NIR Trends: Maximizing Solar Cell Yield and Efficiency with Machine Vision

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As the first decade of the 21^{st} century draws to a close, the easy oil has been harvested and each new barrel will be more expensive to pull from the ground. With world demand for energy still expanding, and the impact of burning carbon based fuels burdening the atmosphere, the development and installation of efficient renewable energy sources has become crucial. Paramount to the widespread adoption of renewables is the need to lower their associated installation and production costs.

Solar energy has the best potential to help as it is by far the biggest source of renewable energy[i]; the amount of energy landing on the Earth's land mass is >2700 times the world's consumption of energy (est. 2004).[ii] However, photovoltaic solar cell production has been too expensive and cell conversion efficiencies too low. Thus, the cost of solar cell electrical output has been and remains too high to compete with mature fossil-fuel-based energy sources. While researchers are experimenting to boost conversion efficiencies of several competing PV cell types, manufacturers are working hard to reduce the production costs of the cell types that can more readily ramp up into volume production. Machine vision is one of the key tools that manufacturers are using to improve the cell uniformity and efficiency, thereby improving yield and driving down the cost of each cell.

Un-cooled indium gallium arsenide (InGaAs) detectors are particularly suited to help in the effort to improve several renewable energy sources. In the wavelength sensitivity range of InGaAs detectors, silicon (Si -the prime material for most solar cells made today) becomes transparent, and light scattering is reduced. In addition, by applying forward bias across the cell terminals, silicon and other PV cell materials will emit light that InGaAs detectors can detect. This light is described by spectroscopists as part of the near infrared (NIR); it is described by infrared detector companies as part of the short wave infrared (SWIR) range. InGaAs imaging technology plays an important role in many renewable energy applications.

- InGaAs-SWIR detectors are being used in LIDAR systems using eye-safe lasers, to map wind currents for placement of wind generators
- Inspection systems use SWIR detection to image inside crystalline silicon ingots (or boules) to find voids, inclusions of foreign material, and other gross defects before sawing the boule into thin-film wafers for solar cells. Many defects are then avoided, thus optimizing the yield from each ingot.
- Polarization imaging systems outfitted with InGaAs detectors easily find cracks and potential failure nodes within silicon wafers, films, cells, and finished modules. These systems use polarized light to map the stresses induced by cracks, chips, or processing anomalies.

- In electroluminescent imaging systems, InGaAs cameras easily capture the glow emitted by the photovoltaic junction of the solar cell under forward bias conditions. Operating at video rates, SWIR-InGaAs cameras image the glow from within the cell, thus revealing any non-uniformity in photodiode junction or in the associated optical layers above. This helps cell manufacturers, panel manufacturers, and solar system installers to screen out weak cells. The cameras can also detect developing problems in older cells that might be a result of poor or decaying seals and they can assist in matching cells of similar efficiencies. The latter application is important in order to obtain the highest power output from solar modules and panels and to improve the reliability of the whole solar energy generation system.

In the following section, we will illustrate the electroluminescent application with SWIR images captured from small solar panels, and we will discuss the results relative to imaging in other wavelength bands.

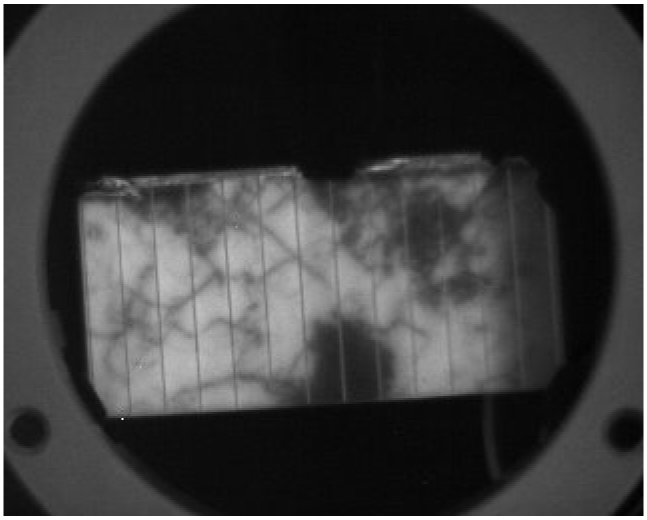

Figure 1 – SWIR video of a small cell biased into electroluminescence by a function generator pulsing at 1 Hz.

Figure 1: Photovoltaics - Solar Cell EL Inspection at 60fps shows a movie of a small solar cell section being driven to luminance by a square wave pulse from a function generator running at 1 Hz. The image was captured under dim lighting conditions with the high-sensitivity Goodrich InGaAs KT camera, using high gain with 16 ms exposures while recording at 60 frames per second (fps). Note the structure evident in the luminescent image, including the obvious dead areas.

