Theoretical models and EPR study of Cr based diluted magnetic semiconductors

M Kuzma*, I Stefaniuk and M Bester
Institute of Physics, University of Rzeszow, 35-959 Rzeszow, Rejtana 16A, Poland

Abstract. The II-VI diluted magnetic semiconductors (DMS) with chromium are good candidates for room temperature ferromagnetic semiconductors. We review the theoretical models of sp-d and d-d exchange interactions applicable for semiconductors containing transition metal ions. The unique magnetic properties of Cr based DMS originate from the following properties of Cr ion in tetrahedral environment: strong Jahn-Teller distortion the position of the donor level and occupation of the $t_{2g}$ orbital. The magnetic properties of samples Cd$_{1-x}$Cr$_x$Te, $x=0.02$ we investigate by electron paramagnetic resonance in the temperature range $T=290-380$ K. The temperature broadening of the epr line points on a ferromagnetic phase transition in the vicinity of the room temperature.

1. Introduction

The main goal of the material engineering for spintronics is to find a magnetic semiconductor which exhibits electrically tunable ferromagnetism at room temperature. It allows to join logic and storage operations on the same chip [1]. The studies on this subject have a long history as they were started in 1970’s when the sp-d exchange interaction in solid solutions of Mn-based II-VI semiconductors was extensively studied. The wide range of experimental as well as theoretical results of such and related investigations were summarised in several reviews (see [2] and references therein). The other types of diluted magnetic semiconductors (DMS) with manganese were also designed, grown and investigated: IV–VI [2] and III-V [3] DMS. The main progress was made since the theoretical paper written by Dietl et al. [4, 5] at al on 5% Mn doped DMS’s showing high Curie temperatures. From calculations presented in these papers the semiconductors Si, Ge, AlP, AlAs, GaP, GaAs, InP, InAs, ZnSe, ZnTe with hole concentration $3.5 \times 10^{20}$ attain the Curie temperature in the range 30-100K. Moreover, the room Curie temperature was derived for C, GaN, ZnO. Unfortunately, the extended experimental investigations do not confirm this optimistic predictions until nowadays, and the task is still open.

A promising group of DMS’s are Cr-based II-VI [6] IV-VI [2, 7-11] and other DMS’s. In a few among them the room temperature ferromagnetism was detected e.g. in Cr:InN [12], Cr:GaN [13], CdCrTe [14], ZnCrTe [15]. This list of room temperature ferromagnetic semiconductors can be completed by Mn-doped InSb, CdGeAs$_2$ and CdGeP$_2$ [16].

In this paper we review the main properties of Cr - DMS’s, focusing the study on microscopic models of the exchange interaction in II-VI diluted magnetic semiconductors with transition metal ions. We also present our experimental results on CdCrTe. The significant aim of the paper is to communicate the unusual magnetic property, room temperature ferromagnetism of our samples of
2. Exchange interactions in DMS’s

Magnetic properties of DMS’s follow from the exchange interactions between spins of the band carriers and localized spins of magnetic ions (sp-d exchange) or between localized spins (d-d exchange). Several microscopic models were used to explain nature of these interactions. Dominated mechanisms in II-VI DMS’s are:

1. Direct or potential exchange interaction based on the Coulomb interaction between spins [17]. This model very well describes the s-d interaction.
2. Kinetic exchange interaction involving hybridization effects [17, 18] (is used for p-d coupling).
3. Indirect exchange of the type of superexchange [19] (provides good results for the d-d interaction).

2.1 Model of the s-d interaction

The interaction between conduction s band electron spins and magnetic ion spins resulting from the Coulomb interaction is of the ferromagnetic type. Its value is close to $N_0\alpha \approx 0.2$ eV almost for all DMS’s. This s-d interaction is described by Kondo-like Hamiltonian [20]

$$H_{ss} = -J(r - R_i)\vec{s} \cdot \vec{S}_i$$

(1)

where $\vec{s}$ is a spin operator of the band electron, $\vec{S}_i$ is a spin operator of the magnetic ion which is localized in the crystal lattice point $R_i$, $J(r - R_i)$ is the exchange integral.

