Infrared Magneto-Optical Studies in $Ga_{1-x}Mn_xAs$ Films

G.Acbas[*], J. Cerne[*], M.Cukr[¶], V. Novak[¶] and J. Sinova[†]

[*]*Physics Dept., Univ. at Buffalo, SUNY, Buffalo, NY*
[¶] *Institute of Physics, Acad. of Sciences of the Czech Republic, Prague, Czech Republic*
[†]*Physics Dept., Texas A\&M Univ., College Station, TX*

Abstract. The mid and near infrared (115-1165meV) complex Faraday and Kerr effects are studied in a $Ga_{1-x}Mn_xAs$ random alloy film (x=0.05 and Curie temperature of 100 K) as a function of frequency and temperature. The strong infrared magneto-optical response shows clear ferromagnetic behavior that is consistent with dc magnetization measurements. The real and imaginary parts of the measured Faraday and Kerr angles are in qualitative and quantitative agreement with the values predicted by effective Hamiltonian models within a mean field treatment.[1] Strong features in the Kerr and Faraday effects, with a peak rotation angle at around 5.5µm (220 meV) is observed consistent with theoretical predictions

Keywords: Faraday Effect, Kerr Effect, Diluted Magnetic Semiconductors, infrared, magneto-optics, GaMnAs.
PACS: 75.50.Pp, 78.20.Ls, 78.30.Fs, 78.66.Fd, 78.20.Jq

The interplay between the magnetic and semiconducting properties of III-Mn-V diluted magnetic semiconductors has been intensely studied in the last few years since it is believed that this will shed light on ways to reach room temperature ferromagnetism in these materials.[2] In particular magneto-optical measurements have been used to obtain information on the hole mediated exchange interaction between Mn ions, the spin-split bands, the magnetic anisotropies, and the presence of segregated second phases, for example.[3]

However, magneto-optical measurements in the 1-11 µm (1165-115 meV) range, which characterizes the energy scale of the valence band electronic structure, are limited. In this paper we extend these types of measurements to this critical wavelength range. Mid-infrared free carrier Faraday-rotation is well known as a technique to determine the effective mass of semiconductors[4] and metals[5] with simple band structures. These measurements can probe a wide range of temperatures and impurity concentrations. Faraday effect experiments have revealed, for example, in p-type GaAs features associated with the transitions between Zeeman split valence sub-bands.[6] For GaMnAs, theoretical calculations based on effective Hamiltonian models predict strong features due to free holes and transitions between spin-split valence sub-bands in this wavelength range.[1]

The Faraday and Kerr effects are measured with a modulation technique using laser sources.[7] Linearly polarized laser light is incident parallel to the magnetic field and normal to the sample surface. The refracted and reflected beams become elliptically polarized with the major axis rotated by an angle. The real (imaginary) part of the Faraday angle θ_F characterizes the rotation (ellipticity) of the transmitted polarization. The rotation angle of the ellipse is due to a difference in the index of refraction for left and right circular polarized light while the ellipticity is due to a difference in absorption. Similarly, the complex Kerr angle θ_K describes the polarization of reflected light. θ_F and θ_K in turn can be used to determine the complex magneto-conductivity tensor.[8] The sample studied in this experiment is a 50 nm GaMnAs film grown by low temperature molecular beam epitaxy on a GaAs substrate with 5 % Mn. After growth the sample was annealed for one hour at 200 °C. The hole concentration of $2.5 \cdot 10^{20}$ cm^{-3} is determined through dc Hall effect measurements at fields up to 9 T and at a temperature of 4K. The hole density is estimated to be within 30% of the high field (~30 T) value.[9] The Curie temperature is approximately 100 K.

Both θ_F and θ_K show hysteretic and non-linear behavior up to 110 K (see inset Fig. 1). The linear magnetic field dependence is subtracted to obtain θ_F and θ_K as functions of temperature and wavelength. The temperature dependence of Re(θ_F) and Im(θ_F) is shown in Fig. 1 for a wavelength of 10.22 µm Notice that the ellipticity changes sign at about 80K. In magnetic circular dichroism experiments the sign of the signal, which depends on the difference between

CP893, *Physics of Semiconductors, 28th International Conference*
edited by W. Jantsch and F. Schäffler

absorption coefficients for left and right circularly polarized light was shown to be influenced by population effects. At this energy (120 meV) transitions between light hole and heavy hole bands dominate together with a tail contribution from the transition between the split-off band and the heavy and light hole bands. Transitions to an impurity band could have the same characteristic energy, but there is no qualitative or quantitative theory to compare with the experimental results.

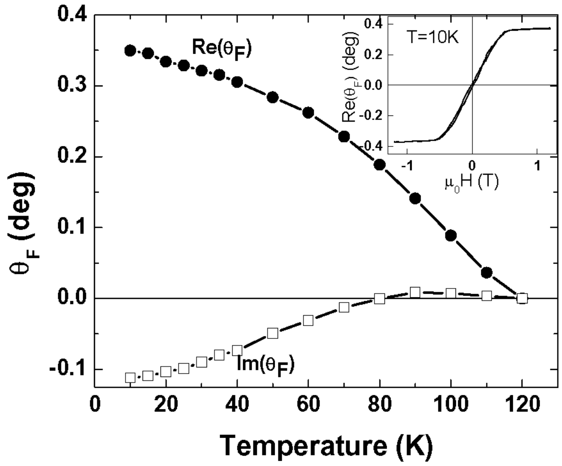

Figure 1. Temperature dependence of the Re(θ_F) and Im(θ_F) at 10.22 µm wavelength. Inset shows hysteresis loop at 10 K.

