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Photoacoustic characterization of the thermal properties of a semiconductor-glass two-layer system

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The photoacoustic technique is used to investigate the thermal properties of a two-layer system, of variable thickness, consisting of a semiconductor polycrystalline thin film and glass. It is shown that the thermal diffusivity and thermal conductivity are completely determined based upon the effective sample model proposed by Mansanares *et al.* [Phys. Rev. B **42**, 4477 (1990)].

Two-layer systems in semiconductors are the most widely used, starting from the simple systems of a semiconductor grown on a substrate to complex heterostructures for making advanced electronic devices. Given the wide applications of these systems, it is important to know their behavior under heating; in other words, it is important to know the thermal parameters, such as thermal diffusivity, thermal conductivity, and specific heat of the composed system.[1] CdTe is one of the most promising materials in high-efficiency solar cell fabrication,[2] such as $Cd_xHg_{1-x}Te$ infrared detectors substrata,[3] quantum wells, etc. In the case of a single-layer CdTe we have reported the thermal properties elsewhere.[4]

In this paper we report, using the photoacoustic technique, the study of the thermal properties of one of the most typical configurations in semiconductor physics: the glass semiconductor. The semiconductor used was CdTe.

The photoacoustic (PA) effect has been proved by several authors[5–7] to be a simple and reliable nondestructive technique for measuring the thermal properties of solid samples. The PA effect looks directly at the heat generated in a sample, due to nonradiative deexcitation processes, following the absorption of light. In the conventional experimental arrangement, a sample is enclosed in an air-tight cell and exposed to a chopped light beam. As a result of periodic heating of the sample, the pressure in the cell oscillates at the chopping frequency and can be detected by a sensitive microphone coupled to the cell. The resulting signal depends not only on the amount of heat generated in the sample (and, hence, on the optical absorption coefficient and the light-into-heat conversion efficiency of the sample) but also on how the heat diffuses through the sample. The quantity which measures the rate of diffusion in a material is the thermal diffusivity α. Apart from its own intrinsic importance, its determination gives the value of the thermal conductivity k, if the density ρ and the thermal capacity c at constant pressure are known, since

$$\alpha = k/\rho c \ . \tag{1}$$

Consider the two-layer system shown schematically in Fig. 1(a) consisting of material 1 of thickness l_1 and of material 2 with thickness l_2, both having the same cross section. Let $l = l_1 + l_2$ denote the total sample thickness, α_i the thermal diffusivity, ρ_i the density, c_i the specific heat at constant pressure, and k_i the thermal conductivity of material i ($i = 1,2$).

From the analogy between thermal and electrical resistances widely used in heat-transfer problems,[8] the effective thermal resistance R of this series two-layer sys-

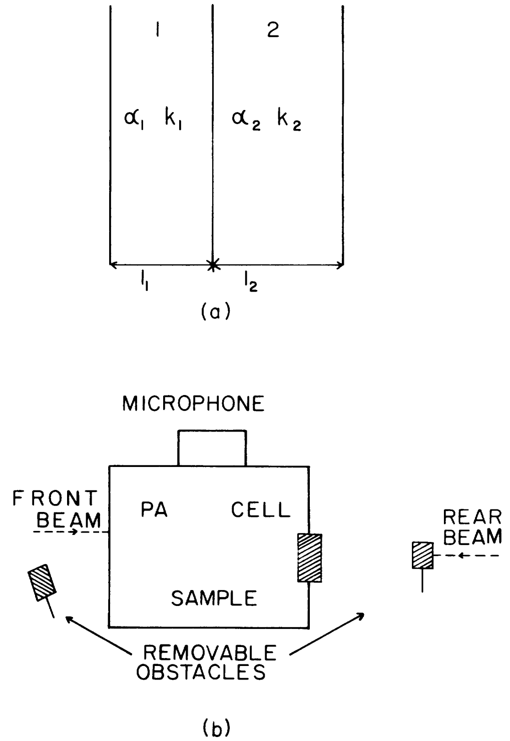

FIG. 1. (a) Geometry for the two-layer system. (b) Schematic arrangement for the two-beam photoacoustic measurement of the thermal diffusivity.