For electrons from conduction band (s electrons) and from valence band (p electrons) the matrix elements of the exchange integrals are denoted as

$$N_0\alpha = N_0\langle S|J|S\rangle, \quad N_0\beta = N_0\langle X|J|X\rangle$$

(2)

respectively.

2.2 Model of the p-d interaction

The experimentally measured interaction between valence charge carriers and localized spins (p-d interaction) is of antiferromagnetic type (negative value of $\beta$). The value $N_0\beta$ is six to eight times greater than s-d interaction $N_0\alpha$. Thus the resulting magnetic properties of DMS are antiferromagnetic ones. Such large value of the p-d interaction does not arise from the simple Kondo model. Dietl [18], Bhattacharjee et al. [17] and Larson [19] explained the experimentally observed values and the sign of the p-d interaction for Mn based DMS by the p-d hybridization effects.

The model Hamiltonian of the multisite Anderson Hamiltonian consists of Hamiltonian term $H_0$ of the s, p energy bands $\varepsilon_{s}(k)$ of the crystal, Hubbard Hamiltonian $H_d$ of Mn d electrons on site $i$ with linearized electron – electron interaction, the Mn 3d – Te 5p hybridization Hamiltonian $H_{pd}$ (termed as kinetic part of $H$) and Mn-d – sp-band potential exchange Hamiltonian $H_\chi$ [19]:

$$H = H_0 + H_d + H_{pd} + H_\chi$$

(3)

In the second order perturbation approach the p-d exchange energy consists of two contributions represented by formulae [19]:

$$H_{pd} = \sum_{i,j} \sum_{\sigma} \sum_{\tau} \sum_{\tau'} \sum_{\sigma'} c_{i\sigma}^{\dagger} c_{j\sigma} c_{j\tau} h_{\sigma\tau}^p c_{i\sigma'}^{\dagger}$$

$$H_\chi = \sum_{i} \sum_{\sigma} \sum_{\tau} \sum_{\tau'} \sum_{\sigma'} \sum_{\sigma''} c_{i\sigma}^{\dagger} c_{i\sigma'} c_{i\sigma''} h_{\sigma\tau\sigma''}^\chi c_{i\sigma'}^{\dagger}$$
\[ N\beta = -32V_{pd}^2 \left( \epsilon_d + U_{\text{eff}} - E_v \right)^{-1} + \left( E_v - \epsilon_d \right)^{-1} \]  \hspace{1cm} (4) 

where \( E_v \) is the valence-band-edge energy, \( \epsilon_d \) and \( U_{\text{eff}} \) are parameters of the Hubbard model: the energy of the \( d \) orbital on site \( i \) and the energy of an electron-electron interaction respectively (see Fig 1a).

Due to symmetry, the \( V_{pd} \) vanishes for \( s \) states; therefore the allowed transitions are those between \( t_{2g} \) states only. Such virtual transitions for \( p \) electrons from the vicinity of the valence band edge are illustrated by diagram in Fig.1a (without changing of \( k \) vector) and in Fig 1b (with change of \( k \) vector).

Blinowski and Kacman \[21, 22\] derived kinetic exchange Hamiltonians of Luttinger \( \Gamma_8 \) states interacting with \( t_{2g} \) impurity states for whole set of transition metal ions using initial Hamiltonian in the form

\[ H = H_i + H_{cr} + H_{\text{hyb}} \]  \hspace{1cm} (5)

Here \( H_i \) is the Parmenter like Hamiltonian \[23\]. Such Hamiltonian commutes with both orbital \( \vec{L} \) and spin \( \vec{S} \) momentum operators, therefore the calculations are applicable also for states different from \( S \)-state.

