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Determination of the life time of excess carriers in silicon with photoacoustic and photocurrent methods

M. Maliński[1], Ł. Chrobak[1]

[1]Department of Electronics and Computer Science
Technical University of Koszalin, 2 Śniadeckich St, 75-453 Koszalin, Poland

E-Mail: miroslaw.malinski@tu.koszalin.pl

Abstract. This paper presents results of both theoretical and experimental studies of the characteristics – phase differences of the photoacoustic (PA) signals versus the frequency of modulation and for the purpose of comparison of characteristics – phase of the photocurrent (PC) signal versus the frequency of modulation. If the life time of excess carriers is the main goal of investigations the PC rather than the PA method should be applied wherever it is possible. The paper shows what advantages and disadvantages of both methods are from the point of view of determination of the life time of excess carriers. Finally the paper presents comparison of the phase PA and PC characteristics and life times extracted from both experiments for the series of silicon samples.

1. Introduction

Recombination parameters of semiconductor materials are essential for many applications. Different methods of their determination can be used. One of them is the photoacoustic method based on the measurement of the frequency dependence of the amplitude or phase of the (PA) signal. The other is the method based on the measurements of the frequency dependence of the amplitude or phase of the photocurrent. The well known in the literature PA approach requires application of the multi parameter fitting method while the PC approach does not require assuming any physical parameter of the sample. The theory of the PA effect, with the diffusion of optically generated carriers, used in this paper is presented in papers [1-10].

2. Theory

For the measurements of the phase of the PA signal versus the frequency of modulation the transmission configuration was chosen. Si p-type wafers had two differently prepared sides: a polished side and the roughened side. For the purpose of determination of the life time of the optically generated excess carriers phase frequency characteristics were measured in two configurations of samples in the PA cell. In the first configuration the polished side of the sample was illuminated while in the second one the roughened side was illuminated. The differences of the phase frequency characteristics measured in these two configurations were investigated both theoretically and experimentally according to the formula below. The parameters of the formula are defined below too.

$$\Delta P = \frac{180}{\pi}\arg((T(d,f,d,R,\alpha,E,E_g,D,\beta,\tau,V_b,V_g) - T(d,f,d,R,\alpha,E,E_g,D,\beta,\tau,V_g,V_b))/\sigma) \quad (1)$$

T is the temperature, d is the thickness of the sample, f is the frequency of modulation, α is the thermal diffusivity of the material, E is the energy of absorbed photons, E_g is the energy gap value of the material, D – diffusion coefficient of carriers, β - optical absorption coefficient, τ - life time of excess carriers, V_b, V_g – recombination velocities of carriers on both sides of the sample: polished or roughened. The difficulty is that the PA phase difference is a function of several experimental and material parameters. The process of extraction of the life time of carriers is based on the multi-parameter fitting, when especially velocities of surface recombination of the polished and roughened sides are not exactly known. From the fitting of theoretical curves to experimental characteristics the life time of carriers was determined. The life times of carriers of p-type samples presented in the paper were from the range: 1μs – 200 μs. For the process of verification of the obtained values of the life times the measurements of the phase of the PC versus the frequency of modulation were performed for the same series of samples and the same range of frequencies with a modified Stevenson method when the polished sides of the samples were illuminated. The phase of PC in the applied method is in fact the function of the life time of excess carriers and the frequency of modulation only what is the considerable advantage of the PC over PA method. The formula for the phase of PC is presented below. The other advantage is that the amplitude of the PC signal practically does not change with the frequency of modulation when compared with the decrease of the amplitude of the PA signal.

$$Phase(PC) = \frac{180}{\pi} \cdot \arctan(-2 \cdot \pi \cdot f \cdot \tau) \tag{2}$$

3. Experimental results

The schematic diagram of the PA chamber used for the measurements of the lifetime of excess carriers is shown in Fig.1.

