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**Shunts due to laser scribing of solar cells evaluated by highly sensitive lock-in thermography**

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**ABSTRACT**

Using a 200 Hz focal plane array (FPA) thermocamera attached to two parallel-running DSP frame grabber boards in a PC, a highly sensitive lock-in thermography system has been built, enabling the detection of periodic surface temperature oscillations below 10 µK (r.m.s). This system has been used to investigate edge leakage currents in silicon solar cells after laser scribing and cleavage.

1. Introduction

If for minor solar applications like battery chargers a certain minimum operating voltage is necessary for a small solar cell area, high-efficiency silicon cells have to be cut into pieces and electrically stacked. Usual technologies of cutting solar cells are diamond saw cutting and laser scribing from the back and cleaving, which is more productive. Unfortunately, these processes may generate shunts in the edge regions of the pieces, which degrade the operating voltage of the cells, especially for low light intensities and small pieces. Therefore, a technique of detecting and quantitatively evaluating shunt currents in solar cells is very important for systematically optimizing the solar cell cutting technologies. In general, any optimization of solar cells with respect to the open circuit voltage and the fill factor requires the detection of shunts. Thermography, evaluating the local surface temperature due to the application of a forward bias in the dark, enables the detection of shunt currents via their local heating effect. However, a sensitivity limit well below 1 mK is necessary to investigate the behaviour of weak shunts at the normal operating point of 0.5 V forward bias or below. Stationary thermography cannot resolve such tiny temperature differences. Moreover, due to the large heat conductivity of silicon, the spatial resolution of stationary thermography on silicon solar cells is very poor.
In the lock-in thermography technique, the heat action is applied periodically, and only the local periodic temperature modulation is evaluated [1]. This technique has several advantages over stationary thermography. Due to this modulation technique only the heat-induced signal is detected, but the stationary and slowly varying image information (topography contrasts, inhomogeneous emissivity, temperature drift, etc.) are omitted. Averaging over many periods allows the signal-to-noise ratio to be enhanced by several orders of magnitude. Finally, the spatial resolution of the lock-in thermography is governed by the frequency-dependent thermal diffusion length of the thermal waves. Thus, depending on the lock-in frequency, the spatial resolution can be drastically increased relative to the stationary thermography.

Dynamic Precision Contact Thermography (DPCT) was the first lock-in thermography technique to match the extreme sensitivity requirements for the solar cell shunt hunting under forward bias [2]. In DPCT, a highly sensitive temperature sensor measures the local surface temperature modulation in the contact mode. By sequentially scanning the surface position via an x-y-z positioning stage, an image of the surface temperature modulation amplitude is formed, which can be interpreted as the image of the local injection current density. However, DPCT has been a very slow technique, requiring about 10 hours to form one image, and the maximum possible lock-in frequency was limited by the heat capacity of the sensor. Moreover, owing to the contacting principle, the unwanted creation of shunts during the measurement, e.g. by impressing dust particles into the surface, could not always be excluded. Therefore, recently we have developed a highly sensitive lock-in infrared thermography system, which essentially yields the same information as DPCT does. However, it requires only a fraction of measuring time, it allows the use of higher lock-in frequencies, and it is really a non-contacting technique.

2. Experimental

The aim of the development of the new lock-in thermography system was to achieve a detection sensitivity as high as possible during an acceptable measuring time. Thus, the IR camera should be as sensitive as possible, with a frame rate as high as possible to deliver a high number of images for the averaging in a given measuring time. We have chosen a camera of the type AE 4128 from Amber, equipped with a liquid nitrogen cooled 128x128 pixel InSb focal plane array (FPA). Its frame rate is 217 Hz, and its noise equivalent temperature difference (NETD, being the RMS noise of the system) is specified to be < 20 mK. The whole system is controlled with a Pentium II PC running under Windows NT. In order to release the host PC from the lock-in processing of the incoming images, the complete lock-in correlation is performed in a digital signal processor (DSP) on the frame grabber board. Thus, during the measure time the PC is free for other works like displaying and processing other images.
The principle of the lock-in correlation procedure is illustrated in Fig. 1. Each pixel of each incoming frame is multiplied by a weighting factor (changing with the next incoming frame) and summed up in a RAM storage. Since the phase of the temperature modulation is not known, both lock-in phase components have to be detected simultaneously. One set of weighting factors approximating a sine function delivers the in-phase (sin) component, and a second set approximating the -cos function delivers the quadrature (-cos) one. The -cos function has been chosen instead of the cos one to achieve positive signal values for a homogeneous signal, which relative to the heating is delayed by 90 degrees. From these two images the amplitude and the phase images are easily calculated. As the frame grabber board we have chosen the Dipix FPG-44 board, which is equipped with a 60 Mhz floating point processor and 2 MB of SRAM on board. However, for the chosen frame rate of 217 Hz, corresponding to a data transfer rate above 7 Mbaud, even this board reaches the limit of its processing power. It turned out that just one board can perform one of the two correlation procedures. Therefore, two identical boards are being used, running exactly in parallel via the same DSP program. They are both connected to the camera controller. They only differ in their set of weighting factors used. After the measurement, the RAM storage of one board contains the in-phase image whereas that of the other board contains the quadrature image. Both images are then transferred to the PC and displayed and stored at choice. Fig. 2 shows the schematic set-up of the complete system. The sample is thermostatted and covered with a 20 µm thin blackened plastic film, which serves as an efficient and homogeneous IR emitter. The bias pulses to the sample are triggered by one frame grabber board and then appropriately amplified. Note that this system approximates a harmonic correlation function. Thus, though the pulsed heating as well as the temperature signal contains also higher harmonics, they are suppressed by the correlation procedure. Solely the fundamental harmonic of the temperature modulation contributes to the result.

