FLIR

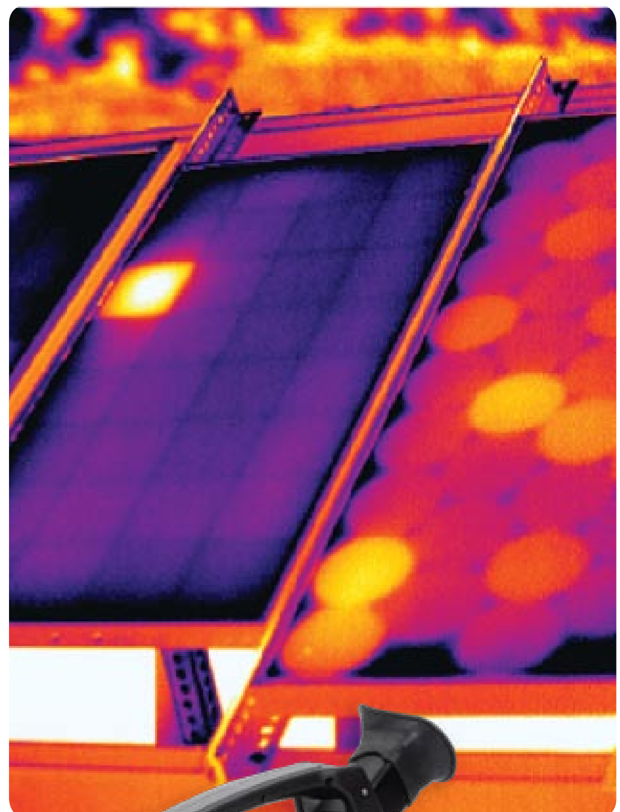
Solar Cell Development

The environmental and political benefits of renewable energy sources are understood by anyone even mildly interested in the future of our planet. Solar cells are getting a lot of attention because they are not only a clean source of renewable energy, but also because their energy input is essentially free. They use photovoltaic (PV) technology to make a direct conversion of the sun's rays into electricity. According to John Boyd, a technology analyst at Semiconductor Insights, "a solar array 150 x 150 km could, in principle, meet all of North America's energy needs." [1] Assuming adequate installation space, and a solution for power grid load balancing, the main problem to be solved is achieving grid parity, the point at which the cost of generating PV power is competitive with that of generating power using existing power plants.

Currently, the cost of generating PV power is approximately $0.20/kWh globally, roughly twice the rate of coal-based alternatives. Silicon solar cells are achieving conversion efficiencies between 15% and 25%, while typical metallic thin film cells have efficiencies in the 5% to 20% range, depending on materials used. R&D efforts are aimed at increasing the efficiency of both solar cell technologies and reducing PV cell power generation costs to around $0.05/kWh.

The primary challenges in reducing the cost of PV power generation exist in the production phase of the development cycle. Too many defects in the semi-conducting material structure go undetected before solar cells are put into use. Identifying these defects requires efficient, cost effective test and measurement methods for characterizing a cell's performance and its electronic structure.

This paper is an overview of the methods in which FLIR Infrared Cameras can be used to characterize solar cell performance.



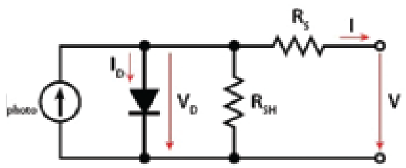


Figure 1. Circuit model of a PV cell.

Typical Cell Defects

A PV cell is typically modeled as an ideal diode in parallel with a photocurrent source, plus parasitic resistances such as shunt resistance (R_{SH}) and series resistance (R_S) (Figure 1).

Origins in Crystalline Structures

The conversion efficiency of today's silicon solar cells is limited by free carrier recombination, a processes by which mobile electrons and electron holes are absorbed or lost, due to defects in the bulk material. This is particularly true in solar cells produced from multicrystalline silicon (mc-Si) wafers, which have significant concentrations of crystallographic non-uniformities such as dislocations, grain boundaries, and impurities.