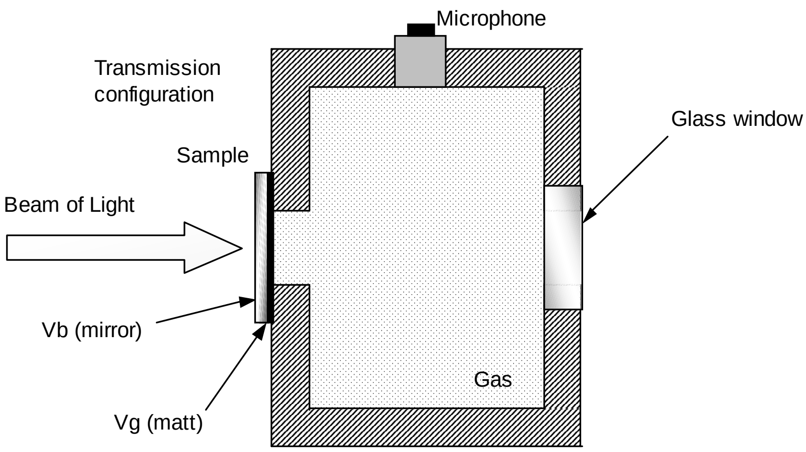

Figure 1. Schematic diagram of the PA chamber used for the measurements of the lifetime of excess carriers with the PA method.

The PC phase frequency characteristics of a series of silicon samples are presented in Fig.2. Lifetimes of excess carriers were determined from the fitting of theoretical curves, of the Stevenson method, to experimental points.

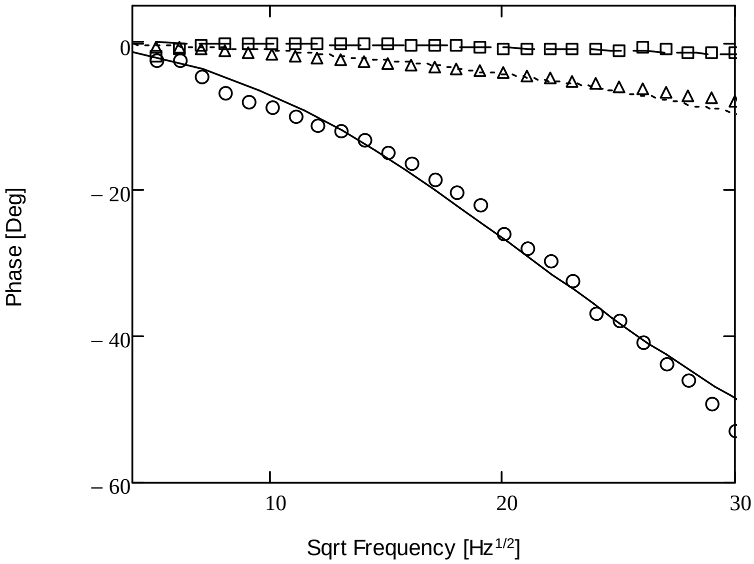

Figure 2. Phase frequency dependences of the photocurrent versus the frequency of modulation: boxes - $\tau < 1$ μs, triangles τ=35 μs, circles - τ=180 μs.

The corresponding PA phase difference characteristics are shown in Fig.3.

