Temperature Dependence of Faraday Effect for $Cd_{1-x}Mn_xTe$ Films

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Abstract

A theoretical treatment of the Faraday effect has been made with respect to $Cd_{1-x}Mn_xTe$ films prepared by ionized-cluster beams. The Faraday rotation spectra are calculated,taking account of a broadening parameter Γ of exciton absorption in a nondegenerate second order perturbation theory. The calculated spectra are compared with the experimental data of $Cd_{1-x}Mn_xTe$ films. The results reveal that the thermal broadening of exciton absorption is due to the scattering of an exciton by longitudinal optical (LO) phonons.

1. Introduction

The ternary compound $Cd_{1-x}Mn_xTe$ is referred to as a semimagnetic semiconductor or diluted magnetic semiconductor, which has both properties of ordinary semiconductors and magnetic semiconductors1)~5). This new ternary compound permits one to vary the band gap, the lattice constant, and the other physical properties by controlling the manganese concentration. There has been considerably interest in the epitaxial film growth or the superlattice of $Cd_{1-x}Mn_xTe$, which were realized by molecular beam epitaxy (MBE)6~8) or atomic layer epitaxy (ALE)9), from the point of view of these ternary nature. On the other hand, much attention to this compound has been attracted for its magneto-optical properties, that is, the Faraday rotation10) due to the strong spin exchange interaction between Mn^{2+} ions and carriers. The Faraday rotation is much larger than those of the other magneto-optical materials in the wavelength shorter than 1μm, and allows the development of the magneto-optical devices, such as an optical isolator11),12).

Our preliminary experiments13)~20) indicated that the epitaxial growth of $Cd_{1-x}Mn_xTe$ films on a sapphire (0001) substrate and their multilayered structure were possible at low substrate temperatures by applying the ionized-cluster beam (ICB) deposition technique, and that many significant results could be obtained with respect to their magneto-optical properties. The films obtained in our experiments exhibited a large dispersion of the Faraday rotation near their band gap energy, depending on the manganese composition and temperature. The dispersion spectra have been theoretically investigated by taking account of the Zeeman splitting of exciton levels calculated using a nondegenerate second order perturbation theory, and the results were compared with the experimental data18~20).

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Recently, we have also reported the electro-optical properties and the effect of an electric field on the Faraday rotation for $Cd_{1-x}Mn_xTe$ films[21)~23)]. These effects strongly suggest the possibility of new optical devices using both the magneto- and electro-optical effects.

In this paper, we will report some results of theoretical investigations on the Faraday effect of $Cd_{1-x}Mn_xTe$ epitaxial films, prepared by the ionized-cluster beam (ICB) deposition technique. We calculated the wavelength dispersion of the Faraday rotation spectra based on the theoretical calculation, which has been reported in Refs. 18 and 19, by taking account of the thermal broadening of exciton absorption. The temperature dependences of the Faraday rotation calculated theoretically were compared with the experimental results of $Cd_{1-x}Mn_xTe$ films.

2. Experimental procedure

The $Cd_{1-x}Mn_xTe$ ($x=0.08\sim0.54$) epitaxial films used in measurements of Faraday rotation spectra were prepared on a sapphire (0001) substrate by applying the ionized-cluster beam deposition technique[14)]. The obtained films were grown epitaxially along the ⟨111⟩ axis perpendicular to the substrate plane, and their thicknesses were of ~ 1μm. Measurements of the Faraday rotation were performed under applying the magnetic field of 5kOe, perpendicular to the film plane, in the wavelength region from 800 to 450nm. The samples were cooled and kept at a temperature adjustable between 100 and 300K in an optical cryostat.

