Optical properties of polycrystalline $Cd_{1-x}Mn_xTe$

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Bulk polycrystalline cadmium manganese telluride, $Cd_{1-x}Mn_xTe$, was manufactured in several compositions by a synthesis process. The structure of the obtained compounds was the characteristic zinc-blende polycrystalline pattern being the grain size 100 ± 20 nm. These materials are manufactured to replace single-crystal compounds in some magneto-optical devices. The cut-off wavelength and the Verdet constant are the same as the single-crystals with identical composition. A polarized laser beam, after having passed through a sample of 0.76 mm thickness, was depolarized less than 2.5%, and 90% of its energy was spread into a 2° cone. Scattering of light is produced because of the polycrystalline structure of these compounds. Some scattering diagrams, due to the diffraction and Mie scattering in the polycrystalline grains are shown.

I. INTRODUCTION

Diluted magnetic semiconductors, also referred as semimagnetic semiconductors, have attracted a lot of interest both because their fundamental properties and applications.[1] Single crystal cadmium manganese telluride, $Cd_{1-x}Mn_xTe$ (CdMnTe), is one of the most interesting members of this class of materials and it is perhaps the most studied. CdMnTe exhibit large Faraday rotation and moderate optical attenuation at visible and near infrared wavelengths.[2] Owing to their large Verdet constant, single crystals of $Cd_{1-x}Mn_xTe$ have been widely used in magneto-optical devices.[3–6]

Mn solves in the zinc-blende structure of CdTe up to $x=0.77$, being a fraction of Cd substituted by the transition magnetic ion Mn^{2+}.[7] It has been shown that Cd and Mn cations occupy the same sublattice in CdMnTe.[8] The large magneto-optic phenomena observed in CdMnTe, which are two orders of magnitude higher than observed in normal semiconductors, are due to the presence of the paramagnetic ion Mn^{2+} which gives rise to localized magnetic moments. These ions interact with conduction-band electrons and valence-band holes via a strong spin exchange interaction. In fact, in CdMnTe the giant Faraday rotation at room temperature is caused by a large exciton Zeeman splitting due to the extremely large g factor observed in a magnetic field.[2] Therefore, the magneto-optical properties are seen to be highly dependent upon Mn concentration range. The gap energies and the lattice constants vary linearly throughout this composition range.[9]

Since the first report about CdMnTe was published in 1978, its optical, magneto-optical and structural properties have been studied in more than 500 publications,[10] most of them about single crystals. However, there are some about polycrystalline CdMnTe.[11–13] In two of these papers the authors report the formation of CdMnTe films and study several fundamental optical properties as optical absorption and refractive index,[11] and photovoltage spectra.[12] In the other is reported the fabrication of bulk polycrystalline CdMnTe and the measurement of diffuse reflectance and the electrical conductivity are reported.[13]

In order to use polycrystalline CdMnTe in optical sensors, we have measured some of its optical properties: cutoff wavelength (λ_c), the depolarization of a light beam after being transmitted through the material and how it scatters a parallel light beam. Other fundamental properties, as transmittance and the Verdet constant dispersion have already been reported by the authors in a previous paper.[14] As this compound scatters light, its transmittance is lower than its single crystal counterpart. However, polycrystalline CdMnTe is suitable to be used in Faraday effect sensors because its Verdet constant dispersion is the same as measured in CdMnTe crystals of identical composition. Some devices which are based on this compound have already been developed.[15,16]

In this paper we present the most relevant optical properties, from the point of view of Faraday effect sensors, of bulk polycrystalline $Cd_{1-x}Mn_xTe$. This compound has been manufactured by us in a simple and reproducible way. The values obtained justify the use of this material in magneto-optical sensors.

