Thermochimica Acta 650 (2017) 33–38

Contents lists available at ScienceDirect

Thermochimica Acta

journal homepage: www.elsevier.com/locate/tca

On measurement of the thermal diffusivity of moderate and heavily doped semiconductor samples using modulated photothermal infrared radiometry

M. Pawlak [a,*], A. Panas [b], A. Ludwig [c,d], A.D. Wieck [c,d]

[a] Institute of Physics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland
[b] Institute of Electron Technology, Al Lotnikow 32/46, 02-668 Warsaw, Poland
[c] Experimental Physics VI, Ruhr-University Bochum, Universitaetsstrasse 150, 44780 Bochum, Germany
[d] Chair of Applied Solid-State Physics, before Experimental Physics VI, Ruhr-University Bochum, Universitaetsstrasse 150, 44780 Bochum, Germany

ARTICLE INFO

Article history:
Received 2 September 2016
Received in revised form 2 February 2017
Accepted 5 February 2017
Available online 7 February 2017

Keywords:
Modulated photothermal infrared radiometry
Silicon
Gallium arsenide
Effective infrared absorption coefficient
Thermal diffusivity

ABSTRACT

In this work, the accuracy of the thermal diffusivity estimation in moderately and heavily doped semiconductor samples using the modulated photothermal infrared radiometry is investigated. The studies were carried out on heavily doped Si and GaAs wafers, and on moderately doped Si and recently studied GaAs and CdSe samples. It is shown, that depending on the infrared properties of the semiconductor sample, the modulated photothermal infrared radiometry signal can yield information about thermal diffusivity, (effective) infrared absorption coefficient and electronic transport parameters (recombination lifetime, carrier diffusivity and surface recombination velocities). For the heavily doped samples, the modulated photothermal infrared radiometry signal consists only of the thermal response yielding information about the (effective) infrared absorption coefficient and thermal diffusivity. The relative expanded uncertainty with 0.95 level of confidence U_r of estimating the thermal diffusivity in this case is about $U_r = 0.05$. For moderately doped samples the modulated photothermal infrared radiometry signal consists of the thermal and of the photocarrier response. The relative expanded uncertainty with 0.95 level of confidence U_r of estimating the thermal diffusivity in this case varies between about $U_r = 0.10$ and about $U_r = 0.30$, depending on the existence of the maximum in the signal phase, but information about the electronic transport properties is derived. It is shown that not only infrared properties have the influence on the accuracy in estimating the thermal diffusivity of moderate doped semiconductor samples, but also the thermal, geometrical (thickness) and carrier recombination properties can play an important role.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

In the last decades thermal wave methods have been successfully used to determine thermal and optical properties of variety of materials [1–7]. Among them, the modulated photothermal infrared radiometry (PTR) is a noncontact method which is based on the measurement of the amplitude modulated infrared (IR) emission (2 μm–12 μm) from the samples in order to get information about thermal and optical properties. In the case of semiconductor materials, additional information about electronic transport (recombination) properties such as carrier recombination lifetime τ, carrier diffusivity D and surface recombination velocities S_1 and S_2 can be obtained due to the change of the emittance caused by the plasma waves [8–12]. It was shown that for high resistivity (undoped or lightly doped) silicon wafers it is possible to obtain information about the thermal diffusivity using the PTR method [8]. The theoretical model used for the interpretation of the PTR experimental results [12] assumed that $\beta_{IR}{\cdot}L \ll 1$, where β_{IR} is the infrared absorption coefficient, and L is the sample thickness. In our earlier papers we proposed theoretical models to interpret experimental results obtained on moderate doped CdSe and GaAs samples, where $\beta_{IR}{\cdot}L \sim 1$, using reflection [13,14] and transmission configurations [15]. In this paper, we investigate both highly doped samples, where $\beta_{IR}{\cdot}L > 1$, and moderately doped samples: Si and studied recently GaAs and CdSe samples. The aim of this paper is to demonstrate that depending on the infrared properties of the samples the modulated photothermal infrared radiometry signal yields information about the thermal diffusivity with different precision. The infrared

* Corresponding author at: Nicolaus Copernicus University, ul. Grudziądzka 5/7, 87-100 Toruń, Poland
E-mail addresses: mpawlak@fizyka.umk.pl, mispawlak@yahoo.pl (M. Pawlak).

http://dx.doi.org/10.1016/j.tca.2017.02.003
0040-6031/© 2017 Elsevier B.V. All rights reserved.

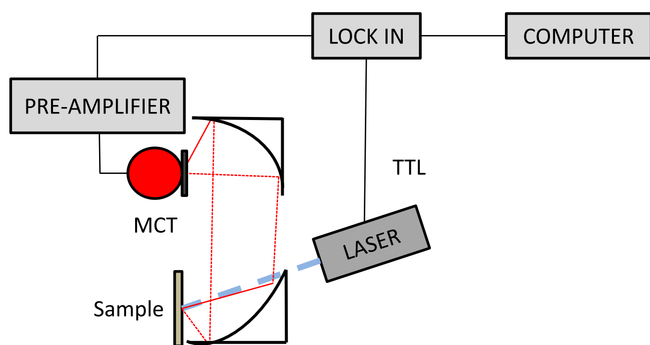

Fig. 1. Experimental modulated photothermal infrared radiometry set-up.

properties of the samples were changed by the dopant concentration of the samples.

2. Experimental setup and materials

2.1. Experimental setup

Fig. 1 shows the modulated photothermal infrared radiometry experiment set-up [14].

