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Measurement of the Thermal Conductivity of Si and GaAs Wafers Using the Photothermal Displacement Technique

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Thermal conductivity and thermal diffusivity of Si and GaAs wafers were measured using the photothermal displacement technique, and the temperature dependence of these two quantities was investigated. Thermal diffusivity was obtained from the phase difference between the heating source and the signal, and thermal conductivity was determined from the maximum value of the signal amplitude in the temperature range 80 to 300 K. It was verified that an increase in doping concentration gives rise to a decrease in thermal conductivity at low temperatures. The experimental results obtained on samples with different types and doping concentrations are consistent with those expected from theoretical considerations.

KEY WORDS: GaAs; impurities; phonons; photothermal displacement technique; semiconductors; Si; thermal conductivity; thermal diffusivity.

1. INTRODUCTION

A variety of processes can be induced at surfaces and in thin films with laser radiation [1]. The photothermal technique is useful for the measurement of the physical properties and/or defects of samples by observation of the thermal variation generated by laser irradiation on the sample. Important features of the photothermal technique include the absence of any electrical or mechanical contact with the sample and the ease of

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application to the study of a wide variety of materials in difficult environments. In particular, the photothermal displacement technique (PDT) has recently been actively investigated and applied [2, 3] since its formulation by Olmstead et al. [4].

Opsal et al. [5] applied PDT to the measurement of the thickness of thin films, and Olmstead et al. [6] used it to study the temperature dependence of Si and Ge surface-state optical absorption. Also using PDT, Welsch et al. [7] measured low-absorption of optical thin films and carried out calculations of the three-dimensional surface deformation [8], and Kuo et al. [9] measured thermal conductivity of a Si film on Si substrate.

PDT is based on the detection of the displacement of the sample surface produced by the absorption of energy from a light beam incident on the sample. The reflected probe beam is deflected by the surface displacement, and information on the thermophysical properties of the sample can be obtained from measurements of deflection. According to theory [4], the PDT signal is determined mainly by the thermal conductivity, thermal diffusion length, and thermal expansion coefficient. The thermal diffusion length (or thermal diffusivity) may be measured from the phase of the signal, and in the high focusing limit (a condition where the thermal diffusion length is sufficiently larger than the radius of the pump beam), the amplitude of the signal is proportional to the ratio of the thermal expansion coefficient to the thermal conductivity. PDT is an excellent tool for the measurement of thermophysical properties, except in special temperature ranges where the sign of the thermal expansion coefficient changes.

The purpose of our paper is to show the effect of temperature and doping in heat conduction in Si and GaAs wafers by measurement of thermal diffusivity and thermal conductivity using a noncontact technique.

2. EXPERIMENTAL

For clarity, let us consider briefly the principle of PDT. Figure 1 depicts the schematic configuration. The modulated pump beam with radius a is focused on the sample and leads to a local deformation of the sample surface caused by partial absorption of the incident laser beam. The sharply focused probe beam incident with the offset distance, r, is directed at the flank of the sample deformation. The measured deflection of the probe beam reflected at the sample surface is mainly proportional to the change in the local slope of the surface displacement U. The experimental apparatus is shown in Fig. 2. An Ar ion laser (less than 300 mW, about 100-μm $1/e$ radius on the sample) is used as a pump beam. It is suitable as a heating source since the energy of the laser beam is about 2.4 eV

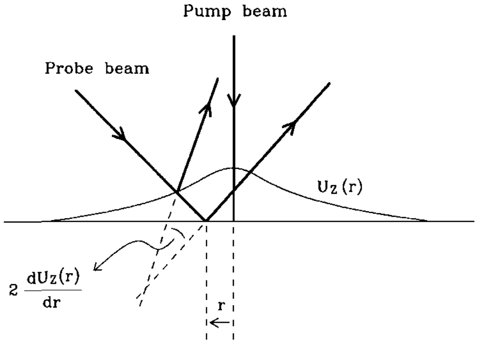

Fig. 1. The schematic configuration for the photothermal displacement technique. $U_Z(r)$ is the surface displacement.

