The interferometric mirage effect method: The determination of the thermal diffusivity of CdMnTe

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Abstract

A Michelson interferometer was used as a precise detector in the Mirage effect configuration in order to determine the thermal diffusivity of the diluted magnetic semiconductor Cd\textsubscript{1-x}Mn\textsubscript{x}Te, in the concentration range 0<x<0.6 at room temperature. This zinc-blende ternary alloy exhibits an almost linear behavior of the thermal diffusivity as a function of Mn concentration. This trend is similar to that of the energy gap against Mn concentration, which increases linearly as the nominal \( x \) value increases. The latter result was tested by electrolytic electroreflectance measurements.

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1. Introduction

The importance of simple thermal diffusivity measurements is crucial in the use of several semiconducting alloys, in particular those with potential applications in solid state lasers based on quantum wells and superlattices.

The commonly experimental methods employed to determine the thermal diffusivity in materials are of three different types, depending on whether the measured heat flow is stationary [1], (conventional method), transient [2] or periodic [3].

The periodic method was introduced in 1863 by Angstrom [3] and it involves periodical heating of one end of a rod-shaped sample and measuring the resulting temperature at another point of the rod. The phase lag between the thermal oscillation at the two points gives a precise determination of the thermal diffusivity.

One of the experimental methods that use the periodic heating of the sample is the photoacoustic technique [4]. It has the advantage of requiring small quantities of the material to be analyzed, permitting the determination of the thermal diffusivity in samples obtained from localized regions of the material. However, this requirement is not convenient if the sample should not be cut into thin disks.

The aim of this work is to determine the viability of using the Mirage effect with an alternative sensor: A Michelson interferometer is used instead of a position-dependent photodetector. The technique has been proved in Cd\textsubscript{1-x}Zn\textsubscript{x}Te [5] and in TiO\textsubscript{2} samples [6], resulting in thermal diffusivity values in accordance with those accepted. In this work, semiconductor semimagnetic alloys of Cd\textsubscript{1-x}Mn\textsubscript{x}Te have been studied by using this alternative detection technique. We have selected such materials because of their peculiar magneto-optical behavior, which has been reported during the last two decades [7,8] and also exhibits nonlinear optical properties intensively studied in recent years, as thermal self-focusing and thermally induced optical bistability [7].

2. Experimental

The crystals were grown by using the modified Bridgman method [8]. The samples were cut and polished to form slabs of thickness 0.165, 0.212, 0.392, 0.168, and 0.238 cm,
antireflection coating on the side opposite the beam-splitter coating. A 12 mm diameter with a focal length of ~12 mm diverging lens was used to spread the laser interference pattern out for easy viewing on the screen.

The excitation source consists of a 200 mW Ar laser, whose monochromatic light beam (488 nm line) is mechanically modulated with a computer-controlled shutter, and focused on the sample by conventional optics, to obtain a circular illuminated region of 3 mm diameter. The probe beam is a 1 mW He–Ne laser that propagates parallel to and near the sample surface. As photodetector a standard two-pin silicon phototransistor was used.

In the calibration of the induced changes in the temperature of the oil medium, a linear relationship between the interference fringe pattern shift and the temperature of the oil was found. Fig. 3 shows clearly this trend in the range of interest.

3. Calculation of the resulting intensity on the screen

The vibrations stemming from the splitted beam into beams S1 and S2 which are both coherent and very similar in intensity and which reach a point on the screen can be expressed as

\[ S_1 = A \exp(jwt) \quad \text{and} \quad S_2 = A \exp[jw(t - \delta)] \]  \hspace{1cm} (1)

where \( w \) is the electromagnetic wave angular frequency and \( \delta \) is the difference in optical path.

