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A SURFACE PHOTOVOLTAGE SPECTROSCOPY SYSTEM USED FOR MINORITY CARRIER DIFFUSION LENGTH MEASUREMENTS ON FLOATING ZONE SILICON

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An original experimental technique for surface photovoltage spectroscopy at temperatures from 65 to 300 K is presented, based on the metal-insulator-semiconductor approach. The technique is employed for spectral measurements and minority carrier diffusion length estimations in floating zone p-Si covered with $(Al_2O_3)TiO_2$. The surface recombination velocity is evaluated from the resulting data.

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1. Introduction

Surface photovoltage (SPV) techniques have been widely used for non-destructive and high sensitive contactless characterisation of various semiconductor bulk materials, multilayers, nanostructures and actual device structures [1-3]. SPV-based minority carrier diffusion length measurements have become very popular, because this is one of the most important parameters controlling the conversion efficiency of solar cell devices, as well as a sensitive tool for the detection of defect concentrations as low as 10^9-10^{11} cm^{-3} [1,2].

In this work, we present an original experimental technique for SPV spectroscopy, based on measurements using a metal-insulator-semiconductor (MIS) structure [1]. It allows SPV measurements from nitrogen to room temperatures, in the spectral range 700 to 1800 nm, keeping the incident photon flux density constant. SPV spectra of floating zone (FZ) p-Si have been measured for a number of light modulation frequencies. The effective minority carrier diffusion length was extracted from the analysis of the spectral data. The surface recombination velocity was evaluated from the diffusion length value obtained at zero frequency.

2. Experimental details

2.1. Experimental set-up

The SPV is defined as the illumination-induced change in the surface potential, i.e. $\delta V_s = V_s - V_{s0}$, where V_s (V_{s0}) is the surface potential under illumination (in the dark) [1]. In the MIS technique [1], the sample and a fixed semitransparent electrode (probe), separated by air or another insulator, form a capacitor which is illuminated by modulated intensity light. Periodic generation of excess carriers and their subsequent redistribution change the surface potential, thus inducing a

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periodic SPV. The change in V_s produces an equal change in the probe potential. This results in an ac voltage, measurable between the two capacitor terminals, which is proportional to δV_s.

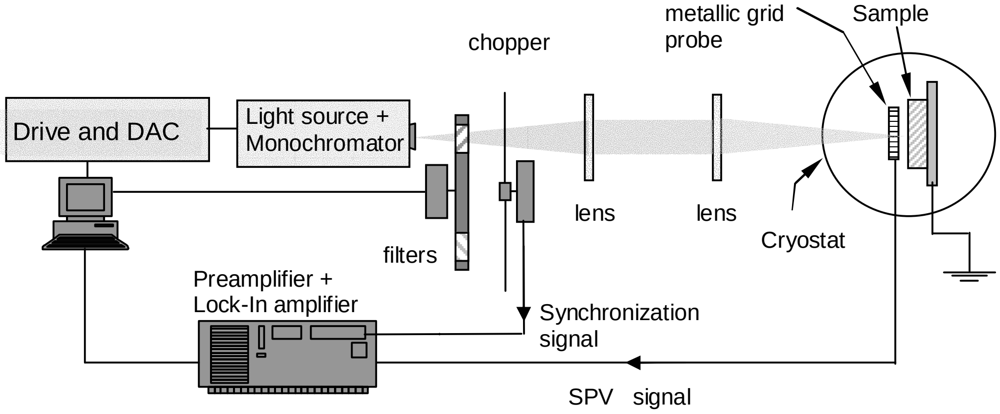

Fig. 1. Scheme of the SPV experimental system.