(wavelength, 514.5 nm) and the energy gaps E_g of Si and GaAs are 1.11 and 1.43 eV, respectively, at room temperature. A He–Ne laser (10 mW, 632.8 nm, about 10-μm $1/e$ radius on the sample) is used as a probe beam. The position sensor is located about 2 m away from the sample and consists of a knife edge and a photodiode connected to a low-noise transformer. An interference filter, mounted in front of the photodiode, suppresses light not originating from the He–Ne laser. The amplitude and phase of the signal are measured by a lock-in amplifier. The samples are placed in

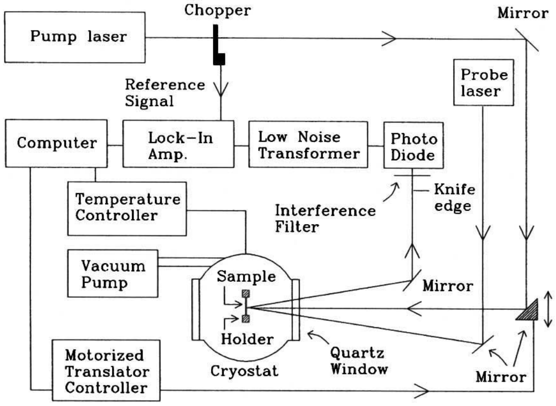

Fig. 2. The experimental apparatus for PDT. The pump laser is an Ar ion laser and the probe laser is a He–Ne laser.

a vacuum chamber of a cryostat, and optical access to the sample is through vacuum-sealed quartz windows.

Figure 3 shows the typical detected PDT signal, the amplitude, and the phase. The signal is for a GaAs wafer (G2; see below) with a chopping frequency of 150 Hz. The measured deflection is proportional to the slope of the surface displacement, as shown in Fig. 1, and the slope is given by Ref. 4.

$$\frac{dU_Z(r)}{dr} = C\frac{\alpha_{\text{th}}}{\kappa}\cdot f(r) \tag{1}$$

where C is a constant, α_{th} is the thermal expansion coefficient, κ is the thermal conductivity, and $f(r)$ is a complex number and rather intricate integral term including thermal diffusion length, etc. Therefore, the phase is determined by $f(r)$ only. From the thermal diffusivity, α, and the chopping frequency, f_c, the thermal diffusion length is given by $L_{\text{th}} = \sqrt{\alpha/\pi f_c}$ and determined from the phase of the signal by Eq. (1) using curve fitting. Especially since the value of $f(r)$ is insensitive to the change in thermal diffusivity at the same r in the high focusing limit, $a \ll L_{\text{th}}$, the effect of $f(r)$ is negligible and the amplitude of the signal is proportional to $\alpha_{\text{th}}/\kappa$. Figure 4 shows the thermal conductivity [10], thermal expansion coefficient [11], and expected signal amplitude obtained by dividing α_{th} by κ for Si. In other words, the thermal conductivity can be calculated from the signal amplitude and thermal expansion coefficient. In signal c, there is a dip in the special temperature range since the sign of the thermal expansion coefficient changes in this range, near 120 and 50 K in the case of Si [12] and GaAs [13], respectively, and measurement is difficult near these points because the signal is very weak. Data are normalized to the maximum amplitude of the signal obtained at room temperature. The thermal conductivities at 300 K are calculated by using a relation $\kappa = \alpha\rho C_p$, where α is the thermal diffusivity obtained from the phase of the signal, C_p is the specific heat [12, 13], and ρ is the density [12, 13]. We assumed that the effect of doping on the specific heat, thermal expansion coefficient, and density is negligible.