Lateral Non-uniformities

Non-uniformities in the current flow across a solar cell are an important issue in thin metallic film PV development. Since larger solar cell modules are constructed by connecting individual PV cells, a few bad cells can affect the performance of the entire module. Often, a high R_{SH} will be present as a result of any of the following:

- **Improper handling during processing**
- **Diamond saw scribing at cell boundaries**
- **Over-firing during cell metallization**
- **Poor edge isolation processes**
- **Random shunts inherent in most production processes**

Series Resistance

The dominant sources of a solar cell's R_S are contact resistance, bus bar resistance, screen-printed "fingers", and lateral conductions in the emitter. The relative importance of each source depends on the bias level and current flow in the cell. For example, points near contact pads typically have a much lower R_S than those near the end of screen-printed fingers. Process defects such as breaks in fingers, or poorly printed areas, add to the variation in R_S.

Measurement Methodologies

All three types of defects mentioned above can have a significant effect on a PV cell's charge carrier characteristics and conversion efficiency. Some of the parameters most commonly measured include resistivity (used to screen silicon wafer materials) and other electronic characteristics of PV cells, such as I-V curves, charge carrier/current density, free charge recombination lifetime, bulk material lifetime, and effective lifetime.

Many different techniques are available for measuring these parameters and detecting defects. They vary greatly in terms of complexity, equipment cost, and the time required for completing a typical set of measurements. Depending on the product development stage, these techniques can be employed in an R&D lab or on a production line. In the latter case, testing may be used for troubleshooting or optimization of production processes, or final testing of completed cells.

In general, PV cell tests are based on three broad areas of technology: spectroscopy, electrical (contact) measurements, and infrared (IR) imaging. Frequently, multiple techniques are employed to collect a wide range of parameters, particularly in R&D labs.

Electrical Testing

For silicon wafers, some of the more commonly used R&D methodologies include capacitance-voltage (C-V) measurements and resistivity profiling. Wafer resistivity can be checked by classical four-point (Kelvin) probe measurements – typically, using the four-point collinear probe method or the van der Pauw method. For accurate resistivity measurements, wafer thickness must be determined, which requires additional optical techniques or capacitive gauging.

The techniques that make electrical contact with a wafer may require special sample preparation steps. As you might suspect, they are often time consuming, which places practical limits on the number measurements and samples that can be processed within available timeframes.

In production and process development testing, typical electrical parameters of interest include short circuit current (I_{SC}), open circuit voltage (V_{OC}), Fill Factor (FF), Ideality Factor (η), series resistance (R_S) at V_{OC}, shunt resistance (R_{SH}) at 0V, and reverse voltage breakdown. FF and η are usually derived from I-V measurements. A recently developed Sun-V_{OC} technique allows reconstruction of the I-V curve in a single light flash without the influence of (R_S). Dark I-V measurements can also reveal lumped series & shunt resistance problems.

Since a solar cell's efficiency is largely a function of its short circuit current, open-circuit voltage, and fill factor, these parameters tend to be the focus of much testing, even in R&D labs. V_{OC} and FF can be characterized by the shape of the forward biased dark I-V curve. Frequently, distribution of forward current density over the entire cell is inhomogeneous. If current density through a given region is higher than the cell average,

this is indicative of a shunt. Therefore, characterizing shunts under forward-bias conditions is important in the efforts to increase efficiency.

Shunts associated with front side metallization can be detected using the Parallel Resistance Analysis by Mapping of Potential method (PRAMP). However, PRAMP cannot detect shunts below the metallization. Another potential drawback arises because a tungsten probe is used to penetrate the cell's antireflection coating, which scratches the surface to a certain degree.