Cooled silicon CCD cameras are offered by some companies to capture similar images, but they require long integration times in complete darkness. This limits their usefulness in a production cell screening process. (All of the images in this article were captured with 320 x 256 pixel resolution; for higher resolution or more field of view, Goodrich also offers 640 x 256 cameras.)

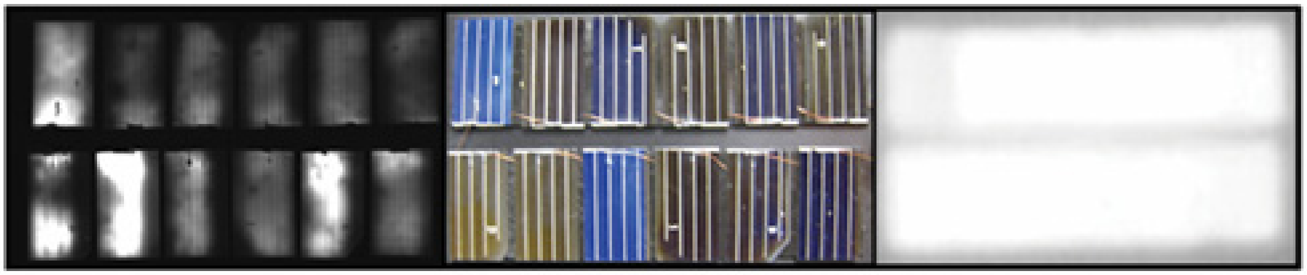

Figure 2a (left) – SWIR image of a small panel of 12 solar cells connected in series and biased at 7.6 V at 80 mA and acquired with a Goodrich SU320KTS-1.7RT Camera. Figure 2b (center) – Color camera image of the same panel of 12 cells. Figure 2c (right) – Microbolometer image of the same panel of 12 cells camera.

Figure 2a shows a panel of 12 cells wired in series, with the SWIR image revealing large variations among and within individual cells. The bright areas directly correlate with cell responsivity. This was demonstrated by measuring the short-circuit current from the panel while illuminating portions of a cell with a multi-mode fiber coupled to a quartz-halogen-tungsten (QHT) lamp. The cell non-uniformity revealed in these images is important to the cell fabricator, as it reveals defects or processing variations in the bulk material or in the junction layers or even in the optical coatings applied in the manufacturing process.

The average luminescent difference between cells is also important to the module or panel integrator. At a glance, one is able to see that the panel in Figure 2a has cells of three or four different average efficiencies. When collecting solar power, the energy from the most efficient cells will end up trying to push current through the weaker ones and the power will be dissipated as heat, instead of charging a battery or powering appliances. To make kW systems, arrays of cells are assembled into solar modules, and then arrays of modules are assembled into larger panels. To match the voltage needed by an application, cells are wired in series, and then sets of these are wired in parallel to generate the current needed. Unmatched efficiencies can unbalance the system, overheating components and damaging systems, especially in high power systems.

Figure 2b shows the same solar cell panel imaged with a consumer digital color camera. Figure 2c shows a lower resolution image captured by a microbolometer camera. Note that the thermal microbolometer image shows very little variation between the cells or within each cell. The SWIR electroluminescence images clearly show that the cells have widely varying regions of efficiency. The microbolometer image shows that the thermal camera does not detect these important variations, it sees the cells radiating uniformly (this was true even when a low bias was applied). This is due to the power dissipating across all of the junctions, and the resulting heat flowing together to reach common temperature equilibrium across the cell.

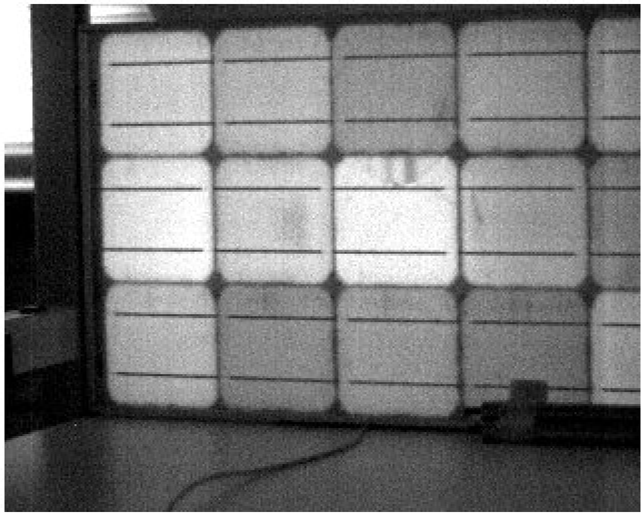

Figure 3 – [SWIR video scanning](#) over the length of a commercial 36 cell panel while forward biased with 18 V.