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tem may be written as

$$R=\frac{l}{k}=R_1+R_2\ , \tag{2}$$

where k is the effective thermal conductivity of the composite sample, and $R_i=l_i/k_i$ is the thermal resistance of layer i. From Eq. (2) one gets

$$k=lk_1k_2/(l_1k_2+l_2k_1)\ . \tag{3}$$

On the other hand, the effective heat capacity $V\rho c$ of the composite sample is given by

$$V\rho c=V_1\rho_1c_1+V_2\rho_2c_2\ . \tag{4}$$

Substituting Eqs. (3) and (4) into Eq. (1) and performing some straightforward algebra, we can write the thermal diffusivity of the two-layer system as

$$\alpha=\frac{1}{x^2/\alpha_1+(1-x)^2/\alpha_2+x(1-x)[\lambda/\alpha_1+1/\lambda\alpha_2]}\ , \tag{5}$$

where $x=l_1/l$ measures the thickness fraction of material 1 in the composite sample, and $\lambda=k_1/k_2$. Equation (5) implies that the thermal diffusivity of the composite sample depends not only on the thermal diffusivity of its constituent materials but also on the ratio of their thermal conductivities, λ.

In Ref. 9 the usefulness of a single modulation frequency method for measuring the thermal diffusivity of solid samples was demonstrated. The method consists of measuring the relative phase lag $\Delta\Phi=\Phi_F-\Phi_R$ at a single modulation frequency, between the rear-surface illumination (R) and the front-surface illumination (F), as follows. Using the thermal diffusion model of Rosencwaig and Gersho[10] for the production of the PA signal, the ratio of the signal amplitude S_F/S_R and the phase lag for front and rear-surface illumination, $\Delta\phi$, are given by[7] [cf. Fig. 1(b)]

$$\frac{S_F}{S_R}=\frac{I_F}{I_R}[\cosh^2(la_s)-\sin^2(la_s)]^{1/2} \tag{6}$$

and

$$\tan(\Delta\phi)=\tanh(la_s)\tan(la_s)\ , \tag{7}$$

where I_F and I_R are the absorbed light intensity for front and rear illumination, l is the sample thickness, and $a_s=(\pi f/\alpha)^{1/2}$ is the sample thermal diffusion coefficient. In arriving at Eqs. (6) and (7) we have assumed that the sample is optically opaque to the incident light (i.e., all the incident light is absorbed at the surface) and that the heat flux into the surrounding air is negligible. Considering the fact that the phase-lag method is independent of power calibrations and surface conditions, renders it a more precise technique than the amplitude ratio method, and we apply it in our measurements.

Polycrystalline CdTe films, containing hole carriers in the range $10^{14}-10^{15}$ cm^{-3} nonintentionally doped, and having 55 μm thickness were grown on glass slides of 0.1 cm thickness by using the close-spaced vapor-transport technique, as described elsewhere.[11] The source and substrate temperatures during the growth process were 650 °C and 550 °C, respectively. CdTe powder 6N from CERAC Inc. was used as material source. The substrate source distance was 0.3 cm. Ar gas from LINDE of purity 99.999% was employed at 1.5 Torr as control pressure. Growth time of 5 min was used. Under these growth conditions we obtained an average grain size of 15 μm.[12] In order to get different ratios $x=l_1/(l_1+l_2)$ to be used in Eq. (5) for a more appropriate fitting we fixed the thickness of the 55-μm semiconductor, whereas we polished the glass for having variable thickness l_2. In this way, the total thickness (and, consequently the parameter x) of our two-layer system could be varied. Blue light (488 nm) from a spectra physics laser at 150 mW, after being mechanically chopped, was divided by a beam splitter and the resulting beams were directed to opposite sides of the photoacoustic cell [cf. Fig. 1(b)]. The photoacoustic cell was a conventional brass cell in which a 0.25-in. condenser microphone (Bruel and Kjaer) was mounted in one of its walls. The sample, in the shape of a 1×1 cm^2 square, was flush against the back wall of the cell which has a 4-mm-diameter hole through which the rear beam passes. In the case of CdTe, without glass, it was around 0.3×0.3 cm^2 and a cell with a hole of 2.5 mm was used. In order to guarantee the opaqueness condition implicit in Eq. (6), we put a thin circular foil (3 mm in diameter, 15 μm in width) of aluminum attached with thermal paste on the glass side. As is evident from Eq. (7), the procedure to determine α is to substitute the experimental values of $\Delta\phi$ in Eq. (7) and solve it for $z=la_s$. Knowing z, the thermal diffusivity is readily given by $\alpha=\pi f(l/z)^2$. The thermal diffusivity of each constituent was measured separately, still using the PA phase-lag method, and yielded $\alpha_1=0.0033$ cm^2/s and $\alpha_2=0.055$ cm^2/s for plate glass and polycrystalline CdTe, respectively. All the experiments were carried out in the 10–50 Hz modulation frequency range. In Table I we summarize the measured values of the thermal diffusivity for our samples. In Fig. 2, we show the PA phase-lag data for α as a function of x. The solid line in Fig. 2 represents the result of the best fit of the data to Eq. (5) leaving α_1, α_2, and λ as adjustable parameters. The data-fitting procedure yielded the following values for the adjustable parameters: $\alpha_1=0.0038$ cm^2/s, $\alpha_2=0.055$ cm^2/s, and $\lambda=0.075$.

