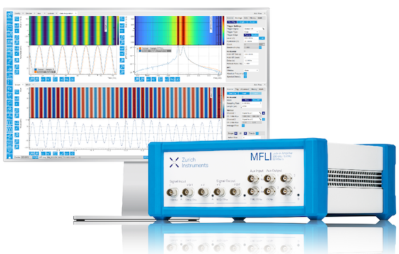
Applied Physics Letters

RESEARCH ARTICLE | JUNE 24 2005

Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescence

Takashi Fuyuki; Hayato Kondo; Tsutomu Yamazaki; Yu Takahashi; Yukiharu Uraoka

Appl. Phys. Lett. 86, 262108 (2005)
https://doi.org/10.1063/1.1978979



Photographic surveying of minority carrier diffusion length in polycrystalline silicon solar cells by electroluminescence

Takashi Fuyuki,[a] Hayato Kondo, Tsutomu Yamazaki, Yu Takahashi, and Yukiharu Uraoka
Graduate School of Materials Science, Nara Institute of Science and Technology, 8916-5, Takayama, Ikoma, Nara 630-0192, Japan

(Received 23 November 2004; accepted 23 May 2005; published online 24 June 2005)

Photographic surveying of the minority carrier diffusion length distribution in polycrystalline silicon solar cells was proposed. Light emission from the cell under the forward bias was captured by a charge coupled device camera. We have found that the intensity distribution of light emission clearly agreed with the mapping of minority carrier diffusion length in polycrystalline silicon active layers. The emission intensity had a one-to-one relationship with the minority carrier diffusion length, which yielded a semiquantitative analysis method of the diffusion length mapping and the detection of the deteriorated areas. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1978979]

In recent years, the production scale of solar cells has increased remarkably to meet with the pressing requirements of practical photovoltaic systems. Among installed systems, more than 90% are crystalline silicon cells, and especially polycrystalline silicon (poly-Si) shows the advantages of low cost and large area with relatively high efficiency. In order to get reliable high efficiency under a mass production process, quick and precise evaluation of cell performance and feedback to production lines are indispensable. Usually the fabricated cells and/or modules are inspected simply by current/voltage output performance under solar simulated light. For a detailed examination of cell performance, the most important material parameter to be monitored is the minority carrier diffusion length (or lifetime), which governs the collection efficiency. The photoconductivity decay method, using microwave reflection,[1] is widely used to check the minority carrier lifetime of substrates, but it requires good surface passivation in order to derive an accurate bulk lifetime. After the formation of p/n junctions, the spectroscopic light-beam-induced current[2,3] (LBIC) or the electron-beam-induced current methods[4] are used, at the laboratory level, to elucidate the minority carrier diffusion length and the effects of defects and/or grain boundaries. In all these methods, the probe tools (light, electron beam, etc.) are required in order to acquire the spatial distribution of the diffusion length.

In this letter, we propose a technique to analyze the minority carrier diffusion length distribution under an as-fabricated cell (or even a module) structure by a simple and quick photographic surveying method. Light emission from solar cells under the forward bias was captured by a CCD camera, and we found that the intensity distribution of emission clearly agreed with the mapping of the minority carrier diffusion length in poly-Si active layers. Takamoto *et al.* reported the application of electroluminescence in single-crystalline InGaP/GaAs tandem solar cells, but they revealed only the nonuniformity of the saturation current density and the current leakage paths.[5] Quantitative analysis of the relation between the emission intensity and the minority carrier diffusion length was discussed. The feasibility of this technique was addressed showing the mapping of the minority carrier diffusion length and the detection of deteriorated areas.

The schematic measurement setup is shown in Fig. 1. A sample cell biased at an appropriate forward voltage emitted infrared light, which was collected by the cooled CCD camera using a selected objective lens. The cooled (at around $-50\ ^\circ C$) CCD could capture $1 \times 1\ cm^2$ cell area by 680×680 pixels in the sensitive wavelength region of 300–1100 nm. Through the data acquisition and smoothing process, the spatial resolution was reduced, and the resolution limit became about 50 μm in length.

The minority carrier diffusion length was calibrated by the light-beam-induced current (or voltage) analysis using four wavelengths of 660, 890, 950, and 980 nm. The spatial resolution of the LBIC was 250 μm. One measuring point of the LBIC method included 5×5 points of the emission intensity measurement, so that an average of 25 values of emission intensity was used when the relationship between the diffusion length and the emission intensity was discussed.

Polycrystalline Si solar cells ($1\ cm \times 1\ cm$) were fabricated through conventional device processes using the cast silicon substrate. The average efficiency of measured samples was 13%–15%. Detailed materials properties and cell configuration are not shown here since these data are not essential for the discussions in this work. The measurement was carried out at room temperature.