Parasitic series resistance is important as it is a major contributor to a PV cell's FF losses and ideality factor, η. Typically, R_S is determined from a set of illuminated and dark I-V measurements. While these use straightforward methods, collecting a complete set can be a bit time consuming.

Conventional IR Imaging Methods

Standard thermographic imaging of solar cells as a means of detecting defects has been used for over a decade. In most cases, it allows fast detection of the major shunts by the application of a reverse bias voltage, or by just observing the temperature of the cell under typical operation. However, the sensitivity and thermal resolution of standard thermography is limited by an IR camera system's inherent detector sensitivity, or noise equivalent temperature difference (NETD). The NETD for cooled cameras with indium antimonide (InSb) detectors is ~20mK, and ~80mK for an uncooled microbolometer) (Figure 2).

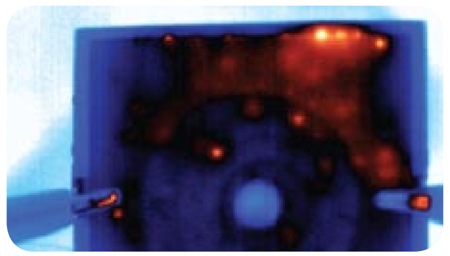


Figure 2. IR image of 60x60mm silicon solar cell showing shunt defects (orange areas) under steady state reverse bias conditions.

This image in Figure 2 was captured using an uncooled microbolometer camera with a spatial resolution of 320 x 240 pixels. The triangular shapes on the left and right of the cell are alligator clips used to apply bias voltage; the circular area is a reflection of the camera lens. The bright orange spots and less bright orange regions in the upper right half of the image indicate increased thermal activity due to shunts. Only severely shunted areas become visible as bright and localized spots. The darker orange regions are a result of weaker shunt defects. Locating the origins of these weaker shunts is extremely difficult, if not impossible due to the thermal diffusion (spreading of thermal energy over time) as well as the weak thermal radiation of the defect itself.

Still, these cameras provide the ability to quickly spot major defects that would not show up in visible light images. Visible light images, however, still provide useful reference points alongside IR images (Fig. 3).

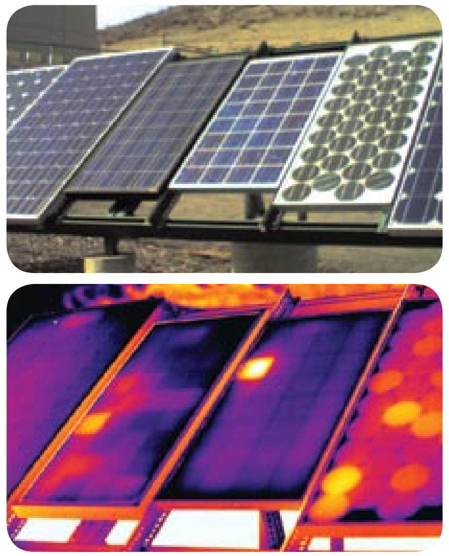


Figure 3. Solar cell testing using an uncooled microbolometer handheld camera.

Today, cameras are available that combine both IR and visual imaging, making fast steady-state testing of solar cells very convenient (Figure 4).

Figure 4. FLIR SC660 camera with both visible light and IR imaging using an uncooled microbolometer detector.

A slightly more complex method of conventional IR imaging to detect defects is moving a heat lamp and camera attached to a fixture across the surface of the cell, or more commonly, a large panel. For example, a major aerospace manufacturer found that their crack detection rate went up and inspection times went down when they had an operator view the digital data image from an InSb camera that was mounted 45 degrees to a large solar panel illuminated with a heat lamp at the opposite 45 degree angle. This technique uses a motion control system that moves the lamp and camera across the large solar panel. The operator has a system to mark defects as they show up on the display. Any cracks in the panel cause the thermal energy to diffuse through the material at different rates and are much more visible in the thermal image than they are by using eyes alone.

