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# PERSISTENT SPIN RESONANCE OF DONOR ELECTRONS AND HOPPING MAGNETOCONDUCTIVITY IN $Cd_{1-x}Mn_xTe_{1-y}Se_y$

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The first observation of electric dipole spin resonance of donor electrons in $Cd_{1-x}Mn_xTe_{1-y}Se_y$ in far-infrared magnetotransmission is reported. Modification of the donor wave function due to non-diagonal exchange interaction with localized magnetic moments and to magnetic fluctuations are believed to allow this resonance. Hopping magnetoconductivity studied in the same crystals shows a behavior typical for wide gap diluted magnetic semiconductors.

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Electric dipole spin resonance (EDSR) of free and donor bound electrons is the most direct and accurate measure of the $g$-factor in semiconductors. In diluted magnetic semiconductors (DMS) [1] the study of EDSR provides accurate information about the modification of the band structure by the exchange interaction between the band electrons and localized magnetic moments. Moreover, the study of this ordinarily forbidden transition provides information about various important perturbations which relax selection rules. For instance, in wurtzite CdMnSe — where the resonance is allowed by the combined effects of spin–orbit interaction and acentric uniaxial symmetry — the EDSR provides a direct measure of the spin–orbit coupling constant [2].

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The aim of the present work was to study far-infrared (FIR) EDSR in zincblende CdMnTe-based crystals. Although CdMnTe is one of the most extensively studied members of the DMS family, EDSR in this material has never been observed before, mainly because of the difficulty in obtaining $Cd_{1-x}Mn_xTe$ with a sufficient concentration of shallow donors. The recent discovery of a strong photomemory effect in $Cd_{1-x}Mn_xTe$-based crystals doped with In and Ga [3, 4], however, provided an opportunity to overcome this longstanding difficulty.

Illumination of In- and Ga-doped CdMnTe and CdMnTeSe with white light at temperatures below 120 K was observed to produce an increase of up to 3.5 orders of magnitude in the concentration $n$ of occupied shallow donors, as determined by the Hall measurements. The decay rate of $n$ after illumination was of the order of a few hours at 77 K, and at 4.2 K it was to slow to measure. The *photomemory effect* was accompanied by a sharp increase in the far-infrared absorption. FIR studies were carried out in Ga and In doped $Cd_{1-x}Mn_xTe_{1-y}Se_y$ crystals with $0.03 \leq x \leq 0.1$, $0 \leq y \leq 0.08$ at a series of fixed wavelengths between 96.5 and 496 $\mu$m, in the temperature range 1.5 K $\leq T \leq$ 20 K and in magnetic fields up to 6 T. The FIR absorption observed after illumination shoved a slow-varying but well defined magnetic field dependence, which we ascribe to optical hopping absorption [5].

Superimposed on this background we also found a weak but strongly temperature dependent resonance line, which we identify as EDSR of persistent shallow donor electrons. Typical FIR transmission data in the vicinity of EDSR are shown in Fig. 1 for several temperatures.

The interpretation of the observed resonance as EDSR is based on the strong temperature dependence of the resonance position, clearly visible in Fig. 1, consistent with the well- known temperature dependence of the effective $g$-factor in DMS alloys. The $g_{\text{eff}}$ can be written in the form [1]:

$$g_{\text{eff}} = g^* - \frac{\alpha M(T,H)}{2\mu_B^2 H}, \tag{1}$$

where $g^*$ is the $g$-factor as determined in the absence of exchange interaction, $\alpha$ is the exchange integral, $M$ is the dc magnetization, and $\mu_B$ is the Bohr magneton. The last term is dominant, and therefore $g_{\text{eff}}$ varies with temperature as the magnetization of the sample.

Furthermore, the magnetic field vs. photon energy positions of our resonances are also consistent with the previous Raman spin-flip scattering experiments on CdMnTe [6].