The modulated photothermal infrared radiometry signal was excited using a diode laser (OmicronLaser) with the output power of $I = 150$ mW at the operating wavelength $\lambda = 405$ nm. The laser beam diameter, measured using Thorlabs Scanning Slit Optical Beam Profilers BP209-VIS/M, was $d = 1.24 \pm 0.02$ mm. The intensity of the beam was electrically modulated in the frequency f – range between 40 Hz and 100 kHz by a rectangular (0–100%) modulation with 1:1 duty cycle. Two Au-coated off-axial parabolic mirrors captured the emitted IR radiation from the sample, focusing it on a photoconductive MCT detector type J15D12 (Teledyne Judson Technologies) with its detectivity peak at the wavelength of 11.3 μm and with 1 mm^2 of active area. The detector was cooled by liquid-nitrogen and has a ZnSe window. Additionally, in order to block the laser radiation, an antireflection-coated Ge window was used. The signal from the detector was processed by a lock-in amplifier SR850 (Stanford Research). The amplitude A and phase φ frequency scans were acquired and analyzed by a personal computer. The calibration of the modulated photothermal infrared radiometry characteristics was achieved with a glassy carbon sample which was thermally thick and optically and infrared opaque. In order to eliminate the transfer function of the experimental set up, the following normalization procedure was used:

$$Norm_Amp(f) = \frac{Amp_{sample}(f)}{Amp_{glassy_carbon}(f)}, \quad (1)$$

$$Norm_Phase(f) = Phase_{sample}(f) - Phase_{glassy_carbon}(f). \quad (2)$$

2.2. Materials

Table 1 presents information about the investigated heavily and moderate doped samples.

Commercial Si and GaAs wafers are used with purities several orders of magnitude purer than the doping levels listed in Table 2. Si wafers were obtained using Czochralski method, incorporating dopants in the melt. While GaAs wafers were made using Vertical gradient freeze method, incorporating dopants in the melt. The CdSe crystals were grown from the melt by the high-pressure (150 atm of Argon) modified vertical Bridgman method using high purity (99.999%) powder of CdSe put in a graphite crucible. The crystals were grown using the procedure described elsewhere [16]. The only difference was the lowering speed of the crucible in the heating zone which caused the difference in the electrical and infrared properties of the samples S6 and S7 [13,15]. Table 2 presents electrical properties of the investigated heavily and moderate doped samples.

For electrical characterization, square (5×4.5 mm^2) samples are contacted by indium solder (alloyed for 5 min at 370 °C in forming gas atmosphere) on the corners of the wafer. The Hall measurements in van der Pauw configuration [17] were performed following by NIST standard [18] using a self-built Hall setup [19]. The Hall setup consists of a Keithley 220 current source and a Keithley 2700 multimeter with a switching card to automatically toggle through all possible contact configurations. The magnetic field for the Hall measurements is determined by an FH 55 Gauss-/Teslameter from MPS to 106 mT and is inverted for better accuracy and reliability. All samples had a polished front surface and an unpolished rear surface.

3. Theoretical model

For the IR semi-transparent sample, the PTR signal can be written as [12,14,15,20]

$$S(f, \beta_{IR}) \propto \int_0^L \beta_{IR} \cdot \Delta T(z, f) \cdot \exp(-\beta_{IR} \cdot z) dz, \quad (3)$$

where L is the sample thickness, β_{IR} is the infrared absorption coefficient, f is the modulation frequency, and

$$\Delta T(z, f) = \frac{I_0}{2k\sigma_t} \frac{1 + R_{mb} e^{-2\sigma_t(L-z)}}{1 - R_{mb} e^{-2\sigma_t L}} e^{-\sigma_t z}, \quad (4)$$

where $R_{ij} = (b_{ij} - 1)/(b_{ij} + 1), b_{ij} = e_i/e_j$. e_i is the effusivity ($i = m$ refers to the material , $i = b = g$ refers to air), $\sigma_t(f) = sqrt((i \cdot 2 \cdot \pi \cdot f)/\alpha)$, where α is the thermal diffusivity, k is the thermal conductivity, and I_0 is the intensity of the incident radiation.

For high resistivity semiconductor samples, when $\beta_{IR} \cdot L \ll 1$, Eq. (3) can be simplified to the following formula [8–12]

$$S_{PTR}(f, \beta_{IR}) = a_{PT}(\beta_{IR}) \int_0^L \Delta T(z, f) dz + b_{PC} \int_0^L \Delta n(z, f) dz. \quad (5)$$

The expressions for the coefficients a_{PT} and b_{PC} as well as those for the thermal wave (temperature modulation) ΔT and the plasma wave (photoinjected free-carrier density) Δn in the case of Si photoconductive devices can be found in [9]. In this model, the infrared absorption coefficient is included in the coefficient a_{PT}. For

Table 1
Information about the investigated heavily and moderate doped samples.

Sample	Material	Dopant	Source	Growing Method
S1	Si	Arsenic	Cemat Silicon	Czochralski
S2	GaAs	Zinc	Wafer Technology Ltd	Vertical gradient freeze
S3	GaAs	Zinc	Wafer Technology Ltd	Vertical gradient freeze
S4	Si	Boron	Cemat Silicon	Czochralski
S5	GaAs	Silicon	Wafer Technology Ltd	Vertical gradient freeze
S6	CdSe	–	N. Copernicus University	Modified vertical Bridgman
S7	CdSe	–	N. Copernicus University	Modified vertical Bridgman

Download English Version:

https://daneshyari.com/en/article/4995986

Download Persian Version:

https://daneshyari.com/article/4995986

Daneshyari.com