Local current–voltage curves measured thermally (LIVT): A new technique of characterizing PV cells

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Abstract

Local current–voltage characteristics measured thermally (LIVT) is a non-destructive technique based on measuring the bias dependence of the local temperature of a small sample area in the ac mode. It is an important supplement to light beam induced current (LBIC), electron beam induced current (EBIC) and Dynamic Precision Contact Thermography (DPCT) techniques allowing to study the nature of the current at a given point on the cell surface. Presented experimental results comprise LIVTs of natural inhomogeneities in multicrystalline silicon solar cells, artificial defects in monocrystalline cells (mechanically damaged regions), as well as LIVTs of several test structures. LIVT data generally confirm existing theories for different current natures. A related technique for n-factor mapping is also presented.

Keywords: Multicrystalline silicon solar cell; Thermal characterization; Forward current density

1. Introduction

In recent years, in solar cell research there was great demand for studying the nature and influence of forward current density inhomogeneities in solar cell p-n junctions. These investigations were especially important for low-cost material solar cells such as multicrystalline material cells, where local current inhomogeneities tend to limit the conversion efficiency. In Ref. [1] it was concluded that structure imperfections leading to a locally reduced diffusion length in polycrystalline Si influence the efficiency

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primarily by reducing the parallel resistance rather than by limiting the carrier collection. The complex non-exponential form of the $I-V$ characteristic of a commercial multicrystalline cell (as, for example, in Ref. [2]) often showing $n$-factor values about 2, or larger, and the increased ohmic current at lower biases also suggests that the current density distribution across the cell area is inhomogeneous. At each given bias, different current mechanisms may dominate simultaneously at different points of the cell. In this case the overall $I-V$ curve is quite difficult to analyze [3].

Cutting cells does not allow local currents to be measured. Usually, for sufficiently small samples edge currents due to cutting dominate the overall current of the sample [4]. Instead, two complicated destructive techniques, namely, the mesadiode analysis of solar cells (MASC) [5, 6] and the analysis of mini solar cells (MSC) [7] were proposed.

The introduction of thermal methods for characterizing solar cells [8] enabled the simple non-destructive mapping of the forward current density (Dynamic Precision Contact Thermography, DPCT, [9, 11]). A similar technique was proposed for microcharacterizing microelectronic semiconductor devices by scanning probe microscopy (see, for example, [12]). However, the nature of the local currents still could not be determined without any damage to the cell [5-7, 10, 11]. For determining the mechanism of the formation of local inhomogeneities it is useful to know the bias dependence of the dark forward current density at critical points of the cell.

2. Brief description of the experimental technique

The experimental technique proposed is based on a procedure of local precise ac temperature modulation measurements described in more detail in Refs. [9, 13]. The setup includes a small thermistor (pearl-type, 0.3 mm diameter) installed in an auto-tuning ac measurement bridge, a thermostatted sample fed by a voltage supply, mechanical positioning and scanning system, and a computer. The computer controls the voltage supply as to provide a periodical pulse bias. It realizes the lock-in detection of the temperature signal, controls the sensor positioning drive, and processes the incoming information. Unlike Ref. [9], for LIVT measurements the temperature sensor is kept in one and the same position during the whole measurement cycle, being pressed to the front surface of the cell. For each predetermined amplitude of bias pulses the temperature modulation amplitude is measured. From the value of the temperature modulation amplitude, the local current density is derived in arbitrary units:

$$ j = \frac{p}{V} \frac{\delta T}{V} $$

where $j$ is the local current density, $p$ is the power density, $\delta T$ is the local temperature modulation amplitude, and $V$ is the amplitude of the applied bias pulses. Varying the bias pulse amplitude one can obtain the whole $I-V$ characteristic of the local area in a given bias range. Measurements under mechanical stress applied to the
sample were performed by putting a curved metal plate below the cell, as described in Ref. [11].

The application of this technique is, however, limited owing to the limited dynamic range of the temperature measuring equipment, mostly allowing significant measurements between 0.1 and 0.6 V of the bias in forward direction applied to a silicon p–n junction. At a bias near zero the calculated current tends to increase infinitely, where the noise dominates over a weak signal. Another drawback is that the area influencing the sensor temperature should be homogeneously heated, otherwise the sensor would measure only some average temperature. The dimensions of this area are defined by the dimensions of the sensor and by the thermal wave extinction length [13]. In this paper, most of the results (except Fig. 2a) refer to an excitation frequency of 3 Hz corresponding to the extinction length of 2.5 mm in silicon. Since the thermal diffusion equation is linearly related to power, the influence of this averaging does not hinder any measurement of LIVT. However, strictly speaking, it does not allow the quantitative comparison of shunts of different size.