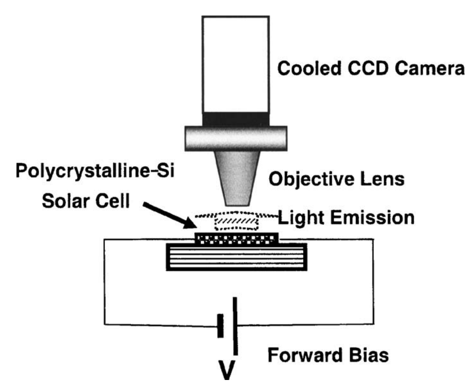


FIG. 1. Schematic diagram of an experimental setup.

[a]Electronic mail: fuyuki@ms.naist.jp

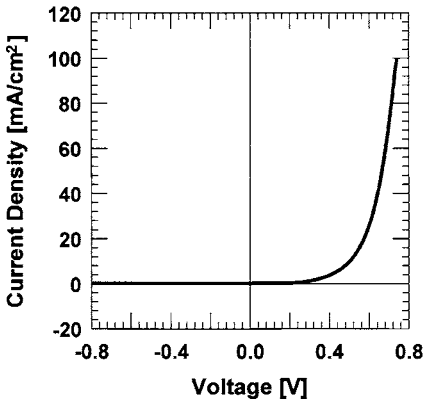


FIG. 2. Current/voltage characteristic of a measured sample.

A typical current/voltage characteristic of the sample is shown in Fig. 2. Forward bias in a range of 0.4–0.6 V was applied to run the current of 6–20 mA/cm^2. Figures 3 and 4 show the distributions of the emission intensity and the minority carrier diffusion length, respectively. The intensity and the diffusion length are expressed in a gray scale in the ranges of 10–50 (intensity, arbitrary unit) and 0–400 (diffusion length, μm), respectively. As can be clearly seen, the distribution of the emission intensity agrees very well with the mapping of the minority carrier diffusion length. The relatively dark areas (circled by A–F) in Fig. 3 coincided with the short diffusion length parts in Fig. 4. This is the experimental evidence of the photographic surveying of minority carrier diffusion length using light emission from the solar cell. In area F of Fig. 3, the coalescence of defects are detected which shows the applicability of this probeless method to get the spatial information of the minority carrier diffusion length.

Figure 5 shows the emission intensity dependence upon the measured diffusion length at the same measuring point on the cell. The absolute value of the diffusion length was calibrated by the LBIC method mentioned earlier. The circles, triangles and squares are for the cases of the forward

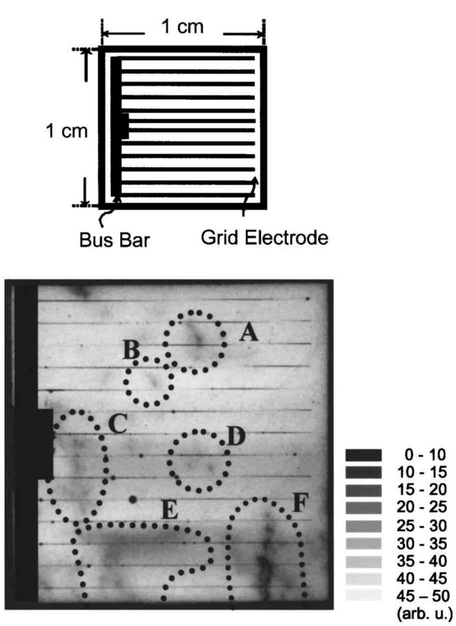


FIG. 3. Emission intensity distribution in polycrystalline Si cell under the forward bias. A schematic viewgraph of the sample is inset.

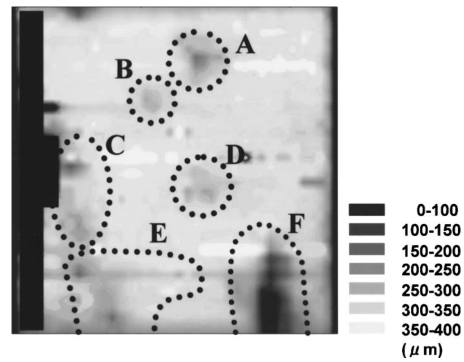


FIG. 4. Distribution of the minority carrier diffusion length in the cell shown in Fig. 3 measured by the LBIC method.

current of 18.7, 13.5, and 6 mA/cm^2, respectively. The solid straight lines show the fitting results by the least squares method. Each of those intensities increases linearly with increasing diffusion length almost from the origin as a starting point. The emission intensity corresponds proportionally to the diffusion length, which reveals that the photographic surveying of the emission intensity is an effective tool for analyzing the diffusion length semiquantitatively. If we know the absolute value of the diffusion length by, for example, the LBIC method at a specific point, we can derive the absolute diffusion length mapping on total area from the spatial variation of emission intensity.

