Ferromagnetic resonance in CdCrTe solid solution

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Abstract. We studied sintered Cd$_{1-x}$Cr$_x$Te solid solution obtained by melting of Cd and CrTe components with x=0.05 Cr mole fraction. Structural studies show homogenous large grain polycrystal structure of the alloy. Measurements of the temperature dependence of the electrical conductivity of the samples reveal the semi-metallic properties with electrical conductivity 0.22 Ohm$^{-1}$cm$^{-1}$. The ferromagnetic resonance (FMR) studies of the single crystal sample taken from the polycrystalline bulk were carried out at room temperature on X band epr spectrometer. The FMR spectra consist of one broad line with a high value of the g factor. The line is of the Lorentz shape with a moderate asymmetry. The angular dependence of the resonance field was analyzed based on the Kittel and Van Vleck theories. We compared the angular dependence of the resonance field with that arising from the Van Vleck theory containing first and second magnetic anisotropy energy approach. The results indicate ferromagnetic properties of the material at room temperature.

1. Introduction

The concept of spintronic devices requires finding semiconducting materials which show ferromagnetism at room temperatures [1]. Additionally, the ferromagnetism should be electrically tuneable which can be effected in the case of carrier induced ferromagnetism based on a coupling between the spins of itinerant electrons and local magnetic moments. Diluted magnetic semiconductors (DMS) with Mn ions diluted in A$^II$B$^VI$ or A$^III$B$^VI$ matrices are classical materials for this purpose [2, 3, 4]. The concept of magnetic semiconductors was addressed over ten years ago [5]. However, the Curie temperature of such material is far below room temperature often, it is helium temperature for carrier mediated ferromagnetism. Relatively higher $T_c >$100K were obtained for InMnAs [6, 7] and GaMnAs [8, 9] belonging to III-V diluted semiconductors. As an alternative materials, the IV-VI ferromagnetic semiconductors, such as SnMnTe, PbSnMnTe and GeMnTe are also proposed by Dobrowolski et al. [10]. It seems to us that the Cd$_{1-x}$Cr$_x$Te solid solution is a diluted magnetic semiconductor (DMS), which should be very promising for spintronics. Blinowski and Kacman [11] have predicted theoretically the ferromagnetic properties of such material at room temperatures. Recently, Ko and Blamire [12, 13] reported this ferromagnetism and the Curie temperature at 395 K. In this paper, we will present results of the magnetic properties Cd$_{1-x}$Cr$_x$Te (x = 0.05) obtained from ferromagnetic resonance (FMR) experiment and of the effect of crystal anisotropy on the resonant field.

In section 2, we recall the fundamental theories on FMR of Kittel [14] which are based on the classical mechanics and that by Van Vleck [15] developed from the quantum mechanics principles. The sample preparation and its basic crystallographic characterization is described in section 3 and partially in section 4, where the experimental results of FMR and its anisotropy are collected as well. In section 5,
we explain the magnetic resonance dependence on crystal orientation according to the theoretical
description outlined in section 2.

2. Anisotropy of the resonance frequency in ferromagnetic resonance
The resonance condition in electron paramagnetic resonance is given by the Larmor condition

\[ \omega_0 = \gamma H_0 \]  

where \( \omega_0 \) is circular frequency of the microwave field at resonance, \( \gamma \) is giromagnetic factor and \( H_0 \) is static magnetic field.

In a paramagnet, the external magnetic field is equal to the local field which determines the unknown g-factor parameter. On the contrary, in a case of ferromagnetism, the local Zeeman field is a superposition of the following contributions: the external field \( H_0 \), the demagnetizing field \( H_d \), the magnetic anisotropy energy of the various type.

The nature of the demagnetising field causes dependence of the resonance condition on the shape of the sample [14]. As an example, the resonance frequency of the small ferromagnetic sphere is given by the Larmor frequency \( \omega_0 = \gamma H_0 \), whereas in the plane surface it is

\[ \omega_0 = \gamma \sqrt{\beta H} \]  

where \( \beta \) is Bohr magneton.

