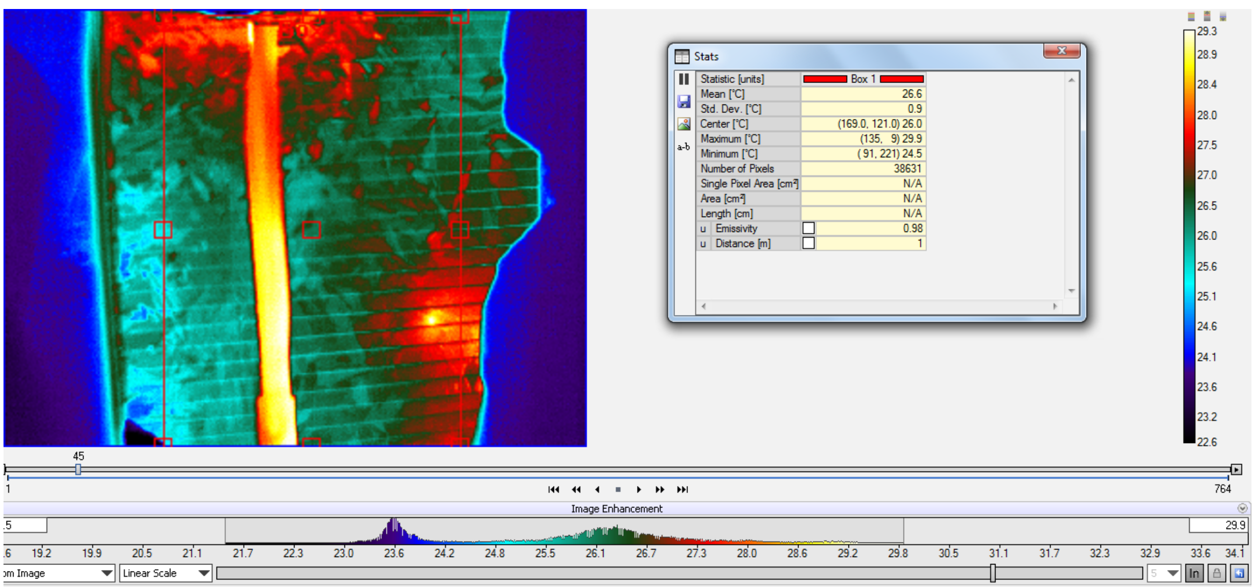

Figure 12e.

Educational Implementation

This work was developed and performed by undergraduate and graduate engineering students in Engineering Technology, Electrical Engineering, and Biomedical Engineering as special problems and student research projects. Dissemination of this work is planned as follows. We will develop laboratory modules (2 to 3 hour session) for combined imaging, thermography, and laser scanning in courses for materials science, renewable energy, measurements, and quality assurance. We are also developing topics for Senior Design Projects and undergraduate independent study. This work offers opportunities for students to work with image processing and analysis that are closely connected to materials performance. The CCD camera (~$100), the thermal camera ($2000 to 10,000 depending on its resolution) and the laser scanner (constructed from less than $400 in parts) are low in cost. These experiments can be done on the desktop, are safe, generate no waste or disposal problems, and require almost no consumables. Thus, they make minimal demands on the resources of educational institutions. Further, much of the analysis work can be done outside of the lab and at home using widely available computer software. We believe these labs would be productive components of on-line courses, where students could be given access to files of images and laser scanning data for analysis at their convenience. Experiments can be demonstrated on videos, or, video imaging can be done using remote computer access to the samples. One task should be comparing and correlating information by the three methods described here. This work can be applied to other thin-film as well as nanotechnologies where areal effects and uniformity are important. Students learning will be assessed in the framework of our course evaluations, including program educational objectives and pre- and post-testing, and self evaluations and surveys. Results will be presented at ASEE Conferences, where we will report in sufficient detail descriptions and operations for dissemination to other schools and institutions.

Discussion and Summary

This report has described simple techniques for probing solar cells as images and two-dimensional maps, and briefly discussed the wealth of information that is accessible to students using inexpensive and easy-to-operate systems. Solar cells provide a convenient and informative object of study for imaging, laser scanning, and thermography due to the variety of microstructures and their impact on readily measured performance parameters.

References

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