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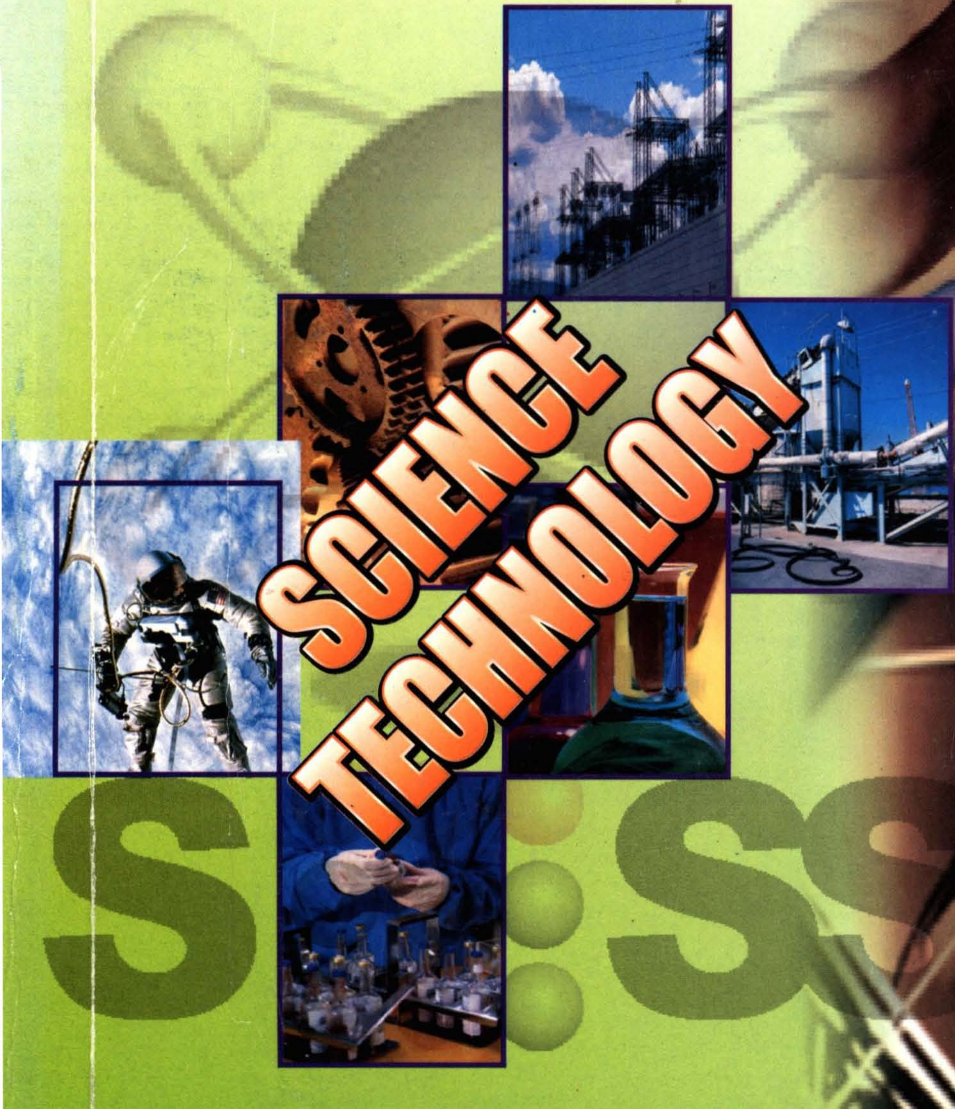

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Measurement of Thermal and Carrier Transport Properties of Si Using Transmission Photoacoustic Techniques

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ABSTRACT

The photoacoustic detection technique heat transmission configurations was utilized to study the thermal and carrier transport properties of boron-doped silicon wafer. The photoacoustic amplitude and phase signals were measured as a function of the optical beam modulation frequency as well as optical beam power. The measurements were performed in an enclosed photoacoustic cell at room temperature. The experimental results shown that in the thermally thick modulation-frequency region, the photoacoustic signal amplitude can single out the heating source responsible for the photoacoustic signal. The thermal diffusivity value and transport parameters (diffusion coefficient, surface recombination velocity, and carrier recombination lifetime) were determined by fitting the experimental photoacoustic phase data to the theoretical model. The present investigation shows a significant step towards demonstrating the use of the photoacoustic technique to perform the quantitative characterization of semiconductor materials.