3. Magneto-optical effect due to excitons

The Faraday effect of $Cd_{1-x}Mn_xTe$ is caused by the large Zeeman splittings of the exciton levels due to the spin exchange interaction between $3d$-electrons of Mn^{2+} ions and carriers. The Zeeman splittings can be calculated using a nondegenerate second order perturbation theory[24)]. The splitting energies $E_i^{\pm}$ of the exciton levels and the relative oscillator strengths $W_i^{\pm}$ of magneto-optical transitions to the levels are shown in Fig.1 for the σ polarization[18),19)]. These magnetic field dependences are closely related to the magnetization M through the spin exchange interaction. $Cd_{1-x}Mn_xTe$ ($x<0.77$) exhibits a paramagnetic behavior above 40K, and its magnetic susceptibility χ is described by the Curie-Weiss law[25)]:

$$M=\chi H=\frac{C_0x}{T+\Theta x}H, \qquad (1)$$

where T is the absolute temperature. In this equation, the Curie constant C_0x and Curie temperature Θx are in proportion to the manganese composition x.

The Faraday rotation θ_F of $Cd_{1-x}Mn_xTe$ can be obtained from the difference between the refractive indices $n^{\pm}$ for the right- and left-circular polarization by

$$\theta_F\ (E)=\frac{E}{2\hbar c}\ [n^-(E)-n^+(E)]. \qquad (2)$$

In order to calculate the refractive indices $n^{\pm}$, the dispersion of the complex dielectric constants $\varepsilon^{\pm}$ for the magneto-optical transitions to exciton levels is required. We assume a classical damped oscillator model[26)],

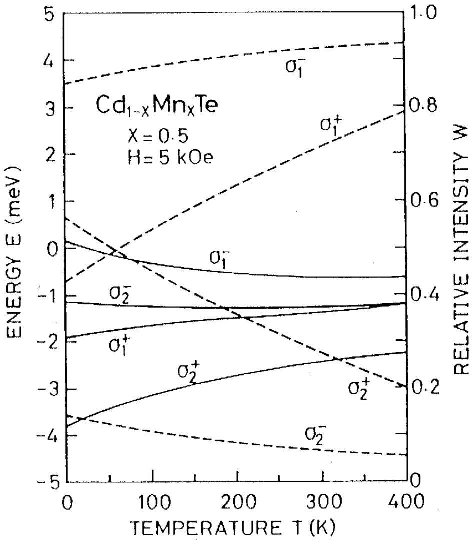

Fig. 1 Temperature dependences of the splitting energies (solid line) and relative oscillator strengths (dashed line) of the exciton states in $Cd_{1-x}Mn_xTe$.

$$\varepsilon^{\pm}(E)=\varepsilon_{\infty}+\sum_i \frac{4\pi\beta_i^{\pm}}{E_i^{\pm 2}-E^2+iE\Gamma_i}, \tag{3}$$

where $4\pi\beta_i^{\pm}$ are the oscillator strengths, which are in proportion to the relative oscillator strengths (i.e. $4\pi\ \beta_i^{\pm}=CW_i^{\pm}$, C : constant), $E_i^{\pm}$ are the energies of exciton levels, and Γ_i are temperature dependent damping constants. We neglect the contribution of the interband Faraday rotation to the dispersion of the Faraday rotation, because the Faraday rotation due to the interband effect is considerably small at the band gap energy as compared with that due to the exciton effect.

The temperature dependent damping constant Γ_i represents the energy width of the exciton absorption, and is related to the scattering of excitons by phonons and imperfections of crystals. The Γ_i is given as follows[27)~29)] :

$$\begin{aligned}\Gamma_i&=\Gamma_0+\Gamma_{ac}+\Gamma_{LO}, \\ \Gamma_0&=a_i, \\ \Gamma_{ac}&=b_iT, \\ \Gamma_{LO}&=\frac{c_i}{\exp(\hbar\omega_l/kT)-1},\end{aligned} \tag{4}$$

where Γ_0, Γ_{ac}, and Γ_{LO} denote the scattering of excitons by imperfections of crystals, acoustic phonons, and longitudinal optical (LO) phonons, respectively. In these equations, constants a_i, b_i, and c_i are taken to be independent of temperature, and $\hbar\omega_l$ is the energy of LO phonons. Below $T \simeq$ 100K, when LO phonons are frozen, acoustic phonons provide the main contribution to Γ_i, and above this temperature LO phonons interact with excitons, resulting that Γ_i increases significantly[28),29)].