According to the same principle, assuming exponential \( I-V \) characteristics, \( n \)-factor mapping is possible if the temperature modulations \( \delta T_1 \) and \( \delta T_2 \) for biases \( V_1 \) and \( V_2 \) are known:

\[
n = \frac{e(V_1 - V_2)}{KT} \ln\left(\frac{dT_1}{dT_2} \cdot \frac{V_2}{V_1}\right)
\]  

(2)

In this case only the relative temperature modulation change is critical, and the temperature coefficients in each particular measurement cancel out. However, the accuracy of this two-point calculation strongly depends on the noise level of the measurement. This expression assumes exponentiality of the LIVT, which is not always the case. If the characteristic is non-exponential, a bias-dependent \( n \)-factor will be defined from the exponential fit of the \( I-V \) characteristic at a given bias.

3. Results and discussion

Several test structures were studied. Instead of a sample a 9 × 23 mm stripe of gold, 1.4 \( \mu \)m thick, was connected and covered with a plastic film before the LIVT measurement. Fig. 1a illustrates the resulting LIVT of this ohmic resistance. Current values plotted along the y-axis in all LIVTs presented in this paper are that of \( \delta T/V \) in mK/V. Here, \( \delta T \) is the value measured at the sensor. Since the thermistor shows finite heat capacitance and the contact to the surface is non-ideal, the temperature modulation value measured at the sensor is about 10 times lower than the actual temperature modulation at the sample surface. This coefficient, relating the temperature modulation of the sample to the sensor, is one of the obstacles in comparing the LIVTs of different shunts. Obviously, its value depends on the pressure of the sensor upon the surface and, for a rough sample, on this roughness. As we work with texturized multicrystalline silicon cell surfaces, the roughness of which depends on the grain orientation, this coefficient may slightly deviate from its average value for different
sensor positions. We see that for a gold stripe, the ohmic resistance of the stripe leads to a linear LIVT. Fig. 1b represents the LIVT of another test structure, which is a base-collector p–n junction of a silicon transistor. This p–n junction can be considered a good approximation to the ideal one, with the doping concentration tending to that of a usual solar cell. Usual $I-V$ measurement yields the $n$-factor 1.0 of this junction, which is in good agreement with 1.18 obtained from its LIVT. If the $I-V$ characteristic is not exactly exponential, a bias-dependent $n$-factor can be defined as the slope of an exponential fit at a certain bias. In Fig. 1b, at lower biases the $n$-factor slightly increases owing to a recombination current getting important. At higher biases, the curve becomes sublinear owing to the influence of a series resistance significant at high currents. So far, the LIVT technique supplies reasonable information, at least for the cases discussed above.

In multicrystalline silicon solar cells there are at least four different types of LIVT behavior. Ohmic shunts (Fig. 2a: DPCT, Fig. 2b: LIVT) mostly occur at the edge of the cell. Particularly, at its edge the cell in Fig. 2 shows a shunt at the crossing point of several grain boundaries, which, however, is not the rule. In Fig. 2, the boundaries appear as dark lines due to the above mentioned dependence of the thermal contact with the sensor on texturization. The image in Fig. 2a was obtained with 20 Hz excitation frequency in order to improve the spatial resolution while investigating this strongly localized and powerful shunt. Black contrast means no temperature variation, while white one corresponds to 20 mK. This value is measured at the sensor and thus is about 10 times lower than the actual temperature modulation at the surface of the cell (for an explanation look above). The LIVT of the linear shunt shows some particularities. Although its shape is quite linear, there are increased disturbances near zero bias owing to the influence of the noise (see above), with the curve getting slightly superlinear at higher forward voltages. This superlinearity can be explained by the superposition of the thermal signal from the shunt and that from the p–n junction around the shunt. In DPCT images this superposition is usually indicated by interferential rings (not visible in Fig. 2a owing to an inappropriate contrast scale). The nature of a linear shunt is due to the short-circuited sites of the cell edge, which may be caused by an insufficient removal of the emitter layer at the edge. Then the shunt current is essentially limited by the ohmic resistance of the current “bridge” across the edge, since the $p^+–n^+$ junction between the “bridge” and the rear $p^+$-layer becomes
transparent by tunneling, resulting in a linear LIVT with the same slope in both directions. In several cases, such linear LIVTs were found significantly shifted to positive values of the current, so that the linear extrapolations of both forward and reverse lines to zero bias did not cross the zero point. This can neither be explained by an incorrect voltage supply, nor by occasional illumination nor by the voltage drop at the p⁺–n⁺ junction. Otherwise, the division by V would disturb the linear shape.

