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Comparison of three nondestructive and contactless techniques for investigations of recombination parameters on an example of silicon samples

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HIGHLIGHTS

- Three nondestructive and contactless techniques (PA, MFCA, PTR) have been compared.
- Presented contactless methods are based on the generation of thermal or plasma waves.
- Recombination parameters of silicon samples have been extracted with these methods.
- Relative determination accuracies for the recombination parameters of have been made.
- Advantages, disadvantages and limitations of presented methods have been discussed.

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ABSTRACT

This paper presents a comparison of three nondestructive and contactless techniques used for determination of recombination parameters of silicon samples. They are: photoacoustic method, modulated free carriers absorption method and the photothermal radiometry method. In the paper the experimental setups used for measurements of the recombination parameters in these methods as also theoretical models used for interpretation of obtained experimental data have been presented and described. The experimental results and their respective fits obtained with these nondestructive techniques are shown and discussed. The values of the recombination parameters obtained with these methods are also presented and compared. Main advantages and disadvantages of presented methods have been discussed.

1. Introduction

Knowledge of the recombination parameters of semiconductors is very essential in the process of designing and production of electronic devices. The recombination parameters of semiconductor samples can be measured with different methods. Nowadays in the investigations of semiconductor materials the nondestructive contactless measuring techniques prove their worth. One of them is the photoacoustic (PA) frequency method especially in the transmission configuration. In this method periodic changes of temperature of the investigated sample are measured by a microphone that detects changes of the gas pressure in the photoacoustic cell. Examples of the photoacoustic characterization of thermal and electronic transport properties were presented in papers [1–4]. The theory of the photoacoustic effect was proposed by Rosencwaig and Gersho [5] and was extended to a two layer case by Fernelius [6]. An application of the PA method for determination of the lifetime of carriers of silicon samples was presented in papers [7–9]. The second method is the modulated free carriers absorption (MFCA) method. In this method the sample is illuminated by an intensity modulated beam of light and the transmission of an infrared beam of light passing through the same spot on the sample is measured and investigated. One of the first applications of this phenomenon has been presented in the Gauster and Bushnell work [10]. Different kinds of the MFCA method and its applications are described in papers [11–15]. The third method is the photothermal radiometry (PTR) method. In the PTR method the sample is illuminated by an intensity modulated beam of the laser light. As a result of the optical absorption of this light a periodical temperature and periodical carrier concentrations arise. The periodical infrared radiation emitted by the sample is detected by the IR cooled detector. A

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detailed principle of this method and the example experimental results were described in papers [16–18]. This method was also successfully applied for investigations of Ar^{8+} and O^{6+} implanted samples [19,20]. Aside from semiconductors this method is one of the widely used contactless and nondestructive techniques for investigations of many other types of solid materials [21–24]. The methods compared in this paper are widely used nondestructive techniques for investigations of semiconductors like other contactless methods such as: photopyroelectric method [25,26], beam deflection spectroscopy [27,28] or a photocarrier radiometry [29,30]. The objective of this paper is to check whether the recombination parameters of carriers measured on the same set of samples with these three methods have relatively similar values. Main advantages and disadvantages of presented methods have been discussed too.

2. Materials preparation and experimental methods

The investigated p-type Si wafers had two different sides: the polished side and the roughened side. The polished side was optically of a mirror type while the roughened side was matt. Details of these samples have been gathered and presented in Table 1.

The experimental set-up for the frequency PA measurements of semiconductor samples in the transmission (rear) configuration is shown in Fig. 1. The thermal waves were excited using a laser diode RLV4512 with a beam diameter smaller than 1 mm, the output power 200 mW and a photon energy 3.06 eV corresponding to the operating wavelength $\lambda = 405$ nm. A lock-in amplifier SR830 was used for phase sensitive measurements and for the modulation of the intensity of the laser beam. The self designed photoacoustic cell with a G.R.A.S. microphone (type 26AK) was used as a detector of the photoacoustic signal. Modeling and a design of such a type of the Helmholtz cell was described in papers [31,32]. Measurements were fully automated and computer controlled. Investigations have been performed at room temperature in the transmission detection configuration.

