Abstract— It has been found out interband Faraday rotation (IFR) depending on the energy of the incident photon, band gap and the film thickness. The decrease of the film thickness results in a strong rise of IFR angle. The contribution of nonparabolicity into IFR angle has been established. By taking into consideration nonparabolicity of energy band IFR angle rise. It has been obtained that by the decrease in the band gap the value of the IFR angle increases too. In a nongap state a substantial increase occurs in IFR angle.

Keywords— semimagnetic semiconductor, thin films, energy spectrum, Faraday rotation, molecular beam condensation.

INTRODUCTION

In recent years semimagnetic semiconductor (SMS) are subjects of considerable attention because of their potential applications in optoelectronic and spintronic devices. In particular, a key point to realize spintronic devices is to fabricate material with ferromagnetic ordering at room temperature. Studies on dilute SMS thin films are of immense importance. Coupled with their semiconducting properties, they have the characteristic magnetic properties, which make them an attractive alternative in a variety of electronic and optoelectronic devices including gas sensors and solar energy conversion devices.

Narrow-band SMS Pb$_{1-x}$Mn$_x$Te are unique materials for infrared (IR) optoelectronics. In comparison with the well-known compounds II$_{1-x}$Mn$_x$B$_{VI}$, they have been studied considerably less. The investigation of Faraday effect in Pb$_{1-x}$Mn$_x$Te thin films of SMS is of a special interest. So it can be used at the construction of optic isolators, amplifiers, IR detectors and other equipments [1].

In the given work Pb$_{1-x}$Mn$_x$Te thin films (SMS) have been produced, the interband Faraday effect in these semiconductors has been theoretically and experimentally studied. We attempt to discuss the mechanism responsible for the giant Faraday effect in SMS, which is based on s, p–d exchange interactions of electrons with magnetic ions. We examine the dependence of Faraday rotation (FR) on band gap, the film thickness, wavelength, magnetic component concentration, temperature, and magnetic field intensity in Pb$_{1-x}$Mn$_x$Te thin film crystals.

I. THEORETICAL CALCULATIONS

In the given work the energy spectrum and wave functions have been theoretically calculated for quantum-sized films of Pb$_{1-x}$Mn$_x$Te SMS. The properties of the electrons and holes in the exchange semiconductors A$^VI$B$^{VI}$ are described by Dimmock model [3]. But at the energies $E_g$, where $E_g$-band gap can be limited by a double-band model, as in this case Dimmock model doesn’t lead to qualitatively new results [4]. For the calculation of the spectra and wave functions double-band Kane model has been used. The $k_x=0$ case is considered. Let’s assume that the surface of the film is perpendicular to the axis x. In the model of rectangular wells with infinite walls in the double-band approximation, when the spin-spin exchange interaction occurs between the electrons in the conductivity band (valence band) and the electrons of half-filled d-shells of manganese ions as well as taking into account electron spins and the band nonparabolicity we have:

$$E_{jx} = \frac{E_g}{2} + x \left( \frac{b}{2} + \frac{d}{2} \right) \pm \sqrt{\left( \frac{E_g}{2} + x \left( \frac{b}{2} + \frac{d}{2} \right) \right)^2 + P_x^2 k_x^2 + P_y^2 k_y^2}$$

(1)

$$\psi_{jx1/2} = \frac{2}{\sqrt{3^d}} \left[ A_{jx1/2} \psi_{jx1/2}(T_j,x) \sin \alpha x + B_{jx1/2} \psi_{jx1/2}(T_j,x) \cos \alpha x \right] e^{IR}$$

(2)

$$A_{jx1/2}(T_j,x) = L_{jx1/2} \left( U_{jx1/2} - \frac{E_{jx1/2}^u}{E_{jx1/2}^v} \right) e^{-iP_x k_x - iP_y k_y}$$

$$A_{jx1/2}(T_j,x) = L_{jx1/2} \left( U_{jx1/2} + \frac{E_{jx1/2}^u}{E_{jx1/2}^v} \right) e^{-iP_x k_x - iP_y k_y}$$

(3)

$$B_{jx1/2} = -L_{jx1/2} U_{jx1/2} \frac{P_x a_{jx1/2}^u}{E_{jx1/2}^u} e^{-iP_x k_x - iP_y k_y}$$

$$B_{jx1/2} = -L_{jx1/2} U_{jx1/2} \frac{P_x a_{jx1/2}^v}{E_{jx1/2}^v} e^{-iP_x k_x - iP_y k_y}$$

Magnitooptic properties of the Pb$_{1-x}$Mn$_x$Te semimagnetic semiconductors’ thin films

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\[ L = \left( \frac{E_{2j} + E_2 - E_j + A}{2E_{2j} + E_2 - E_j + A} \right)^{1/2} \]

where \( E_2 \) is the band gap, \( j^\pm \) is \( c, v \). \( P_A \) is the Kane constant.

\[ A = \frac{1}{2} N_A^\alpha \left( \mathcal{S}_a \right), \quad B = \frac{1}{2} N_A^\beta \left( \mathcal{S}_a \right) \]

Are exchange parameters, arrows indicate the spin state.