Kittel [14] derived a general form of the equation for resonance condition of ferromagnetic sample. The starting point was the equation of motion of the magnetic moment \( \vec{M} \) referred to the unit volume of material

\[ \frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{H} \]  

Assuming that the \( x, y, z \) axes of the coordinate system are parallel to the principal axes of the ellipsoid of the material and that the external static field and microwave magnetic field are directed to the \( z \) and \( x \) axes, respectively i.e. \( H = H_z, H^{\text{rf}} = H_x \) (figure 1), we obtain the following components of an intrinsic magnetic field

\[ H^i_x = H_x - N_x M_x \]
\[ H^i_y = -N_y M_y \]  
\[ H^i_z = H_z - N_z M_z \]  

where \( N_i (i=x, y, z) \) are demagnetizing factors, \( M_i (i=x, y, z) \) are components of magnetization \( \vec{M} \).

Then, the Bloch equations are

\[ \frac{dM_x}{dt} = \gamma \left[ H_z + \left( N_y - N_z \right) M_z \right] M_y \]
\[ \frac{dM_y}{dt} = \gamma \left[ M_z H_x - \left( N_x - N_z \right) M_x M_z - M_x H_z \right] \]
\[ \frac{dM_z}{dt} \equiv 0 \]  

2
The solutions of the equations (5) offer the resonance frequency:

$$\omega_0 = \gamma \left[ H_z + (N_y - N_z)M_z \right] \times \left[ H_z + (N_x - N_z)M_z \right]^{1/2}$$

(6)

**Figure 1** (a) Relations of the crystal axes [100], [010], [001], ellipsoid axes (X, Y, Z) and an external reference frame (x, y, z); b) Orientation of external magnetic field $H_0$ and microwave field $H_{rf}$.

The resonance condition (resonance field at a constant frequency of the microwave magnetic field or the changes of a microwave magnetic field frequency at a fixed external magnetic field) is alternated by the anisotropy energy. Thus, in a single crystal sample the resonance field depends on the direction of the crystal axes relative to the axes connected with the shape of a sample. In a polycrystalline sample, the resonance line is usually broadened as the distribution in space of the direction of magnetization vector causes a distribution of the resonance field value.

The anisotropy energy is a part of the energy of ferromagnetic crystal which depends on the direction of the magnetization vector in respect to the crystallographic frame system of the sample. In a cubic crystal, this energy (in respect to the unit volume of the material) may be written as

$$f = K_1 \left( \alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_1^2 \alpha_3^2 \right) + K_2 \alpha_1^2 \alpha_2^2 \alpha_3^2 + Q$$

(7)

Where $\alpha_i$ (i=1,2, 3), $(\cos \xi_i=\alpha_i)$ are direction cosines of magnetization relative to the cube axes, $K_1$, $K_2$ are the first and the second order anisotropy constants, respectively. The third term in equation 7 denoted as Q contains higher orders of anisotropy energies.

The effect of the anisotropy energy is usually introduced by an equivalent field $\hat{H}^e$ defined by the torques acting on the specimen: it is such a field for which both torque resulting from anisotropy energy $\partial f / \partial \theta$ and from the equivalent field $\hat{M} \times \hat{H}^e$ are equal:

$$\frac{\partial f}{\partial \theta} = \hat{M} \times \hat{H}^e$$

(8)

where $\theta$ is the rotation around the axis parallel to the direction of $\hat{M} \times \hat{H}^e$. $\hat{H}^e$ is not determined synonymously, as either its magnitude or direction are arbitrary. It is convenient to choose $\hat{H}^e$
parallel to x or y axes of the specimen. Then one can express the equivalent field by the equivalent demagnetization factors $N_x^e, N_y^e$:

$$
H_x^e = -N_x^e M_x \\
H_y^e = -N_y^e M_y
$$

(9)

In the case when $N_x^e = N_y^e$, a convenient choice is $\hat{H}_z^e$ parallel to the z axis.

The anisotropy field acts on the resonance condition via equivalent demagnetizing factors $N_x^e, N_y^e$ which are added to the obvious demagnetizing factors in formulae for FMR frequency (equation 6) yielding

$$
\omega_0 = \gamma \left\{ H_z + \left( N_y + N_y^e - N_z \right) M_z \right\} \times \left\{ H_z + \left( N_x + N_x^e - N_z \right) M_z \right\}^{1/2}
$$

(10)

where the static magnetic field $H_z$ is directed along one of the principal axes of the ellipsoid (X, Y, Z).

