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Analytic findings in the electroluminescence characterization of crystalline silicon solar cells

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The electroluminescence intensity from Si cells under the forward bias was found to have one to one quantitative agreement with the minority carrier diffusion length. Based on the diffusion equation and simple *p-n* diode model, the electroluminescence intensity was analyzed relative to the cell performance. Electroluminescence intensity is proportional to the product of the injected minority carrier density and the effective diffusion length. The diode ideality factor *n* can be deduced by measuring the electroluminescence intensity as a function of the forward injection current. Among various crystalline silicon cells including single and polycrystalline types, the measured electroluminescence intensity at a fixed forward current has a tight relationship with the open circuit voltage of each cell, which gives a very convenient way to evaluate cell performance. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2431075]

I. INTRODUCTION

In recent years, quick and precise evaluation of material properties of silicon (Si) is strongly required to get high efficiency and reliable performance of crystalline Si solar cells reproducibly under mass production process. For the detailed characterization and optimization of cell performance, the most important material parameter to be analyzed is the minority carrier diffusion length (or lifetime), which governs the short circuit current and open circuit voltage. Besides the conventional methods such as the photoconductivity decay[1] and the spectroscopic laser beam induced current[2] (LBIC) and the electron beam induced current (EBIC) methods,[3] we have proposed a technique of photographic surveying[4] to analyze the minority carrier diffusion length distribution in as-fabricated cells or modules. Solar cells under the forward bias emit infrared light which can be captured by a Si charge coupled device (CCD) camera. The intensity distribution of emission clearly agrees with the mapping of minority carrier diffusion length in polycrystalline silicon active layers. This technique can be expanded to detect the mechanical damage (substrate cracks and/or electrode breakdown) and process deficiencies during cell fabrication, and has become a very versatile tool named "luminoscopy" to produce reliable high efficiency cells.[5] In this paper, analytic findings in the electroluminescence characterization technique will be discussed by the quantitative examination of the relationship between the emission intensity and the current voltage characteristics of cells. Analytic background to deduce the solar cell performances such as open circuit voltage is discussed based on the simple *p-n* diode model.

II. EXPERIMENTS

The schematic measurement apparatus is shown in Fig. 1. A sample cell biased at an appropriate forward bias emitted infrared light, which was collected by a cooled (at around -50 °C) Si CCD camera with 512×512 pixels. The maximum forward current was set at about 40 mA/cm^2, which corresponded to the typical short circuit current under 1 sun solar irradiation. Data acquisition time was 100–500 ms/frame. Spatial resolution of analysis was limited by the optical system and varied based on the magnification scale of the frame. For example, if the cell of 10 cm^2 was measured in one frame, then the spatial resolution was 10 cm/512 pixels, i.e., around 0.2 mm. An IR filter to pass longer than the wavelength of 850 nm was used to reduce the disturbance of surrounding light. The minority carrier diffusion length was calibrated by the LBIC analysis using multiple wavelengths. Measurement was carried out at room temperature. The measured samples were single and polycrystalline silicon solar cells which were made by the conventional process. Typical energy conversion efficiency was 15%–18% with a short circuit current of 30–35 mA/cm^2 and an open circuit voltage of 0.55–0.65 V. Detailed description of the cell fabrication process and material properties were not shown here since they were out of the scope of this paper.

III. ELECTROLUMINESCENCE

Figure 2 shows a typical emission spectrum (bold solid line) taken by an infrared sensitive Ge photodetector cooled

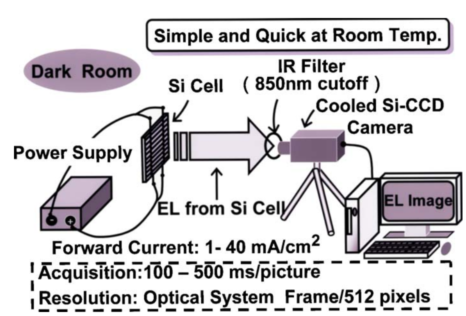

FIG. 1. Schematic plan of experimental setup.

