Rare Metal Materials and Engineering
Volume 38, Issue 6, June 2009
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2009, 38(6): 0951–0954.

ARTICLE

Faraday Rotation in $Cd_{1-x}Mn_xTe$ Single Crystals

Luan Lijun [1,2], Jie Wanqi[1]

[1]*Northwestern Polytechnical University, Xi'an 710072, China;* [2]*Chang'an University, Xi'an 710061, China*

Abstract: The Faraday rotation of $Cd_{0.8}Mn_{0.2}Te$ and $Cd_{0.9}Mn_{0.1}Te$ single crystals grown in our laboratory was measured at room temperature. We analyzed our Faraday rotation data in terms of a modified multi-oscillator model by improving the value of the band gap at L point in the Brillouin zone (E_1) and obtained the values of the gap at the Γ point in the Brillouin zone (E_0) for $Cd_{0.8}Mn_{0.2}Te$ and $Cd_{0.9}Mn_{0.1}Te$ from the fitting to 1.667 eV and 1.804 eV, respectively. The values of E_0 are more close to the calculated ones than nearly all of the previous studies.

Key words: faraday rotation; $Cd_{1-x}Mn_xTe$; modified multi-oscillator model; vertical bridgman method

There have been considerable interests in the properties of the semi-magnetic semiconductors cadmium manganese tellurium ($Cd_{1-x}Mn_xTe$ or CMT), particularly in its large magneto-optical interactions[1-2]. Its potential applications stem from the tunability of the energy gap by means of both varying Mn content and applying magnetic field. In the last two decades, many efforts have been done to specify the regularity of the Faraday rotation in CMT and other related Ⅱ-Ⅵ compound semi-magnetic semiconductors[3-5]. The Faraday rotation as a function of magnetic ion concentration (x), temperature and magnetic field in detail has been investigated. The research findings indicate that the Faraday rotation results from the magnetic-field induced energy splitting including the conventional Zeeman splitting and the exchange-induced splitting near the band gap. Here the exchange is referred to sp-d exchange interaction between the magnetic moments of magnetic ions and the free-carrier spins[1]. Upon analyzing the Faraday rotation data, the key is the application of the Kramers-Kronig relations to the refractive index for a given material. The fundamental models analyzing the Faraday rotation are single-oscillator and multi-oscillator models. The single-oscillator model is a simplified method, which expresses the refractive index involving an interband excitonic transition at the fundamental gap E_0. But, its working conditions are limited by the magnetic ion concentrations for $x \geqslant 0.05$ and the very strong excitonic effects at the absorption edge, etc. Multi-oscillator model is first put forward by Pinkhtin and Yas'kov for fitting the refractive index of semiconductors with diamond and zinc-blende structures[6]. Their refractive index expression includes the fundamental-gap contribution at the Γ point, as well as the contributions from interband transitions at the L and X points of the Brillouin zone. Later, Jiménez-González and Aggarwal developed the multi-oscillator model for the Faraday rotation using that analytical expression for the refractive index suggested by Pinkhtin and Yas'kov[7]. This Faraday rotation multi-oscillator model is proven to be used in more wide-ranges of magnetic ion concentrations and temperatures for undoped semi-magnetic semiconductors. However, Upon analyzing the Faraday rotation data of CMT (x up to 0.268), they did not take the value of the E_1 gap for the Mn concentrations under study but used the CdTe E_1 value. One would expect that the exact use for the value of the E_1 was certainly a valuable improvement.

For this purpose, we investigated the room-temperature Faraday rotation of $Cd_{0.8}Mn_{0.2}Te$ and $Cd_{0.9}Mn_{0.1}Te$ single crystals grown in our laboratory by a self-designed experimental setup. In this study, we fit the data of the Faraday rotation in terms of a modified multi-oscillator model.

1 Theories

Faraday rotation results from the difference in phase velocity of left (σ^-) and right (σ^+) circularly polarized light propagating through a medium along B. The phase difference $\Delta\varphi$ is given by

Received date: December 12, 2008
Foundation item: Key Project of National Natural Science Foundation of China (50336040)
Biography: Luan Lijun, Candidate for Ph. D., College of Material Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, P. R. China, Tel: 0086-29-88486065, E-mail: nmllj050@chd.edu.cn

$$\Delta\varphi = \frac{\omega l}{c}(n_- - n_+) \quad (1)$$

where ω is the angular frequency of the light, c is the speed of light in vacuum, l is the distance of the light traveling in the medium, and $n_\pm$ is the refractive indices for the two circular polarizations $\hat{\sigma}_\pm$. Then, Faraday rotation angle θ_F is given by the well known expression

$$\theta_F = \frac{El}{2\eta c}(n_- - n_+) \quad (2)$$

where E is the photon energy and η is Planck's constant divided by 2π.