II. EXPERIMENT

Polycrystalline CdMnTe was synthesized in several compositions ($x=0.37$, 0.40, 0.45, 0.50) by melting all the elements in a fused quartz tube held under a vacuum of $\leqslant 10^{-6}$ Torr. The tube was heated with a three stages thermal cycle (Fig. 1). In the first stage the temperature was higher than the melting point of the Cd (320.9 °C). In the second stage the melting point of the Te (449.5 °C) was

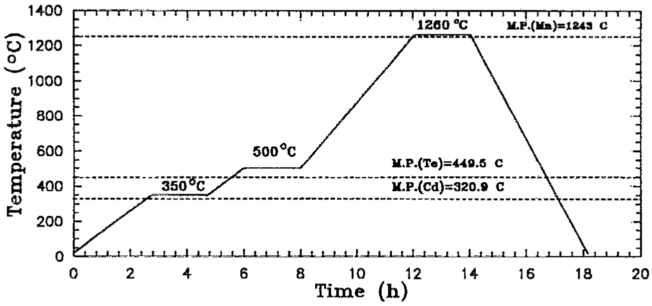

FIG. 1. Thermal cycle employed to manufacture the polycrystalline $Cd_{1-x}Mn_xTe$.

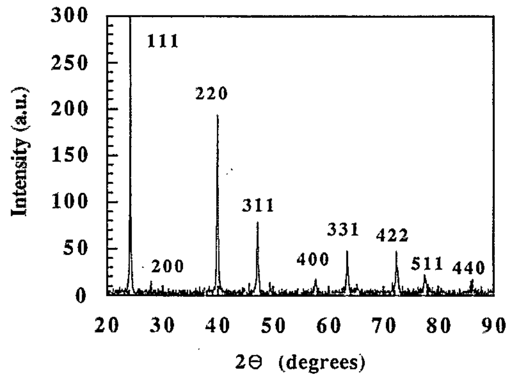

FIG. 2. X-ray diagram of polycrystalline $Cd_{0.55}Mn_{0.45}Te$. The diffraction peaks correspond to those of the zinc-blende.

also overshot, in this way the Cd and the Te reacted to form CdTe. In the last stage the Mn was melted to allow its diffusion throughout the CdTe displacing some Cd ions from its position. When the temperature was down to room temperature, bulk polycrystalline $Cd_{1-x}Mn_xTe$ was obtained.

In order to check the structure of the resulting compound, a x-ray diffraction pattern was determined by means of a D5000 automatic Siemens Diffractometer, with a Cu-anode x-ray generator and a Ni filter. The characteristic zinc-blende diagram was obtained for all compositions.

The cut-off wavelength was determined with an UV-VIS spectrophotometer (Perkin-Elmer Lambda 2). In order to measure the grade of light depolarization, the Stokes parameters of a light beam before and after being transmitted through a sample of this compound were measured. A plate of 0.76 mm of thickness of $Cd_{0.55}Mn_{0.45}Te$ was employed. From the Stokes parameters (I, Q, U, and V) we obtained the polarization ellipse parameters a, ψ, and χ.[17] I, Q, U, and V where determined with a linearly polarized He-Ne (500:1), a beamsplitter (to obtain a reference beam), a $\lambda/4$ waveplate for 632.8 nm and a Glan-Thompsom prism polarizer. A two channel optical power-meter (Hewlett–Packard 8152A) was used to measure the single beam/reference beam ratio.

The optical characterization of the polycrystalline CdMnTe was completed with the measurement of the effects in the transmission of a collimated laser beam through a plate of this material. Scattering of the beam after passing through a sample of thickness $L=0.76$ mm of CdMnTe ($x=0.45$) was observed. The laser beam profile was determined with and without the plate, with a CCD camera (Pulnix DC-37) connected to a digital oscilloscope (Hewlett–Packard 54502A). The camera was positioned at about 15 cm from the sample. The angular distribution of the beam intensity was also measured. For this purpose a goniometrical arrangement was used with the sample placed in the center of rotation of an arm where a detector of 1 mm diam was positioned. Four measurements where done at several sample-detector distances: 40, 66, 100, and 150 mm.

III. RESULTS AND DISCUSSION

The x-ray diagram for $x=0.45$ is shown in Fig. 2. The interatomic distance for all the compositions, calculated from a fit of the position of the diffraction peaks from 20° to 90°, is represented in Fig. 3; CdTe interatomic distances taken from the JCPDS cards are also shown. By measuring the full width at half-maximum (FWHM) height of the diffraction maxima, a grain size of $\sim$60 nm is determined. In order to confirm this value, the grain size was measured more accurately by scanning-electron microscope photography to lie in the range 100 ± 20 nm (Fig. 4). As we shall see later, this result is very relevant with respect to the appearance of the Faraday effect and its excitonic origin.