The experimental apparatus is installed on an optical table to reduce the effects due to vibration. The samples are 0.52-mm-thick p-type Si and five GaAs samples: (G1) semiinsulating GaAs; (G2) semiinsulating GaAs, resistivity of $10^7\ \Omega\cdot\text{cm}$; (G3) n-type GaAs, resistivity of $1\ \Omega\cdot\text{cm}$, doping concentration of $\sim 10^{16}\ \text{cm}^{-3}$; (G4) n-type GaAs, resistivity of $0.1\ \Omega\cdot\text{cm}$, doping concentration of $2.7\times 10^{17}\ \text{cm}^{-3}$; and (G5) p-type GaAs, resistivity of $0.01\ \Omega\cdot\text{cm}$, doping concentration of $9.3\times 10^{17}\ \text{cm}^{-3}$. For GaAs samples, the thickness is 0.35 mm except for sample G1, which is 0.5 mm thick.

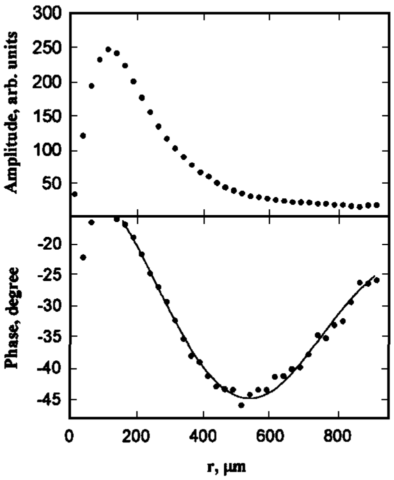

Fig. 3. The amplitude and phase of the PDT signal. Data are for GaAs (G2) and the solid line indicates the fitting result.

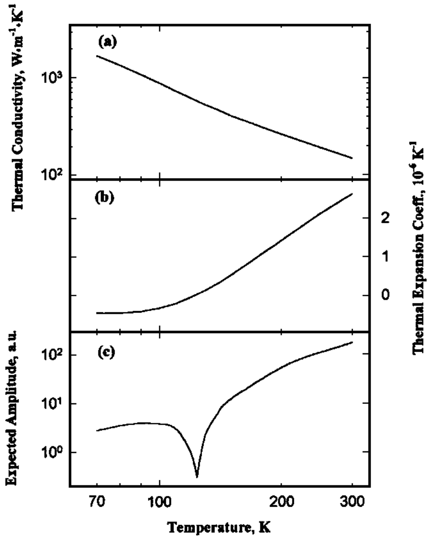

Fig. 4. (a) The thermal conductivity, (b) thermal expansion coefficient, and (c) expected signal for the pure Si sample.

3. RESULTS AND DISCUSSION

Figure 3 shows the signal of the sample G2 at room temperature, and the solid line represents the best-fitting result. The thermal diffusivity obtained from the phase was $0.29 \pm 0.01\ \text{cm}^2 \cdot \text{s}^{-1}$. This result is reliable since the pure GaAs crystals have an α of $0.31 \pm 0.02\ \text{cm}^2 \cdot \text{s}^{-1}$ at 300 K [14]. In Fig. 3 at $r = 0$, the center of the surface displacement (heated region), there is no slope of the surface displacement, and therefore, the probe beam is not deflected and there is no signal at this position. The data for $r < 0$ are not shown in Fig. 3 and the signal has a mirror image in the amplitude and phase except that the phase is shifted by 180° due to the change in the slope of the surface displacement at $r = 0$. Since the phase of the signal does not have a stable value in the range $|r| < a$, data for $r > a$ were used for the fitting procedure.

