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Experimental investigations of the dependence of the lifetime of the optically generated minority carriers in *n-type* silicon on the intensity of its illumination

***Abstract**. This paper presents experimental and theoretical dependences of the lifetime of minority carriers in n-type silicon on the intensity of its illumination. The experimental characteristics have been interpreted theoretically in the frame of Shockley Read Hall (SRH) statistics. The lifetimes of minority carriers for a low intensity of illumination were measured with the Surface Photovoltage (SPV) method while for the high intensity a Modulated Free Carrier Absorption (MFCA) method was applied. The obtained results clearly show that the experimentally obtained lifetimes of carriers can be compared only for the same conditions of illumination of the sample.*

***Streszczenie**. Praca przedstawia doświadczalne i teoretyczne zależności czasu życia nośników mniejszościowych w krzemie typu n od natężenia światła. Charakterystyki doświadczalne zostały zinterpretowane teoretycznie w modelu Shockley Read Hall (SRH). Czasy życia nośników dla małych natężeń światła oświetlajacch próbkębyły mierzone metodą SPV podczas gdy dla dużych natężeń światła wykorzystano metodę Modulacji Absorpcji Światła na Swobodnych Nośnikach (MFCA). Uzyskane rezutaty jasno pokazują, że czasy życia uzyskane eksperymentalnie mogą być porównywane tylko dla tych samych warunków oświetlanie próbek. (**Badania eksperymentalne zależności czasu życia optycznie generowanych nośników mniejszościowych w krzemie typu n od natężenia światła**).*

Keywords: carrier lifetime, SPV, MFCA, intensity of light
Słowa kluczowe: czas życia nośników, SPV, MFCA, natężenie światła

Introduction

The lifetimes of carriers are measured for silicon with the use of different methods such for example as: Surface Photovoltage (SPV), Modulated Free Carrier Absorption (MFCA), Photoacoustic (PA), Microwave Photo Conductance Decay (µPCD), Photo-Thermal Radiometry (PTR) and Photoluminescence Decay (PLD). An example of the application of the photoluminescence method for determination of the minority carrier diffusion length and the lifetime both in bulk and doped silicon epitaxial layers is presented in paper [1]. Lifetimes of carriers are most often extracted from the experimental frequency or time domain characteristics of the measured signal. The characteristics are then analyzed in the appropriate theoretical model and very often compared. Various methods for characterization of the charge carrier lifetimes are reviewed in paper [2].

The problem is however that the intensities of illumination of the samples during experiments are often not given. The experimental results presented in this paper show that the influence of the intensity of illumination is essential and without this information the comparison of the experimental results of the lifetimes is not possible.

Paper [3] presents the influence of light intensity on the lifetime of carriers in n-type silicon investigated by a PA method. The character of the dependence was interpreted in terms of Shockley Read Hall (SRH) statistics. The idea of this PA method for determination of the lifetimes of carriers is presented in paper [4]. The experimental results illustrating the influence of ion implantation on the recombination parameters of p and n type implanted Si samples investigated by means of the PTR are presented in paper [5]. The minority carrier recombination lifetimes in n-type CdMgSe mixed crystals measured by means of the PTR method are presented in paper [6].

For the measurements of the lifetimes of minority carriers, described in this paper, two experimental methods were used: MFCA and SPV.

The MFCA method of determination of lifetimes of carriers in Si wafers, is described in papers [7,8]. The Shockley Read Hall statistics, used for interpretation of the experimental characteristics, is described in papers [9-11]. Paper [12] presents a numerical study, in the SRH recombination model, of the lifetime of minority carriers in iron contaminated *p-type* silicon solar cell. Papers [13,14] describe results of studies of recombination behavior of carriers in the monocrystalline silicon doped with oxygen at different doping levels, by the analysis of the injection - dependent minority carrier lifetime measurements. The recombination parameters were also analyzed in terms of SRH statistics. The oxygen precipitation gives rise to recombination centers reducing the lifetime of carriers and thus reducing solar cell efficiencies. The analysis of the influence of iron on the lifetime of carriers in silicon for arbitrary injection levels and doping levels are presented in paper [15].

The SPV method, also used in this paper, was introduced by Goodman in 1961 [16]. A particular techniques such as a 'Constant Flux' or 'Constant SPV' have been included in standards, for example [17]. The measuring SPV techniques are applied for determination of both short [16] and long diffusion lengths [18].