In the given work the interband Faraday effect in size-quantized films of \( \text{Pb}_{1-x}\text{Mn}_x\text{Te} \) SMS has been theoretically studied. The initial formula for IFR involving photons with the energy of \( \hbar \omega \) has the form [5], [6]:

\[ \theta(\hbar \omega) = -\frac{\mathcal{H}_A^2}{2\pi \alpha_d} \int_0^\infty \frac{\omega}{\omega} \left( \frac{\alpha_+ \omega}{\omega^2 - \omega_0^2} \right) d\omega \]

where \( \alpha_{\pm} \) and \( n_{\pm} \) are the coefficients of absorption and the diffraction indices for right (+) and left (-) circular polarized radiation, \( \mathcal{H}_A \) is the tension of the magnetic field, \( d \) is the film thickness, \( d_0 \) is the sample thickness.

On the basis of the found formulae an analytical equation has been found out for interband Faraday rotation (IFR) depending on the energy of the incident photon, band gap and the film thickness.

\[ \theta(\hbar \omega_d) d = \theta_{\text{cTV}} d + \theta_{\text{cUV}} d \]

\[ \theta_{\text{cTV}} d = -\frac{\mathcal{H}_A^2 \pi^2}{8\alpha_d c_h} \sum_{j=1} \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega} \left( \ln|K_j| + \frac{2\gamma}{\alpha^2} \ln|K_j| \right) - \frac{\mathcal{H}_A^2}{2\alpha_d} \]

\[ \theta_{\text{cUV}} d = -\frac{\mathcal{H}_A^2 \pi^2}{8\alpha_d c_h} \sum_{j=1} \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega} \left( \ln|K_j| + \frac{2\gamma}{\alpha^2} \ln|K_j| \right) - \frac{\mathcal{H}_A^2}{2\alpha_d} \]

where \( \alpha = \frac{\mathcal{H}_A^2}{2\alpha_d}, \quad K = 1 - \frac{\mathcal{H}_A^2}{2\alpha_d}, \quad J = 1 + \frac{\mathcal{H}_A^2}{2\alpha_d}, \)

\[ y = 2\pi^2 \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega}, \quad \gamma = \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega}, \quad E_0 = \frac{1}{2} \mathcal{H}_A + A + \frac{\alpha_+ \omega}{2\alpha_d}, \]

\[ K_1 = \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega}, \quad K_2 = \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega}, \quad K_3 = \sqrt{K_1^2 + 2y}, \]

\[ J_1 = \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega}, \quad J_2 = \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega}, \quad J_3 = \sqrt{J_1^2 + 2y}. \]

The formula of parabolic approximation has been also obtained. In the parabolic approximation, i.e. at \( E_0 \to \infty \), the obtained formula for IFR angle has the following form:

\[ \theta_{\text{cUV}} d = \frac{\mathcal{H}_A^2 \pi^2}{2\alpha_d c_h} \sum_{j=1} \frac{\alpha_+ \omega}{\alpha_+ \omega - \alpha_- \omega} \left( \ln|K_j| - y \right) + \frac{\mathcal{H}_A^2 \pi^2}{2\alpha_d c_h} \left( \ln|K| - y \right) \]

\[ \frac{1}{2\pi^2} \left[ (1 + \frac{x}{x-J}) \ln|K| - x + y - \left( 1 - \frac{x}{x-J} \right) \ln|U| + x + y \right] \]

In Figure the dependence of IFR angle on photon energy, band gap and the film thickness are shown, which have been built on the basis of the formulae (6)-(8). It has been specified that the decrease of the film thickness leads to a strong increase of IFR angle (Fig.1). As it can be seen from the Fig. 2 and Fig.3 the decrease of the film thickness results in a strong rise of IFR angle which should be expected [7].

Fig.1 Dependence of IFR angle on band gap energy for for the \( \text{Pb}_{1-x}\text{Mn}_x\text{Te} \) \( x=0.01 \) thin films, \( d_0=100\AA \), 1- \( \hbar \omega_d = 0.117\text{eV}, \) 2- \( \hbar \omega_d = 0.15\text{eV}, \) the film surface perpendicularly to z axis.
Fig. 2 Dependence of IFR angle on $\hbar \omega / E_g$ for the Pb$_{1-x}$Mn$_x$Te (x = 0.01) thin films at T = 1.8K, H = 1T, $d_o$ = 100Å, the film surface perpendicularly to z axis. 1- parabolic case, 2- $E_g = 0.19$eV, 3- $E_g = 0.01$eV