The direct dependence of the resonance frequency on the orientation of the sample can be obtained from the general formula (10) with effective demagnetizing factors determined for a given experimental situations. For example, in a cubic crystal oriented so that $H_x$ and $H_z$ are parallel to [100] directions these factors are

$$
N_x^e = \frac{2K_1 \cos 4\theta}{M_s^2} \\
N_y^e = \frac{2K_1 + \frac{1}{2}K_2 \sin^2 2\theta}{M_s^2}
$$

(11)

where $\theta$ is the angle between z axis and the [100] direction.

Inserting (11) into (10) we obtain the following angular dependence of the resonance frequency in the (100) plane

$$
\omega_0^2 = \gamma^2 \left\{ H_z + \left( N_y - N_z \right) M_z \right\} \times \left\{ H_z + \left( N_x - N_z \right) M_z \right\}
$$

(12)

Alternatively, Van Vleck [15] considered the anisotropy of the ferromagnetic resonance spectrum basing on quantum mechanics principles. The starting point was assumption that the anisotropy is a result of the quadrupolar coupling between spins

$$
H^q = \sum_{k>j} K_{jk} r_{jk}^{-4} \left( \vec{S}_j \cdot \vec{r}_{jk} \right) \left( \vec{S}_k \cdot \vec{r}_{jk} \right)^2
$$

(13)

Van Vleck derivated Kittel’s formula (10) for resonance condition in FMR experiment directly from Hamiltonian involving exchange and dipole-dipole interactions between elementary spins

$$
\hat{H} = \hat{H}_0 + \beta \sum_j S_j + \sum_{k>j} A_{jk} \vec{S}_j \cdot \vec{S}_k + \sum_{k>j} D_{jk} [\vec{S}_j \cdot \vec{S}_k - 3(\vec{r}_{jk} \cdot \vec{S}_j)(\vec{r}_{jk} \cdot \vec{S}_k)]
$$

(14)
where:
\[ \beta = \frac{e\hbar}{2mc} \]
\( \vec{S}_j \) is the spin of atom j (measured in multiples of unit \( \hbar/2\pi \)),
\[ \tilde{H}_g \beta \sum_j S_{-z_j} \] is the Zeeman energy of the spin \( j \) in the constant magnetic field directed along \( z \) axis,
\[ \sum_{k>j} A_{jk} \vec{S}_{-j} \cdot \vec{S}_k \] is the spin-dependent part of the exchange energy (\( A_{jk} \) is an exchange integral multiplied by constant factor),
\[ \sum_{k>j} D_{jk} [\vec{S}_{-j} \cdot \vec{S}_k - 3r_{jk}^{-2} (\vec{r}_{jk} \cdot \vec{S}_j)(\vec{r}_{jk} \cdot \vec{S}_k)] \] is the dipolar interaction
\( D_{jk} = \frac{g^2 \beta^2}{r_{jk}^3} \).

The equations of motion for particular spins \( \vec{S}_j \) are
\[ \frac{d\vec{S}_j}{dt} = \frac{2\pi i}{\hbar} \left[ \tilde{H} \vec{S}_j - \vec{S}_j \tilde{H} \right] \] (15)

Introducing the total spin
\[ \vec{S} = \sum_j \vec{S}_j \] (16)

we get the following equations of motion
\[ \hbar \frac{dS_x}{dt} = -Hg \beta S_y + 3 \sum_{k \neq j} D_{jk} \left( \alpha_{jk} S_{xj} + \beta_{jk} S_{yj} + \gamma_{jk} S_{zj} \right) \left( -\beta_{jk} S_{zk} + \gamma_{jk} S_{yk} \right) \]
\[ \hbar \frac{dS_y}{dt} = -Hg \beta S_z + 3 \sum_{k \neq j} D_{jk} \left( \alpha_{jk} S_{xj} + \beta_{jk} S_{yj} + \gamma_{jk} S_{zj} \right) \left( \alpha_{jk} S_{zk} - \gamma_{jk} S_{xk} \right) \] (17)
\[ \hbar \frac{dS_z}{dt} = 3 \sum_{k \neq j} D_{jk} \left( \alpha_{jk} S_{xj} + \beta_{jk} S_{yj} + \gamma_{jk} S_{zj} \right) \left( -\alpha_{jk} S_{yk} + \beta_{jk} S_{xk} \right) \]

where \( \alpha_{jk}, \beta_{jk}, \gamma_{jk} \) are the direction cosines of \( \vec{r}_{jk} \) relative to axes \( x, y, z \) see figure 1a.