The resulting wave amplitude can be expressed as

\[ S = A[1 + \exp(-j\phi)]\exp(jwt) \]  \hspace{1cm} (2)

where

\[ \phi = 2\pi\delta/\lambda \]  \hspace{1cm} (3)

where \( \lambda \) is the wavelength.
The intensity at the phototransistor is proportional to the square of the amplitude:

\[ I = S^2 = A^2 [1 + \exp(-j\phi)][1 + \exp(j\phi)] \]  

Then,

\[ I = 2A^2 [1 + \cos 2\pi \delta/\lambda] \]  

The phototransistor is coupled to the storage unit through a series capacitor in order to reject the DC component. Thus, the signal converts to

\[ V = V_0 \sin \left( \frac{2\pi \delta}{\lambda} \right) \]  

The position of the viewing screen is adjusted so that the phototransistor is aligned at the intensity inflection point of one of the fringes in the interference pattern. In this condition, the light intensity measured by the phototransistor is almost linear as a function of the radial position on the screen, at least for small fringes shifts.

A fraction of the pumping incident light is converted into heat that dissipates through the oil medium. Then, temperature fluctuations are induced through the cell, changing the refractive index of the oil, and thus, the optical path of the probe beam.

In our experiments, the exposition time to the pumping laser is short, which causes small shifts of the diffraction pattern (a small fraction of a fringe). Then, we can consider the signal as proportional to the difference in optical path (Eq. (6)) and, consequently, to the induced change of temperature \( T \), in accordance with the calibration procedure mentioned above

\[ V \sim V_0 \frac{2\pi \delta}{\lambda} \sim T \]  

4. The temperature distribution

Referring to the geometry shown in Fig. 4, we assume that the liquid region is optically nonabsorbent and region \( p \) is the only absorbing medium. This \( p \) region has an optical absorption coefficient \( \beta(\lambda) \), and it is uniformly illuminated with a light beam of wavelength \( \lambda \) whose intensity is modulated in time at a frequency \( w \).

The sample has a thickness \( p \) and is supported by a transparent backing material of thickness \( b \). The surface dimensions along the \( yz \) plane are large compared to the width \( L \) of the incident beam. The sample absorbs the incident radiation according to Beer’s law, and is in thermal contact with the transparent fluid. The temperature of the oil layer adjacent to the sample surface presents small periodical changes due to nonradiative deexcitations in the periodically illuminated solid.

Due to the changes in the refractive index caused by the heat transfer from the absorbing solid, the laser beam probe presents variations in the optical path in a periodic way.

In the three regions shown in Fig. 4, the temperature satisfies the heat diffusion conditions

\[ \frac{\partial^2 T_i(x,t)}{\partial x^2} = \frac{1}{\alpha_i} \frac{\partial T_i(x,t)}{\partial t} \]  

\( i = a \) (fluid), \( b \) (backing), \( p \) (sample), \( \alpha_i \) (thermal diffusivity).

At the two surface contacts the temperature satisfies the following boundary conditions

\[ \frac{\partial T_a(0,t)}{\partial x} = \eta \frac{\partial T_p(-p,t)}{\partial x} = \frac{\partial T_p(0,t)}{\partial x} \]  

\[ Q(x = -p) = \eta[T_p(-p,t) - T_b(-p,t)] \]  

\[ k_p \frac{\partial T_p(-p,t)}{\partial x} = k_b \frac{\partial T_b(-p,t)}{\partial x} \]  

Fig. 4. Geometry of the heat transmission configuration.
\( \eta \) is the surface thermal conductivity at the interface between the sample and the backing material, which is defined in Ref. [11]. Assuming a perfect thermal contact, this parameter will be considered as \( \eta \to m \).

For the region defined by \( -p < x < 0 \), the sample heating rate \( Q(x,t) \) is

\[
Q(x,t) = \frac{1}{2} f_0 \beta e^{-\beta |x|} \text{Re}[1 + e^{i\omega t}]
\]

(10)

where \( \zeta \) is the quantum efficiency associated to a nonradiative process.

Let the solution of interest denoted as \( T_s(x,t) \), which describes the temperature departure from its ambient value \( T_0 \) in this region. Thus the actual temperature profile in the fluid is given by:

\[
T_s(x,t) = \text{Re}[T_{s\alpha}^\infty(x,t)] + T_{DC}(x)
\]

(11)

where \( T_{DC}(x) \) is the position-dependent stationary increase in temperature.