To improve crack detection in PV panels requires a more sophisticated approach. The drawback of using a "slow" heat or excitation source is that the resulting thermal diffusivity will be significant, negatively affecting the spatial resolution and definition of the crack.

Now there are commercial, off-the-shelf systems for solar panel inspections, such as the "SolarCheck" system from MoviTHERM, Irvine, CA, USA (www.movitherm.com), that use either a Xenon flash or a modulated laser excitation for crack detection. The SolarCheck system synchronizes the excitation source to the camera and performs a "Lock-in" thermography measurement, which collects a sequence of hundreds of images. This has the distinct advantage of eliminating problems arising from reflections of other heat sources, such as human body radiation, overhead lights, etc. An additional benefit is the significant increase in sensitivity of the system due to the "Lock-in" principle. This brings the detection threshold of the system down below the noise floor of the camera by a factor of 100 to 1000.

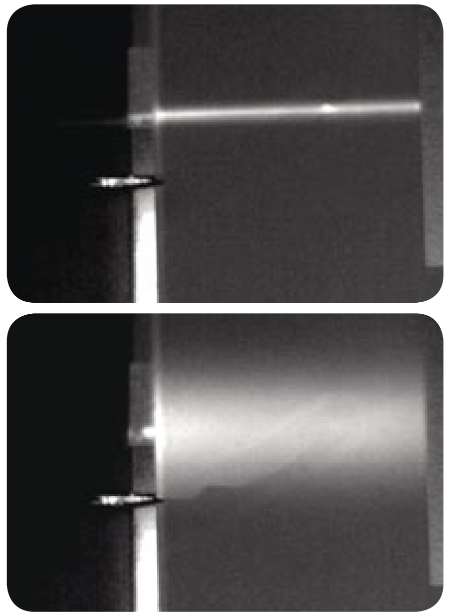


Figure 5. *Top: a solar panel being exposed to a short laser pulse, shown as a bright white horizontal line at t = 0ms on the crystalline PV cell. Bottom: the same PV cell at t = 200ms after laser exposure and heat propagation. The lighter area with the irregular boundary line clearly reveals a crack.*

Figure 5 illustrates the benefits of this technique. The measurement was performed with a "SolarCheck" system using a single-sided (reflective) setup. The laser and the camera were located on the same side of the PV cell (backside).

Electroluminescence (EL) & Photoluminescence (PL) Techniques

EL and PL are techniques used to generate spatially resolved images of solar cells that reveal localized shunts, series resistance, and areas of charge carrier recombination. EL applies a forward voltage and current to cause localized irradiance due to carrier recombination (Figure 6). PL uses light irradiation for the same purpose.

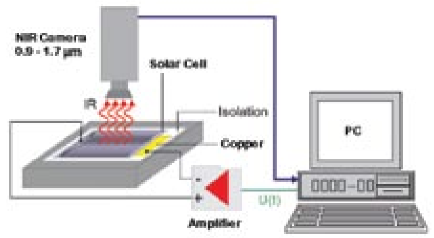


Figure 6. *Measurement setup for "Emission Analysis" using MoviTHERM's IR-NDT system "SolarCheck." The PV cell (or solar panel) is being electrically stimulated (electroluminescence technique).*

Figure 6 illustrates an EL test setup in which the current flow causes the PV cell to emit light in the near infrared (NIR) range of the spectrum. This measurement setup is able to examine the uniformity of the solar cell with respect to its ability to convert photons into electrons. This is shown in Figure 7.