Introduction

Photoacoustic (PA) spectroscopic technique has been recently established as a promising and valuable tool for investigation of optical, thermal and the electronic transport properties of semiconductor materials (Pinto et al. 1990, Alvarado and Miguel 2001). The principle of PA technique is based on the generation of an acoustic wave in the enclosed cell containing air in contact with a sample. When a sample is periodically heated by modulated light the air pressure in the cell oscillates at the chopping frequency which can be detected by a sensitive microphone coupled to the cell.

In semiconductors, when an intensity modulated monochromatic light beam with high energetic photons impinges on the sample surface, the absorption of radiation with photon energy $h\nu$ greater than the band-gap energy E_g creates an excess carrier distribution in the sample with an energy ($h\nu$-E_g) above the conduction band. This excess energy is released in the form of heat by non-radiative recombination in the bulk and at the surface (Mandelis 1987; Bhandari and Rowe 1988; Sze 2002; Dramicanin et al. 1995).

In the present work, we have carried out an investigation on the thermal diffusivity and carrier transport properties of boron-doped silicon wafer by applying the photoacoustic (PA) heat transmission technique. Using this technique, the thermal and transport properties of silicon samples were evaluated by recording their PA signal amplitude and phase as a function of the modulation frequency (45- 300) Hz. The objective of the work is to study the dependence of the carrier transport parameters on laser power and surface qualities (polish and rough surfaces).

Materials and Method

In semiconductors, there are three processes by which the excess carriers release energy to the lattice: (i) instantaneous (~1ps) intraband non-radiative thermalization of conduction electrons with energy higher than E_g (ii) non-radiative electron-hole pair recombination in the bulk by band to band transitions, after diffusing a distance $(Dt)^{1/2}$, where D is the excess carrier diffusion coefficient and t is the non-radiative band to band bulk recombination lifetime (iii) non-radiative electron-hole pair recombination at the surface, characterized by the surface recombination velocity v.

The Mathematical expression for the PA signal in semiconduting samples has been obtained by resorting the thermal-piston model of Rosencwaig and Gersho (1976). According to this model for the optically opaque semiconductor sample, the PA signal phase has established the following relation (Pinto et al. 1990)

$$f = \frac{\pi}{2} + \tan^{-1}\left[\frac{(aD/v)(\omega\tau_{eff}+1)}{(aD/v)(1-\omega\tau_{eff})-1-(\omega\tau_{eff})}\right] \quad (1)$$

where $t_{eff} = t[(D/a)-1]$ and $a = (pf / a_s)^{1/2}$, v represents the surface recombination velocity (cm/s), a is the thermal diffusivity (cm^2/s), and t is band to band recombination lifetime. The phase angle Df decreases with the increasing modulating frequency when bulk and surface recombination mechanism becomes the dominant processes.

The sample used in the present investigation was silicon wafer, p-Si(100) with the resistivity of 0.085 Wcm. The carrier concentration of the sample is 7 ´ 10^{12} cm^{-3} and the sample thickness is 668 mm. The photoacoustic measurements were performed at room temperature using a home made PA cell with a diode laser as an optical excitation source. The laser beam was mechanically chopped by an optical modulator (SR540) and the beam spot size was made large enough in order to eliminate the effects of lateral diffusion in the measured sample.

The experimental set up of the photoacoustic technique has been described in our previous paper (Mat Yunus 1999). The PA signal is generated by the pressure fluctuation in a small volume of air between the sample and the microphone. The signal is then detected using a highly sensitive electret microphone kept inside PA chamber. Finally, the amplitude and phase of the PA signal as a function of the modulation frequency is amplified by a preamplifier and further analyzed using a dual phase digital lock-in amplifier (SR530).

In this investigation, the thermal and carrier transport mechanisms of the silicon samples were studied at different laser powers (i.e. 260, 300, 350, 400 and 450 mW) and at different sample thickness (668 mm to 514 mm). Different thickness of the silicon sample was obtained by polishing silicon wafer with abrasive silicon carbide (P1000) sandpaper. The measurements were carried out for both rough-polish (RS-PS) and polish-rough (PS-RS) configurations. The PA signal in each measurement was measured and analyzed in the frequency range from 45Hz to 300Hz. Within this frequency range the effect of thermoelastic and electronic deformation effect on PA signal is small and insignificant.