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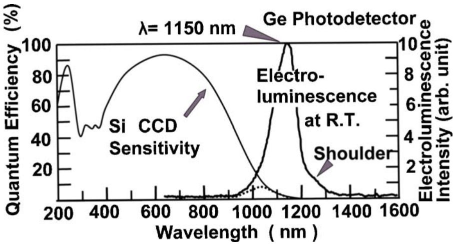

FIG. 2. Typical emission spectrum and the sensitivity of the Si CCD camera.

at liquid nitrogen temperature. It should be noted that the sample was at room temperature. The dominant emission peak was 1150 nm, which might be the band to band radiative recombination assisted by phonons.[5] It should be noted that the sensitivity of the Si CCD was up to 1200 nm, as shown by the light solid line in Fig. 2. The limited portion of emission (schematically shown by the dotted line with a peak $\lambda = 1050$ nm) could be detected by this system, but still we could get clear image and precise measurement of electroluminescence from Si cells. In addition, the absorption coefficient at $\lambda = 1050$ nm is 16.3 cm^{-1} in Si, and so reabsorption of emission was negligible in the case of typical Si cells with a thickness of 200–300 μm.

Figures 3–5 show a comparison of the images of the typical polycrystalline Si sample cell by the scanning electron microscope (SEM), the LBIC, and the electroluminescence emission intensity mapping, respectively. In the LBIC image, some electrically active defects and grain boundaries were observed (they could not be detected by SEM). The electroluminescence viewgraph shows the clear agreement of the grain boundary structures. It should be noted that the LBIC measurement needs a beam scan and is rather time consuming. On the contrary, the electroluminescence technique shows the attractive feature of fast imaging of grain boundaries and defects by one shot photograph.

This emission intensity has a quantitative relationship with the minority carrier diffusion length. We compare the diffusion length determined by the conventional multiwavelength LBIC method and the electroluminescence intensity at identical points in the polycrystalline Si sample cell.[4] As shown in Fig. 6, the electroluminescence intensity increased linearly with increasing diffusion length at a fixed forward current. This behavior was kept when the current density was

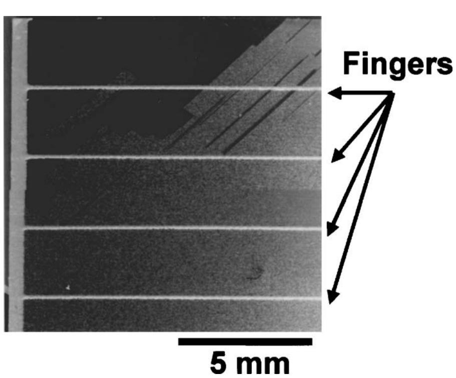

FIG. 3. Surface view of typical polycrystalline Si cell taken by scanning electron microscope.

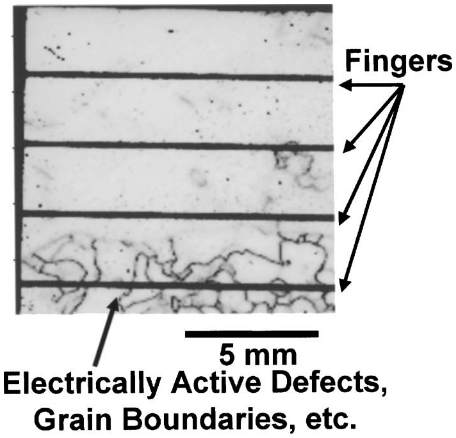

FIG. 4. Laser beam induced current mapping of the same cell in Fig. 3. Electrically active defects and grain boundaries are shown.

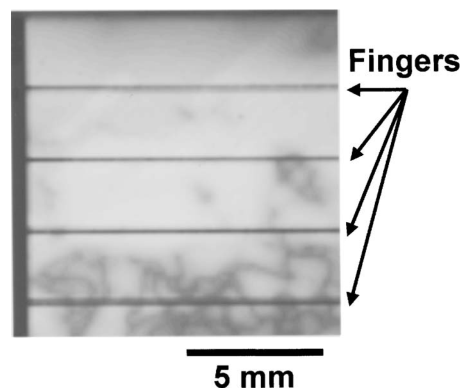

FIG. 5. Electroluminescence image of the cell in Fig. 3. Defects and grain boundaries agree well with the laser beam induced current image (Fig. 4).

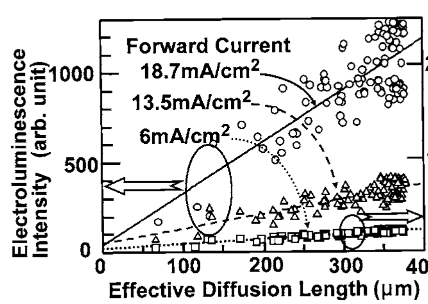

FIG. 6. Electroluminescence intensity as a function of the effective diffusion length in the cases of forward current densities of 6, 13.5, and 18.7 mA/cm^2, respectively.

