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A novel approach to the surface photovoltage method

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A B S T R A C T

The surface photovoltage technique allows contactless measurement of some electrical parameters of semiconductors. Unfortunately, a contemporaneous approach to steady-state surface photovoltaic (SPV) effect cannot explain the photovoltage spectra, and its application to the determination of the diffusion length is limited to thick samples with thin space charge region (SCR). In this paper a complete theory of steady-state SPV effect is presented that agrees well with the experiment. Consequently, important parameters can be evaluated from the measurements independently of thickness and resistivity of samples. The use of the theory for determining the diffusion length and thickness of the SCR is shown.

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1. Introduction

Semiconductor surfaces often display a multitude of states. The charge localized in the states is supplied predominantly by majority carriers from the underlying bulk so that its charge neutrality is consequently disturbed (Fig. 1). The thickness of this space charge region (SCR) is denoted as w. Concentration of carriers in the semiconductor is usually characterized by potential $\varphi = (E_F - E_i)/e$ where E_F is the Fermi level of the semiconductor under study and E_i is the Fermi level of the intrinsic semiconductor. Potential φ is locally variable and reaches the value φ_s at the surface and φ_b at the bulk. In the non-degenerate case it holds for the concentration at the surface:

$$n_s = n_b \exp[e(\varphi_s - \varphi_b)/kT], \ p_s = p_b \exp[e(\varphi_b - \varphi_s)/kT] \quad (1)$$

where n_b and p_b are concentrations of carriers in the bulk at the boundary with the SCR. Relation (1) is used when solving the Poisson equation, which gives the charge localized in the SCR [1]:

$$Q_{sc} = \frac{\sqrt{2}\varepsilon kT}{eL_D} F\left(\frac{e\varphi_s}{kT}, \frac{n_b}{p_b}\right) \quad (2)$$

where L_D is the Debye screening length, ε is the permittivity of the semiconductor, T is the absolute temperature, k is the Boltzmann constant, e is the charge of electron and F is the function defined e.g. in Ref. [1].

After illumination the concentrations n_b and p_b change to n_b^* and p_b^* and the surface potential is φ_s^*. The Fermi level in this non-equilibrium case splits into two quasi-Fermi levels. The surface photovoltage V is equal to the change in the band bending after illumination divided by the electron charge. Relations similar to (1) hold if the levels are position independent, which is denoted as the "flat quasi-Fermi level" (FQL) approximation [2].

Electric field in the SCR sweeps the minority carriers from e–h pairs diffusing from the bulk. The charge Q_{sc} changes to [3]

$$Q_{sc}^* = \frac{\sqrt{2}\varepsilon kT}{eL_D} F\left(\frac{e\varphi_s^*}{kT}, \frac{n_b^*}{p_b^*}, \Delta n\right) \quad (3)$$

Δn is concentration of the minority carriers injected into the SCR from the bulk. To find Δn, diffusion equation in the bulk (for $x > w$) must be solved

$$\frac{d^2 \Delta n}{dx^2} - \frac{\Delta n}{L^2} = -\frac{\alpha I \exp(-\alpha w)}{D} \exp(-\alpha x) \quad (4)$$

Here I is the photon flux density entering at $x = 0$ into the sample of thickness d, w is the thickness of the SCR, α is the absorption coefficient, L is the diffusion length of minority carriers and D is their diffusion coefficient. For thick bulk ($\alpha d \gg 1$, $d \gg L$) only one boundary condition is needed. Moss [4] in 1955 introduced it in the form

$$D\frac{d\Delta n}{dx}\Big|_{x=w} = s\Delta n(w) \quad (5)$$

Eqs. (4) and (5) yield the concentration Δn at the SCR–bulk boundary:

$$\Delta n(w) = I \exp(-\alpha w) \frac{\alpha L}{1 + \alpha L} \frac{1}{s + D/L} \quad (6)$$

Goodman [5] assumed that the photogenerated voltage V is unknown but monotonic (single valued) function of $\Delta n(w)$.

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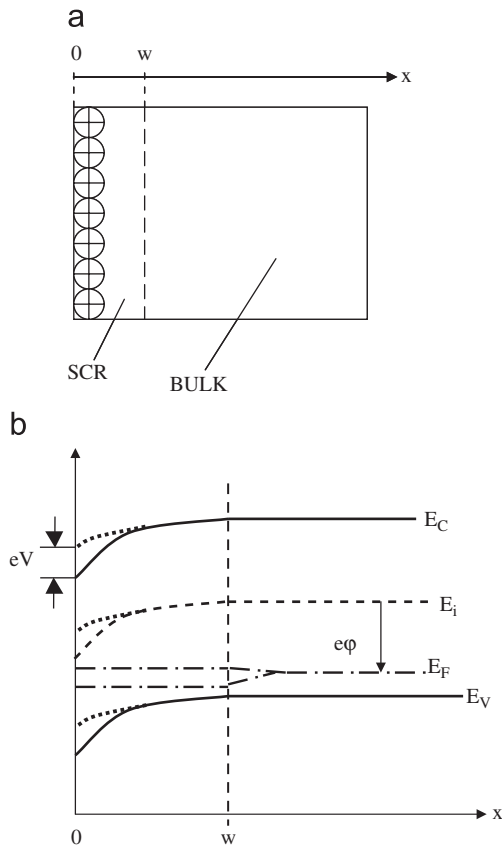E-mail address: jiri.tousek@mff.cuni.cz (J. Toušek).