Figure 2 shows the dispersion spectra of Faraday rotation for $Cd_{1-x}Mn_xTe$ at different temperatures, which were calculated from the results in Fig.1 using Eqs. (2) and (3) assuming that Γ_i was independent of temperature. The shift of the dispersion wavelength is related to the temperature dependence of the band gap. An increase in the Zeeman splittings of exciton levels of $Cd_{1-x}Mn_xTe$ with decreasing temperature,

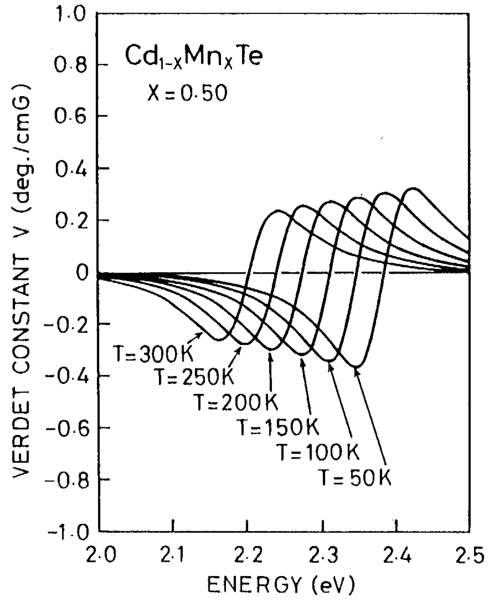

Fig. 2 Faraday rotation spectra of $Cd_{1-x}Mn_xTe$ at different temperatures without respect to the temperature dependences of Γ_i (Γ_1=93meV and Γ_2=228meV).

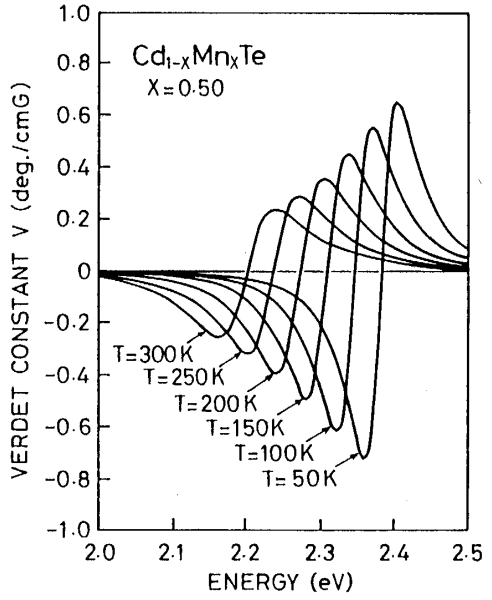

Fig. 3 Faraday rotation spectra of $Cd_{1-x}Mn_xTe$ at different temperatures by taking account of the temperature dependences of Γ_i given in Eqs. (4) (a_1=50meV, a_2=150meV, b_1=0, b_2=0, c_1=50meV, c_2=100meV, and $\hbar\omega_l$=20meV).

as shown in Fig. 1, leads to an increase in the peak height of the Faraday rotation. The increase in the peak height, however, is slight, as compared with the experimental results.

The Faraday rotation spectra of $Cd_{1-x}Mn_xTe$ were calculated by taking account of the temperature dependence of Γ_i given in Eqs. (4). Figure 3 shows the calculated results at different temperatures. As compared with the results in Fig. 2, the peak height of Faraday rotation increases markedly and the shape of the dispersion becomes sharp with decreasing temperature.