The temperature \( \text{ac} \) component of the solution in the fluid region is given by:

\[
T_{s\alpha}^\infty(x,t) = \frac{A}{\beta^2 - \sigma_p^2} \left\{ \frac{(f-1)(b+1)e^{\sigma_p x} - (f+1)(b-1)e^{-\sigma_p x}}{2(b-e^{-\beta x}) + (f+1)(b+1)e^{\sigma_p x} - (f-1)(b-1)e^{-\sigma_p x}} \right\} e^{\sigma_p x + i\omega t}
\]

(12)

where \( r = (1-f)(\beta/2\alpha_p) \), \( b = (a_0 \kappa_0/a_p \kappa_p) \), \( f = (a_0 \kappa_0/a_p \kappa_p) \), and \( a_0 = (\omega/2\alpha_p)^{\frac{11}{2}} \).

In the limit case of optically opaque and thermally thick samples we have \( \beta \omega \gg 1 \) and \( \exp(-\sigma_p) \ll 1 \); in this case the magnitude of the temperature change is

\[
|\theta_s(x,t)| = \frac{\zeta \beta f_0}{\kappa_0 \sqrt{2\alpha_p} + \kappa_p \sqrt{2\alpha_p}} \frac{e^{-\sqrt{2\alpha_p} x}}{\sqrt{1 + (\beta + 2)^2/\sqrt{2\alpha_p}^2}}
\]

(13)

In this approximation, the temperature change of the fluid region is independent of the sample thickness.

5. Results and discussion

The shift of the interference pattern (maximum phototransistor voltage) as a function of the square root of the modulation frequency for the five samples is shown in Fig. 5.

In Fig. 5, the vertical values of the curve corresponding to sample with \( x=0.25 \) has been multiplied by a factor 2, only for presentation purposes.

The continuous lines are the fittings of Eq. (13) to the experimental data. The results of the thermal diffusivity measurements are shown in Fig. 6.

The trend is almost linear, as that of the energy gap obtained by electroreflectance. This behavior is compatible with that of the effective thermal diffusivity we would expect for a homogeneous binary mixture of CdTe and MnTe. According to the theory of binary mixtures [12], the effective thermal diffusivity may be written, in the first approximation, as

\[
\alpha_{\text{eff}} = [(1-x)\rho_1 \kappa_1 + x\rho_2 \kappa_2]/[(1-x)\rho_1 \kappa_1 + x\rho_2 \kappa_2]
\]

(14)

where \( \rho \), \( c \), is the specific heat capacity and \( k \) is the thermal conductivity.

Here, the subscripts 1 and 2 refer to CdTe and MnTe, respectively.

Eq. (14) fits reasonably well with the following fitting parameters: \( k_1 = 0.04 \text{ W cm}^{-1} \text{ K}^{-1} \), \( k_2 = 0.10 \text{ W cm}^{-1} \text{ K}^{-1} \), \( \rho_1 \kappa_1 = 2.6 \text{ J K}^{-1} \text{ cm}^{-3} \), and \( \rho_2 \kappa_2 = 1.3 \text{ J K}^{-1} \text{ cm}^{-3} \).
It is worth to obtain $\alpha_{\text{eff}}$ when $x = 0$ using Eq. (14). The value obtained is $\alpha = 0.0154 \text{ cm}^2/\text{s}$, which corresponds to CdTe. This value is in accordance with that obtained in a previous work [5] for this compound, which was $0.0159 \pm 0.02 \text{ cm}^2/\text{s}$.

6. Conclusions

In this work we proved the use of interferometric means as a precise detection instrument when the Mirage effect technique is used for the diffusivity determination of solid samples. In particular the diffusivity for the ternary compound Cd$_{1-x}$Mn$_x$Te was determined, and the obtained values are reasonable according to the case $x = 0$. The behavior of the thermal diffusivity as a function of the Mn concentration corresponds to that of binary mixtures.

A more complete model taking into account the 3D character of the incident excitation laser and possible thermal contact effects at the oil/sample and sample/backing interfaces is under progress.

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