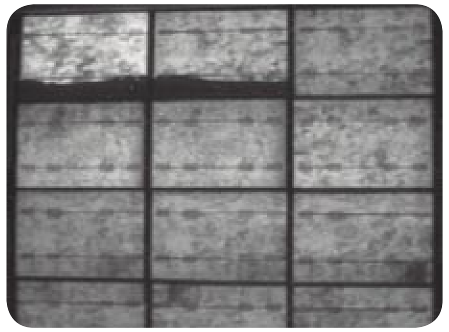


Figure 7. *Image of solar cell defects identified through "Emission Analysis." This image results from the test setup in Figure 6. The dark areas near the bottom of two cells in the upper left represent defects.*

Since EL and PL techniques only work in the NIR region, both types of system require a camera with a cooled NIR detector. (Uncooled microbolometer detectors are long wave IR instruments and therefore not suitable here.) A typical indium gallium arsenide (InGaAs) IR camera used for EL and PL defect studies is the FLIR SC6000 (Figure 8).

Figure 8. *The FLIR SC6000 IR camera with a cooled InGaAs detector can be used to map solar cell defects using EL or PL techniques.*

Care must be taken during EL testing, however, to avoid applying a destructive amount of current to the solar cells. In cases where the solar cells may be more vulnerable to damage from EL test currents, lock-in thermography presents an alternative method.

Lock-in Thermography

Refined thermal methods are needed to detect a wider variety of shunt conditions, particularly those below a solar cell's metallization layer. Since around the year 2000, researchers have used the technique of lock-in thermography (LIT) to overcome the limitations of conventional thermographic imaging.

By stimulating a PV cell with pulsed light, heat, or electrical signals, a lock-in amplifier tuned to the excitation frequency of the stimulus allows the system to detect subtle thermal responses beyond the noise floor limitations of the camera. This technique

is capable of detecting temperature differences with microKelvin resolution, far exceeding the 20mK resolution of modern InSb cameras.

Historically, these test systems were custom in-house developments and no commercial-off-the-shelf solution existed. Now MoviTHERM supplies a system that integrates FLIR IR cameras with software modules from a German company, Automation Technology (www.automationtechnolody.de) for a complete, commercially available LIT test solution called "SolarCheck".

Figure 9 is an image of shunt defects identified with this type of LIT system. The illuminated LIT technique allows mapping of forward current density distribution, and can also reveal series resistance and sites where there is heightened carrier recombination.

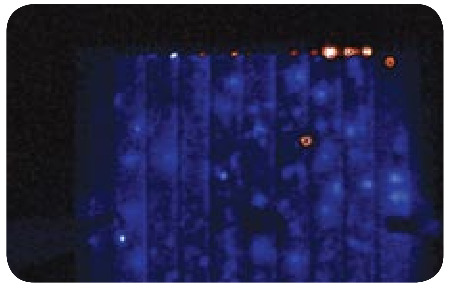


Figure 9. *Image of the same solar cell in Figure 2, now showing shunt defects more clearly (orange areas) when mapped with an LIT technique, using the MoviTHERM's "SolarCheck" system.*

Compare Figure 9 to Figure 2. Note that the image resolution in Figure 9 is better (i.e., not diffused and blurry), with localized shunt defects more sharply defined by the orange areas. With LIT, the reflection of the camera lens and outlines of the alligator clips no longer obscure large portions of the image, as they do in Figure 2. LIT also requires significantly less energy input to the solar cell compared to conventional thermography. One reason is because measurement sensitivity is about 1000X better – around 0.02mK. These sharp LIT images provide additional information, such as non-uniform heating of the cell, as revealed by lighter and darker blue areas.

Lock-in Thermography for Shunt Detection

Figure 10 shows the results of LIT testing for shunt defects on cells that were electrically excited with a sine wave. It illustrates the effect of modulation frequency on the thermal diffusion, and in turn on the resulting spatial resolution of the phase image.