The next shunt type also appears near the edge of the cell. Sometimes grain boundaries crossing the edge occur at such sites [10]. The LIVT investigation (Fig. 3a) allows one to easily distinguish this type of shunts from the linear edge ones. The LIVT shape is not linear and the n-factor is high: n = 6.6 at 0.5 V. The original hypothesis which is now doubted is that the microcrack nature of this type arises from the mechanical damage to the cell edge when the wafer is cut out of the silicon block [11]. The LIVT investigation of a crack made on purpose in a monocrystalline sample shows a different characteristic shape and a considerably lower n-factor of n = 2.1 at 0.45 V (Fig. 3b). The thermal signal of the crack is out of noise only beyond 0.35 V, but has a good exponential dependence until the series resistance shows itself. However, the emitter layer formation process may have influenced the non-linear edge shunt.

Fig. 2. DPCT 10 × 10 mm² image (a) and LIVT (b) of a linear shunt.

Fig. 3. LIVTs of a non-linear edge shunt (a) and a crack in a monocrystalline cell (b); the shape is different.
behavior. There was no significant current flow when this edge shunt was reverse-biased (below 0.05 a.u. up to \(-5\) V). Since between 0.3 and 0.6 V a linear part of the curve is visible in linear coordinates, the whole shunt behaves as if a low-barrier diode were connected via a high series resistance. This type of shunts is still being investigated.

In the DPCT images “Schottky type” shunts appear as small bright points under the front grid (Fig. 4a), sometimes at grain boundaries. In Fig. 4a, the white contrast corresponds to an amplitude of 0.3 mK (at the sensor). These shunts are obviously due to the direct contact between the metal grid and the bulk of silicon in positions with no top emitter layer, forming a non-ideal Schottky junction. This happens, for example, when the surface of the cell was damaged mechanically before the grid formation [11]. Recently, several such cases were observed, the exact nature of the damage, however, has not always been determined. These shunts always disappeared after the removal of the front grid. An example of LIVT of such a shunt is shown in Fig. 4b. It has a high \(n\)-factor \(n = 9.7\) and an increased reverse current. The increase of the values closer to zero is again due to the influence of noise.

In the lower part of Fig. 4a, a small shunt occurs probably induced by impressing a dust particle during the measurement procedure. The sensor was moving from right to left when the shunt appeared. Its halo was clearly visible during the following scans, hence the damage became a permanent shunt.

Non-localized stress-sensitive shunts appeared as relatively large spots in the DPCT images. The intensity of these shunts decreased significantly after cutting the cell into pieces. However, they reappeared when mechanical stress was applied to the cell by slightly bending it. The profile of the temperature modulation through the shunt in the sample with and without mechanical stress is shown in Fig. 5a. For the sample of Fig. 5, bending in any direction increases the shunt amplitude. These changes are reversible: after measuring under stress the sample was released and the shunt was proved to redisappear. The nature of the stress sensitivity is not related to the impurity gettering: after 8 h the amplitude of the shunt had not changed. Fig. 5b

![Image](image_url)

Fig. 4. DPCT 5 x 5 mm² image (a) and LIVT (b) of a Schottky type shunt.
shows a LIVT of the same region but under convex stress. In Fig. 5b the $n$-factor of the stress-sensitive shunt is 2.7.

For comparison, a LIVT of a “good” region is shown in Fig. 6a, having a typical S-shape and, at higher biases, governed by series resistance. At lower biases, the $n$-factor exceeds $n = 2$. One possible explanation, based on the recombination current, is discussed in Ref. [14].

Fig. 6b presents a map of $n$-factor values for a power transistor collector junction. Unfortunately, the sensitivity of the temperature measurements still does not allow one to perform similar investigations for solar cells at their usual working point. Black contrast in Fig. 6b corresponds to $n = 1$, white one corresponds to $n = 1.7$.

4. Conclusions

Applying the LIVT technique to the study of local shunts in multicrystalline silicon solar cells has provided detailed insight into the subject of shunt formation. The shunt types are classified according to the respective experimental results. The LIVT technique is useful in industry applications for troubleshooting in the solar cell production, and besides, it can be applied to a wide variety of semiconductor structures.
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References