The wavlength dependence of the Re(θ_K) is shown in Fig. 2. The solid and dotted lines correspond to theoretical calculations using a 8 band $\vec{k}\cdot\vec{p}$ effective Hamiltonian model,[1] for hole density of $2.2\cdot10^{20}$ cm^{-3} and $3.3\cdot10^{20}$ cm^{-3}, respectively. Disorder effects have been taken into account by the introduction of a fixed hole lifetime dominated by impurity scattering. The points correspond to Kerr angle measurements at 10 K.

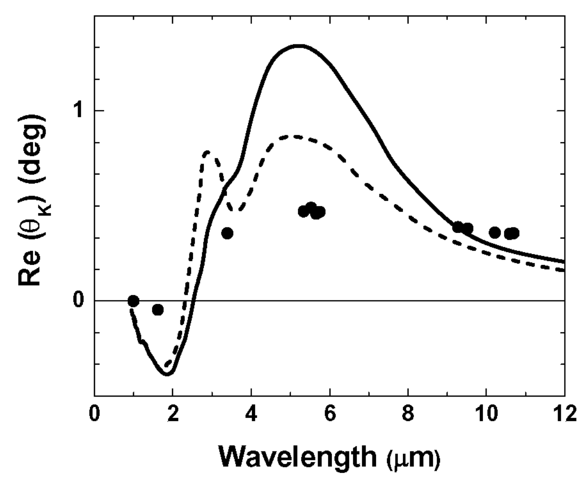

Figure 2. Re(θ_K) as function of the wavelength. Theoretical lines[1] at T=0K, solid line for p=$2.2\cdot10^{20}$ cm^{-3}, dotted line for p=$3.3\cdot10^{20}$ cm^{-3}; the experimental points are taken at 10 K.

The Kerr rotation peak in the 5-6µm (200-300 meV) range, and the change of sign in the 2-3µm range are consistent with predictions from the model. Additional laser lines in the 2-5µm range are needed in order to differentiate between contributions due to transitions from the light hole to split-off band, and transitions from the heavy hole to split-off band. The spectral dependence appears broader than the 100 meV value used in the theory. Some broadening is due to the thermal fluctuations which are not taken into account in the theoretical calculations.

Our data show resonance behavior in all components of the complex Faraday and Kerr angles, and provide information on the carrier mediated magnetism. Systematic analysis as a function of hole density is under way to provide a more complete understanding of the electronic band structure of GaMnAs.

Acknowledgments: This work was supported by DARPA/ONR N0001400-1-0951 (Buffalo), Research Corporation Cottrell Scholar Award (Buffalo), NSF-CAREER-DMR0449899 (Buffalo), NSF-CAREER-DMR-0547875 (Texas A&M). and GACR-202/04/1519 (Prague).

REFERENCES

1. E. M. Hankiewicz , J. Sinova et al., Phys. Rev. B **70**, 245211 (2004).
2. T. Jungwirth, J. Sinova, J. Mašek, J. Kučera, and A. H. MacDonald, Rev. Mod. Phys. **78**, 809-864 (2006).
3. K. Ando, T. Hayashi, M. Tanaka, and A. Twardowski. Appl. Phys. **83**, 6548 (1998); B. Beschoten, P.A. Crowell, I. Malajovich, D.D. Awschalom, F. Matsukura, A. Shen, and H. Ohno, J. Szczytko, W. Mac, A. Twardowski, F. Matsukura and H. Ohno, Phys. Rev. B **59**, 12935 (1999); D. Hrabovsky, E. Vanelle, A. R. Fert, D. S. Yee, J. P. Redoules, J. Sadowski, J. Kanski and L. Ilver, Appl. Phys. Lett. **81**, 2806 (2002); R. Lang, A. Winter, H. Pascher, H. Krenn, X. Liu, J.K. Furdyna, Phys. Rev. B **72**, 024430 (2005).
4. I.M. Boswarva, R.E. Howard, A.B. Lidiard, Proc. Royal Soc. London A **269**, 125 (1962).
5. J. Cerne, D.C. Schmadel, M. Grayson, G.S. Jenkins, J. R. Simpson, and H., D. Drew,Phys. Rev. B **61**, 8133 (2000).
6. T. H. Lee, H.Y Fan, Phys. Rev. **165**, 927 (1968).
7. J. Cerne, D.C. Schmadel, L. Rigal, and H.D. Drew, Rev. Sci. Instr. **74**, 4755-4767 (2003).
8. M.-H. Kim, G. Acbas, M.-H. Yang, I. Ohkubo, H. Christen, M.Cukr, V. Novak, Z. Schlesinger, and J. Cerne, in preparation (2006).
9. G.B. Kim, M. Na, G. Acbas, B.D. McCombe, S. Wang, M. Cheon, H. Luo, X. Liu, Y. Sasaki, and J.K. Furdyna, Proc. Int. Conf. High Mag. Fields Semicond. Phys. 16, 285-293 (2005).