By means of the classical demagnetizing factor as
\[ N_z = N^{-1} \sum_k \left[ 1 - 3\alpha_{jk}^2 \right] r_{jk}^{-3} + \left( \frac{4\pi}{3} \right) \] (18)

The equations (17) become
\[
\begin{align*}
\hbar \frac{dS_x}{dt} &= -g\beta HS_y + (N_z - N_y)g\beta MS_y \\
\hbar \frac{dS_y}{dt} &= g\beta HS_x - (N_z - N_x)g\beta MS_x \\
\frac{dS_z}{dt} &= 0
\end{align*}
\] (19)

where \(N\) is the number of atoms per unit volume.

Equations (19) are fully equivalent to the Kittel’s equations (5).

In order to take into account the quadrupolar interaction between spins, Van Vleck [15] added the energy (13) to the Hamiltonian (14). The new equations of motion gave the following expression for resonance frequency

\[
\omega_0^2 = \left(\frac{g\beta}{\hbar}\right)^2 \left[H + (N_y - N_z)M - Qg^{-1}\beta^{-1}f(z, y)\right]
\]

\[
\begin{align*}
&+ 9g^{-2}\beta^{-2}Q^2\left[g(x, y) + g(y, x)\right]^2
\end{align*}
\] (20)

where

\[
f(a, b) = \lambda_a^4 + \mu_a^4 + \nu_a^4 - 3(\lambda_b^2 \lambda_a^2 + \mu_b^2 \mu_a^2 + \nu_b^2 \nu_a^2),
\]

\[
g(a, b) = \lambda_b^3 \mu_a^3 + \mu_b^3 \mu_a^3 + \nu_b^3 \nu_a^3, \quad (a, b = x, y, z),
\] (21)

\[
Q = \frac{2}{3} \sum K_{jk} \left[1 - 5(\lambda_{jk}^2 \mu_{jk}^2 + \mu_{jk}^2 \nu_{jk}^2 + \nu_{jk}^2 \lambda_{jk}^2)\right] \left[\frac{1}{2}S(S + 1) - \frac{3}{2}\left\langle S_j^2\right\rangle_{\text{AV}}\right] \left[-\frac{M}{Ng\beta} + \frac{1}{2}\right]
\]

\[
\omega = \left[\frac{1}{2}S(S + 1) - \frac{3}{2}\left\langle S_j^2\right\rangle_{\text{AV}}\right] f\left[-\frac{M}{Ng\beta} + \frac{1}{2}\right].
\] (22)

The direction cosines \(\lambda_{ij}, \mu_{ij}, \nu_{ij}\) have now the meaning of these of \(\vec{r}_{ijk}\) relative to the set of cubic axes \([100], [010], [001]\). Those cosines \(\alpha, \beta, \gamma\) are expressed now in terms of these new ones. The \(\lambda_{ij}, \mu_{ij}, \nu_{ij}\) are direction cosines connecting axis \(i(i = x, y, z)\) with axes \([100], [010], [001]\).

The formulae (20) is more then Kittel’s result while the constant magnetic field is oriented arbitrary in respect to the principal cubic axes, whereas Kittel assumed that both constant and microwave magnetic fields are in the (100) plane. For that case the angular dependence (20) takes form which correlates with Kittel’s formulae.

\[
\omega_0 = g\beta h^{-1} \left\{H + (N_y - N_z)M + 2K_i M^{-1}\left(\frac{3}{4} \frac{1}{4} \cos 4\theta\right)\right\}^{\frac{1}{2}}
\]

\[
\left[H + (N_y - N_z)M + 2K_i M^{-1} \cos 4\theta\right]
\] (23)

For the plane (110) the angular dependence of the resonance was obtained by Bickford [16].
\[ \omega_0 = \mu_0 \left[ \left( H_z + \left( N_y + N_y e - N_z \right) M_z \right) \times \left( H_z + \left( N_x + N_x e - N_z \right) M_z \right) \right]^{1/2} \]

with

\[ \mu_0 N_x e = \left( 2 - \sin^2 \theta - 3 \sin^2 \left( 2\theta \right) \right) \frac{K_1}{M_z} \]

\[ \mu_0 N_y e = 2 \left( 1 - \sin^2 \theta - \frac{3}{8} \sin^2 \left( 2\theta \right) \right) \frac{K_1}{M_z} \]

3. Experimental

We prepare polycrystalline Cd\(_{1-x}\)Cr\(_x\)Te solid solution by liquid-state synthesis of stoechiometric (x=0.05) powered quantities Cd and Cr\(_2\)Te\(_3\) (Aldrich 99.9). Synthesis was accomplished in vacuum in quartz ampoule at 1320 K. The ingot obtained was cut into disks of 3 cm diameter and 1 mm thick. The averaged chemical composition of the wafer was checked by X-ray fluorescence analyses revealing a homogenous distribution of Cr in ingot. Samples in the averaged shape of about 1x2x3 mm\(^3\) rectangular were formed by the proper breaking of the wafer.