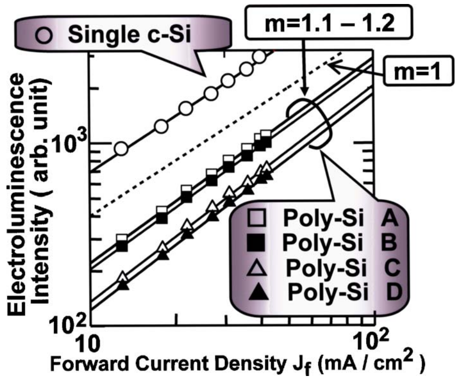

FIG. 7. Electroluminescence intensity as a function of the forward current density in several single and polycrystalline Si solar cells.

varied in the range of 6–40 mA/cm^2, which was the common generating photocurrent under 1 sun (the experimental results were shown in the cases of 6, 13.5, and 18.7 mA/cm^2, respectively).

In Fig. 7, the electroluminescence intensity is plotted as a function of the forward current density in various samples including the single crystalline Si cell. They show linear dependences using logarithmic scale on both axes, and the slope was 1 in the case of single crystalline Si. In the case of poly-Si cells, we averaged the intensity of each sampling point, and the slope varied in a range of 1.1–1.2 depending on the samples.

IV. ELECTROLUMINESCENCE INTENSITY DEPENDENCE ON FORWARD VOLTAGE AND CURRENT

In order to explain the experimental results of the electroluminescence intensity dependence on the diffusion length (Fig. 6) and the forward current (Fig. 7), the simple *p-n* diode model was used as a first order approximation. The excess minority carrier distribution under the forward bias was schematically shown in Fig. 8. The total excess minority carrier number N along the depth x in the p active layer will be expressed as follows:

$$N = \int_0^{+\infty} n_{p(0)} \exp(-x/L_e)dx = n_{p(0)}L_e, \tag{1}$$

in which $n_{p(0)}$ is the excess minority carrier number at the *p-n* junction edge, and L_e is the effective diffusion length. The electroluminescence (EL) intensity I_L was considered to be proportional to N integrated along the depth, and then to L_e at the fixed injection condition $n_{p(0)}$. The observed emission peak was at 1050 nm, and so reabsorption in Si was neglected as mentioned before. So, the EL intensity distribution will agree with the spatial variation of the effective diffusion length as shown in Fig. 6. In this model, only an active p layer was considered since conventional Si cells had a very thin n layer, and the electroluminescence from n layers was negligible compared with that from p layers.

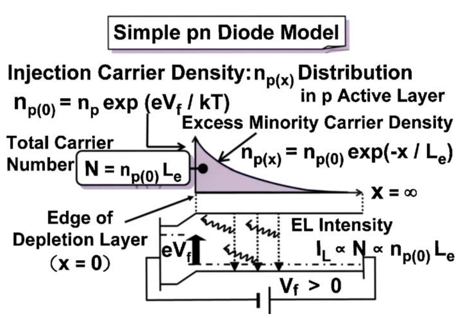

FIG. 8. Schematic viewgraph of excess minority carrier density distribution in the typical n^+p Si solar cell.

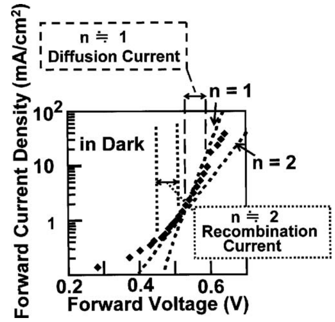

FIG. 9. Current/voltage characteristic in a typical single crystalline Si cell under the dark condition.

We will discuss about the electroluminescence intensity dependence on $n_{p(0)}$. The EL intensity was also proportional to $n_{p(0)}$, which is governed by the applied forward voltage V_f (equal to the quasi-Fermi level difference of the minority carrier) by the following equation:

$$n_{p(0)} = n_p \exp(eV_f/kT), \tag{2}$$

where n_p, e, k, and T are the equilibrium minority carrier density in the p layer, electron charge, Boltzmann constant, and measurement temperature, respectively. So, when the forward current was varied, the electroluminescence intensity will be expressed as a function of V_f as follows:

$$I_L = A \exp(eV_f/kT), \tag{3}$$

$$\text{then } \ln I_L = A' + (e/kT)V_f \quad (A, A'\text{: constant}). \tag{4}$$

On the other hand, the injected forward current J_f was expressed by the well-known equation

$$J_f = J_o \exp(eV_f/nkT), \tag{5}$$

where n is the diode ideality factor and J_o is the dark saturation current. Then, the electroluminescence intensity is expressed by the following equation as a function of J_f;

$$\ln I_L = A'' + n \ln J_f \quad (A''\text{:constant}). \tag{6}$$

It should be noted that in the dependence of I_L on J_f, there appears a diode ideality factor n.