The experimental set-up for the frequency MFCA measurements of semiconductor samples is shown in Fig. 2. There are two sources of light in this set-up. The first one is a pumping laser working at the wavelength 405 nm (~3.06 eV) and the output power 200 mW exciting carriers from the valence band to the conduction band. Energy of photons of the pumping laser must be larger than the value of the energy gap of the investigated semiconductor (~1.1 eV). The second source of light was a semiconductor laser working at the wavelength 1600 nm (~0.78 eV) as a probing laser. Energy of photons of the probing light is smaller than the value of the energy gap of the semiconductor. The intensity of the probing beam (200 mW) of the laser light is constant in time and is absorbed by free carriers. The intensity of the pumping laser beam is modulated by a Thorlabs LDC205C controller and the TTL signal of the lock-in amplifier. The periodic component of the intensity of the probing infrared beam was measured by a Thorlabs PDA20CS-EC IR detector and a lock-in amplifier.

The experimental set-up for the frequency PTR measurements of semiconductor samples, used in the described measurements, is shown in Fig. 3. The thermal and plasma waves in the sample were excited using a laser diode with a beam diameter smaller than 1 mm, output power 200 mW and a photon energy 3.06 eV corresponding to the operating wavelength $\lambda = 405$ nm. The intensity of the laser beam was modulated by the Thorlabs controller and TTL signal of the lock-in amplifier. The infrared radiation was collected from the sample surface and focused on the active surface of the infrared photovoltaic detector PVI-3TE-5 produced by the VIGO System S.A. The active area of the detector was 0.5 $\times$ 0.5 mm^2. The detector was equipped with an immersion lens BaF_2. The spectral range of the IR detector was optimized for the wavelength 5.5 μm. The detector included a transimpedance amplifier (10 Hz–1 MHz) and was cooled with the three level thermoelectric system. Because the lifetime of carriers depends on the intensity of the pumping beam of light, the intensity of the pumping laser was kept constant in all three investigated methods.

3. Theory

In the PA method frequency characteristics in the transmission configuration were measured for two positions of the sample in the PA cell. The transmission configuration means that one side of the sample is illuminated and the temperature of the other side of the sample is measured by the microphone as the periodical overpressure in the photoacoustic cell. In the first position the mirror side of the sample is illuminated, in the second position the matt side of the sample is illuminated. For the numerical analysis of the amplitude and phase experimental results in the PA method the expression (1) was used.

$$\Delta PA(f) = [T(d,f,\tau,D,V_1,V_2)/T(d,f,\tau,D,V_2,V_1)] \quad (1)$$

Symbols in the equations presented above are the following: d is the thickness of the sample normal to the surface, f is the frequency of modulation of the intensity of the beam of light, τ is the lifetime of excess carriers, D is the diffusion coefficient of carriers, V_1, V_2 are velocities of surface recombination of carriers on both sides of the sample.

The temperature of the surface of the sample, arising as a result of its illumination by the intensity modulated beam of light, is in general a function of several physical parameters and is described below. Detailed description of these equations was presented by Dramicanin et al. in paper [1].

$$T(d,f,\tau,D,V_1,V_2) = \Theta_T(d,f) + \Theta_{NRR}(d,f,\tau,D,V_1,V_2) + \Theta_{SR}(d,f,\tau,D,V_1,V_2) \quad (2)$$

where

$\Theta_T(d,f)$ is the surface temperature being the result of the intraband thermalization of carriers,
$\Theta_{NRR}(d,f,\tau,D,V_1,V_2)$ is the surface temperature being the result of the volume nonradiative recombination of carriers, and
$\Theta_{SR}(d,f,\tau,D,V_1,V_2)$ is the surface temperature being the result of the surface recombination of carriers.

For the analysis of the $MFCA(f)$ signal the expression (3) was used.

$$MFCA(f) = F \cdot \left(1 - a \cdot \int_0^d \partial n(x,f,\tau,D,V_1,V_2)\,dx\right) \quad (3)$$

where F and a are number coefficients and $\delta n(x)$ is the spatial distribution of the concentration of optically generated excess carriers

Table 1
Details of the investigated silicon samples.

Sample	Growth method	Resistivity (Ω·cm)	Dopant concentration (cm^{-3})	Thickness (cm)
#1	Czochralski	800–1000	~10^{13}	0.063
#2	Float Zone	7–10	~10^{15}	0.053