Theory

According to the SHR theory the carrier lifetime τ depends on the concentration of optically excited excess carriers Δp given by Shockley and Read in [25]

$$(1)\quad \tau(\Delta p)=\frac{\tau_{p0}\left(n_0+n_1(Et)+\Delta p\right)+\tau_{n0}\left(p_0+p_1(Et)+\Delta p\right)}{p_0+n_0+\Delta p}$$

$n_0 \approx N_D$ (valid at room temperature) is a donor doping concentration in the sample, p_0- the holes concentration in the sample computed as $p_0=n_i^2/N_D$; p_1, n_1 are statistical equilibrium concentration of holes/electrons being the result of existence of traps of a given energy E_t in the sample; τ_{n0}, τ_{p0} are electron/hole capture time constants, related to the capture cross section σ_n, σ_p and concentration of traps N_t, according to equations (2, 3).

$$(2)\quad p_1(E_t)=N_v\exp\left(-\frac{E_t-E_v}{kT}\right);\; n_1(E_t)=N_c\exp\left(-\frac{E_c-E_t}{kT}\right)$$

(3) $$\tau_{p0} = \frac{1}{\sigma_p \upsilon_{th} N_t}\ ;\ \tau_{n0} = \frac{1}{\sigma_n \upsilon_{th} N_t}$$

υ_{th}=10^{7}cm/s is thermal velocity of carriers; kT is electrothermal potential equal to 26mV in RT, $\sigma_{n,p}$ is a cross section for the capture of carriers, N_t is a concentration of traps.

For a n-type silicon at room temperature $n_0=N_d$ and $p_0<<N_d$ and $p_0<<\Delta p$ an equation (1) takes a form:

(4) $$\tau(\Delta p) = \frac{\tau_{p0}\left(N_d + n_1(Et) + \Delta p\right) + \tau_{n0}\left(p_1(Et) + \Delta p\right)}{N_d + \Delta p}$$

From equation (4) for a high level of illumination (hl) the lifetime of carriers equals to:

(5) $$\tau_{hl} = \tau_{p0} + \tau_{n0}$$

For a low level illumination (ll) the lifetime of carriers equals to:

(6) $$\tau_{ll} = \frac{\tau_{p0}\left(N_d + n_1(Et)\right) + \tau_{n0} p_1(Et)}{N_d}$$

From the experiment one can determine the values of τ_{hl} and τ_{ll} and write a set of equations (5) and (6).

One can derive formula for τ_{p0} and for τ_{n0} as a function of τ_{hl}, τ_{ll} and Et.

(7) $$\begin{cases} \tau_{p0} = \dfrac{\tau_{ll} N_d - \tau_{hl} p_1(Et)}{N_d + n_1(Et) - p_1(Et)} \\ \tau_{n0} = \dfrac{\tau_{hl}\left(N_d + n_1(Et)\right) - \tau_{ll} Nd}{N_d + n_1(Et) - p_1(Et)} \end{cases}$$

From these data one can compute and draw the dependence of $\tau(\Delta p)$ for different values of Et and experimental values of the lifetimes for low and high intensities of illumination τ_{ll}=3.3 μs and τ_{hl}=28 μs.

The results of computations of the function of the lifetime of carriers on the concentration of the excess carriers Δp for different values of Et are presented in Fig.1.

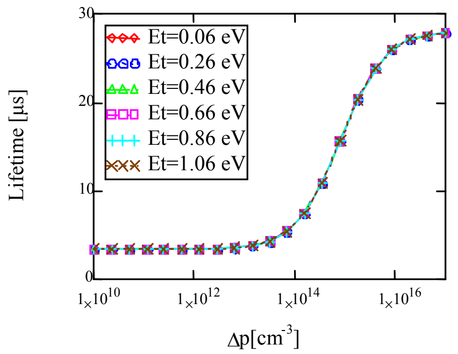


Fig.1. Dependence of the lifetime of carriers on the concentration of excess minority carriers Δp for different values of Et

The concentration of optically excited carriers Δp is related to the intensity of illumination I and is given by the formula:

(8) $$\Delta p = G(I) \cdot \tau \approx (1 - R)\frac{I}{\beta^{-1} \cdot E_{ph}}\tau$$

where: $G(I)$ is the average generation rate, τ is the carrier lifetime, I is the intensity of light, E_{ph} – energy of photons, β is optical absorption coefficient, β^{-1} is the optical penetration depth, R is the optical reflection coefficient of silicon.