Results and Discussion

Figure 1 shows the typical variation of the PA signal amplitude as a function of the modulation frequency for PS-RS configuration obtained at five different laser powers. The PA signal amplitude obtained at five laser power follows the modulation frequency dependence of $\sim f^{-1.50}$. This indicates that the sample exhibits the thermally thick behavior. In this case the PA signal was mainly contributed by non-radiative electron-hole pair recombination process (Pinto et al. (1990) and Alvarado et al. (2001)).

The typical variation of PA signal phase data as a function of modulation frequency at different laser powers for PS-RS sample configuration is shown in Figure 2. It is noticed that the signals decrease with the increasing of modulation frequency. This observation is similar to those reported by Barbu et al. (1997) and Pinto et al. (1990. Similar behavior is also observed for the silicon sample with RS-PS configuration which indicates that the transport parameters are power independence. By fitting the experimental PA phase data to Equation (1), the carrier transport properties were obtained to be D = 18.6 cm^2/s, v = 852cm/s, a = 0.92 cm^2/s and t = 12 ms.

As we known that the surface quality of semiconductor samples has a pronounced effect on the carrier recombination properties especially the surface recombination velocity of the photoexcited carriers (Nikolic et al 1995, Nikolic et al. 1996). Figure 3 shows the change of the PA signal amplitude and PA phase signal versus the modulation frequency obtained for different surface quality. The PA signal amplitude for rough surface (RS-PS) configuration is higher than the polished surface (PS-RS) as observed in Figure 3(a). The thermal diffusivity value a = 0.92 cm^2/s obtained in this work is in a good agreement with the recorded literature values for silicon (0.85 - 1.06 cm^2/s) (Pinto et al. 1990).

The values of carrier diffusion coefficient and recombination lifetime obtained for both RS-PS and PS-RS sample configurations were the same (i.e. D = 18.6 cm^2/s and t = 12 ms,). However, the surface recombination velocity v = 1100 cm/s obtained for the RS-PS configuration is higher than the illuminated polished surface (PS-RS). The value of v for (PS-RS) surface is only 852 cm/s.

Conclusion

The PA heat transmission techniques has been used to investigate the thermal and carrier transport properties silicon sample. From the frequency dependence of the photoacoustic signal, it was found that the PA signal was contributed by the heat source generated from the non-radiative bulk and surface recombination process. The phase of photoacoustic signal decreases as the modulation frequency increase, demonstrating the mechanism of heat generation in semiconducting materials. By fitting the photoacoustic phase spectra to theoretical model, the values for transport parameters were obtained. The carrier transport parameters are independent on the laser power. However the surface quality gave a significant effect on the surface recombination velocity. This work shows a significant step towards the understanding of the PA signal generation in semiconductors and demonstrating the capability of the PA technique to determine the carrier transport and thermal characterization of semiconductor materials.

Acknowledgement

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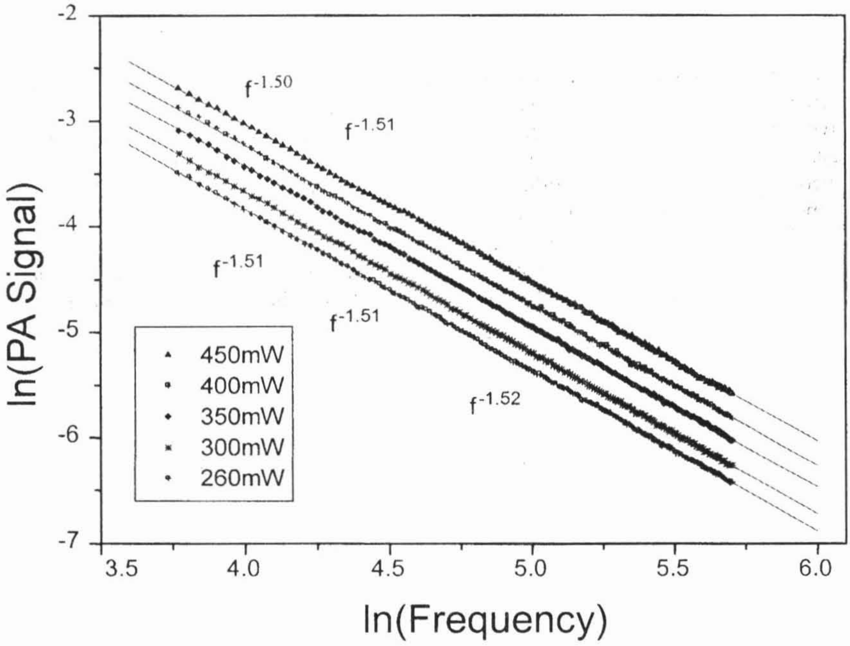

Figure 1: Ln(PA) signal versus ln (frequency) measured at different laser powers for PS-RS configurations.