4. Experimental results and discussions

The theoretical curves of the Faraday rotation for $Cd_{1-x}Mn_xTe$ films can be fitted fairly well to the experimental results by controlling the values of Γ_i. The values of Γ_i, which are calculated as a fitting parameter, are plotted as a function of temperature in Fig.4. In this figure, the Γ_1 and Γ_2 correspond to the energy widths of exciton absorption for the allowed and forbidden transition, respectively, in the absence of a magnetic field. The width Γ_1 is narrower than Γ_2, and those values increase with an increase of temperature. In Fig.4, the solid lines indicate the theoretical curves calculated from Eqs. (4). The values of the constants in Eqs. (4) are given in Table 1, in which the contributions of acoustic phonons are neglected ($b_i=0$). For the value of the energy $\hbar\omega_l$ of LO phonons, the value (21.3meV) reported in CdTe[27], which was a parent crystal for $Cd_{1-x}Mn_xTe$, was used. Eqs. (4) describe the temperature dependences of Γ_i quite well, and it is found that the scattering of excitons by LO phonons contributes mainly to the thermal broadening of exciton absorption. The constant c_1 for the allowed transition is in good agreement with the value (48meV) reported in CdTe[27]. On the other hand, the values of a_i are one order of magnitude

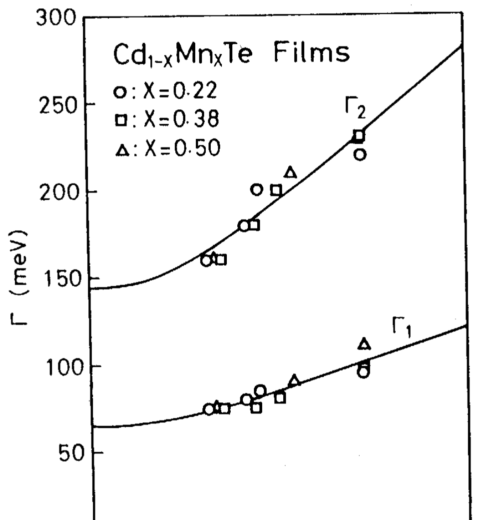

Fig. 4 Temperature dependences of Γ_i. Solid lines are the results fitted by Eqs. (4).

Table 1 Fitting parameters in Eqs. (4).

i	a_i(meV)	b_i(meV/K)	c_i(meV)	$\hbar\omega_l$(meV)
1	65.7	0	46.6	21.3[27]
2	146.0	0	114.1	21.3[27]

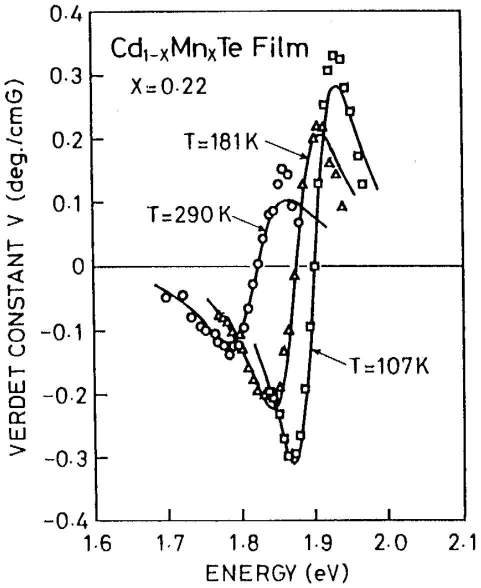

Fig. 5 Faraday rotation spectra of the $Cd_{1-x}Mn_xTe$ ($x=0.22$) film at different temperatures. Solid lines indicate the calculated spectra.