The cut-off wavelength λ_c is defined as the wavelength at which the transmittance gets down to 0. This magnitude is the edge of the absorption band produced by the excitonic absorption levels in the crystal. Being the Faraday effect in a material due to the absorption bands, the Verdet constant is increased as wavelength trends to λ_c. λ_c is directly related with the composition (x) of Mn in the semiconductor, and it allows to select the transparency range depending upon the application that is intended. According to our experimental results of λ_c at room temperature

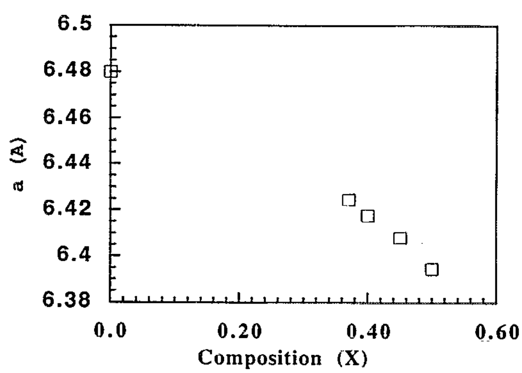

FIG. 3. Interatomic distance for all the composition of polycrystalline $Cd_{1-x}Mn_xTe$ manufactured. CdTe distance taken from JCPDS tables is also represented.

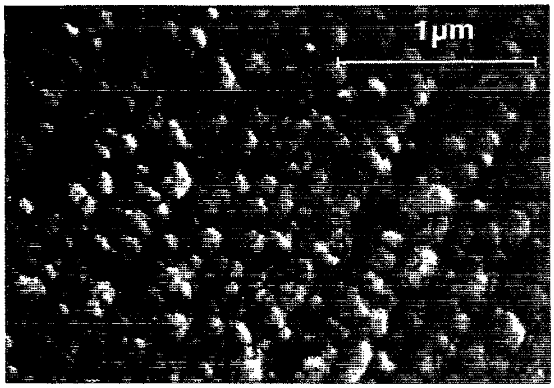

FIG. 4. Scanning-electron microscope photography of $Cd_{0.55}Mn_{0.45}Te$. The grain size lie in the range of 100±20 nm.

(Fig. 5) we obtained the following relation for the absorption edge energy

$$E_a=\frac{hc}{\lambda_c}=1.47+1.33x. \qquad (1)$$

This expression does not differ significantly from others obtained for single crystals.[4,6]

This absorption band, equivalent to the one appearing in single crystals, justifies the existence of excitons in polycrystalline CdMnTe, in agreement with the experimental results working out the equality of the Verdet constant in both type of materials.[2,14] The existence of excitons in polycrystals will be related with the grain size; in our case it seems that 100 nm is enough for the appearance of the excitons.

Polycrystalline $Cd_{1-x}Mn_xTe$ has been manufactured to be used in Faraday effect sensors, therefore it is very important to measure how it depolarizes a linearly polarized light beam. As the material scatters light there must be a rate of depolarized light. We made three measurements of Stokes parameters on a plate of polycrystalline $Cd_{0.55}Mn_{0.45}Te$. The relative Stokes parameters ($I_r=l$, $Q_r=Q/I$, $U_r=U/I$, $V_r=V/I$) of the incident laser beam without the beamsplitter and the metallic support for the polycrystalline plate are shown in Table I. The highly polarized input laser beam ($y/x=43$) decreases its polarization grade after passing through the beamsplitter and the metallic support ($y/x=20$). This is the initial polarization state for our measurements. From Table I we can conclude that (a) the percentage of polarized light (I_p/I) diminish between 1.2% and 2.6%. (b) The ellipse of polarization does not rotate appreciably (ψ), and (c) The relation among the polarization ellipse semiaxis ($\tan\chi$) decrease from values of about 20 to values of about 9. Therefore, the change in the light polarization state is very small and therefore, polycrystalline CdMnTe can be used in Faraday effect sensors.