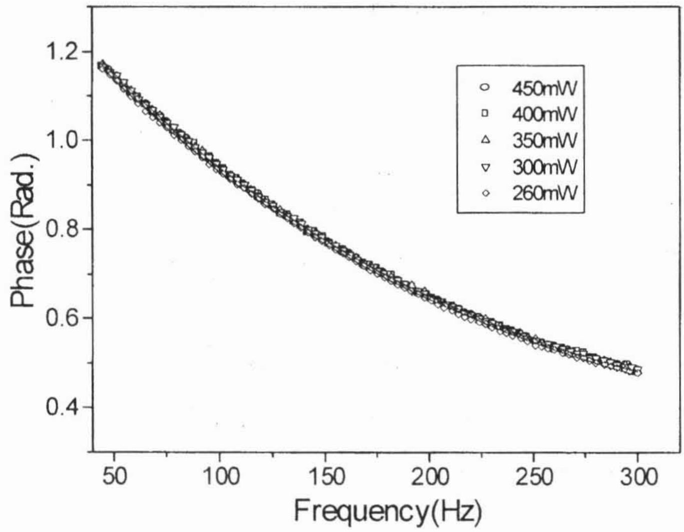

Figure 2: Typical variation of PA signal phase as a function of modulation frequency at different laser powers for PS-RS configuration.

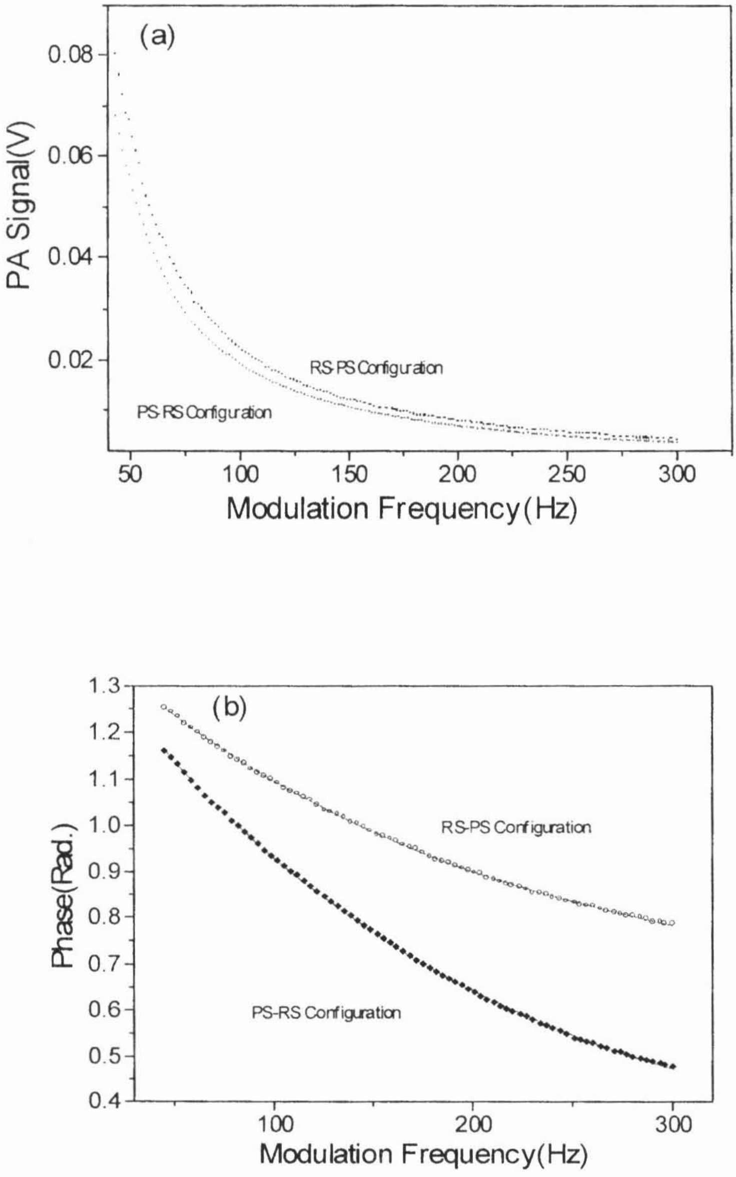

Figure 3: PA signal amplitude and phase versus modulation frequency (a) RS-PS and (b) PS-RS configurations

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