Influence of light intensity on the lifetime of carriers in silicon investigated by a photoacoustic method

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The paper presents experimental results of the lifetime of light induced excess carriers in the n-type silicon. The lifetimes of carriers of silicon crystals were analysed as a function of the intensity of light illuminating the sample. As a measurement method of the lifetime of carriers, the photoacoustic method in a transmission configuration with different surfaces was used. The dependence character was next analysed in the frame of the Shockley Reed Hall statistics in approximation of the light low intensity.

Keywords: photoacoustics, carrier lifetime, SHR statistics.

1. Introduction

Lifetime of optically excited excess minority carriers in silicon can be measured using series of experimental methods. Among them the MFCA (modulated free carrier absorption) [1–5], PTR (photothermal radiometry) [6–9], PCR (photo-carrier radiometry) [10–12] and PA (photoacoustic) [13–15] methods are often used. Interpretation problem arises when one wants to compare experimental results even for the same silicon sample but obtained with different methods. It is connected with the fact that the lifetime of carriers depends, among others, on the intensity of light illuminating the samples. Aim of the research presented in this paper was to investigate experimentally dependence of the lifetime of carriers on the intensity of light illuminating the samples. For this purpose the frequency photoacoustic method of detection in a transmission configuration was applied. The transmission configuration means that a sample is illuminated on one side and a PA signal is detected on the other (opposite) side.

2. Experimental results

The n type silicon samples with the concentration of donors $N_D = 2 \cdot 10^{15} \text{ cm}^{-3}$ ($\rho = 3\text{--}5 \, \Omega \cdot \text{cm}$) were investigated. Photoacoustic method that was applied for investigations of dependence of the lifetime of carriers on the intensity of light (I) illuminating samples was presented and described in Refs. 16 and 17. The samples, according to the method, had

their sides prepared in a different way. One side of the samples was polished (mirror type side) and the other was rough (matt side). In the experiment two frequency characteristics of the amplitude and phase of a photoacoustic signal were measured in a transmission configuration. The first characteristics were measured when the mirror side of the sample was illuminated and the second characteristics were measured when the matt side of the sample was illuminated. The experimental and theoretical amplitude and phase photoacoustic characteristics are presented in Fig. 1. The amplitude PA characteristics were normalized to 1 at the frequency of modulation $f = 100 \text{ Hz}$.

The lifetimes of carriers obtained by fitting of theoretical characteristics to the experimental data are $20 \, \mu\text{s}$, $50 \, \mu\text{s}$, $70 \, \mu\text{s}$, respectively. The following parameters were taken for computations: $D_e = 36 \text{ cm}^2/\text{s}$, $V_g = 500 \text{ cm/s}$, $V_b = 20\,000 \text{ cm/s}$ where D_e is the diffusion coefficient of carriers for n-type silicon, V_g and V_b are the velocities of the surface recombination of carriers for mirror and matt side of the samples, respectively.

The experimental data and theoretical frequency characteristics, presented in Fig. 2, are the amplitude ratio (AR) and the phase difference (PD) of photoacoustic signals in the transmission experimental configuration. It is an amplitude ratio or a phase difference of the PA signal, when the mirror side is illuminated, to the photoacoustic signal, when the matt side is illuminated. Lines are theoretical curves, triangles, circles and diamonds symbols are experimental data.

Theoretical characteristics of $AR(f, \tau)$ and $PD(f, \tau)$, presented in Fig. 2 were computed with the following equations, for different lifetimes of carriers

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Fig. 1. Photoacoustic normalized amplitude a) and phase b) frequency characteristics in the transmission experimental configuration for different intensities of light of the illuminating laser beam. Diamonds ($I = 0.7 \text{ W/cm}^2$), open circles ($I = 2 \text{ W/cm}^2$), triangles ($I = 9 \text{ W/cm}^2$) illumination of the mirror side of the sample. Filled circles illumination of the matt side of the sample ($I = 2 \text{ W/cm}^2$). The wavelength of the illuminating light was of 808 nm. Lines are theoretical characteristics, symbols are experimental data.

$$AR(f, \tau) = \frac{|PA_{tr}(f, \tau, De, Vg, Vb, d, \beta, \alpha)|}{|PA_{tr}(f, \tau, De, Vb, Vg, d, \beta, \alpha)|}, \quad (1)$$

$$PD(f, \tau) = \frac{180}{\pi} \{ \arg[PA_{tr}(f, \tau, De, Vg, Vb, d, \beta, \alpha)] - \arg[PA_{tr}(f, \tau, De, Vb, Vg, d, \beta, \alpha)] \}, \quad (2)$$

where Vg is the surface recombination velocity of the mirror and Vb matt side of the sample. PA_{tr} is the photoacoustic signal measured in the transmission configuration. The equation for PA_{tr} is given in Ref. 13.