Experimental results using a single crystalline Si cell clearly proved the explanation discussed above. Figure 9 shows a typical experimental result of current/voltage characteristic of the measured sample in dark. Figures 10 and 11 show the electroluminescence intensity dependences on forward voltage V_f and forward current J_f, respectively. In Fig. 9, in a lower voltage region of 0.45–0.55 V, the recombination current dominated and the ideality factor n was 2. In a higher voltage region of 0.55–0.6 V, the diffusion current

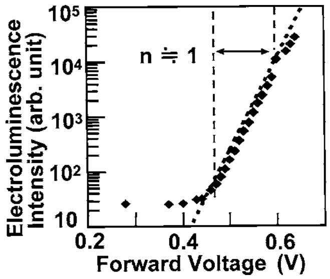

FIG. 10. Electroluminescence intensity as a function of the forward voltage in the sample of Fig. 9.

became dominant, which gave $n=1$. In Fig. 10, the semilogarithmic plot of electroluminescence intensity showed a linear increase with V_f in the whole range, and the slope was e/kT (i.e., $n=1$) as expected from Eq. (4). Figure 11 shows the logarithmic plot of I_L and J_f on both axes. In the lower current region around 1 mA/cm^2, the ideality factor n was 2, and in the higher current region around 10 mA/cm^2, n became 1 as expected from Eq. (6). In summary, if we set the logarithmic plot of electroluminescence intensity as a function J_f in logarithmic scale, the slope gives the diode ideality factor. When we go back to the analysis in Fig. 7, each slope was considered to correspond to the diode ideality factor of each sample cell. In the case of the single crystalline Si, n became 1 (the forward current of 10 mA/cm^2 or higher was in the diffusion current dominant region). In the polycrystalline Si cells, n became 1.1–1.2 depending on the junction quality. The electroluminescence intensity dependence on the forward current is considered to be identical to the measured dark current/voltage characteristic, which expresses the p-n diode quality.

V. ELECTROLUMINESCENCE INTENSITY AND OPEN CIRCUIT VOLTAGE

Figure 12 shows the schematic explanation of the electroluminescence measurement. The center figure shows the typical current/voltage characteristics under the dark condition (solid line) and under the minority carrier injection (dashed line), respectively. Point A is a typical electroluminescence measurement condition (forward voltage V_f and current J_f). If we assume that we inject the same number of $n_{p(o)}$ as that in the EL measurement condition by some methods, e.g., photoirradiation, the current voltage curve shifts downwards and point A becomes point B; the origin ($V_f=0$

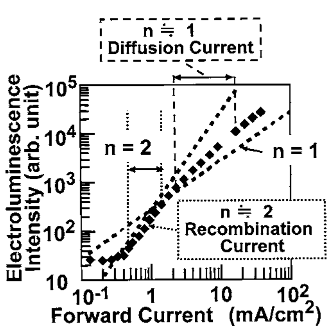

FIG. 11. Electroluminescence intensity as a function of the forward current density in the sample of Fig. 9.

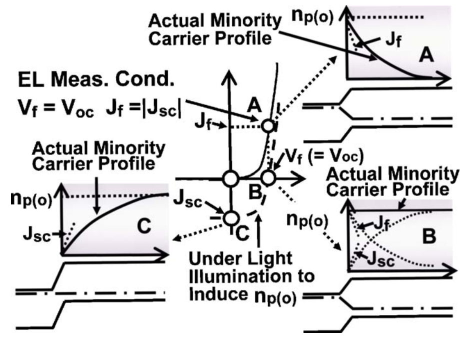

FIG. 12. Schematic viewgraphs of the minority carrier distributions for several conditions of current/voltage status. Point A: Typical electroluminescence measurement condition. Point B: Open circuit condition. Point C: Short circuit condition.

and $J_f=0$) becomes point C. The energy band diagrams and the distributions of injected minority carriers are illustrated by the insertions. As you can see, at point B, the injected minority carrier density $n_{p(o)}$ exists throughout the sample which represents the so-called open circuit condition. The constant minority carrier density in the sample is considered to be the convolution of the minority carrier profiles of points A and C (point C stands for the "short circuit" condition). As we discussed in Sec. IV, the electroluminescence intensity is proportional to $n_{p(o)}$, which is determined by V_f. The value of V_f is identical to V_{oc}, which locates the same number of $n_{p(o)}$ throughout the sample. Then we can deduce the very important relationship between the electroluminescence intensity and the open circuit voltage as mentioned below.