In zero-field, according to Kramers-Kronig relations, Pikhtin and Yas'kov derived a multi-oscillator model for refractive index n [6]

$$n^2 = 1 + \frac{0.7}{\pi\sqrt{E_0}}\ln\frac{{E_1}^2 - E^2}{{E_0}^2 - E^2} + \frac{F_1}{{E_1}^2 - E^2} + \frac{F_2}{{E_2}^2 - E^2} + \frac{F_{TO}}{{E_{TO}}^2 - E^2} \quad (3)$$

where E_0, E_1 and E_2 are the band gaps at or near the Γ, L and X points in the Brillouin zone, respectively. E_{TO} is the energy of the zone-center TO phonons. F_1, F_2 and F_{TO} are the corresponding oscillator strengths for E_1, E_2 and E_{TO} transitions.

This expression for n is obtained from the application of the Kramers-Kronig relations to the imaginary part of the dielectric constant $\varepsilon_2(\omega)$ in the limit of low absorption. For photon energies lower than E_0 the details of the $\varepsilon_2(\omega)$ dispersion are not important and we need to keep the major factors[6]. It is possible then to model $\varepsilon_2(\omega)$ as a multi-oscillator model, which contain a constant between E_0 and E_1 followed by two undamped oscillators at E_1 and E_2 as shown in Fig.1. Between E_0 and E_1 we take constant amplitude A of 0.7 ${E_0}^{-1/2}$ which is the average of $\varepsilon_2(\omega)$[6].

For small ΔE_i the difference $(n_- - n_+)$ can be expressed as

$$(n_- - n_+) \approx \sum_i \frac{\partial n}{\partial E_i}\Delta E_i \quad (4)$$

where ΔE_i is the difference between the transition energies for σ^- and σ^+ polarizations in the presence of a magnetic field.

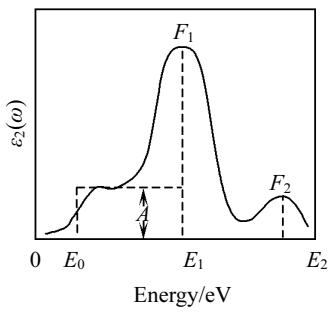

Fig.1 General tendency of the imaginary part of complex dielectric constant to the variation of the energy for a typical zinc-blende semiconductor. The dot lines denote the model used to approximate ε_2

For $E < E_0$, the splittings at the E_2 and E_{TO} energies were neglected. This is a reasonable approximation since; first, for the wavelengths of interest, the dispersion from E_2 and E_{TO} is relatively small; secondly, including of these transitions would increase the number of fitting parameters.

Taking partial derivatives for Eq. (3) with respect to E_0 and E_1, we get

$$\frac{\partial n}{\partial E_0} = -\frac{0.7}{n\pi {E_0}^{3/2}}\left[\frac{1}{4}\ln\left(\frac{{E_1}^2 - E^2}{{E_0}^2 - E^2}\right) + \frac{{E_0}^2}{{E_0}^2 - E^2}\right] \quad (5)$$

$$\frac{\partial n}{\partial E_1} = -\frac{E_1}{n\left({E_1}^2 - E^2\right)^2}\left[F_1 - \frac{0.7}{\pi\sqrt{E_0}}\left({E_1}^2 - E^2\right)\right] \quad (6)$$

Using Eqs. (2), (4), (5), (6), we obtain

$$\theta_F = -\frac{El}{2\eta c}\left(\frac{\partial n}{\partial E_0}\Delta E_0 + \frac{\partial n}{\partial E_1}\Delta E_1\right) \quad (7)$$

We use analytical expressions for ΔE_0 and ΔE_1 derived by Jiménez-González and Aggarwal[7],

$$\Delta E_0 = \left[\frac{xN_0(\alpha-\beta)g_{Mn}\mu_B S(S+1)}{3k_B T\left(1 - \frac{\Theta_0}{T}x\right)} + \Delta {E_0}^{(Z)}\right]B \quad (8)$$

$$\Delta E_1 = \left[\frac{1}{26}\frac{xN_0(\alpha-\beta)g_{Mn}\mu_B S(S+1)}{3k_B T\left(1 - \frac{\Theta_0}{T}x\right)} + g_1\mu_B\right]B \quad (9)$$

where x is the Mn^{2+} ions concentration, N_0 is the number of unit cells per unit volume, α and β are exchange constants for the conduction- and valence-band electrons, respectively, g_{Mn} = 2 is the Landé g factor of the Mn^{2+} ions, μ_B is the Bohr magneton, S =5/2 is the spin of the Mn^{2+} ions, k_B is the Boltzmann constant, Θ_0 is a constant of CMT having values of –470[8], and $N_0(\alpha-\beta)$=1.10 eV and $\Delta {\varepsilon_0}^{(Z)}$ =–8.0×10^{-5} eV/T for CMT[9-10], g_1 is the effective interband g factor at the L point used here as a fitting parameter.