The amplitude of the signal decreases for $r > a$ as r increases. The main factor of the decay rate is thermal diffusion length, that is, faster decays correspond to lower thermal diffusion lengths. Figure 5 shows the effect of the thermal diffusion length on the phase of the signal in Si and sample G4. The phase of the signal relative to the mechanical chopper also varies with the thermal diffusion length. A lower chopping frequency corresponds to a greater thermal diffusion length and a lower variation of phase difference for r. At the same frequency, 150 Hz, the shape of the phase reflects the difference of thermal diffusivity between the two samples, including the effects

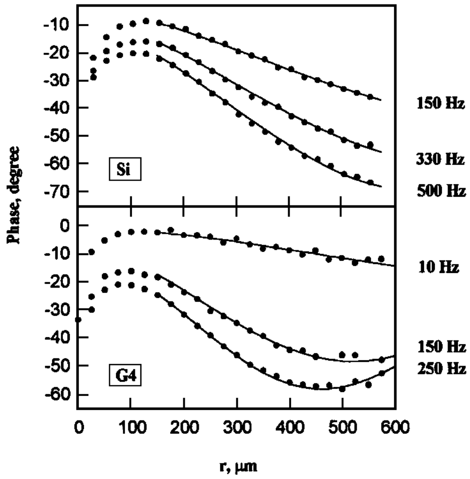

Fig. 5. The effect of the thermal diffusion length on the phase of the signal in Si and GaAs (G4).

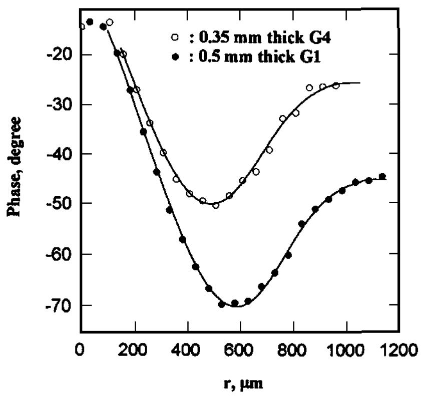

Fig. 6. The effect of the sample thickness. The solid line indicates the fitting result, and the two samples have similar thermal diffusivities.

of thickness as well as absorption. It is found that with an increase in the relative beam position *r*, the phase difference increases up to a certain position, then starts to decrease (Figs. 3 and 5). For a relative beam position greater than a few thermal diffusion lengths, the phase does have an asymptotic value, which is due to the combination of the effects of thermal diffusion length, optical absorption coefficient, and thickness of the sample. In the case of thermally thinner samples, reflection of the thermal wave from the rear surface becomes important, and the asymptotic region occurs closer to the center of the displacement, as shown in Fig. 6.

The thermal diffusivity was also measured in the air environment. Heating of the sample by the pump laser beam also heats the air layer adjacent to the sample surface, and the refractive index varies with the temperature rise. As a result, the air layer acts as an optical lens, and a probe beam is deflected at a wider angle by this thermal lens than it is in the vacuum state. The thermal lens effect decreases with distance from the heated region, which leads to a faster decay or a lower thermal diffusion length; that is, the thermal lens effect leads to the lower thermal diffusivity. For all samples, the measured results have values about 15% lower than those recommended in the literature. A theoretical model for the thermal lens effect has been investigated [5]. However, since this was not our primary interest, we have only briefly considered a qualitative analysis for the lower measurement values.

The effect of doping on thermal conductivity is related mainly to phonon scattering by impurities and carriers, etc., and is negligible at room temperature [15]. Indeed, we obtained results equal to the literature values for all samples; that is, doped samples had thermal conductivities similar to those of pure samples (the error between samples was about 5%). The thermal diffusivity can be obtained from the phase of the signal below room temperature. However, with a drop in temperature, the signal amplitude becomes weak due to the increase in thermal conductivity and the decrease in the thermal expansion coefficient. In general, it is known that phase is more unstable than amplitude in the signal of a lock-in amplifier, when the amplitude of the signal is weak. Therefore, the measurement of thermal diffusivity from the phase of the signal is difficult at low temperature, and the lower limit was about 200 K in this work (not shown). The thermal conductivity can be obtained from the maximum amplitude of the signal with the condition that $a \ll L_{\mathrm{th}}$ at low temperature. Figure 7 shows the maximum amplitude and phase of the signal and the measured thermal conductivity of Si. The solid line shows the expected signal (a) and the thermal conductivity (c) of the high-purity Si. Signal b shows that the phase is shifted by about 180° due to the change of the sign of the thermal expansion coefficient. Figure 7c shows the decrease in thermal conductivity at low temperatures even if the error bars are rather large. Figure 8 shows the measured thermal conductivity of GaAs. One can