![Figure 2. SEM of the sample used in the FMR experiment: shape of the sample (a), surface after cutting and polishing (b), structure of the fracture surface(c).](image)

In the aim to investigate the structural properties we study the samples by scanning electron microscopy (SEM) (figure 2) and by powder X-ray diffraction (XRD) (figure 3). SEM studies of the fracture obtained show a large-grain polycrystalline structure of the samples (figure 3c). The powder X-ray diffraction studies (figure 2) indicate that the crystals studied have zinc-blende structure (the same as for pure CdTe) and that they are free from other phases.

In this work we examine six samples selected from several ones, such that seem to be single crystals taken from a polycrystalline ingot. The samples are referred to here as 4p1c, 4p2c, 4p1r, 4p2r, 4p1x and 4p2x. The FMR experiments were carried out in 9.4GHz epr spectrometer at room temperature. Angular dependence of the spectra was measured using one-axis goniometer.
Figure 3. XRD pattern of the sample 4p1r (a) and 4p2r (b).

4. Results
Samples 4p1c and 4p2c were characterised by measuring their dc conductivity in the temperature range 20-120°C (see figure 4 as an example). The samples show metallic dependence of resistance with temperature increasing. Electric resistivity is rather high (1.5 kΩ cm⁻² and 2 kΩ cm⁻² for the samples 4p1c and 4p2c, respectively).

Figure 4. Temperature dependence of resistance of the sample 4p1c.

The example of X-band spectra of the sample 4p2r is presented in figure 5. In both cases the spectrum consists of one wide line. The effective g factor is very high, about 4 - 5.4. Such a high value shows that not all the spectra lines are visible. Nevertheless, one can deduce that the lines are slightly asymmetric.
Figure 5. Angular dependence of FMR spectra in the plane A (sample 4p2r).
The shape of the lines are approximately Lorentzian (figure 6) according to Van Vleck’s theory [17]. The visible asymmetry should be interpreted taking into account the substantial linewidth (about 150 mT) with respect to the resonance field value. In such a case, instead of the Lorentzian line shape, a modified Bloch line shape should be used [18]:

\[
F(B_r, \Delta_B) = \frac{1}{3\sqrt{3} \pi \Delta_B^3} \left( \frac{B_r - B}{1 + \frac{1}{3}(B_r - B)^2 / \Delta_B^2} \right)^2 - \frac{B_r + B}{1 + \frac{1}{3}(B_r + B)^2 / \Delta_B^2} \right) \tag{26}
\]

where the first term means a resonant contribution and the second one is a non-resonant (anti-Larmor) part. The \( \Delta_B \) in (26) is linewidth parameter which approaches peak-to-peak half width of the Lorentz curve in a derivative view in the case \( \Delta_B \ll B_r \).

Figure 6. Fitting of the FMR signal (from figure 4) with the Lorentz function.

In figure 7 we present angular dependence of the spectra for sample 4p2r in three perpendicular planes A, B and C. There are significant periodical changes in the intensity of the line, its position as well as peak-peak width change as a function of an angle (figure 7).
Figure 7. The intensity of line its position as well as peak-peak width as a function of an angle for planes a, b, c of the sample 4pr2.