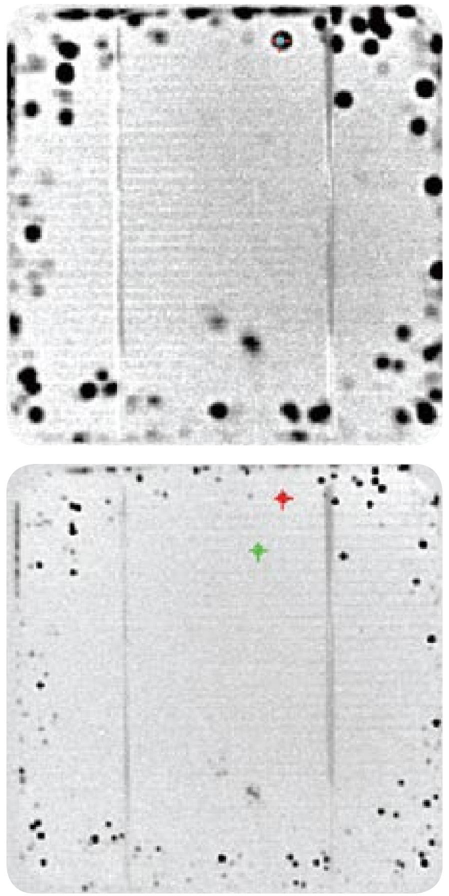


Figure 10. *Phase images of shunt defects from lock-in measurements performed with the SolarCheck system at 10Hz (top) and 200Hz (bottom) sine wave stimulation.*

Figure 11 is another LIT test result. In this example a comparison is presented for 10Hz and 200Hz excitation frequencies. At 10Hz, many of the defects go undetected. Only the more severely shunted areas show up faintly at this excitation frequency. On the right image with the 200Hz excitation, the shunt defects are much more pronounced and exhibit an improved spatial resolution. Some experimentation may be required to find the best stimulation frequency in electrically excited LIT measurements.

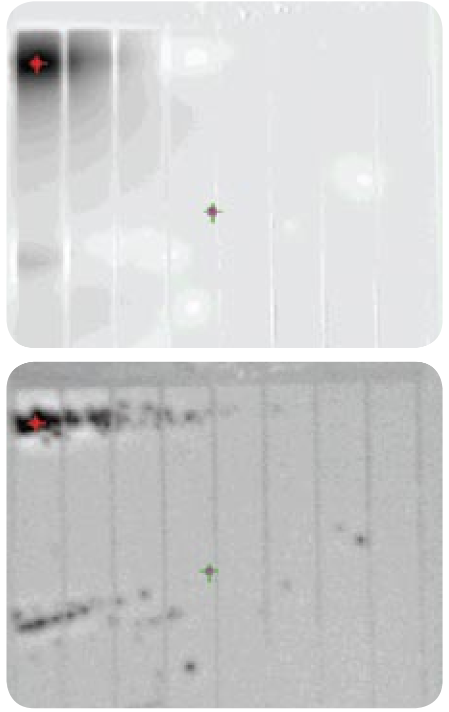


Figure 11. *LIT phase images intended to show shunt defects. Note that in the top view (10Hz stimulation) many defects are all but invisible. They show up clearly in the bottom view as dark areas with 200Hz stimulation.*

When modulated light is used as the PV cell stimulus, LIT does not require electrical contact with the DUT to make the measurements (Figure 12). However, if V_{OC} measurements are desired, this option does require electrical probes, as shown in Figure 6. Regardless of the type of stimulus used, the power dissipated by PV cell defects is amplitude-modulated, and therefore the resulting thermal image is one of periodic temperature modulation.

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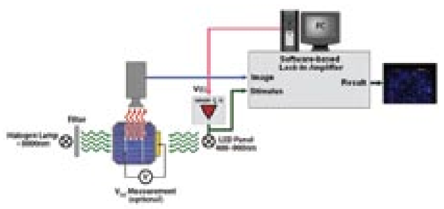

Figure 12. Non-contact LIT test configuration using modulated light as the PV cell stimulus. Optional V_{OC} measurements do require electrical probing of the cell.