The total fitting formula of interband Faraday rotation of CMT is then obtained by inserting Eqs. (5), (6), (8) and (9) into Eq. (7).

2 Experimental

$Cd_{0.8}Mn_{0.2}Te$ and $Cd_{0.9}Mn_{0.1}Te$ single crystals were grown by using Vertical Bridgman (VB) method in our laboratory[11]. In order to reduce intended impurities, high-purity raw materials of Cd (99.99999%), Mn (99.999%) and Te (99.99999%) were used to synthesize the CMT compound. The Mn concentration was determined by the designed composition of the ingots for x=0.1, 0.2. The as-growth ingots were cut predominantly into the wafers of (111) orientations, which were mechanically polished, and then etched with 5% Br-methanol

solution for 1 min. The final thicknesses of the wafers were 1 mm.

Faraday rotation measurements were made at room temperature using a self-designed experimental setup. A bromine-halogen lamp was used as the radiation source, and a triple grating monochromator (WGD-300A) with high resolution was used to yield monochromatic light. After passing through a focusing lens and a polarizer, the monochromatic light became parallel polarizing monochromatic light and subsequently propagated through the sample placed in the electromagnetic field up to 0.2 T, and eventually the rotation angle of emergent light was read from the analyzer plate with the sensitivity of 0.05°.

3 Results and Discussions

Fig.2 shows the room-temperature Faraday rotation spectra of CMT (x=0.1 and 0.2). As seen that the CMT single crystals exhibit an intensive Faraday effect （Verdet constant about 10^3deg/T·cm）. Particularly when the photon energy is close to the band gap, the Verdet constant increases rapidly. A comparison of the Faraday rotation spectra between $Cd_{0.9}Mn_{0.1}Te$ and $Cd_{0.8}Mn_{0.2}Te$ shows that the Faraday effect increases when Mn concentration increases. This is because that when Mn concentration is low, every Mn spinning can be seen as a single. In this case, when Mn content increases, the exchange interaction between localized Mn^{2+} ions and band electrons strikingly intensifies. Our data are in agreement with the measured values by Chen and Wang[12].

The data of the Faraday rotation are fitted to the modified multi-oscillator model expressed by Eq. (7). With respect to the parameter of F_1, we use the x = 0 (CdTe) value similar to Ref.[7], where F_1 = 64.375[6]. However, in regard to the parameter of E_1, we do not use the CdTe E_1 value of 3.5 eV [6], but take the value of the E_1 gap for the Mn concentrations under study. The E_1 values of $Cd_{0.9}Mn_{0.1}Te$ and $Cd_{0.8}Mn_{0.2}Te$ are 3.32 and 3.34 eV, respectively, which are obtained by the empirical formula E_1=3.311+0.063x+0.358x^2 put forward by Becla et al according to the measured reflectance spectra of CMT[13]. Finally, we leave with only two fitting parameters E_0 and g_1, which are shown in Table 1.The difference of the E_1 value between the CMT and the CdTe somewhat makes the fitting results an improvement.

As seen from Tab.1 that E_0 = 1.667 eV for $Cd_{0.9}Mn_{0.1}Te$ and E_0 = 1.804 eV for $Cd_{0.8}Mn_{0.2}Te$, respectively. These values are more close to the calculated values based on Liu et al [14] than nearly all of the previous studies. At the same time, they are also reasonably close to the measured values and the fitted values by Nikitin et al [15]. From Tab.1 we also see that g_1 = 4.76 for $Cd_{0.9}Mn_{0.1}Te$ and g_1 = 5.56 for $Cd_{0.8}Mn_{0.2}Te$, they are somewhat greater than the fitted values in Ref.[15]. Not only in this study but also in Ref.[15], the values of g_1 for $Cd_{0.8}Mn_{0.2}Te$ is greater than that for $Cd_{0.9}Mn_{0.1}Te$, which indicates that Zeeman splitting at the L point of the Brillouinzone increases with increasing of manganese concentration.