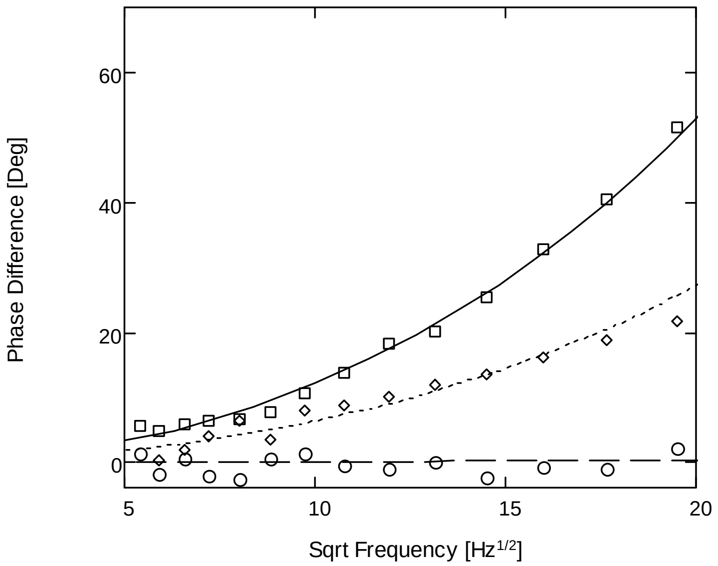

Figure 3. Phase difference of the PA signals versus the frequency of modulation. Lines are theoretical curves, symbols are experimental points. Boxes – τ =140·μs, d=0.058 cm, L=0.046 cm, triangles – τ =50 μs, d=0.049 cm, L=0.027 cm, Circles – τ=1·μs, d=0.075 cm, L=0.0038 cm, V_g=1500 cm/s, V_b=100 cm/s, D=15 cm^2/s, α=0.95 cm^2/s.

In the PA method the phase difference can be applied because the phase difference exhibits the saturation effect i.e. it changes slowly with the velocity of surface recombination of the roughened side of the sample as it is presented in Fig.4 below.

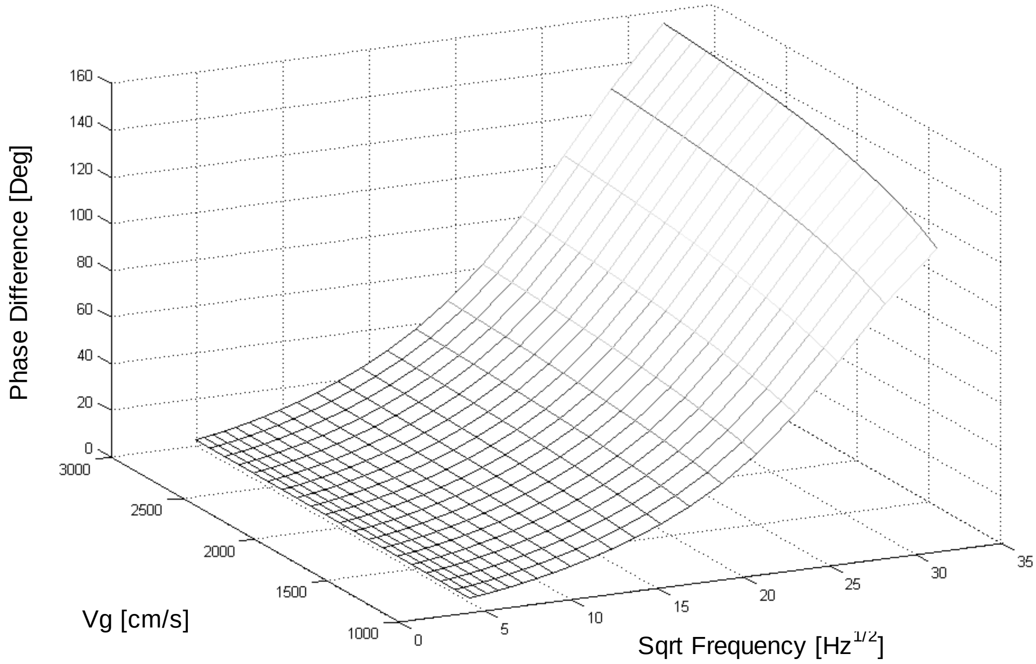

Figure 4. Phase difference versus the velocity of the surface recombination of the roughened side of the sample and V_b=100 cm/s assumed for the polished side.

4. Conclusions

It is possible to measure the lifetime of excess carriers with the PA phase difference method assuming the following values of the velocities of surface recombination: V_g=1500 cm/s for the roughened side of the sample, V_b=100 cm/s for the polished side of the sample. Phase difference shows the saturation effect for these velocities. Nevertheless the measurement of the kinetics of the photocurrent gives the same or similar results with the strong advantage – it is a function of only the lifetime of carriers. With so many parameters involved in the PA multiparameter fitting procedure the uniqueness of the fitted results is a really serious issue. This approach has one advantage – it is contactless. The PC method, on the other hand, is a function of only one parameter – a life time. It has however one disadvantage – it is a contact method. The comparison of obtained values of the life times in the PA and PC method presented below proves that the results are comparable i.e. PC (< 1 μs, 35 μs, 180 μs), PA (< 1 μs, 50 μs, 140 μs).

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