WAVELENGTH AND TEMPERATURE DEPENDENCE OF THE FARADAY EFFECT IN Cd(1 − x)Mn(x)Te

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The wavelength dependence of the Faraday effect at fixed temperature and the temperature dependence at fixed wavelength have been measured in Cd(0.55)Mn(0.45)Te. These results can be explained quite well using a simple exciton model and the known temperature dependence of the magnetic susceptibility and exciton energy.

INTRODUCTION

ONE OF THE UNIQUE features of the semimagnetic semiconductors is the unusually large Faraday effect that they exhibit [1]. Since the original observations, the large Faraday effect has been attributed to exciton effects even though no careful comparison between theory and experiment had been made. This behavior is different from most III–V and II–VI compounds where the contribution from excitons is generally considered important only very close to the exciton energy [2]. In this letter we examine the wavelength and temperature dependence of the Faraday effect and find that indeed a simple exciton model provides a quantitative description of the observed behavior.

EXPERIMENTAL

The temperature dependent measurements were made using a He–Ne laser (633 nm) in the Faraday geometry with the analyser parallel to the initial polarization. The magnetic field from a Varian magnet was adjusted to provide a null in the transmitted light intensity. The field between nulls was used to determine the Verdet constant. Typically this magnetic field difference was about 18 kOe. The temperature of the sample was controlled using a Varian nitrogen gas flow system with a thermocouple at the sample. The experimental results for Cd(0.55)Mn(0.45)Te are shown in Fig. 1.

The wavelength dependence of the Faraday effect was measured at room temperature using the various lines of a krypton laser in the conventional Faraday geometry. The analyzer was set at 45 degrees to the input polarization so that modulation of the polarization direction resulted in amplitude modulation of the beam. A time varying magnetic field was generated by placing the sample in a micro-stripline with the laser beam perpendicular to the strip. The light beam was
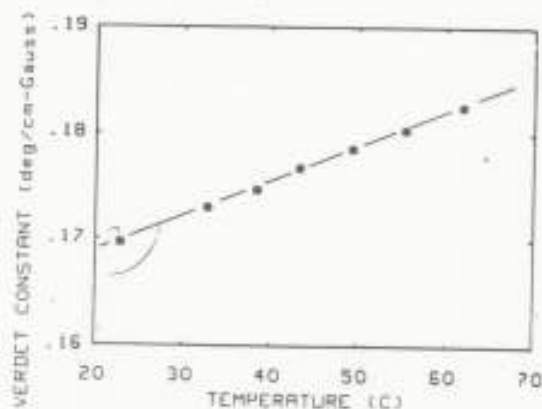

Fig. 1. Temperature dependence of the Faraday effect in Cd(0.55)Mn(0.45)Te at 633 nm.

modulated at 200 Mhz and the signal detected with a fast photodiode and a spectrum analyzer. Further details of the experimental arrangement have been published elsewhere [3].

WAVELENGTH DEPENDENCE

Recently a quantitative expression was derived for the Faraday rotation θ produced by a simple exciton [4]:

$$\theta = \frac{-19\pi}{18\lambda n} \frac{E_p^2 E_0}{(E_0^2 - E^2)^2} f\beta N_0 x \langle S_z \rangle, \tag{1}$$

where n is the index of refraction, λ is the wavelength of light in vacuum, E_p is the plasma energy, E_0 is the exciton energy, E is the photon energy, f is the oscillator strength, β is the Mn-hole exchange interaction, N_0 is the number of cations per unit volume, x is the Mn concentration, and $\langle S_z \rangle$ is the thermal average of the Mn spins along the applied field. In order to compare this expression with the experimental results,
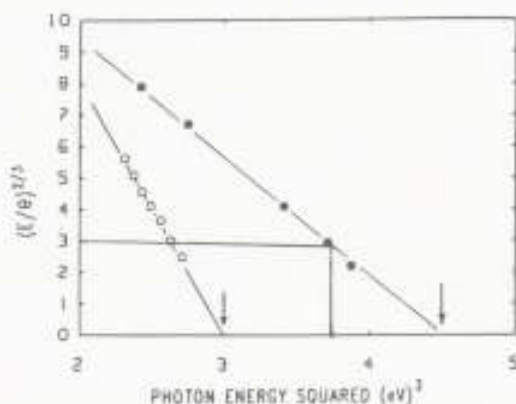
PHOTON ENERGY SQUARED (eV)^2