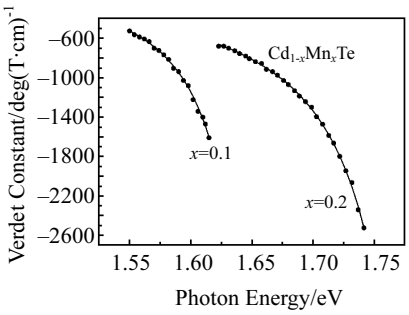

Fig.2 Room-temperature Faraday rotation of CMT for x=0.1, 0.2 as a function of photon energy. The dots are experiment results, and the solid lines indicate the best fit to the modified multi-oscillator model

Table 1 Fitting parameters for the Faraday rotation of CMT at room temperature

Material	E_0^a /eV	E_0^b/eV	E_0^c/eV	E_0^d/eV	$-g_1^a$	$-g_1^d$
$Cd_{0.9}Mn_{0.1}Te$	1.667	1.665	1.660	1.650	4.76	3.5
$Cd_{0.8}Mn_{0.2}Te$	1.804	1.802	1.791	1.780	5.56	4.8

[a] Fitted values from our experimental results; [b] calculated values according to formula: $E_g(x) = E_g(0) + x\Delta E_g$ in Ref. [14]; [c] measured values in Ref. [15]; [d] fitted values in Ref. [15]

4 Summary

Faraday rotation of $Cd_{0.8}Mn_{0.2}Te$ and $Cd_{0.9}Mn_{0.1}Te$ single crystals grown in our laboratory has been measured at room temperature by using a self-designed experimental setup. We analyze our Faraday rotation data in terms of a modified multi -oscillator model. We take the value of the E_1 gap for the Mn concentrations under study, using 3.34 eV for $Cd_{0.8}Mn_{0.2}Te$ and 3.32 eV for $Cd_{0.9}Mn_{0.1}Te$, and do not use the CdTe E_1 value of 3.5 eV. This modification makes the fitting results a valuable improvement.

References

1 Gaj J A, Galazka R R, Nawrocki M. *Solid State Commun*[J], 1978, 25(3): 193
2 Gaj J A, Ginter J, Galazka R R. *Phys Suatus Solidi B*[J], 1978, 89(2): 655
3 Bartholomew D U, Furdyna J K, Ramdas A K. *Phys Rev B*[J], 1986, 34(10): 6943
4 Nikitin P I, Savchuk A I. *Usp Fiz Nauk*[J], 1990, 160(11): 167
5 Butler M A. *Solid State Commun*[J], 1987, 62 (1): 45
6 Pikhtin A N, Yas'kov A D. *Fiz Tekh Poluprovodn*[J], 1978, 12(6): 1047
7 Jiménez-González H J, Aggarwal R L, Becla P. *Phys Rev B*[J], 1992 , 45(24): 14011
8 Spalek J, Lewicki A, Tarnawski Z *et al*. *Phys Rev B*[J], 1986,

33(5): 3407
9 Aggarwal R L, Jasperson S N, Becal P *et al*. *Phys Rev B*[J], 1985, 32(8): 5132
10 Gaj J A, Planel R, Fishman G. *Solid State Commun*[J], 1979, 29(5): 435
11 Zhang J J, Jie W Q, Wang T *et al*. *Materials Research Bulletin*[J], 2008, 43(5-6): 1239
12 Chen C J, Wang X Z, Liu J Z *et al*. *Acta Scientiarum Naturalium Universitatis Pekinensis*[J], 1992, 28(1): 101
13 Becla P, Kaiser D, Giles N C *et al*. *J Appl Phys*[J], 1987, 62(4): 1352
14 Liu Y H, Zhang LS. *Progress in Physics*[J], 1994, 14(1): 82
15 Nikitin P I, Savchuk A I. *Sov Phys Usp*[J], 1990, 33(11): 974

单晶体 $Cd_{1-x}Mn_xTe$ 中的法拉第旋转

栾丽君[1,2]，介万奇[1]
(1. 西北工业大学，陕西 西安 710072)
(2. 长安大学，陕西 西安 710061)

摘　要：室温下测量了本实验室生长的 $Cd_{0.8}Mn_{0.2}Te$ 和 $Cd_{0.9}Mn_{0.1}Te$ 单晶体的法拉第旋转谱。通过提高布里渊区中心 L 点的能隙值（E_1）改进了法拉第旋转的多振子模型。用改进的模型拟合实验结果，得到 $Cd_{0.8}Mn_{0.2}Te$ 和 $Cd_{0.9}Mn_{0.1}Te$ 单晶体布里渊区中心 Γ 点的能隙值（E_0）分别为 1.804 eV 和 1.667 eV。该 E_0 值比以往任何研究都更接近于计算值。

关键词：法拉第旋转；$Cd_{1-x}Mn_xTe$；改进的多振子模型；垂直布里奇曼法

作者简介：栾丽君，女，1976 年生，博士生，西北工业大学材料学院，陕西 西安 710072，电话：029-88486065，E-mail: nmllj050@chd.edu.cn