Theoretical dependence of the amplitudes' ratio of the photoacoustic signal on the lifetime of carriers in the photoacoustic method in a transmission configuration is presented in Fig. 3.

Fig. 2. Photoacoustic amplitude ratio a) and phase difference b) frequency characteristics in the transmission experimental configuration for different intensities of the illuminating laser. Diamonds ($I = 0.7 \text{ W/cm}^2$), open circles ($I = 2 \text{ W/cm}^2$), triangles ($I = 9 \text{ W/cm}^2$). Solid lines are theoretical characteristics obtained for the lifetimes of carriers $\tau = 20 \mu\text{s}$, $50 \mu\text{s}$, $70 \mu\text{s}$. Dash and dash-dot lines are theoretical curves for $120 \mu\text{s}$ and $10 \mu\text{s}$, respectively. Symbols are experimental data.

Fig. 3. Theoretical dependence of the amplitude ratio photoacoustic signals on the lifetime of carriers in a transmission configuration calculated at 1.8 kHz.

One can see from Fig. 3 that it is possible to investigate the lifetimes of carriers in this method in the range from a few microseconds to one hundred microseconds.

Dependence of the lifetime of carriers on the intensity of laser beam light is presented in Fig. 4.

These experimental and theoretical characteristics can be expressed as a dependence of the lifetime of carriers on the concentration of the optically generated excess carriers according to Eq. (3).

$$\Delta n = G\tau \approx (1-R) \frac{I}{d \cdot Eph} \tau, \quad (3)$$

where: G is the average generation rate, τ is the carrier lifetime, I is the intensity of light, Eph is the photons' energy of

Fig. 4. Theoretical and experimental dependence of the lifetime of carriers on the intensity of light of the laser beam illuminating the sample obtained from the photoacoustic method. Symbols are experimental data. Solid line is a theoretical curve.

a wavelength of 808 nm, d is the sample thickness equal to 630 μm , $R = 0.3$ is the optical reflection coefficient of silicon.

The resulting dependence of the lifetime of carriers on the concentration of the light induced excess carriers is presented in Fig. 5.

For the computation of the theoretical characteristics the following Eq. (4) was used

$$\tau = \tau_{n0} \frac{p_0 + p_1 + \Delta n}{n_0 + p_0 + \Delta n}, \quad (4)$$

where: $\tau_{n0} = 80 \mu\text{s}$, $n_0 \approx N_D = 2 \cdot 10^{15} \text{ cm}^{-3}$, $p_0 = n_i^2/n_0 = 5 \cdot 10^4 \text{ cm}^{-3}$, $n_i = 9,4 \cdot 10^9 \text{ cm}^{-3}$, $\tau_{p0} = 0$, n_i is the intrinsic carrier concentration in silicon, Δn is the concentration of excess optically excited carriers, p_1 is the statistical equilibrium concentration of holes being the result of existence of traps of a given energy in the sample [see Eq. (5)]. In Fig. 5 this parameter was treated as a fitting parameter. The fitting was performed in the least squares method.

It is the Shockley-Read-Hall dependence of the lifetime of carriers on the concentration of carriers in the case when only one type of traps is taken for considerations [18–20].

Energy of traps estimated from the determined parameter p_1 equals $E_T \approx 0.3 \text{ eV}$ a typical value of the energy of traps in silicon. This value was computed from Eq. (5).

$$E_T = kT \cdot \ln \left(\frac{p_1}{N_v} \right), \quad (5)$$

where $kT = 26 \text{ mV}$ in 300 K, N_v is the effective density of states in a valence band equal to $1.8 \cdot 10^{19} \text{ cm}^{-3}$ in 300 K.

Fig. 5. Theoretical and experimental dependence of the lifetime of carriers on the concentration of the light induced excess carriers. Symbols are experimental data. Solid line is the theoretical curve for $p_1 = 2 \cdot 10^{14} \text{ cm}^{-3}$ obtained from the fitting procedure. Dashed line is the theoretical curve computed for $0.1 \cdot p_1$ and a dash-dot line is for $10 \cdot p_1$.

3. Conclusions

It was observed experimentally that the 15 times increase of the intensity of light illuminating the sample caused about 5 times increase of the lifetime of carriers in the n-type silicon. The dependence of the lifetime of carriers on the concentration of the optically excited carriers is in accordance with the Shockley-Read-Hall equation in the approximation of the low concentration of the optically generated carriers respective to the concentration n_0 equal to the concentration of donors. This experimental result is important when one wants to compare the lifetimes of carriers obtained with different experimental methods when the intensity of the illuminating light is often not given.

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