\[ H_i = \epsilon_d \hat{N} + \left( J - \frac{U'}{2} \right) \hat{N}^2 + \left( \frac{1}{2} \right) \hat{N}^2 - J \hat{\vec{S}} \hat{\vec{S}} \] \hspace{1cm} (6)

where \( \epsilon_d \) is here the energy of \( d \) state, \( \hat{N} \) is an occupation number operator, \( U' \) is nondiagonal Coulomb integral and \( J \) is non-diagonal exchange integral, \( H_{cr} \) is the Hamiltonian of the band electrons restricted to electrons with energy \( \epsilon_p \) in a vicinity of the center of the Brillouine zone.
The hybridization Hamiltonian

\[ H_{\text{hyb}} = \sum_{nk} \sum_{m\sigma} (V_{m\sigma, nk} a_{m\sigma, nk}^\dagger + h.c.) \]  

(8)
couples the p electrons with the t_{2g} d electrons only.
For Mn\(^{2+}\) the effective kinetic p-d exchange Hamiltonian is [22]

\[ H_{ex} = -(1/\Omega)2B_3 \langle \vec{S} \rangle \vec{J} \]  

(9)

After thermodynamic averaging over randomly distributed Mn ions, the mean-field Hamiltonian takes the form

\[ H_{ex} = -\frac{1}{3} xN_0 \beta_N \langle \vec{S} \rangle \vec{J} \]  

(10)

where \( xN_0 \) is a concentration of the magnetic ions, \( J_\parallel \) is the projection of the fictitious angular momentum \( j=3/2 \) of the valence band electron onto external magnetic field, \( \beta_N \) is exchange constant:

\[ \beta_N = -\frac{V_{pd}^2}{S} \left[ \frac{I}{E_{N-l/2}^S + E_p - E_N^S} + \frac{I}{E_{N+l/2}^S - E_p - E_N^S} \right] \]  

(11)

where \( V_{pd} \) is hybridization constant

2.3 Model of the d-d interaction
The direct Heisenberg exchange interaction between localized spins (direct d-d interaction)

\[ H_{dj} = -2J_{dj} \vec{S}_i \vec{S}_j \]  

(12)
is much smaller than the sp-d interaction.
Larson et al [19] studied the d-d mediated superexchange interaction between two Mn spins in II-VI DMS. It appears that this process is dominated in Mn-Mn interaction. The theory was developed in the frame of the band picture of MnTe and CdMnTe compounds. The Mn-Mn interaction has been described by Heisenberg Hamiltonian

\[ H_N = -\sum_{i \neq j}^N J_{dd} (R_{ij}) \vec{S}_i \vec{S}_j \]  

(13)
To calculate the exchange integral \( J_{dd} \) Larson took into account the effect of the \( H_{pd} \) Hamiltonian on an intermediate states in which the occupation of Mn d states is different from five. In the forth-order perturbation formalism the Mn-Mn interaction constant \( J_{dd} \) is expressed as [19]:

\[ J_{dd} = -\sum_{i \neq j}^N J_{dd} (R_{ij}) \vec{S}_i \vec{S}_j \]  

(13)
\[-2\left(\frac{5}{2}\right)J^{dd}(R^d) = \sum_{l_1,l_2,l_3} \left\langle f \left| H_{pd} I_1 I_1 I_2 H_{pd} I_3 I_3 H_{pd} I_j \right| I_i I_i I_i \right\rangle \left( E_0 - E_j \right) \left( E_0 - E_j \right) \left( E_0 - E_j \right) \right] \tag{14}\]

where \( |i> \) and \( |f> \) are initial and final states and \( |I_i> \) (where \( i = 1,2,3 \)) are intermediate states. The sum of terms in formulae (16) can be decomposed into three terms \( J^{dd}_{hh}, J^{dd}_{ee}, J^{dd}_{he} \) consisting of Mn intermediate states formed by transfer of two electrons respectively from the valence band, from conduction band, as well as one electron from conduction band and one from valence band.

\[J^{dd}(R^d) = J^{dd}_{hh}(R^d) + J^{dd}_{ee}(R^d) + J^{dd}_{he}(R^d) \tag{15}\]

These three mechanisms are presented schematically in Fig. 2.