Fig. 2. Photon energy dependence of the Faraday effect in Cd(0.55)Mn(0.45)Te (filled circles) and Cd(0.85)Mn(0.15)Te (open circles) plotted to display the expected functional dependence for excitons. See equation (3). The 15% Mn data is from [6]. The arrows indicate the known exciton energies squared from [7, 8].

it is necessary to explicitly take into account the wavelength dependence of the index of refraction. If it is assumed that all this dependence arises from the exciton transition, then the index of refraction will have the following functional form [5]:

$$n \propto \frac{E_0 f}{(E_0^2 - E^2)^{1/2}} \qquad (2)$$

From these two equations the dependence on photon energy will be given by:

$$\frac{\theta}{E} \propto \frac{E_0 \langle S_z \rangle}{(E_0^2 - E^2)^{3/2}} \qquad (3)$$

The terms in equation (3) contain all the expected dependences on photon energy and temperature. In Fig. 2 we plot $(E/\theta)^{2/3}$ vs photon energy squared. From equation (3) this should give a linear plot with the exciton energy squared as the intercept. Indeed, our data for the 45% Mn sample and the data from [6] for a 15% Mn sample both exhibit this behaviour. Inclusion of the data from [6] is important because the 45% Mn sample has a Mn($d - d$) transition close to the exciton energy [7] which could modify the wavelength dependence of the refractive index. From the linearity of the plots it apparently does not make a significant contribution. The linear plots over a wide range of photon energies and the good agreement between the intercepts and the measured exciton energies shows that the simple exciton model provides a good description of the functional form of the Faraday effect in these materials.

A comparable fit to the data can be obtained using models of the Faraday effect which attribute the photon energy dependence to interband transitions [2]. However, these fits require a bandgap that is smaller than the measured exciton energy.

It would be possible to use equation (1) to predict the magnitude of the Faraday effect as well as the functional dependence if all of the parameters are known. However the oscillator strength of the exciton is unknown. Instead we will use equation (1) and the measured Faraday rotation to estimate the oscillator strength of the exciton. Using the Verdet constant from Fig. 1, $E_0 = 2.12$ eV, $E_p = 20$ eV [9], $\beta N_0 = 0.88$ eV [10], $n = 3.0$ and estimating $\langle S_z \rangle$ from the known susceptibility, the oscillator strength necessary to explain the Faraday rotation within the framework of the simple exciton model can be shown to be about $f = 7 \times 10^{-4}$. This value can be shown to be reasonable by estimating the corresponding optical absorption using Smakula's formula [11]. In this case no local field corrections are used since the exciton wavefunction is fairly extended and a Gaussian lineshape is assumed. Then:

$$N_0 f = n(0.97 \times 10^{16}) \alpha \Gamma, \qquad (4)$$

where α is the peak optical absorption in cm^{-1}, $\Gamma = 40$ meV is the full width at half height and the other parameters have been previously defined. This expression gives a value for α of about 10^3 cm^{-1}. Unfortunately the corresponding measurements in CdMnTe have not been made and this value can only be compared to the estimated peak absorption of 5×10^3 cm^{-1} for the exciton in CdTe [9]. The agreement is reasonable considering the uncertainties in using Smakula's formula [12] and the unknown effects of the Mn content on the exciton wavefunction.

This order of magnitude agreement shows that attributing the Faraday rotation completely to exciton effects is not unreasonable. However, the similarity in wavelength dependence for exciton and interband transition models means that a combination of both effects is not completely ruled out.