However, the system shown in Figure 12 uses a software-based lock-in amplifier. This employs a technique called phase sensitive detection to single out the signal at a specific test frequency. Because the lock-in amplifier only measures AC signals at or near the test frequency, noise signals at other frequencies are largely ignored. Typically, a test frequency of only a few Hz is used to get below the frequency of most noise sources, and thereby optimize system sensitivity. This allows the LIT system to detect thermal changes well below the noise floor of the camera.

Thus, FLIR InSb and InGaAs cameras can be used for LIT, and image resolution is limited primarily by the pixel resolution of the camera's focal plane array detector and selected optics. The pixel size of the FLIR SC6000 is 25µm and a wide range of optics is available, from a wide field of view down to microscopes capable of 6um/pixel spatial resolution.

The amplified signals from the DUT is multiplied by both a sine and a cosine wave with the same frequency and phase as the stimulus and then put through a low pass filter. This multiplication and filtering can be done with analog circuits, but is more commonly performed digitally within the lock-in amplifier on the DUT's digitized response signal. The outputs of the low pass filters are the real (in phase) and imaginary (out of phase) content of the PV cell response signal.

As opposed to the amplitude image obtained with conventional thermography, LIT produces a phase image on a pixel by pixel basis from the camera's temporal (time varying) data. This means that emissivity, reflection, and absolute temperature measurement no longer affect the results obtained.

Images and cell parameters are calculated by the system software running on a PC. With appropriate software, the processed signal from the IR camera's detector can be used to make quantitative measurements of I-V characteristics associated with a localized shunt, calculate the reduction in cell efficiency due to shunts, and map saturation current density and ideality factor over the entire cell.

Quantifying Charge Carrier Behavior

In addition to spatial identification of defects, most researchers want to characterize charge carrier behavior in PV wafers and cells. A number of techniques have been developed for this purpose. For example, the electronic properties of silicon wafers can be characterized using surface photovoltage (SPV), microwave photoconductivity decay (µW-PCD), charge density imaging (CDI) techniques, and quasi-steady-state photoconductance (QSSPC). Some of these techniques can also be used to monitor PV cell production. For example, metallization processes influence the effective lifetime of charge carriers, which becomes an important parameter to monitor.

However, many of the techniques mentioned require special wafer preparation and are rather time consuming. CDI is one exception. It can be implemented with LIT, and used to map saturation current density, and other parameters, over an entire PV cell.

Flash CDI is based on free-carrier absorption of photo-generated excess carriers, and thus allows the imaging of charge carrier lifetime properties. With lock-in processing of the signal, much shorter lifetimes can be measured.

In this technique a black body source emits IR, which is transmitted through the DUT and measured by an IR camera. In addition, excess free-carriers are generated by the chopped light from a semiconductor laser, which modulates IR absorption and transmission. Carrier generation is controlled by adjusting the laser intensity to approximately a 1-sun level. The laser light is chopped at a low Hz rate, to ensure steady-state conditions and help reduce lock-in measurement noise. With proper calibration, effective lifetime is obtained, and test time can be on the order of seconds. An entire CDI wafer map can be created in a minute or so at a resolution better than that obtained with many other techniques, some of which are an order of magnitude slower.

Actual CDI test times depend on the length of the effective lifetimes being measured. A larger number of image frames need to be processed for lower lifetimes, which takes longer. Nevertheless, higher injection levels can help shorten test time.

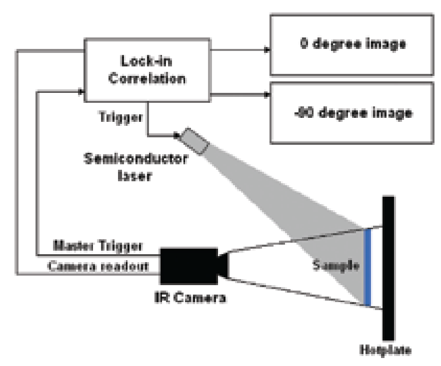

Figure 13. Block diagram of a Carrier Density Imaging system using LIT based on the SolarCheck system.