TABLE I. Values of the thermal diffusivity α in cm^2/s for the plate-glass–polycrystalline CdTe system of variable thickness, as a function of the ratio x (the thickness of the CdTe layer divided by the total system thickness).

$x=l_1/(l_1+l_2)$	α (cm^2/s)
0	0.055
0.31	0.011
0.69	0.0059
0.76	0.0055
0.79	0.0047
0.833	0.0044
1.0	0.0033

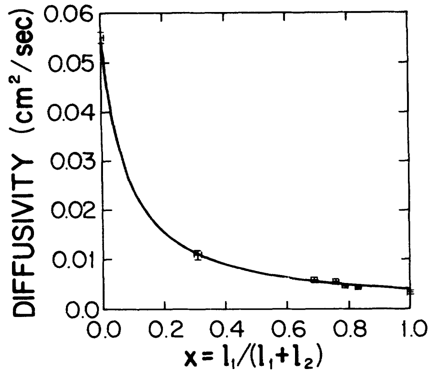

FIG. 2. Effective thermal diffusivity of the CdTe-glass system as a function of the parameter x. The solid line represents the best fit of the data to Eq. (5) of the text.

The thermal conductivities were measured using the temperature-rise method under continuous white-light illumination.[13] The samples were in the shape of 1×1 cm^2 squares (in the case of CdTe without glass 0.3×0.3 cm^2) and had both surfaces sprayed with black paint. In this way, we ensured not only a good light-absorbing surface, but also the same heat transfer coefficient for each surface. The samples were adiabatically suspended in a Dewar which was subsequently vacuum sealed. Under these conditions the main heat-loss mechanism is the loss by radiation. The Dewar had an entrance optical glass window through which the continuous white-light beam was focused onto one of the sample surfaces. On the opposite surface we attached a thermocouple to the sample using thermal paste; in this way, the temperature evolution of the back surface could be monitored as a function of time. Care has been taken to prevent the heating light from reaching the thermocouple. Since the sample thicknesses, typically 300 μm, were much smaller than their widths, the simple, one-dimensional heat diffusion equation with radiation losses could be applied to our experiment.

In solving the one-dimensional heat diffusion equation it can be shown that the long-term time evolution (i.e., for times greater than the heat diffusion time $\cong l^2/\alpha$) of the back surface temperature rise is given by

$$\Delta T=\frac{I_0\alpha\tau}{lk}(1-e^{-t/\tau})\ , \qquad (8)$$

where I_0 is the intensity of the incident light beam, and $\tau=lk/2\alpha H$ is the rising time. Here $H=4\sigma T_0^3$ where σ is the Stefan-Boltzman constant and T_0 is the ambient temperature and H is the radiation heat-transfer coefficient. In Fig. 3(a) we show the back surface temperature rise of a 220-μm-thick plate-glass sample as a function of time. Also shown in Fig. 3(a) is the temperature cooling of the back surface when the illumination is switched off. The solid line in Fig. 3(a) represents the results of the best fit of the experimental data to Eq. (8). From the adjusted value of τ we have then calculated the thermal conductivity for the plate-glass sample; the value obtained within a 10% error was $k_1=0.003$ W/cm K. In Fig. 3(b) we show our results for the temperature evolution of the back surface of a CdTe polycrystalline sample. Repeating the same data-fitting procedure as above, we got, for the thermal conductivity of the CdTe sample, $k_2=0.0363$ W/cm K. From these values of k_1 and k_2 one obtains $\lambda=0.09\pm0.018$ which is in good agreement with the value of $\lambda=0.075$ obtained from the effective thermal diffusivity data fitting.