Fig. 1. Surface photovoltaic effect in a p-type semiconductor. (a) Localization of majority carriers in traps at the surface. (b) The band diagram of the semiconductor surface. After illumination, the band bending decreases and the Fermi level splits into two quasi-Fermi levels.

Fig. 2. Schematic arrangement of the SPV experiment.

Fig. 3. Experimental dependence of the photon flux density I needed to keep the voltage on a constant value is plotted against the reciprocal value of the absorption coefficient (points). Theory according to Eq. (7) (full line). Silicon sample with concentration $10^{16}\,cm^{-3}$ and thickness $460\,\mu m$ was measured in the arrangement as in Fig. 2. $L = 181.4\,\mu m$ was found using the linear part of the graph.

Measurement that maintains the surface photovoltaic (SPV) constant implies a constant $\Delta n(w)$ and, consequently, the right-hand side of Eq. (6) is constant for all α studied. Neglecting absorption in the SCR ($\alpha w \ll 1$), expression (6) for any wavelength λ can be rearranged to the form [5]

$$I(\lambda) = const(1/\alpha(\lambda) + L) \qquad (7)$$

Assuming $w \ll L$ Goodman explains the constant s as the surface recombination velocity at the illuminated surface. It means that s characterizes the losses of the bulk current in the SCR. The linear function (7) serves for extraction of L from the SPV spectra in the case of a thick bulk and a thin SCR. Schematic arrangement of the experiment is shown in Fig. 2. The voltage is measured between a semitransparent conductive top electrode and a bottom ohmic electrode. The impinging light is chopped to obtain an alternating signal. An example of application of Eq. (7) is shown in Fig. 3. The absorption coefficients were taken from Ref. [6]. High intensity I at large α means a decrease of the SPV signal causing a deviation from the linear plot. It is an influence of recombination in the SCR that was not included in the model.

According to Eq. (5) the diffusion of minority electrons into the SCR is proportional to s. On the other hand (see Eq. (6)), the increase in s decreases the concentration $\Delta n(w)$ and also decreases the injection. This disproportion leads to doubts about the validity of condition (5). Nevertheless, relation (7) holds. It can be derived in a different more rigorous way as shown in the next section. The SPV theory, comprehensively summarized in paper [7], gives the evidence that calculation of the free carrier concentrations at the surface is extremely difficult and till now it was not satisfactorily solved. Conse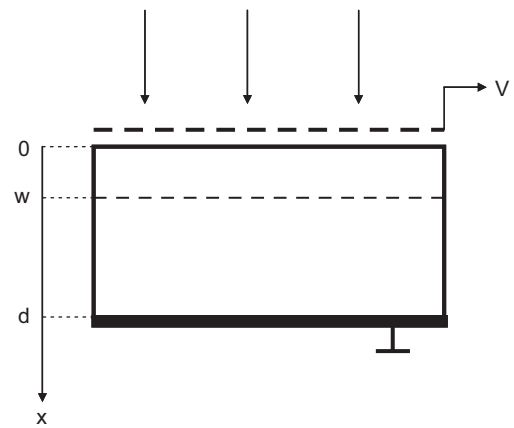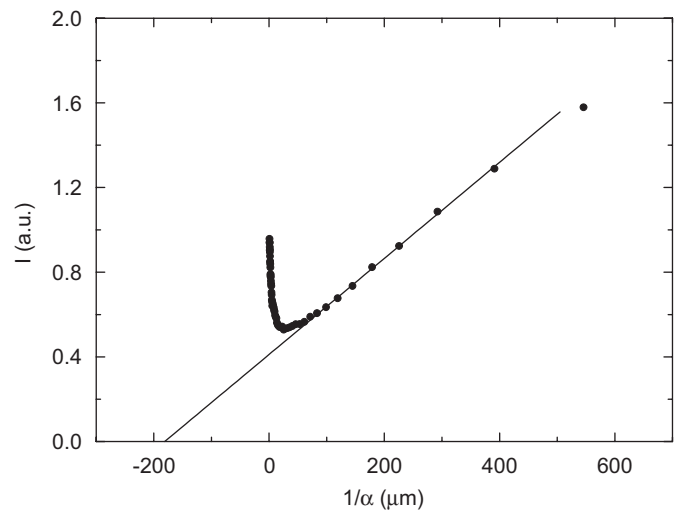quently, it is a problem to find an analytical expression for the photovoltage. Goodman's treatment avoids this difficulty and allows an evaluation of diffusion length in thick samples with thin SCR, but the theory entirely fails in the case of thin wafers with thickness comparable with the diffusion length. This handicap excludes the application of the SPV diagnostics even for most of the silicon wafers for solar cells. Individual authors [8,9] presented a complete theory of the steady-state SPV technique including generation and recombination in the SCR and losses of carriers at the free surface of the sample. In agreement with Goodman [5], they supposed that the recombination processes also influence the bulk current J_b injected in the SCR. This would mean that the diffusing photocarriers are exposed to additional losses in the SCR and they would always generate lower SPV signals than photocarriers generated in the SCR. Consequently, the SPV signal at a constant photon flux should increase with absorption of light and saturate at the maximum value, which is often inconsistent with experiment.

2. A novel model for SPV

In this section we describe our approach to the SPV effect. Instead of concentrations, it is based on a calculation of