A CDI version of an LIT system is shown as a block diagram in Figure 13. The hotplate provides black body radiation, while the pulsed laser light generates minority carriers in the PV cell. For each of the IR camera detector pixels, the signal output is proportional to image intensity. The resulting signal is a step function, with amplitude levels that can be designated as D_{ON} and D_{OFF}. The difference, ΔD, is proportional to absorbed light intensity, and therefore represents the free carrier concentration at that pixel point in the camera's field of view. The complete set of pixel outputs produces an image of the carrier density distribution (or effective carrier lifetime), with a contrast that is proportional to ΔD (Figure 14).

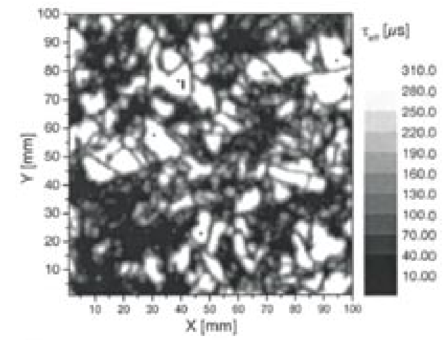

Figure 14. Spatial map of PV cell area showing effective carrier lifetimes (τ_{eff}) in microseconds.

As implied above, the intensity of each pixel, I_A, is equal to ΔD. By assuming that carrier lifetime is homogeneous over the entire sample width, and applying a sinusoidal correlation procedure, it can be shown that:

$$\Delta D = k\,\Delta m\,W,$$

where k is the sinusoidal correlation factor, m = excess minority carrier concentration, and W is the sample width.

The correlation procedure sets the camera's frame rate based on the lock-in frequency. This allows measurements under a steady-state condition for the carrier density during every half period of the stimulus signal. The steady-state measurements of Δm values can be used to calculate the effective carrier lifetime according to:

$$\tau_{eff} = \Delta m W / G = I_A / -kG,$$

where G is the local generation rate for the sample area.

Since a PV cell can be modeled as an ideal diode in parallel with a photocurrent source, LIT can be used to thermally measure local I-V characteristics that reveal non-ideal behavior, i.e., parasitic series and shunt resistance. Non-ideal diode properties of the PV cell are also expressed in the Ideality Factor,

$$\eta = \delta V / \delta \ln(I).$$

By accounting for source resistance, R_S, and shunt resistance, R_{SH}, a relationship between η and PV cell voltage can be established, which leads to a better understanding of charge carrier transport mechanisms.

LIT can be combined with illuminated and dark I-V measurements to derive other PV cell parameters. For example, the Fill Factor is also lower than ideal due to R_S and R_{SH}. It can be expressed as:

$$FF = I_{mpp} V_{mpp} / I_{SC} V_{OC},$$

where mpp is the maximum power point.

Conclusions

A major advantage of LIT compared to many other test methods is the short time required to complete a set of measurements without elaborate sample preparation. Once an LIT system is configured, significant amounts of data can be acquired in seconds, compared to minutes or hours with other methodologies. This makes LIT a good candidate for process related testing, as well as for use in the R&D lab. The MoviTherm SolarCheck system, with appropriate stimulation sources and accessories, can be used for all common IR solar cell testing methods including crack detection, electroluminescence, photoluminescence, lock-in thermography, and charge density imaging.

Acknowledgements

The thermographic measurement capabilities of the LIT systems mentioned in this paper are based on IR cameras supplied by FLIR Systems, Inc. Many of the parameter extractions are provided in Lock-In software "IrNDT" supplied by Automation Technology GmbH, Germany (www.autmationtechnology.de). Complete, integrated LIT systems, such as the "SolarCheck" system can be ordered from MoviTHERM, Irvine, CA, USA (www.movitherm.com). Engineers and scientists of these companies have contributed to, or performed peer reviews of this paper.

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