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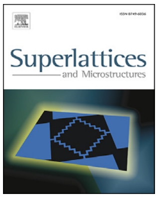

Diffusion length and grain boundary recombination activity determination by means of induced current methods

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ABSTRACT

The application of induced current methods for a quantitative description of multicrystalline silicon solar cell properties is demonstrated. For the minority carriers' diffusion length (L) and grain boundary recombination velocity (Vs) determination three types of measurements were used. They included the measurement of EBIC signal dependence on electron beam energy and of EBIC and XBIC grain boundary contrast profiles. The L and Vs values obtained by means of minimization the residual function between measured and model induced current curves are presented. The inaccuracy of obtained parameters is discussed for each of three types of measurements.

1. Introduction

Nowadays solar cells made of cast silicon and various amorphous and polycrystalline semiconductors are routinely manufactured. In solar cells and other devices made from multicrystalline or polycrystalline materials, the recombination of minority carriers at grain boundaries (GB) is a critical limitation of their performance [1]. Researchers and manufacturers need methods [2] to quantify grain boundary parameters (commonly, recombination velocity *Vs*) in order to be able to ascertain their impact on device performance and to measure the effectiveness of grain boundary passivation techniques [3], which are intended to decrease their impact.

Electron beam induced current (EBIC) method is the most widely used tool for a characterization of semiconductors and extended defects in them. The measured dependence of induced current (IC) in defect-free region on electron beam energy can be used for diffusion length *L* determination [4–6] by the means of adjusting model curve to measured one. Additionally, IC contrast profile across the grain boundary can be used for both *L* and *Vs* determination. But a disadvantage of EBIC method is that electron beam penetrates into the sample not very deep (to a depth of about electron range that is of about 10 μm for beam energy of dozens keV). That's why for large *L* values the calculated profile of EBIC contrast varies poorly with *L* and it becomes impossible to determine the diffusion length correctly. In contrast, for current induced by X-ray (XBIC) and laser (LBIC) beam penetration depth can be rather large. Thus it can be expected that using XBIC data instead of EBIC one would result in more accurate estimations of *L* and *Vs*.

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In the present work the results of diffusion length and recombination velocity determination for these three types of measurements (IC dependence on electron beam energy and GB contrast profiles for EBIC and XBIC methods) are compared and the accuracy of parameters' determination is discussed.

2. Experimental

The sample under investigation was multicrystalline silicon (m-Si) intentionally contaminated with iron (Iron contamination is known to increase the extended defect recombination contrast [7]). The Al Schottky barrier was thermally evaporated on the sample for EBIC and XBIC investigations. EBIC measurements of sample were carried out at room temperature in the scanning electron microscope Jeol JSM 840. Beam current of 10^{-10}A was used that corresponded to total electron-hole pair generation rate of $5.5 \times 10^{13}\mathrm{c}^{-1}$. During the measurement of IC dependence on electron beam energy in defect-free region the energy was varied from 4 to 38 keV. Induced current mapping of sample was carried out at beam energy of 35 keV to increase the penetration depth. The Keithley 428 current amplifier was used for signal detection in EBIC investigations.

XBIC investigations were carried out using the laboratory X-ray source with a rotating molybdenum anode [7]. The X-ray beam was focused by polycapillary lens with focal spot of about 10 μm. The value of the induced current was measured using picoammeter Keithley 6485.

On EBIC and XBIC induced current maps the profiles $I_c(x)$ was obtained perpendicular to GB direction in the same place of sample. The profiles of grain boundary contrast was defined as $C_{GB}(x) = 1 - I_c(x)/I(x)$, where $I(x)$ is the IC in a defect-free region. The energy dependence of EBIC current $I_{ED}(E)$ was normalized to its maximum value, so that $C_{ED} = I_{ED}/\mathrm{MAX}(I_{ED})$.

3. Calculation and modeling

For XBIC GB contrast calculations the model described in Refs. [8,9] was used. Calculations of EBIC induced current and GB contrast were carried out in the same way as in Ref. [10]. The diffusion length and GB recombination velocity values were obtained by a minimization of the residual function. The residual function was defined as

$$RESIDUAL(\{P\}) = \frac{\int dX[C_{ex}(X) - C_{\mathrm{m}}(X,\{P\})]^2}{\int dX[C_{ex}(X)]^2} \times 100\%,$$

where $C_{ex}(X)$ and $C_m(X,\{P\})$ are the experimental and simulated curves (C_{GB} for XBIC and EBIC GB contrast and C_{ED} for energy dependence). Here X is the variable, on which these curves depended, for C_{GB} it is the distance from a grain boundary x and for C_{ED} it is the electron beam energy.

Simulated curves C_m were also the functions of the sets of parameters $\{P\}$ that characterized a sample and a probe beam. These parameters $\{P\} = \{Pv, Pc\}$ consisted of varied ones $\{Pv\}$, being changed during the residual calculations, and non-varied $\{Pc\}$. In the case of GB contrast for the EBIC method they were $Pv = \{L, Vs\}$ and for XBIC $Pv=\{L,Vs,\sigma\}$, because due to specific of focusing by the polycapillary lens used the X-ray beam size σ was not known precisely. The non-varied parameters had the following values: the depletion region (DR) width $W = 0.1$ μm, the electron probe size of 10 nm, the diffusivity of 36 cm^2/s, the electron's transport length of 13.3 μm (corresponds to probe energy of 35 keV) and the X-ray photons' absorption coefficient of 15.6 cm^{-1} (matches the x-ray beam energy of 17.4 keV, MoKα). For the EBIC dependence on beam energy the varied parameters were the diffusion length L, the DR width W and the thickness of evaporated metal t_m ($Pv=\{L,W,t_m\}$).

4. Results and discussion

The values of parameters L and Vs, at which the residual functions reach their minimum values, are listed in Table 1 for three types of measurements. Fig. 1 shows the contrast profiles calculated for the values minimizing the residuals in comparison with the experimental curves. It should be noted that in a close correlation with [10] the calculated constant level surfaces of the residual functions were elongated and had strongly non-spherical shape. Conventional optimization techniques (such as coordinatewise descent, random search methods, etc.) usually do not deal correctly with such functions.

Table 1
Determined L and Vs values and their error intervals.

	EBIC IC energy dependence	EBIC GB contrast	XBIC GB contrast
L, μm	22	36	15
ΔL, μm	19–33	17–79	10–24
Vs, 10^5 cm/s	–	0.66	0.98
ΔVs, 10^5 cm/s	–	0.4–1.17	0.28–3.0
Residual min. val., %	0.014	0.8	2.1
Residual min. val. with noise, %	0.025	3.69	3.24

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