An original probe is used in our experimental system. The semitransparent electrode is a gold grid stretched over a metallic holder, which has an opening 3 mm in diameter. An insulator sheet (8 μm polyimide) is positioned below the grid and glued on the edges of the holder. Its purpose is to separate the grid from the sample without absorbing the incident light. Therefore, it has the same opening as the metal holder. The opposite end of the holder is tightly fixed against an insulating support together with a solid plate. By means of a screw in the plate, the holder can be bent. In this way, the probe moves down to press the sample against a grounded copper platform. The platform and the probe are mounted on a copper rod, which is positioned in a continuous flow optical cryostat. The sample surface is illuminated through the grid with a 3 mm diameter light spot, by means of a 50 W halogen tungsten lamp along with a 0.22 m SPEX grating monochromator, a filter system to cut off the high-order diffraction and a light chopper (Fig. 1). The lamp voltage is previously calibrated in order to achieve a constant photon flux density incident on the sample at each wavelength. A wire soldered to the probe holder is used to collect the probe signal, which is fed to a Nanovolt preamplifier (amplification factor 10^3) and then measured by an EG&G 5207 lock-in amplifier. The overall system is controlled by a computer.

Room temperature measurements were performed at normal incidence, with light chopped at a number of frequencies, f. The light wavelength λ was scanned from high toward low values, keeping the photon flux density Φ constant in the 10^{13} cm^{-2}s^{-1} range, within ± 2 %, for all wavelengths.

2.2. Sample

The sample studied, of thickness d = 330 μm, was cut from a FZ p-type Si wafer of resistivity of 7 Ω cm, doped with B acceptors at a level of $2\text{x}10^{15}$ cm^{-3}. Its front surface was covered with a 105 nm thick $(Al_2O_3)TiO_2$ dielectric film, prepared by spin coating from a sol solution with additional thermal annealing [4]. This dielectric is thermodynamically stable in direct contact with Si, and has a refraction index of 1.58. An ohmic contact was prepared on the back sample surface.

2.3. SPV method for minority carrier diffusion length measurements

In the Goodman approach [5] for the estimation of the minority carrier diffusion length, δV_s has to be measured for a number of wavelengths in the super-band-gap range. Usually, δV_s is a monotonic function of the minority carrier density $\delta n(w)$, at the edge of the space charge layer, w. The continuity equation has a simple solution for $\delta n(w)$:

$$\delta n(w)=\frac{\alpha(\lambda)}{1+\alpha(\lambda)L_n}\frac{L_n}{S+D_n/L_n}\Phi(\lambda)[1-R(\lambda)] \qquad , \tag{1}$$

where α (R) is the absorption (reflection) coefficient, L_n (D_n) is the minority carrier diffusion length (coefficient) and S is the surface recombination velocity. Eq. 1 holds under the following constraints [1,2]: i) $\delta n << p_0$ (p_0 is the majority carrier density); ii) $w << \alpha^{-1} << d$; iii) $w << L_n$; and iv) $L_n/d \leq 1/4$. For low excitation regime ($\delta V_s \leq 1$ mV [6]) $\delta V_s \sim \delta n(w)$, then in the constant photon flux density implementation of the SPV method ($\Phi(\lambda)$ = const) [6] one obtains from Eq. 1:

$$\frac{1}{\delta V_s}=const\cdot[\frac{1}{\alpha(\lambda)}+L_n] \qquad , \tag{2}$$

assuming $R(\lambda)$ is constant and neglecting the variation of S with δV_s, because δV_s changes little in the considered spectral range. The above expression implies that if $1/\delta V_s$ is plotted as a function of $1/\alpha$, the X-axis intercept is equal to $-L_n$ [1,2].

3. Results and discussion

Typical SPV spectra measured with $\Phi \approx 5 \times 10^{13}\text{cm}^{-2}\text{s}^{-1}$ and different light modulation frequencies are shown in Fig. 2. For f = 30 Hz, a sharp increase corresponding to the Si absorption edge is clearly seen between 1180 and 1100 nm. This is followed by a rounded peak at ~1080 nm and a slow monotonic increase for λ < 1020 nm. At 1150 nm, the spectrum reveals a slight shoulder, the energy position of which corresponds to the energy of electron transitions between the B acceptor level and the conduction band. With increasing f, the overall SPV signal decreases and the peak at 1080 nm is progressively reduced to a shoulder.