Fig. 3 Dependence of IFR angle on $\hbar \omega / E_g$ for the Pb$_{1-x}$Mn$_x$Te (x = 0.01) thin films at $E_g = 0.19$eV, the film surface perpendicularly to z axis. 1- $d_o$ = 500Å, 3- $d_o$ = 100Å, continuous curve – theoretical, dotted lines – experimental

Fig. 4 Dependence of IFR angle on the thickness of Pb$_{1-x}$Mn$_x$Te (x = 0.01) thin films at $E_g = 0.19$eV, film surface perpendicularly to z axis, 1- $h \omega / E_g = 0.4$eV, 2- $h \omega / E_g = 0.3$eV, 3- $h \omega / E_g = 0.2$eV, 4- $h \omega / E_g = 0.1$eV

Fig. 5 Dependence of IFR angle on $\hbar \omega / E_g$ for the Pb$_{1-x}$Mn$_x$Te (x = 0.01) thin films at $E_g = 0.19$eV, $d_o$ = 500Å, 1- film surface perpendicularly to z axis, 2- film surface perpendicularly to x axis

Fig. 6 Dependence of IFR angle on $\hbar \omega / E_g$ for the Pb$_{1-x}$Mn$_x$Te (x = 0.01) thin films at T = 1.8K, H = 1T, $d_o$ = 100Å, film surface perpendicularly to x axis, 1- $E_g = 0.1$eV, 2- $E_g = 0.19$eV

Fig. 7 Dependence of IFR angle on $\hbar \omega / E_g$ for the Pb$_{1-x}$Mn$_x$Te (x = 0.01) thin films, $E_g = 0.19$eV film surface perpendicularly to x axis, 1- $d_o$ = 100Å, 2- $d_o$ = 300Å, 3- $d_o$ = 500Å
The contribution of nonparabolicity into IFR angle has been established, so taking into consideration the band nonparabolicity results in the increase of IFR angle. By taking into consideration nonparabolicity of energy band IFR angle rise and \( E(\hbar\omega_0) \rightarrow \mathcal{O} \) at \( \hbar\omega_0 \rightarrow \mathcal{O} \) (Fig.2).

It has been shown from spectral dependences that by the decrease in the band gap the value of the IFR angle increases too. In a nongap state \( E_0 = \mathcal{O} \), a substantial increase occurs in IFR angel.

In the calculations the values have been used: \( A=2.544 \text{ meV} \), \( B/3=0.834 \text{ meV} \), \( P=4.4 \times 10^{-5} \text{meV}\cdot\text{cm} \), \( P=1.37 \times 10^{-5} \text{meV}\cdot\text{cm} \).

II. THE METHOD OF PRODUCTION OF THIN FILMS AND EXPERIMENT

The obtained results are in a good conformity with the experimental data.

Pb\(_{1-x}\)Mn\(_x\)Te \((x=0.005 \pm 0.06)\) thin films have been grown at BaF\(_2\) substrates by the method of molecular beam condensation. The optimal conditions of producing thin films with high crytalline perfection, electrophysical and optical parameters have been determined [2].

It has been shown that in epitaxial films of Pb\(_{1-x}\)Mn\(_x\)Te \((x=0.005 \pm 0.06)\) crystalline perfection and charge carriers mobility \( (\mu) \) depend on condensation rate \( (\nu_c) \). By increasing \( \nu_c \) crystalline perfection and \( \mu \) increase, reach maximum and then decrease.

By using during the growth an additional compensating tellurium vapor source increasing of \( \mu \), as well as change of the conductivity type, high crystalline perfection have been achieved.

Spectral dependence of FR in thin films Pb\(_{1-x}\)Mn\(_x\)Te \((x=0.01)\), presented on fig.3, is measured in magnetic field \( H=1T \) at temperature \( T = 1.8K \) for different thickness: 1- \( d_0=150 \text{ Å} \), 2- \( d_0=100 \text{ Å} \). The value of FR increases with the growth of film thickness.

III. CONCLUSION

From obtained formula for IFR angle in size-quantized films of Pb\(_{1-x}\)Mn\(_x\)Te for various orientations of crystal directions to a film surface follows, by the decrease in the band gap the IFR angle increases. In parabolic approach rotation of polarization plane occurs because of the difference of two contributions, differing in spins and in exchange parameters, i.e. of the electron transitions from magnetic and exchange sublevels of a valency band to magnetic and exchange sublevels of a conductivity band. Theoretically and experimentally defined, that with increase in a thickness of film, the IFR grows and at some value of \( d_0=300 \text{Å} \) there is a saturation, i.e. the next increase in a thickness of the sample does not influence to the IFR process.

IFR for various orientations of crystal directions to a film surface differs on some degree and are various on a sign that it is possible to explain by strong anisotropy in Pb\(_{1-x}\)Mn\(_x\)Te. Besides, optical processes on size-quantized levels of anisotropic semiconductors strongly depend on film geometry. Moreover, in Pb\(_{1-x}\)Mn\(_x\)Te the anisotropy amplifies because of the exchange interaction.

REFERENCES


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