5. Discussion

A. Properties of chromium in CdTe
Chromium is one of the to the 3d transition-metal impurities which forming deep localised states in semiconductor matrices. This group of impurities shows several interesting features. They can exist in various charge states [19] e.g. Cr$^{1+}$, Cr$^{2+}$, Cr$^{3+}$. The separation of ionisation energy of these states does not exceed the energy gap value of the host crystal (in contrast to significant differences in atomic ionisation energies). The impurity levels of transition metals in a similar group of compounds e.g. A$^{II}$ B$^{VI}$ or A$^{III}$ B$^{V}$ have a relative position in the energy gap in all compounds of this group. This means that these impurity levels are not pinned to the nearby band edges. This feature can be utilized for the prediction of the band-edge discontinuities in semiconductor heterojunctions [20]. In figure 8, the chromium level alignments in different host crystals are exampled. Depending on the host crystal, the Cr impurity forms a donor, acceptor or a resonant states. Cr is an acceptor in CdTe, ZnSe, and ZnS single crystals.
In CdTe the chromium substitutes Cd atom lattice sites. The most popular ionic state of such an impurity in $A_{II}B_{VI}$ matrices (ZnS, ZnTe, CdS, CdSe, CdTe) is divalent state $Cr^{2+}$, whose spectra (infrared, epr) were found to be very similar for all these crystals. The crystal field for this Cr ion shows tetragonal symmetry and there is a substantial tetragonal static Jahn-Teller distortion [21-25]. As a result, the $Cr^{2+}$ ion is displaced along one of three equivalent directions (100), (010) or (001). This reduces the crystal field symmetry and splits the energy levels. In figure 9, the structure of the energy levels of $Cr^{2+}$ ions in CdTe matrix is presented.

![Energy levels splitting of the Cr$^{2+}$ (3d) ion in CdTe matrix by the crystal field, Jahn-Teller, spin orbit and spin-spin interactions.](image)

**Figure 8.** Impurity energy levels of Cr in $A_{II}B_{VI}$ and $A_{III}B_{V}$ crystals.

**Figure 9.** Energy levels splitting of the $Cr^{2+}$ (3d) ion in CdTe matrix by the crystal field, Jahn-Teller, spin orbit and spin-spin interactions.

**B. Electron Paramagnetic Resonance in $A_{II}B_{VI}$ semiconductors doped with Cr**

The epr experiments [21, 22] on $A_{II}B_{VI}$ semiconductor crystals with low concentration of Cr are in agreement with the model of the crystallographic properties presented above. The epr results are well described by the spin Hamiltonian involving the fine structure of the spectra observed:
\[
\hat{H} = \mu_B g_\parallel S_z H_z + \mu_B g_\perp \left( S_x H_x + S_y H_y \right) + D S_z^2 + E \left( S_x^2 - S_y^2 \right) \\
+ \frac{F}{180} \left[ 35 S_z^4 - 30 S(S+1) S_z^2 + 25 S_z^2 \right] + \frac{1}{6} a \left( S_1^4 + S_2^4 + S_3^4 \right)
\]

(27)

where \( \mu_B \) is the Bohr magneton, \( \hat{H} \) is the magnetic field, and \( S \) is the spin quantum number of \( \text{Cr}^{2+} \) ion \((S = 2)\) and \((1,2,3)\) are cubic axes. The \( D, E, F \) and \( a \) parameters are fine structure constants taking values \([21]\): 

\[
g_\parallel = 1.90 \pm 0.15 \, \text{cm}^{-1}, \quad g_\perp = 1.980 \pm 0.015 \, \text{cm}^{-1}, \quad D = 0.260 \pm 0.004 \, \text{cm}^{-1}, \quad E = 0, \\
\]

\[
a = 0.05 \pm 0.01 \, \text{cm}^{-1}, \quad F = -0.05 \pm 0.02 \, \text{cm}^{-1}. \quad \]

These Cr based DMS (with small \( x: 0.001 < x < 0.01 \)) show paramagnetic properties and fulfill the intermediate case between Brillouin and Van Vleck paramagnetism while the ground state concludes a multiplet of the nearby located states (figure 8).

C. Ferromagnetic Resonance of \( \text{Cd}_{1-x} \text{Cr}_x \text{Te} \)

Our samples contain a substantial amount of Cr ions: \( x = 0.05 \). Therefore, we expect the ferromagnetic properties as description the theoretical works of Blinowski, Kacman and Majewski \([11, 26, 27, 28]\). Such ferromagnetic behaviour was earlier discovered in zinc chalcogenides (\( \text{ZnS}, \text{ZnSe}, \text{ZnTe} \)) with \( \text{Cr}^{3+} \) paramagnetic ions \([28]\). The p-d exchange interaction between \( \text{Cr}^{2+} \) ions with an adequately high concentration is responsible for this type of ferromagnetism \([11, 28]\). The same theory explains the ferromagnetism in cadmium chalcogenides (\( \text{CdS}, \text{CdSe}, \text{CdTe} \)) for which the transfer energies in p-d and d-d exchange are almost identical with those in \( \text{Zn} \) compounds \([27]\). Our measurements of magnetic resonance (figure 5) confirm the presence of ferromagnetism in the \( \text{CdCrTe} \) samples studied. The spectra reveal typical features of the FMR: anisotropy of the resonance field as well as the anisotropy of the peak-peak width of the line. The Lorentzian shape of the lines (figure 6) contributes to this conclusion as well.