The power of using SWIR cameras on commercial solar panels to gauge efficiency uniformity is demonstrated by the video in Figure 3. The SWIR camera sweeps across a panel composed of 3 rows of 12 cells, with the panel nominally rated as 18 V output. Applying that same voltage to the panel caused the cells to glow at different intensity levels (this was recorded during the day in a room with drawn mini-blinds). Careful viewing of the cells shows several with defects; zooming in to the cells to the left of center reveals that one of the cells is cracked, with some of the portions dead. The cell above it shows some scattered defects (see Figure 4).

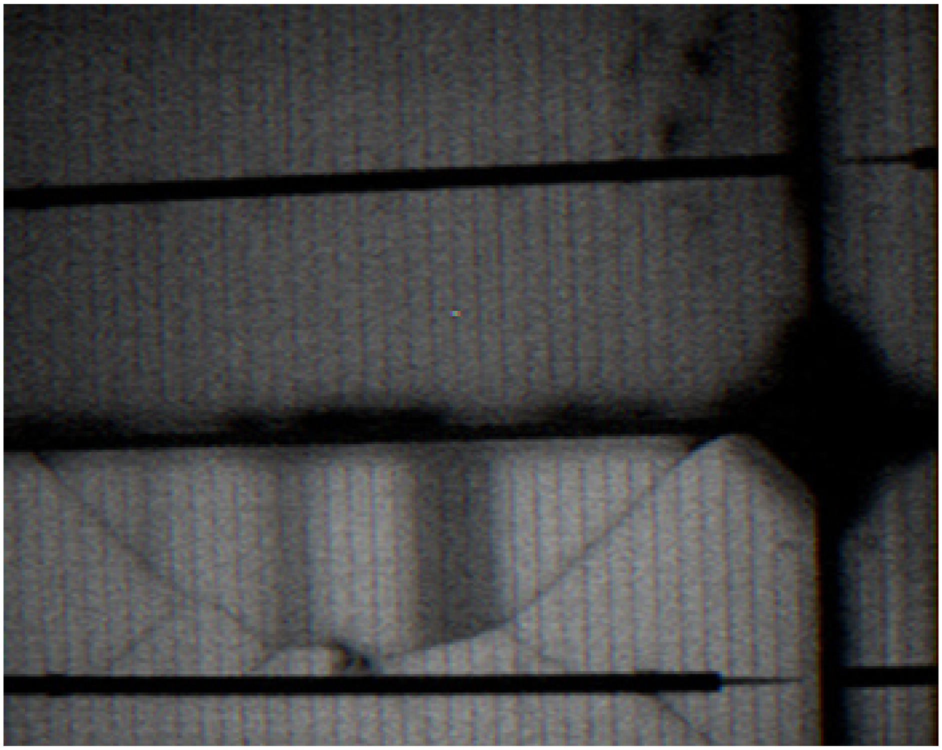

Figure 4 – Close-up view of two cells with defects visible in the Figure 3 video, revealing a semi-circular crack in the lower cell, dead sections, and a scatter of defects in the upper cell. (The diamond shaped dark area indicates that these cells were cut from a round silicon ingot.)

With the KT camera on its highest sensitivity range, and the imaging system in complete darkness, test systems can even map the turn-on voltage within and across cells at video rates. For the panel shown in Figure 2a, by pulsing the bias voltage, it was possible to detect the first glow from the most efficient cells at 3.5V (the panel output is rated as 6V at 50 mA). It has been demonstrated that the cell regions that light up first and that have the brightest glow at high bias voltages, were also the most responsive when scanned by a light spot. Therefore, mapping the turn-on voltage of the electroluminescence is highly valuable for predicting the PV cell's efficiency and fabrication uniformity. Further, under reverse bias and complete ambient darkness, point defects can be revealed, pointing to structural problems.

Scanning solar cells with motorized microscope stages equipped with Goodrich 1-D linescan cameras enable users to image at a higher resolution than is possible with area cameras. Both 1-D and low-sensitivity 2-D cameras are quite useful for imaging electroluminescence from solar cells, as they just require a higher forward bias to be applied to the cells to see the electroluminescence patterns. The solar cells are quite robust and are very capable of handling much higher forward bias currents and voltages than their rated outputs.

Scientific-grade cooled CCD cameras can also be used for imaging silicon electroluminescence, but typically require seconds of integration time, compared to the video rates possible with SWIR cameras. Though electronically more sensitive than InGaAs due to lower read noise, silicon cameras need more integration time because the spectral glow from the silicon solar cell is at the bandgap edge, which is also where the material's quantum efficiency falls rapidly as it becomes transparent. Si cameras are adequate for periodic testing by the quality lab but faster cameras are needed for production screening. The silicon electroluminescence emission is right in the middle of the spectral range of InGaAs cameras, permitting them to image at the fast rates needed for production. This is illustrated in Figure 5, which shows the emission of the cells biased at 7.6 V along with the quantum efficiency curves for standard area camera InGaAs compared to the QE curve for a back-illuminated, deep absorption CCD optimized for NIR response.

