Far-infrared electroluminescence characteristics of an Si-based photodiode under a forward DC bias current*

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At room temperature, the bias dependence of a far-infrared electroluminescence image of a photodiode is investigated in the dark condition. The results show that the electroluminescence image can be used to detect defects in the photodiode. Additionally, it is found that the electroluminescence intensity has a power law dependence on the dc bias current. The photodiode ideality factor could be obtained by a fitting a relationship between the electroluminescence intensity and the bias current. The device defect levels will be easily determined according to the infrared image and the extracted ideality factor value. This work is of guiding significance for current solar cell testing and research.

Keywords: photodiode, electroluminescence images, electroluminescence intensity

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1. Introduction

Currently, solar photovoltaic power generation is regarded as an important way to solve the current energy crisis, in which a solar cell is the core component.[1−3] The preparation of a solar cell requires screen printing, high temperature sintering, and other processes. The mechanical and thermal stresses in those processes can cause device defects which seriously affect the performance of the solar cell.[4,5] Therefore, the effective defect detection technique is regarded as a very important tool to ensure a high-quality solar cell.

In recent years, the electroluminescence (EL) imaging method has been proposed as a novel tool for fast spatially resolved solar cell characterization.[6−9] However, the EL intensity and characteristics are controlled by the bias condition[10] and device structure.[11,12] In fact, due to the lack of a comprehensive physical model describing the far-infrared EL intensity of the solar cell, the experimental results obtained are still elusive. Generally speaking, a traditional solar cell is just a large area photodiode. In this work, bias dependence of far-infrared EL imaging of a photodiode is measured experimentally. Then, theoretical analyses are carried out. It is observed that the EL emission decreases with the increase of defect concentration in the photodiode. The associated EL intensity profile can effectively reflect defect distribution over the entire cell area. Furthermore, the EL intensity has a power law dependence on the dc bias current. The photodiode ideality factor could be obtained by fitting a relationship between the EL intensity and the bias current. The device defect levels will be determined according to infrared images and extracted ideality factor value.

2. Experimental setup and measurements

A schematic diagram of the experimental setup used for the measurements is shown in Fig. 1. A

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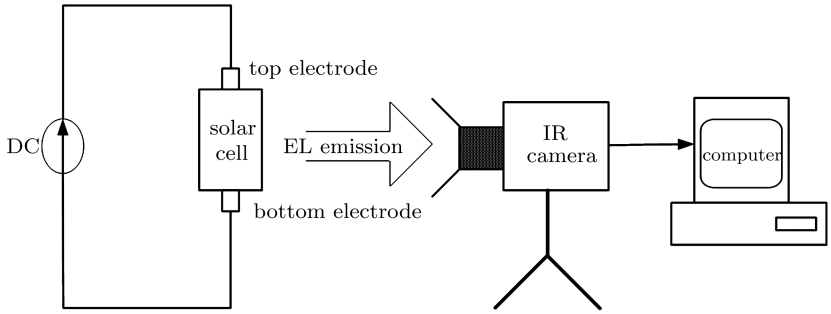


Fig. 1. Schematic diagram of the setup for the far-infrared electroluminescence measurement (not to scale).

A 4 mm × 3 mm Si-based photodiode (number 2CU006 made by Shanghai Hengfang Electronics Co Ltd) with only a P–N junction structure is mounted in an x–y–z micrometer positioner. The thickness of the photodiode is about 0.44 mm. When the photodiode works under a forward bias, the emitted photons can be captured with a far-infrared camera to obtain an image of the distribution of radiative recombination in the cell. In order to align the camera with the optical axis, the photodiode could be adjusted by the positioner. Then, the EL images are sent into a computer for processing.

In the real experiment, the power supply model LM1719A was selected as a DC bias source. The camera (number VC hr Research 780 made by InfraTec GmbH) was used for data acquisition at a suitable resolution of 640 × 480 pixels, which has a linear response function. The camera works in a wavelength range from 7.5 μm to 14 μm. All the experiments were accomplished under room temperature and dark conditions.

3. Results and discussion

In Fig. 2, the contour map of the measured far-infrared thermal image is shown under a forward dc bias current of 0.15 A. The contour curves correspond to the EL intensities at 76 (solid), 62 (dash), 48 (dot), and 34 (dashed–dotted) (a.u.), respectively. It can be seen that the maximal light intensity exists in the vicinity of two electrodes. With the increase of distance from the electrodes, light intensity starts a gradual decline (indicated by arrows in Fig. 2). It can be interpreted as follows: for a high carrier density near the electrode region, there is a high recombination probability which leads to a strong light intensity. There is an obvious difference in the EL image between the top and bottom electrodes. This may be due to welding pollution which brings about a bad top electrode. In addition, the dashed–dotted curve is not especially symmetric with respect to the centre of the cell (zone A and zone B in Fig. 2). This may be due to local doping concentration changes in those zones. From the above description, it can be determined that there are flaws in this photodiode. After the level of bias current is changed, the same results are also obtained.