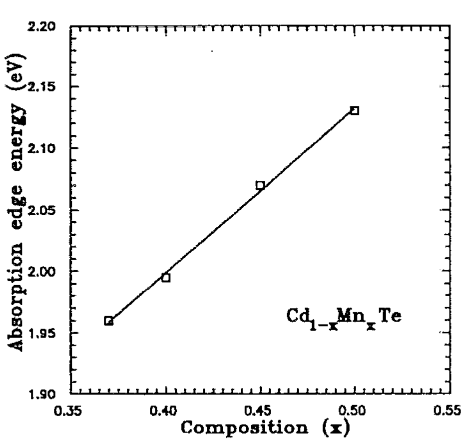

FIG. 5. Absorption edge energy measured at room temperature for all the manufactured compositions of $Cd_{1-x}Mn_xTe$.

The laser beam profile images supplied by the CCD camera, are shown in Figs. 6(a) and 6(b). Some TV -lines measured with the oscilloscope are displayed in Figs. 7(a) and 7(b). The images shown in Figs. 6(b) and 7(b) are possibly due to two different phenomena related with the grain structure of the polycrystal: diffraction and Mie scattering. As we saw at the beginning of this paper, the grain size is ~100 nm. Light is propagated without any obstacle across the interior of the grain, but in the grain boundary, due to the high density of interband defects, it is absorbed and highly dispersed. In this sense each grain can be considered as an aperture, and the polycrystal as a serial of adjacent planes, each one constituted by a random array of apertures. In fact, Fig. 6(b) resembles to the Fraunhoffer diffraction pattern for a random array of N circular apertures.[17] The maxima which appear in the beam profiles of the Fig. 7(b) can be considered as corresponding to the diffraction pattern of the grains. These maxima can be observed because the condition for the Fraunhoffer diffraction is verified: *Observation distance* $\gg$ (*aperture size*)$^2/\lambda$.[18] The aperture size is $\approx 1/6$ of the employed wavelength (632.8 nm) and therefore the distance at which the diffraction diagram has been observed (15 cm) verifies the former relation.

The other phenomena that we have mentioned is Mie scattering. This is a scattering effect due to the partial penetration of the light into a conducting material, which produces different scattering effects. The parameter that defines the Mie scattering for spherical particles is

$$q=\frac{2\pi\lambda}{a}, \qquad (2)$$

where a is the radius of the sphere. In our case $q\approx 0.50$, that corresponds to a forward pattern of Mie scattering. This result agrees with our observations in which the laser beam after being transmitted across the plate is dispersed in all directions but holds its tendency to forward propagation.

The output angular diagram show in all cases that 90% of the energy of the laser beam is spread into a 2° cone after passing through the sample. Therefore, the amount of energy lost in a plate of polycrystalline CdMnTe of ~1 mm thickness is negligible for sensor applications.

TABLE I. Experimental results of the measurement of the relative Stokes parameters for a sample of 0.76 mm of thickness of $Cd_{0.55}Mn_{0.45}Te$. The measurements were done with and without the plate of CdMnTe.

		Laser + beam splitter + sample holder					
	Laser +CdMnTe	1st measurement		2nd measurement		3rd measurement	
			+CdMnTe		+CdMnTe		+CdMnTe
I_r	1	1	1	1	1	1	1
Q_r	−0.998	−0.995	−0.975	−0.994	−0.984	−0.995	−0.972
U_r	2.49×10^{-2}	4.45×10^{-2}	-3.7×10^{-2}	3.1×10^{-4}	-2.85×10^{-2}	-4.95×10^{-2}	-5.63×10^{-2}
V_r	4.9×10^{-2}	7.87×10^{-2}	0.149	0.109	2.9×10^{-2}	9.38×10^{-2}	3.71×10^{-2}
ψ	−0.7°	−1.3°	−1.1°	0°	−0.8°	1.4°	1.7°
$y/x=\tan\chi$	42.8	19.7	8.9	11.3	10.9	21	8.6
$I_p/I(\%)$	100%	99.9%	98.7%	100%	98.5%	100%	97.4%

IV. CONCLUSIONS

In this paper we have presented some of the fundamental properties of the polycrystalline compounds $Cd_{1-x}Mn_xTe$. Four different compositions of these materials have been developed by the authors to replace CdMnTe single crystals in some magneto-optical devices. These compounds are polycrystals with the zinc-blende structure. The grain size was determined by scanning electron microscope photography to lie in the range 100±20 nm.