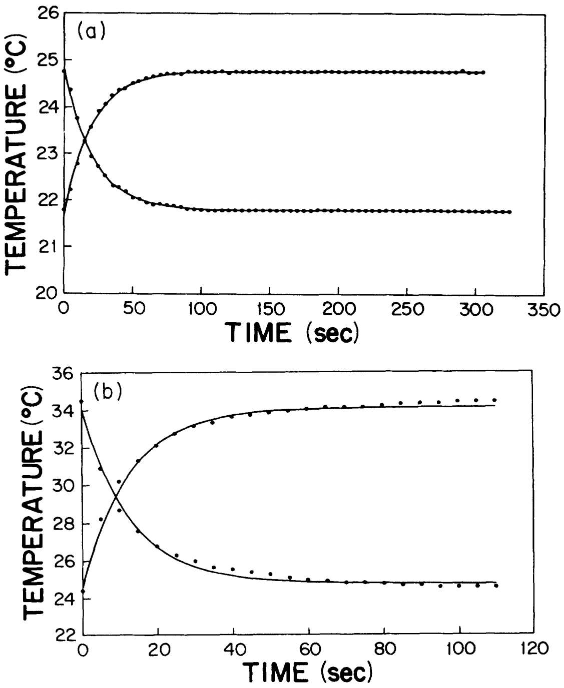

FIG. 3. (a) Back-surface temperature evolution of a 220-μm-thick black-coated plate glass as a function of time under continuous white-light illumination. The solid line represents the best fit of the data to Eq. (8) of the text. (b) Back-surface temperature evolution of the 300-μm polycrystalline CdTe sample, as a function of time under continuous white-light illumination. The solid line represents the best fit of the data to Eq. (8) of the text.

In summary, in this paper we have discussed the photoacoustic measurements of the thermal properties of the CdTe on glass system. The measurements were carried out using the phase-lag method. The data were interpreted in terms of the effective thermal resistance for a series of two-layer system. The data are adequately described by the model, even though our system is formed by two qualitatively very different materials, glass and CdTe. An important application of our technique is in the nondestructive characterization of the thermal properties of semiconductors deposited on different substrata. We can use the substratum as a standard material, then by varying the standard layer thickness we can generate a set of data for α as a function of $x=l_1/(l_1+l_2)$ (i.e., the ratio of the test sample thickness to the total system thickness).

These data are then best fitted to Eq. (5) from which the values of the thermal diffusivities as well as λ, the ratio of the thermal conductivities of the component are obtained. From the value of λ, the thermal conductivity of the test sample is readily found.

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[1] M. A. Afromowitz, J. Appl. Phys. **44**, 1292 (1973).
[2] J. Britt and C. Ferekides, Appl. Phys. Lett. **62**, 2851 (1993).
[3] R. N. Bicknell, R. W. Yanka, N. C. Giles, J. F. Schetzina, T. C. Magee, C. Leung, and H. Kawayoshi, Appl. Phys. Lett. **44**, 313 (1984).
[4] J. J. Alvarado, O. Zelaya-Angel, F. Sánchez-Sinencio, G. Torres-Delgado, H. Vargas, and J. González-Hernández, J. Appl. Phys. (to be published).
[5] R. T. Suimm, Appl. Phys. Lett. **42**, 955 (1983).
[6] H. Vargas and L. C. M. Miranda, Phys. Rep. **161**, 43 (1988).
[7] O. Pessoa, C. L. Cesar, N. A. Patel, H. Vargas, C. C. Ghizoni, and L. C. M. Miranda, J. Appl. Phys. **59**, 1316 (1986).
[8] W. Karplus and W. W. Soroka, *Analog Methods* (McGraw-Hill, New York, 1959).
[9] A. M. Mansanares, A. C. Bento, H. Vargas, N. F. Leite, and L. C. M. Miranda, Phys. Rev. B **42**, 4477 (1990).
[10] Rosencwaig and Gersho, J. Appl. Phys. **47**, 64 (1975).
[11] C. Menezes, C. Fortmann, and J. Casey, J. Electrochem. Soc. **132**, 709 (1985).
[12] O. Zelaya, F. Sánchez-Sinencio, J. G. Mendoza-Alvarez, M. H. Farias, L. Cota-Araiza, and G. Hirata-Flores, J. Appl. Phys. **63**, 410 (1988).
[13] I. Hatta, Rev. Sci. Instrum. **50**, 292 (1978).