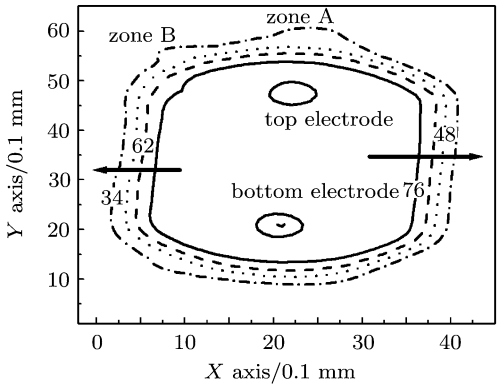


Fig. 2. Far-infrared electroluminescence image contour map under a foward DC bias current of 0.15 A.

In Fig. 3, the measured mean EL intensity of each far-infrared image is obtained as a function of the forward dc current. There is not a simple linear relationship. The curve first slowly lifts upwards, and then increases rapidly as bias current increases.

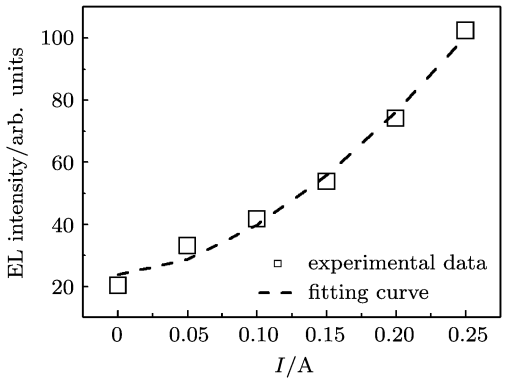


Fig. 3. Mean EL intensity versus forward DC bias current.

For the purpose of explaining the experimental results, the simple p–n diode model is used. The total excess minority carrier number N along the depth x in the p active layer will be expressed as follows:[13−15]

$$N = \int_0^{+\infty} n_{\rm p}(0)\exp(-x/L_{\rm e})\,{\rm d}x = n_{\rm p}(0)L_{\rm e}, \quad (1)$$

in which $n_{\rm p}(0)$ is the excess minority carrier number at the p–n junction edge, and $L_{\rm e}$ is the diffusion length which tends to a constant at room temperature.

The $n_{\rm p}(0)$ is subject to an applied forward voltage V by the following equation:[16]

$$n_{\rm p}(0) = n_{\rm p}\exp(eV/kT), \quad (2)$$

where $n_{\rm p}$, e, k, and T are the equilibrium minority carrier density in the p layer, the electron charge, the Boltzmann constant, and the measured temperature, respectively.

The EL intensity $I_{\rm EL}$ is considered to be proportional to N integrated along the depth. Therefore, the $I_{\rm EL}$ is also proportional to $n_{\rm p}(0)$ for fixed diffusion length $L_{\rm e}$. So, when the forward current is varied, the bias voltage will change. Then, the $I_{\rm EL}$ will be expressed as a function of V as follows:

$$I_{\rm EL} = A\exp(eV/kT), \quad (3)$$

where A is a constant related to doping density and temperature.

In addition, forward current I can be determined by the well-known Shockley diode equation,

$$I = I_0[\exp(eV/nkT) - 1], \quad (4)$$

where n is the diode ideality factor and I_0 is the dark reverse saturation current. The ideality factor n varies from 1 to 2, depending on the fabrication process and semiconductor material.

It is noted that the ideality factor is also known as the emission coefficient which accounts for the influence of device defects on the characteristic of light emission.[17] In fact, defects drive the recombination process. If there is no defect present, the total diode current would be a diffusion current and n would be 1. More defects mean more space–charge recombinations, and thus drive n up to 2.

If condition ($\exp(eV/nkT) \gg 1$) is satisfied (This is true especially when the bias voltage is large enough), the above equation can be simplified as follows:

$$I \approx I_0\exp(eV/nkT). \quad (5)$$

Then, combing Eq. (3) and Eq. (5), the EL intensity follows that

$$I_{\rm EL} \approx A\left(\frac{I}{I_0}\right)^n, \quad I_{\rm EL} \propto I^n. \quad (6)$$

Therefore, the number of photons generated by electroluminescence has a power law dependence on current. It should be noted that the diode ideality factor can be deduced by measuring the EL intensity as a function of the forward injection current. In order to further confirm these conclusions, the fitting curve is shown in Fig. 3. The extracted ideality factor value is about 1.70735 ± 0.2536 which is in the scope of theoretical values and is close to 2. From the above fitting results, it can be seen that there are defects in our sample. This conclusion is consistent with the finding from the IR thermal image contour map in Fig. 2.

4. Conclusion

In order to understand the far-infrared electroluminescence characteristics of a solar cell, experiments and theoretical analyses for a photodiode are carried out. It is clearly observed that the EL image can be used to detect defects. And, the EL intensity has a power law dependence on the dc bias current. The device ideality factor could be obtained by a fitting a relationship between the electroluminescence intensity and the bias current. Those results reasonably agree with the theoretical analyses. The defect level of the device will be effectively determined according to the infrared image and the extracted ideality factor value. This work is very significant for the research, testing, and production of solar cells.

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