Taking into account equation (4) the following formula for τ as a function of the intensity of light I has been obtained:

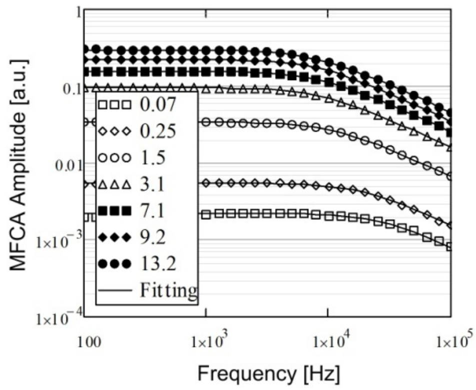
(9) $$\tau(I) = \frac{\tau_{hl}}{2} - \frac{N_d}{2G(I)} + \sqrt{\left(\frac{Nd}{2G(I)} - \frac{\tau_{hl}}{2}\right)^2 + \frac{\tau_{ll} N_d}{G(I)} \frac{N_d + n_1(Et) + p_1(Et)}{N_d + n_1(Et) - p_1(Et)}}$$

(10) $$G(I) = \frac{I \cdot (1 - R)}{E_{ph} \cdot \beta^{-1}}$$

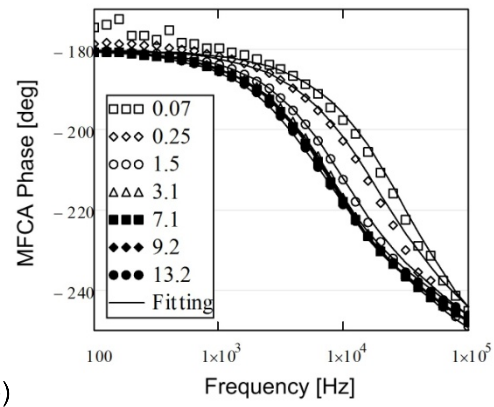
These formula (8, 9, 10) enable numerical interpretation of the dependence of the lifetime of carriers τ both on the intensity of the sample illumination I and on the concentration of carriers Δp.

Experimental results

N-type silicon sample, with donor concentrations N_D=0.8·10^{15} cm^{-3} and the resistivity 3-5Ωcm was measured. For the investigated silicon sample, several MFCA amplitude and phase frequency characteristics were measured for different medium and high intensities of illumination. They are presented in Fig.2. From the fitting of theoretical curves to experimental data the lifetimes of carriers were extracted.



a)



b)

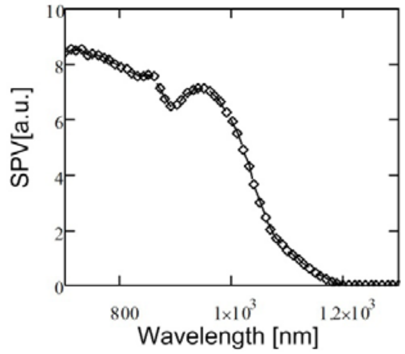
Fig.2. a) MFCA amplitude signal and b) MFCA phase signal characteristics, obtained for different levels of excitation (from I=0.07 to 13.2 W/cm^2) and the wavelength of the illuminating light λ=808 [nm]. Solid lines represent theoretical lines, symbols are experimental data

For low intensities of illumination the spectral SPV method for determination of the lifetimes of carriers was applied. The example spectral SPV characteristics, measured for the same samples, is presented in Fig.3a and 3b.

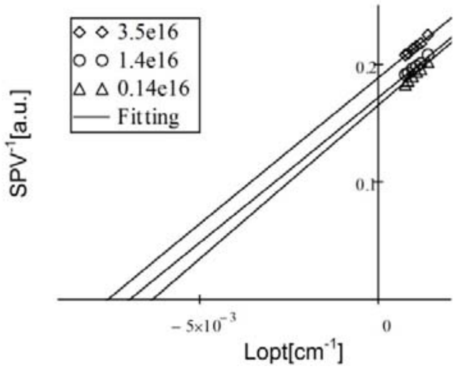
The absorption coefficient spectra of silicon was calculated from equation (11) according to [16]:

(11) $$\beta = \left(\frac{83.15}{\lambda} - 74.87\right)^2$$

where the wavelength λ is in [μm].



a)



b)