If we measure the electroluminescence in two samples (t: target, r: reference) at the same forward current J_f, the electroluminescence intensity of the target, I_{Lt}, and that of the reference, I_{Lr}, are expressed as follows:

$$I_{Lt} = n_{p(o)} \times L_{et} = (J_f L_{et}/eD) \times L_{et} = (J_f/eD) \times L_{et}^{\ 2}, \quad (7)$$

since $J_f = eDdn_p/dx$, at $x=0$

$$J_f = eDn_{p(o)}/L_{et} \quad [n_p = n_{p(o)} \exp(-x/L_{et})],$$

where L_{et} is the effective diffusion length in the target cell.

When we compare the electroluminescence intensity at the same forward current J_f,

$$I_{Lt}/I_{Lr} = L_{et}^{\ 2}/L_{er}^{\ 2}, \quad (8)$$

where L_{er} is the effective diffusion length in the reference cell.

On the other hand, let us consider $n_p(o)$ in the open circuit condition under the minority carrier injection by 1 sun irradiation. In the conventional continuity equation,

$$dn_p/dt = g - n_p/\tau, \quad (9)$$

where g is the generation rate and τ is the lifetime. Under equilibrium condition, dn_p/dt becomes 0. Then,

$$n_{p(o)} = g \times \tau = (g/D)L_e^{\ 2}. \quad (10)$$

If we consider the target and reference cells,

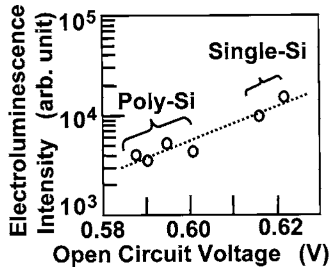

FIG. 13. Electroluminescence intensity at a fixed forward current as a function of the open circuit voltage for several single and polycrystalline silicon solar cells.

$$n_{p(o)t}/n_{p(o)r} = L_{et}^{2}/L_{er}^{2}, \tag{11}$$

where $n_p(o)t$ and $n_p(o)r$ are the injected minority carriers in the target and the reference cells, respectively.

The $n_p(o)t$ is expressed by Eq. (2), so

$$L_{et}^{2}/L_{er}^{2} = n_{p(o)t}/n_{p(o)r} = \exp(eV_{\rm oct}/kT)/\exp(eV_{\rm ocr}/kT)$$
$$= \exp[e(V_{\rm oct} - V_{\rm ocr})/kT], \tag{12}$$

where $V_{\rm oct}$ and $V_{\rm ocr}$ are the open circuit voltages of the target and reference cells, respectively. The majority carrier density in a p active layer is assumed to be the same in order to simplify the discussion. Then, from Eqs. (8) and (12) the important relationship between the electroluminescence intensity and the open circuit voltage of the cell was deduced,

$$I_{Lt}/I_{Lr} = \exp[e(V_{\rm oct} - V_{\rm ocr})/kT]. \tag{13}$$

The electroluminescence intensity of several samples including single and polycrystalline silicon cells was measured at the same forward current density and plotted as a function of each open circuit voltage of cell under 1 sun (Fig. 13). Logarithmic plot of electroluminescence intensity clearly showed a linear relationship with open circuit voltage and the slope was e/kT at room temperature as was expected by Eq. (13). When we set a reference sample whose open circuit voltage is known, we can estimate the open circuit voltage of the target cell by Eq. (13) simply by comparing the electroluminescence intensity at the same forward current. This gives a very quick and easy evaluation of the cell performance by electroluminescence measurement.

VI. CONCLUSIONS

Analytic findings of the electroluminescence intensity characterization technique of Si solar cells were presented. The electroluminescence intensity under the forward bias was found to show the one to one quantitative relationship with the effective minority carrier diffusion length. The diode ideality factor was also deduced from the dependence of the electroluminescence intensity on the forward current. The logarithm of the electroluminescence intensity ratio corresponds to the difference of the open circuit voltage when we measure at the same forward current. The electroluminescence technique is useful not only to evaluate the minority carrier diffusion length distribution but also to give an easy and quick way to estimate the diode ideality factor and the open circuit voltage of solar cells.

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