In order to identify the mechanisms which allow the transition, we performed careful studies of the selection rules for various polarizations of the FIR signal. We found that the resonance is observed *with the same intensity* in all experimental geometries, i.e. in the Faraday configuration with both cyclotron resonance active (CRA) and cyclotron resonance inactive (CRI) circular polarizations, and in the Voigt configuration with both $\boldsymbol{E} \perp \boldsymbol{H}$ and $\boldsymbol{E} \parallel \boldsymbol{H}$. Moreover, the EDSR line intensity did not depend on the orientations of $\boldsymbol{H}$ or $\boldsymbol{E}$ relative to the crystallographic directions of the samples.

This behavior is entirely different from that which governs EDSR in either

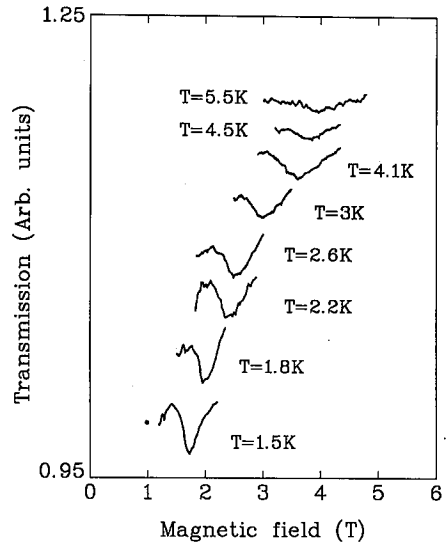


Fig. 1. FIR magnetotransmission in the vicinity of the EDSR transition observed at 118.8 $\mu$m in Ga-doped $Cd_{0.95}Mn_{0.05}Te$. The data were taken at several temperatures in the Faraday geometry in the CRA circular polarization. The magnetic field dependent background was numerically subtracted.

CdMnSe or in non-magnetic systems (such as InSb), and new mechanism allowing this transition must be sought to explain the observed behavior. In this connection we note that two new EDSR mechanisms specific to DMS have recently been predicted, both of which lead to the mixing of wave functions with different spin: *non-diagonal terms* in the spin–spin exchange Hamiltonian [7], and modifications of the donor wave function by *fluctuations* of magnetization [8]. Both mechanisms are independent of the FIR incident polarization, and we expect that either one or both are responsible for the EDSR reported here.

We note, therefore, that EDSR may constitute a valuable handle for investigating such off-diagonal aspects of the spin–spin exchange andór magnetization fluctuations in DMS crystals.

We also carried out magnetotransport measurements on the same DMS crystals. From the temperature dependence of the resistivity we showed that below 10 K, electrical transport is dominated by hopping conductivity. In this conductivity range CdMnTeSe revealed — characteristically for $n$-type wide gap DMS crystals — first a positive, and then a negative magnetoresistance (MR) on both sides of the metal–nonmetal (M–NM) critical point.

Using the model first proposed for CdMnSe [9], we interpret the low-field positive MR as arising mainly from the quantum corrections to the conductivity and spin-splitting induced cross-over to the "high magnetic field" (or even "spin-polarized") universality class. The negative MR presumably results from a destructive effect of the magnetic field on bound magnetic polarons, as well as

from a redistribution of electrons between the spin-split subbands. Similar MR in CdMnTe was also observed by others [3, 10].

At zero magnetic field resistivity drops of up to 5 orders of magnitude was observed after illumination. We also noted that the hopping activation energy decreases strongly with the dose of illumination, clearly indicating an approach toward the M–NM transition. Although we did not find any specimen that would undergo a clear, light-induced NM–M transition at $T \geq 1.5$ K, the observed trend indicates that experiments at mK temperatures appear promising in this respect. Since $Cd_{1-x}Mn_xTe$ is a DMS alloy, the discovery of the photomemory effect in this material may allow one to study three dimensional phase diagrams (magnetic field, concentration, and conductivity) of the NM–M transition in a spin-polarized "universality class" [11].

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