The proportional relation between the emission intensity and the minority carrier diffusion length is explained as follows. The emission intensity is affected by many physical properties, such as the surface recombination velocity and the recombination at defects, etc. However, for brief consideration, the emission intensity will be proportional to the number of minority carriers (electrons in p-Si layer), which is determined by the diffusion length following the first-order approximation. We assume the localized effective diffusion length L_e, which involves the effect of defects, impurities, and the surface recombination velocity at the rear surface, etc. It varies spatially on the cell surface but is considered to be averaged and constant along the depth from the surface. The number of electrons in the p layer at a distance x from the p-side edge of the pn junction is expressed as follows:

$$n(x) = n_o \exp(-x/L_e), \tag{1}$$

where n_o is the number of injected electrons at the p-side edge of the pn junction. The total number of electrons N in the p layer is shown by

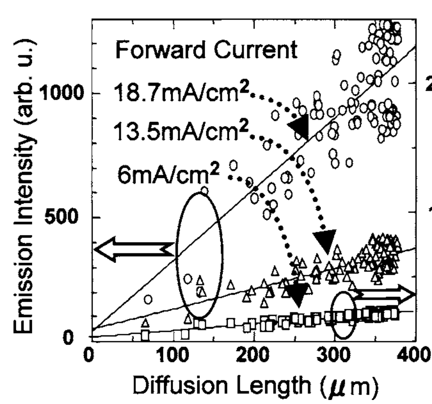


FIG. 5. Emission intensity as a function of the diffusion length at the corresponding measurement points. Solid lines are the fitting lines by the least-squares method.

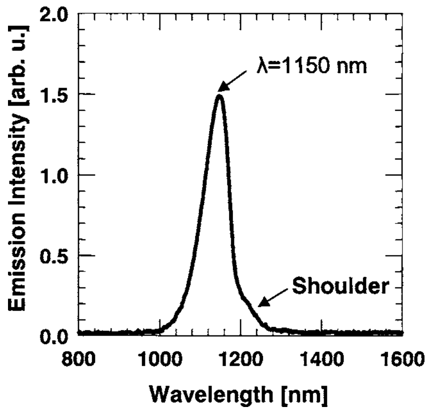


FIG. 6. Typical emission spectrum.

$$N = n_o \int_0^W \exp(-x/L_e)dx = n_o L_e[1 - \exp(-W/L_e)], \qquad (2)$$

where W is the thickness of the cell. When the term $\exp(-W/L_e)$ is considered to be much less than 1, N becomes nearly proportional to L_e. The emission intensity will then be proportional to the effective minority carrier diffusion length L_e. The experimental results shown in Fig. 5 roughly fulfill this relationship, but more accurate analysis is required.

Figure 6 shows a typical emission spectrum measured by an infrared-sensitive Ge photodetector at room temperature. The dominant emission mechanism will be the band-to-band radiative recombination with the phonon assist, as the main emission peak at 1150 nm can be seen. We could see a shoulder in a longer wavelength region. The peak shift was derived to be about 60 meV by deconvoluting the spectrum, so that the shoulder was considered to be a phonon sideband. Detailed assignment will be done in the future by measurement at low temperatures.

Photographic surveying of the minority carrier diffusion length in polycrystalline silicon solar cells was proposed. Light emission from the cell under the forward bias was captured by a CCD camera. The emission intensity was found to show the one-to-one relationship with the minority carrier diffusion length, and a semiquantitative analysis method of the diffusion length distribution was investigated. Emission intensity increased linearly with the diffusion length, and a possible emission mechanism was discussed. This effective technique can be applied not only to as-fabricated cells, but also molded modules, and further development correlating the analysis of emission with cell performance will be needed.

[1]J. A. Eikelboom, C. Leguijt, C. F. A. Frumau, and A. R. Burgers, Sol. Energy Mater. Sol. Cells **36**, 169 (1995).
[2]O. Porre, M. Stemmer, and M. Pasquinelli, Mater. Sci. Eng., B **24**, 188 (1994).
[3]N. Sakitani, K. Nishioka, T. Yagi, Y. Yamamoto, Y. Ishikawa, Y. Uraoka, and T. Fuyuki, Solid State Phenom. **93**, 351 (2003).
[4]W. Seifert, M. Kittler, and J. Vanhellemont, Mater. Sci. Eng., B **42**, 260 (1996).
[5]T. Takamoto, E. Ikeda, H. Kurita, and M. Yamaguchi, Proceedings of the 14th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 1997.