Fig. 3 shows the temperature modulation amplitude rms-noise level, measured by this system at an object temperature of 25°C as a function of the integration time for a typical lock-in frequency of 13.5 Hz. The plot clearly matches the expected $1/\sqrt{t_{\text{int}}}$ behaviour. This noise level is consistent with a mean NETD of the camera of 6 mK, which is exactly the value given in the manufacturer's camera test report. After less than one minute the noise level is below 0.1 mK, which already allows one to see most of the shunts in solar cells. After an integration time of 1800 seconds (1/2 hour) the noise level is below 10 µK, which is more than sufficient for highly sensitive shunt investigations.

Standard monocrystalline silicon solar cells have been laser cut from their back contact side using a repetitively Q-switched Nd:YAG laser with an average output power between 5 and 10 W and typical pulse widths of 180 ns at a repetition rate of 10 kHz. The laser spot size was about 10 µm and the cutting
speed was between 2 and 4 cm/s. The cutting depth was varied by varying the cutting speed and the laser power. The resulting dependence of the cutting depth on both parameters is illustrated in Fig. 4.

3. Results

Figure 5 shows lock-in thermograms of sections of a standard monocrystalline silicon solar cell. All images have been taken at a lock-in frequency of 3.4 Hz, applying a pulsed forward bias of 0.5 V in the dark. Bright contrasts indicate shunting activities. The dark spot at the bottom of all thermograms is due to the electrical contact attached to the samples. The cell thickness is about 300 µm. The section in Fig. 5(a) is a corner section with original cell edges at the top and the left hand side and laser scribed and cleaved edges at the right and the bottom. The sample additionally contains one vertical and one horizontal laser scribe at the back, both in the center of the area, which are not yet cleaved. The cutting depth of the vertical laser cuts was about 150 µm, but that of the horizontal ones was nearly the wafer thickness so that this cell was partly perforated at the horizontal cutting lines before cleavage. Laser-induced shunts are clearly visible in the bottom edge, but also slightly indicated at the middle horizontal scribing line. In the center, where the horizontal and vertical cuts meet, another strong shunt has been created by the joint action of both scribing. The uncleaved vertical laser cut in the center and also the cleaved vertical one at the right, however, do not show any shunting action on this temperature scale.

Figure 5(b) is the image of another section of the same cell of the same size, measured under the same conditions. However, the laser energy used for all laser cuts was low, yielding cutting depths of always 150 µm. The left edge, showing a distinct shunting activity, is an original one of the cell. Here, all cleaved edges are less shunt active than in (a) and all inner cuts are really invisible, in spite of the much lower displayed signal level (1 mK compared to 5 mK). This points to the fact that, for a cutting depth of only 150 µm, the laser scribing procedure itself does not yet generate any shunting damage. After this investigation also the inner cuts have been cleaved. The pieces have been positioned in their original arrangement and electrically connected in parallel with a 10 µm thin Al foil, which does not affect the thermographic investigation. Now also these edges become weakly visible as shunting regions, as Fig. 5(c) proves.

4. Discussion

Highly sensitive lock-in thermography is a simple, reliable, and sensitive tool to localize and investigate shunting phenomena in solar cells. As Fig. 5(a) shows, laser scribing alone may lead to unwanted leakage currents, if the laser energy chosen is too high. Under optimum scribing conditions the
laser-cut groove should have a depth of roughly half the wafer thickness. Then the as-scribed regions do not show any excess leakage current, and the samples are easy to cleave. After cleavage these edges show a clearly lower leakage current than the original cell edges do. However, even these cleaved edges show a low but measurable residual leakage current. This result corresponds well with an earlier investigation [3] that even the edges of solar cells cleaved after diamond scratching from their back show a distinct leakage current across the cleaved edges. Hence, this residual leakage current is due to the cleavage itself, but not due to the laser scribing.