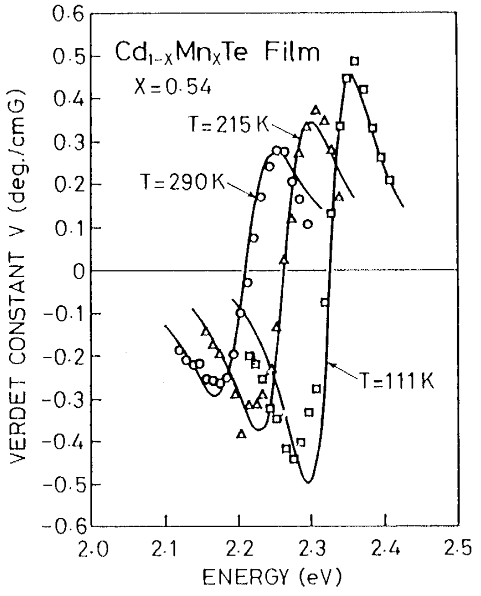

Fig. 6 Faraday rotation spectra of the $Cd_{1-x}Mn_xTe$ ($x=0.54$) film at different temperatures. Solid lines indicate the calculated spectra.

larger than those of bulk crystals of semiconductors, caused by the defects or dislocations of the films.

Figures 5 and 6 show the Faraday rotation (Verdet constant) spectra at different temperatures for $Cd_{1-x}Mn_xTe$ films with $x=0.22$ and 0.54, respectively. The dispersion of Faraday rotation is broadened with increasing temperature. In these figures, the soild lines indicate the theoretical curves calculated by taking account of the temperature dependences of Γ_i. These theoretical curves agree well with the experi-

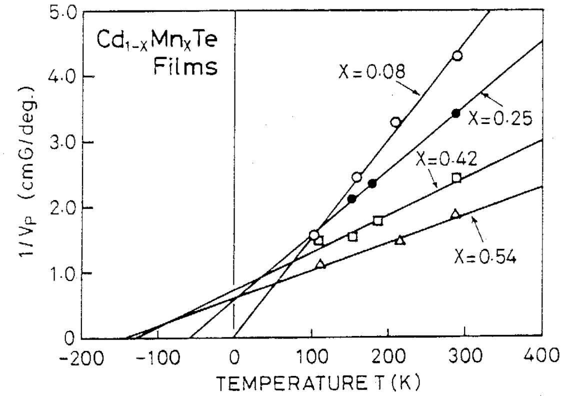

Fig. 7 Inverse peak height of the Faraday rotation for $Cd_{1-x}Mn_xTe$ films with different compositions as a function of temperature.

mental results for either film at any temperature.

The inverse peak height of the dispersion in the Faraday rotation spectrum for $Cd_{1-x}Mn_xTe$ films with different compositions is plotted as a function of temperature in Fig. 7. The inverse peak height changes linearly in proportion to temperature, and the straight-line fit intercepts the negative temperature axis at $T = T_{AF}$. The slope of these straight lines decreases and the temperature T_{AF} increases with increasing the composition x of the films. These temperature dependences are attributed to the magnetization of the films with the Curie-Weiss behavior as shown in Eq. (1), which influences the Zeeman splittings of exciton levels and oscillator strengths of magneto-optical transitions to the levels. The temperature T_{AF}, however, is quite different from the Curie temperature Θx. This can be explained by the fact that the Faraday rotation of $Cd_{1-x}Mn_xTe$ is related to not only the magnetization but also the energy width Γ of exciton absorption.

5. Conclusion

The Faraday effect of $Cd_{1-x}Mn_xTe$ films prepared by the ICB technique was discussed theoretically by taking account of the temperature dependence of the energy width of exciton absorption, and compared with the experimental data. From the results, it was found that the temperature dependences of the Faraday rotation for $Cd_{1-x}Mn_xTe$ were attributed to not only the Zeeman splittings of exciton levels but also the energy width of exciton absorption. The scattering of excitons by LO phonons provides the main contribution to the thermal broadening of exciton absorption. The theoretical curves of Faraday rotation spectra calculated by taking account of the thermal broadening parameter Γ_{LO} due to LO phonons were in good agreement with the experimental data.

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