For determining the value of L_n, we measured SPV spectra in the range 720 - 900 nm with $\Phi \approx 1\text{x}10^{13}\text{cm}^{-2}\text{s}^{-1}$. The SPV signal before amplification was typically around 1 mV, which allowed us to conclude that the required linear relationship between δV_s and $\delta n(w)$ was present [6]. As a first approximation, we neglected the effect of the dielectric layer on the reflectivity and assumed $R(\lambda)$ to be constant. The Si absorption coefficient at 300 K in the considered range was calculated (in cm^{-1}) by the following empirical formula, in which λ is in μm [7]:

$$\alpha=(\frac{83.18}{\lambda}-74.87)^2 \tag{3}$$

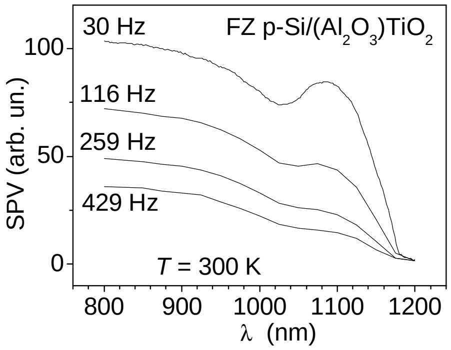

Fig. 2. SPV spectra measured at 300 K with different light modulation frequencies.

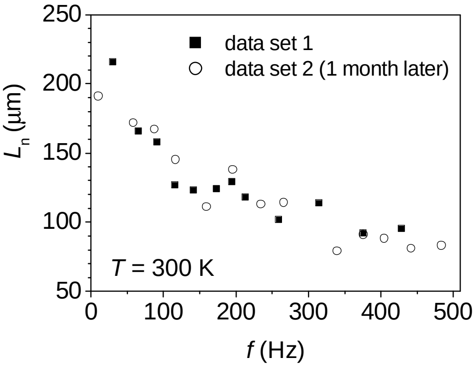

Fig. 3. $L_n(f)$ dependence derived from the SPV spectra taken at different light modulation frequencies.

Its values varied between 1932 and 308 cm^{-1} and were high enough to prevent illumination of the back contact. The doping level of the sample implied $w < 1$ μm [1]. Taking into account the values of w, α and d, as well as the fact that the obtained L_n was of the order of 100-200 μm (see below) we could check that conditions ii) and iii), necessary for the validity of Eq. 1, were fulfilled in our case. Our calculations showed that δn was more than two orders of magnitude lower than p_0, so condition i) also held. As to condition iv), the ratio L_n/d was in the range 0.27 to 0.67 depending on the light modulation frequency (see below). Taking into account the discussion in [1] (p.125) we could conclude that these values were satisfactory for an assessment of the diffusion length.

Fig. 3 represents the obtained diffusion length derived from the SPV spectra measured at different light modulation frequencies. The two sets of data have been obtained with a time delay of more than one month, and show good repeatability within the experimental error. L_n decreases with increasing f. When f approaches zero, L_n approaches the value $L_{n0} = 220$ μm.

Furthermore, we used typical values for FZ p-Si: an electron diffusion coefficient $D_n = 34$ cm^2/s and a bulk recombination lifetime $\tau_B = 50$ μs. From the L_{n0} value and the relation $L_{n0} = (D_n \tau_{eff})^{1/2}$ we obtained an effective recombination lifetime of $\tau_{eff} = 14$ μs. Then, employing the relations $\tau_{eff}^{-1} = \tau_B^{-1} + \tau_s^{-1}$ and $\tau_s = d/2S$ we estimated the surface recombination lifetime and the surface recombination velocity to be $\tau_s = 20$ μs and $S = 830$ cm/s, respectively. The same results have been obtained using the Quasi-Steady-State Photo-Conductance method [8].

4. Conclusions

An experimental technique for SPV spectroscopy from nitrogen to room temperatures in the spectral range 700-1800 nm has bee elaborated, including an original probe electrode. The technique was applied for measuring SPV spectra in p-Si/(Al_2O_3)TiO_2. The minority carrier diffusion length and the surface recombination velocity in the sample under study were estimated from the experimental data, and reasonable values were obtained. The technique can be applied for the non-destructive, high sensitive and contactless characterisation of a wide range of semiconductor bulk materials, multilayers and nanostructures.

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