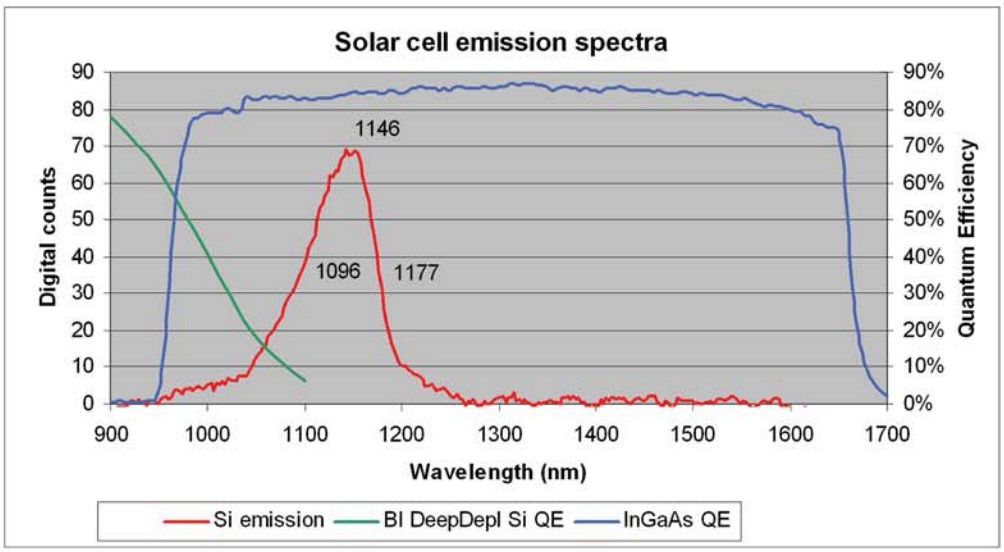

Figure 5 – Spectra of electroluminescence from crystalline silicon solar cells shown in Figure 2a while biased with 7.6 V at 100 mA. Also shown are the QE curves for the InGaAs area camera and a CCD camera optimized for NIR response.

Other semiconductors are also being used to create solar cells, including sandwiches of indium gallium phosphide (InGaP), InGaAs, and germanium (Ge). These triple junction devices have their bandgaps tailored to absorb solar energy in the same proportion as the distribution of solar power that reaches ground level. When forward biased, these cells also exhibit electroluminescence, with the emission at the bandgap energy of each layer, including a red glow visible to the eye at 700 nm, another at 980 nm, and the third beyond 1500 nm (characteristic emission for one type of triple junction cell). All three wavelength bands can be captured by InGaAs cameras with their range extended to shorter wavelengths, such as the Goodrich SU320KTSX-NIR or SU640KTSX-NIR (see Figure 6). The high sensitivity and high quantum efficiency of these cameras are ideal for screening triple junction cells. (The extended range is achieved by using a substrate-thinning method first demonstrated and published by Goodrich engineers in 2001 when the group was known as Sensors Unlimited, Inc.). By using bandpass filters for each emission band, manufacturers of concentrator-type solar cells are able to inspect each junction for defects and non-uniformity, and to ensure that all three layers are properly connected. This is particularly important for concentrator systems, which focus as much light as the equivalent of 500 suns onto the surface and generate high currents. If one of the junctions is not producing its share of output, damage could result.

Figure 6 – Photo of Goodrich's SU320KTSX and SU640KTSX - NIR Cameras

Another application of great interest to solar manufacturers is the use of SWIR-InGaAs cameras to image silicon ingots for defects prior to cutting into individual cells. The cameras can detect inclusions of carbon or other contaminates, they can find cracks, and they can see the orientation of grain boundaries. This prevents the significant waste of materials, of cutting tools, and of time, while it also helps engineers tune the manufacturing process to produce higher quality ingots. As with the other applications described above, the SWIR-InGaAs cameras can make significant contributions to improving yield, quality, and production rates, leading the way to reducing the cost of solar energy.

IMPORTANT NOTICE: Goodrich area cameras (2-D) and associated technical data are subject to the controls of the International Traffic In Arms Regulations (ITAR). Export, re-export or transfer of these items by any means to a foreign person or entity, whether in the US or abroad, without appropriate US State Department authorization, is prohibited and may result in substantial penalties.

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[i] Paolo Bosshard, et al*, "Technical Assessment Report: An Assessment of Solar Energy Conversion Technologies and Research Opportunities"*, Global Climate and Energy Project, Stanford University, 2006, available at: http://gcep.stanford.edu/pdfs/assessments/solar_assessment.pdf

[ii] Ibid, calculation based 38000 TW hitting the continents, and 13.7 TW total energy consumption.