Fig.3. An example characteristics of a) the SPV spectrum obtained in a constant photon flux mode ($\Phi \approx 10^{16}$cm^{-2}s^{-1}) b) SPV^{-1} vs. Lopt= β^{-1}. 'diamonds', 'circles' and 'triangles' are experimental points obtained for a constant photon flux mode (Φ: 3.5·10^{16}, 1.4·10^{16} and 0.14·10^{16}cm^{-2}s^{-1}), measured in the wavelength range from 740 nm to 820 nm and taken for the analysis. Solid lines – fitting lines taken for L_d calculation

Carrier diffusion lengths obtained from the points where the fitting line intercepts *Lopt* axis are equal to 0.0076, 0.0069 and 0.0063cm. The carrier lifetimes calculated from eq.(12) are equal to 4.8, 4.1 and 3.3 µs where D=12 cm^2/s was assumed.

(12) $$\tau = \frac{Ld^2}{D}$$

The resulting dependences of the lifetime of carriers on the concentration of the light induced excess carriers and on the intensity of illumination are presented in Figure 4.

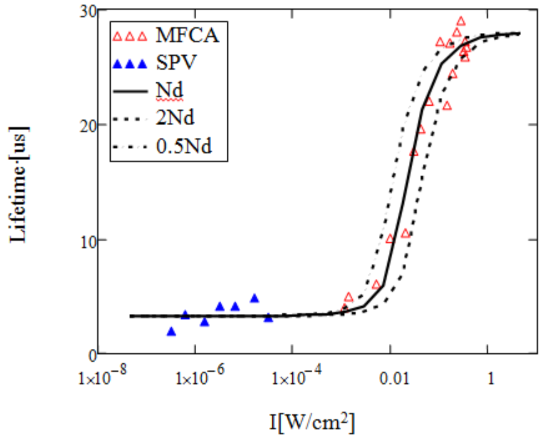


Fig.4. Theoretical and experimental dependence of the lifetime of carriers on the intensity of illumination. Symbols are experimental data, open triangles – MFCA results, closed triangles – SPV results. A solid line is the theoretical curve for different values of Nd. A dashed line is the theoretical curve computed for 2·Nd and a dash-dot line is for 0.5·Nd, $n_0 \approx N_D$=0.8·10^{15}cm^{-3} and lifetimes of carriers for low and high intensities of illumination τ_{ll}=3.3 µs and τ_{hl}=28 µs

Conclusions

In this paper the dependence of the lifetime of the minority carriers in the n-type silicon on the intensity of illumination was investigated with the SPV and a MFCA methods. Silicon samples with the concentration of donors N_D=0.8·10^{15}cm^{-3} were investigated. The wavelength of the illuminating light 808 nm was used to fulfill the condition of the bulk recombination. For shorter wavelengths of light and smaller optical penetration depth the influence of the traps related to the silicon oxide layer was expected. These traps could considerably decrease the lifetime of carriers.

The lifetime of minority carriers in traps free n-type silicon samples is given by formula (13) according to paper [26].

(13) $$\tau_{bulk} = \frac{1}{(N_d + \Delta p)\left(1.8 \cdot 10^{-24} N_d^{0.65} + 3 \cdot 10^{-27} \Delta p^{0.8} + 9.5 \cdot 10^{-15}\right)}$$

It results from the analysis of this formula that the lifetime of carriers in the n-type traps free silicon sample should decrease with the increase of the Δp or the intensity of the sample illumination.

In investigated n-type silicon samples the lifetime of carriers showed a strong increase of the lifetime with the increase of the intensity of illumination. It indicated for the presence of traps in the investigated samples.

Theoretical analysis of the experimental characteristics of the lifetime of carriers was performed in the frame of a SRH recombination model with a concentration of traps Nt. The proposed procedure depended on the measurement of the lifetimes of carriers for the low and high intensities of illumination and solution of the appropriate set of equations. It led to the theoretical dependence of the lifetime of carriers on the intensity of illumination and the experimental values of the lifetimes for low and high intensities of illumination (9). It enabled computations of the lifetime of carriers for any intensity of illumination of the sample.

This model well reproduced the experimental characteristics of the lifetime of carriers versus the intensity of illumination of the samples. Additionally a general conclusion could be drawn that the experimental values of the lifetimes of minority carriers, determined with different methods, can be compared only for similar intensities of illumination of the samples used in the experiment. It results from the observation that in the performed experiments the lifetimes of minority carriers increased almost ten times with the change of the intensity of illumination of the samples.

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