The absorption edge, the depolarization of the light and the scattering of a collimated laser beam have been measured. With the obtained results we can deduce the following. (1) These compounds have the same absorption band that single crystals of the same composition, (2) the modifications introduced into the polarization state of a light beam are quite negligible for most based Faraday effect sensors, and (3) there is a spread of a collimated beam after passing through the sample; this could be mainly due to diffractive effects and Mie scattering. With the previous conclusions and others that indicates the same Verdet constant than single crystals and an acceptable transmittance (>20%),[14] we conclude that these materi-

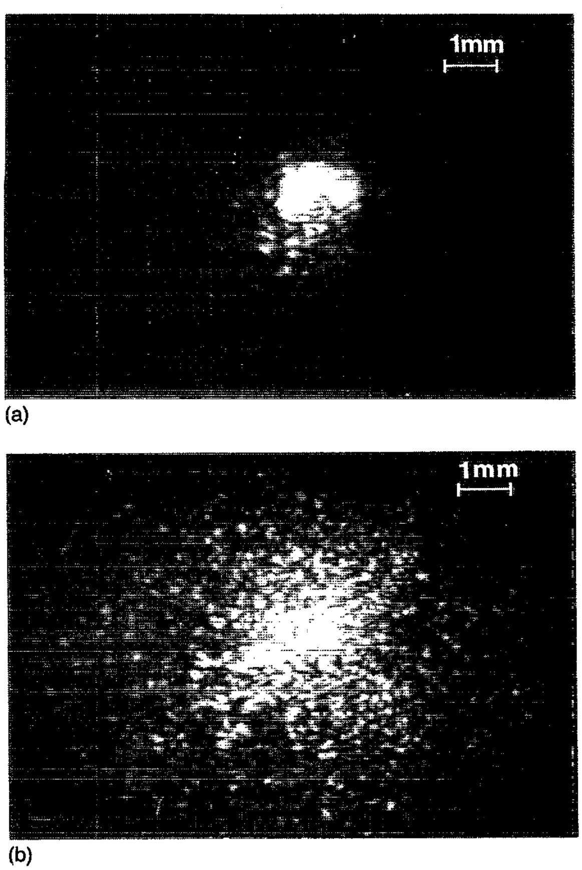

FIG. 6. CCD photographies of a laser beam profile (a) before and (b) after having passed through a sample of 0.76 mm of thickness of $Cd_{0.55}Mn_{0.45}Te$. The image was taken at about 15 cm from the sample.

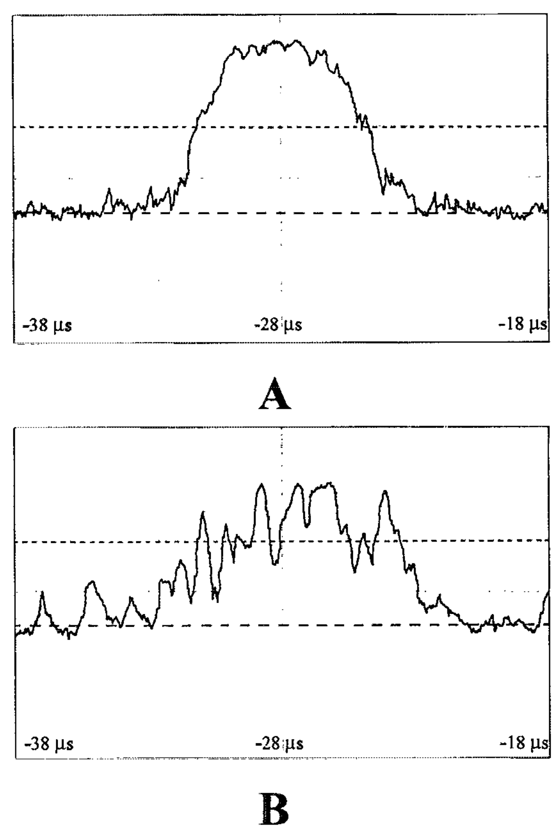

FIG. 7. TV lines taken from the photographies shown in Fig. 6.

als are quite suitable to be employed as sensing element in Faraday effect sensors. The replacement of the single crystal by these polycrystals have some economical and practical advantages.

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