The twofold symmetry of the line position changes in an angular dependence (figure 10) indicates that the plane "a", in which the anisotropy was registered, is the crystallographic plane \((110)\). We compare these data with Bickford’s equations (24) (25), which can be written a new together as:

\[
\omega_0 = \gamma \mu_0 \left[ \frac{H_z + \left( N_y + 2 \left( 1 - 2 \sin^2 \theta - \frac{3}{8} \sin^2 2 \theta \right) \frac{K_1}{M_z^2 \mu_0} - N_z \right) M_z}{\left( H_z + \left( N_x + \left( 2 - \sin^2 \theta - 3 \sin^2 2 \theta \right) \frac{K_1}{M_z^2 \mu_0} - N_z \right) M_z \right)} \right]^{1/2}.
\]

(28)

In order to apply this formula to a description of the results of the magnetic domain experiment, i.e. \( \nu_0 = \text{const} \), \( H_z = H_{\text{res}} = H_{\text{res}}(\theta) \) one can derive the angular dependence of \( H_{\text{res}} \) from equation (28), as below:

\[
H_{\text{res}} = -\frac{1}{2} N M_z + \frac{H_1}{2} \left( 4 - 5 \sin^2 \theta - \frac{15}{4} \sin^2 2 \theta \right) + \\
+ \frac{H_z}{2} \left( \frac{1}{2} \sin^6 \theta + 3 \sin^2 \theta \cos^4 \theta - 7 \sin^4 \theta \cos^2 \theta - \sin^2 \theta \cos^2 \theta \right) + \\
+ \sqrt{R^2 + \left( \frac{\omega}{\gamma} \right)^2}
\]

(29)
where

\[ R = -\frac{1}{2} NM_z + \frac{H_1}{2} \left( \frac{9}{4} \sin^2 2\theta - 3\sin^2 \theta \right) + \]
\[ + \frac{H_2}{2} \left( -\frac{1}{2} \sin^6 \theta - 3\sin^2 \theta \cos^4 \theta + 4\sin^4 \theta \cos^3 \theta - \sin^2 \theta \cos^2 \theta \right) \]  \hspace{1cm} (30)

There are three unknown parameters in equations 29 and 30:

\[ NM_z, \quad H_1 = \frac{K_1}{M_z} \quad \text{and} \quad H_2 = \frac{K_2}{M_z} \]

A general graphical view of the angular dependence of the resonance field (equation 29) in the plane (110) is presented in figure 11. This plot was obtained for (100) plane in which three nonequivalent axes [001], [110] and [111] were indicated.

**Figure 10.** Angular dependence of the resonance magnetic field (figure 3.4.5b) for CdCrTe in the plane “a” (110) (figure 7) with principal axes [001], [221] and [110].
Figure 11. Angular dependence of the resonance magnetic field in the plane (110) of a cubic crystal (according to equation (29) for the following parameters: $H_1=0.12$ kOe, $H_2=0.1$ kOe, $NM_z=1.2$ kOe, $\omega/\gamma=3.8$ kOe).

The shape of the curve in figure 10 resembles that in figure 11. However, the distance between the two axes is about 20° rather than 54°. This is in agreement with the presumption that in our crystal the axis [221] (see figure 12) is more significant than [111]. Therefore we describe the extrema of the angular dependence studied as it was indicated in figure 10.

Figure 12. Nonequivalent axes in (110) plane of CdCrTe crystal for the three elementary cells shown here.

5. Conclusions
The solid solution Cd$_{1-x}$Cr$_x$Te ($x = 0.5$) grown by us shows ferromagnetic properties at room temperature. The properties of the ferromagnetic resonance line suggest on the sp-d interaction in the samples studied. Based on the experimental results presented here we are not able to estimate the contribution of the other CrTe phases to the ferromagnetism of the samples. Such foreign phases could be also ferromagnetic [29] and may appear as nanoclusters in the samples. However, the XRD studies we have conducted are indicative that this contribution is not dominant.
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