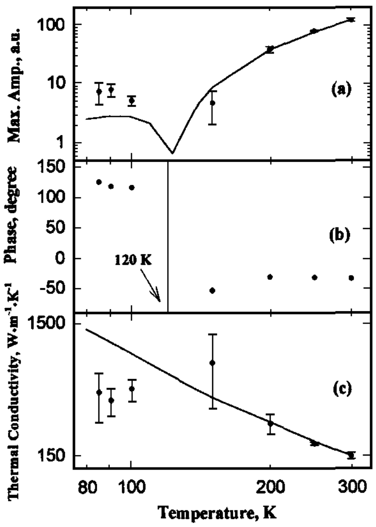

Fig. 7. (a) The maximum amplitude of the signal, (b) phase of the signal, and (c) thermal conductivity as a function of temperature for Si.

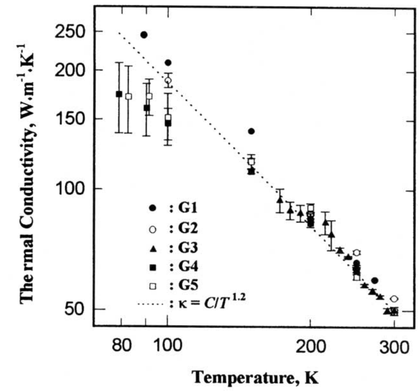

Fig. 8. Thermal conductivity as a function of temperature for GaAs samples.

see an obvious difference between semiinsulating materials and doped materials. In Fig. 8, the dashed line represents an empirical formula pointed out by Jordan [16] when the temperature T is above 77 K. Parameter C depends on the doping level. This formula has an error of about 20% and gives only limited information.

The absence of electronic effects brings a considerable simplification to the analysis of thermal conductivity data. Such is the case for insulating crystals and semiconductors having negligible concentrations of donors or acceptors. With some materials, group IV and III–V semiconductors, it is reasonable to expect that their purity and crystalline perfection are so high that only boundary scattering and three-phonon processes will be effective in giving rise to thermal resistance [17]. For more heavily doped semiconductors it will be necessary to allow for electronic (or hole) heat conduction, as well as scattering of phonons by electrons, holes, neutral donors, and neutral acceptors. Actual heat conduction by free carriers is nearly always relatively small and can be separated from the lattice heat conduction. For the PDT the electronic effects in the signal influence the thermal conductivity results. With the restriction of the experimental temperature range to 80 to 300 K, the thermal conductivity decreases due to three-phonon scattering (that is, the Umklapp process) as the temperature increases. In the case of doped samples, the thermal conductivity is lower than for semiinsulating samples at low temperatures, as shown in Fig. 8. This is due to phonon scattering by impurities and carriers, etc. According to the literature [13, 14], samples with 1×10^{18}-cm^{-3} donors or

3×10^{18}-cm^{-3} acceptors (i.e., p-type samples with acceptor concentrations three times higher than those of n-type samples) have very similar thermal conductivities at temperatures above 77 K for GaAs. In this work, sample G4 and sample G5 belong to this case and had similar values.

In conclusion, it was verified that the thermal conductivity decreases (due to three-phonon scattering) as the temperature increases, and an increase in doping concentration leads to a decrease in thermal conductivity at low temperatures. The thermal conductivity of semiconductors is measured by the application of the well-known photothermal displacement technique without in-depth theoretical considerations for free carriers, and the experimental results obtained on samples of different types and doping concentrations are consistent with the theoretical predictions.

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