TEMPERATURE DEPENDENCE

Both exciton and interband transition models have the general functional form [1]:

$$\theta = \theta_0(E_0, \langle S_z \rangle) F(x), \qquad (5)$$

where $x = E/E_0$. All of the wavelength dependence is contained in the F function and other dependences are contained in θ_0. Without further specifying the functional form of (5) it can be shown that the temperature dependence is given by:

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Table 1. Temperature dependent Faraday rotation in Cd(1 − x)Mn(x)Te

Mn(%)	E/E_0	$\left(\dfrac{1}{\theta_0}\dfrac{\partial\theta_0}{\partial T}\right)$	$-\dfrac{1}{\theta}\dfrac{\partial\theta}{\partial E}\left(\dfrac{E}{E_0}\right)\left(\dfrac{\partial E_0}{\partial T}\right)$	$\left(\dfrac{1}{\theta}\dfrac{\partial\theta}{\partial T}\right)_{calc}$	$\left(\dfrac{1}{\theta}\dfrac{\partial\theta}{\partial T}\right)_{exp}$
45	0.925	-2.1×10^{-3}	$+5.5 \times 10^{-3}$	$+3.4 \times 10^{-3}$	$+2.0 \times 10^{-3}$
15	0.948	-3.5×10^{-3}	$+5.6 \times 10^{-3}$	$+2.1 \times 10^{-3}$	$+2.0 \times 10^{-3*}$

* From [6].

$$\frac{1}{\theta}\frac{d\theta}{dT} = \frac{1}{\theta_0}\frac{\partial\theta_0}{\partial T} - \frac{1}{\theta}\frac{\partial\theta}{\partial E}\frac{E}{E_0}\frac{\partial E_0}{\partial T} \qquad (6)$$

This expression can be easily evaluated using known experimental numbers. The second term on the right side of equation (6) comes from the temperature dependence of the exciton or interband transition and is well-known [7, 8]. The dominant contribution to the first term is believed to arise from the temperature dependence of the Mn spin susceptibility [6, 13] which is also well-known. Thus the expected temperature dependence of the Faraday effect in these materials can be estimated without specifying the origin of the effect.

The room temperature calculated values are compared with the experimental results in Table 1. In column 3 is shown the temperature dependence of θ_0. This temperature dependence is due principally to the magnetic susceptibility and thus is larger for the 15% Mn sample because the effective Curie–Weiss constant is smaller. There is also a small contribution from E_0 which has been included by assuming the simple exciton dependence from equation (3). In column 4 is shown the temperature effect due the movement of the exciton energy which is quite similar in the two samples. In column 5 these two contributions are combined to give the total calculated temperature dependence. Note that the total calculated temperature dependence is the difference between the two contributions. The last column gives the measured temperature dependence of the Faraday rotation which is to be compared to the calculated numbers in column 5. The agreement is quite good for the 15% Mn sample and fair for the 45% Mn sample. Because the total effect is the difference of the terms in columns 3 and 4, the discrepancy for the 45% Mn sample could be explained by a 20% error in column 4. This error is plausible because the laser lines used to obtain $\partial\theta/\partial E$ are quite widely spaced making it difficult to obtain an accurate value. This is not the case for the 15% Mn sample where the data points are closer together [6].

Thus the temperature dependence of the Faraday effect can be quantitatively explained by taking into account the temperature dependence of the exciton energy and the magnetic susceptibility.

CONCLUSIONS

In this paper we have shown that the Faraday rotation in Cd(1 − x)Mn(x)Te can be described by a simple exciton model. This model provides the correct functional form for the wavelength dependence and an estimate of the magnitude for the effect that is consistent with the exciton intensity in CdTe. The temperature dependence of the Faraday rotation in these alloys is quantitatively explained by considering the temperature dependence of the exciton energy and the magnetic susceptibility.

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