We assume that positive oxide charges of the native oxide at the cleaved faces may be responsible for this residual leakage current. Since these charges repel holes, a surface depletion region with a certain barrier height $E_b$ may form at the cleavage face above the p-region. This potential barrier would provide a preferred injection path for electrons from the emitter into this surface layer, which is illustrated in Fig. 6, schematically showing the two-dimensional potential distribution of a plane crossing both the surface (in front) and the pn-junction. Thus, in order also to get rid of this residual leakage current it is necessary to compensate the positive surface charge or to increase the surface doping level, since the formation of space charge layers strongly depends on the doping level. Alternatively, n-type based solar cells should not have these edge leakage currents, since such a surface depletion layer should neither form above the n-region nor above the high-doped p$^+$-emitter. Thus, for producing small-area silicon solar cells, p$^+$n structures should be preferred, as their edges usually do not produce these residual edge leakage currents after cleavage. Maybe, the p$^+$n structures would show a short circuit current somewhat lower than that of n$^+$p structures (due to the lower hole mobility), but their open circuit voltage and fill factor should be superior.

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REFERENCES


**Figure captions**

Fig. 1: Principle of the lock-in thermography technique

Fig. 2: Schematic description of the developed lock-in thermography system

Fig. 3: Dependence of the measured noise level of the system on the integration time of the measurement

Fig. 4: The typical laser scribing depth as a function of the average laser output power for cutting speeds of 20 mm/s and of 40 mm/s

Fig. 5: Lock-in thermograms of sections of silicon solar cells. (a): Horizontal laser cuts applying a high laser power, and vertical ones applying low laser power, inner cuts not yet cleaved. Scale: 0... 5 mK, 5 minutes measure time; (b): All laser cuts applying a low laser power, inner cuts not yet cleaved. Scale: 0...1 mK, 40 min. measure time; (c): The sample of (b) after cleaving the inner cuts. Scale: 0...1 mK, 1 hr measure time.

Fig. 6: Schematic 2-dimensional potential distribution on a positively charged surface (in front) crossing an n+p-junction. $E_c$: conduction band edge, $E_v$: valence band edge, $B$: surface potential barrier height.
Figures:

Fig. 1: Single incoming frames

2-point corrected

noise: 6 mK r.m.s.

Fig. 2: vacuum

IR-camera:
- Amber
- AE 4128
- InSb FPA
- LN$_2$ cooling
- 3...5µm
- 6 mK

thermostat
- 0...100 °C

pulse amplifier
- (0...12V, 0...6A)

trig.

camera controller
- incl. on-line 2-point pixel correction
- 128x128 Pixel
- frame rate: 217 Hz

Pentium-II PC
- incl.
- 2x dipix FPGA-44

Power Frame-Grabber
- digital interface
- 7.11 Mbaud

Black-painted plastic film

2-point corrected result

Amplitude, phase ...

Multiplication with weighting factors

$\Sigma_1$

$\Sigma_2$

$\sum_1$

$\sum_2$

Vacuum sample

Single incoming frames

$\sin(t)$

$\cos(t)$

$\Delta t = 5$ ms

$F(t)$

$\sin(t) \cdot F(t)$

$-\cos(t) \cdot F(t)$

$-\cos(t)$

$\sin(t)$

$-1$

$1$

$\sin(t) = \frac{1}{2}$

$\cos(t) = \frac{\sqrt{3}}{2}$

$-\cos(t) = -\frac{\sqrt{3}}{2}$

$\sin(t) = \frac{1}{2}$

$\frac{1}{2} \cdot F(t)$

$-\frac{\sqrt{3}}{2} \cdot F(t)$

Single incoming frames noise: 6 mK r.m.s.

Result:

$0^\circ$

$-90^\circ$

$\Rightarrow$ amplitude, phase...
Fig. 3:

![Graph showing the relationship between noise (effective value in mK) and integration time (s). The line indicates noise at f = 13.5 Hz.]

Fig. 4:

![Graph showing the relationship between scribing depth (µm) and average output power (W) for two different speeds: 20 mm/s and 40 mm/s.]

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Fig. 5:

![Image of laser cut samples with cracks labeled](image)

a

b

c

Fig. 6:

![Diagram of semiconductor structure](image)