Fig.2. The three mechanisms of kinetic d-d interactions.

For II-VI DMS the dominant contribution follows from the \( J^{dd}_{hh} \) terms (Fig.2a). They can be calculated as [19]:

\[J^{dd}_{hh}(R^d) = [A,B,C,D] + [C,D,A,B] + [A,C,D,B] + [C,A,D,B] + [C,A,B,D] = \]

\[-2 \sum_{k,k',n,n'} |\tilde{V}_{pd}(n,k)|^2 |\tilde{V}_{pd}(n',k')|^2 \cos \left[ (k - k') \cdot R_{ij} \right] \times \]

\[\left\{ U_{eff} \left[ \epsilon_n(k) - \epsilon_d - U_{eff} \right]^{-1} \left[ \epsilon_n(k') - \epsilon_d - U_{eff} \right]^{-1} - \left[ \epsilon_n(k) - \epsilon_d - U_{eff} \right]^{-2} \left[ \epsilon_n(k') - \epsilon_d - U_{eff} \right]^{-1} \right\} \tag{16}\]

where the symbols \([A,B,C,D]\) and its permutations are sums of terms of Eq. (14) corresponding to the intermediate state sequences showed. Exemplary calculations performed by Larson for real CdMnTe crystals give results being in good agreement with experiments.

### 2.4 Three level model of the hole mediated superexchange.

Basing on calculations presented above Larson [19] proposed the simplified expression for the superexchange in materials related to CdMnTe as well as to many other DMS
where \( \varepsilon_d \) is energy of occupied d level, \( \varepsilon_d + U_{\text{eff}} \) is the energy of an unoccupied d level, \( E_v \) is energy of p electrons at the top of valence band, \( V_{pd} \) is hopping parameter which connects the p level to both d levels, \( f(r) \) is the constant describing the influence of \( R_{ij}/a \) on \( J_{dd}^{hh} \). This constant should be determined for each material within particular approximation separately.

3. Magnetic properties of Cr-DMS
The sp-d exchange interaction in magnetic semiconductors controls their unusual magnetic properties such as giant magneto – optical effects (e.g. Zeeman splitting, Faraday rotation). The nature of the exchange interaction depends on the magnetic ion and determine the type of long–ranged interactions in material which results in paramagnetism, antiferromagnetism, spin-glass or ferromagnetism depending on the magnetic ion and temperature. Almost all DMS’s show antiferromagnetic properties. In the paramagnetic temperature regime the DMS’s with Mn, Co are Brillouin paramagnets (these ions have multiplet ground states and orbital momentum \( L=0 \)) whereas in Fe: DMS (ground state is singlet (\( L=2, S=2 \)) the Van Vleck–type paramagnetism is observed. The separate group of magnetic semiconductors are those containing chromium. In these semiconductors the sp-d interaction is ferromagnetic and paramagnetic properties are intermediate between Brillouin and Van Vleck type (ground state is semidublet but excited states lie close enough to generate magnetic moment).

The unique magnetic properties of the II-VI DMS based on Cr follow from several features of Cr ion in a tetrahedral environment:
1. Cr ion is strongly affected by Jahn–Teller distortion.
2. The position of chromium donor level \( t_{2g} \) is in close vicinity to the top of the valence band.
3. One \( t_{2g} \) orbital of \( \text{Cr}^{2+} \) is not occupied.

The model of p-d interaction proposed by Blinowski and Kacman [22] presented in preceding section (Eq. (9)) is applicable for all transition metal ions. Kacman [24] interpreted the dependence of one electron orbital filling on magnetic properties in that model. The Mn, Fe, Co ions have the same filling (singly with spin up) of \( t_{2g} \) orbitals (see Fig. 3). The exchange interaction between these ions is antiferromagnetic.

### Fig.3 Filling of one-electron orbitals in transition metal ions.

Opposing, the ions Sc, Ti, have the \( t_{2g} \) orbitals empty. Therefore the virtual transition are in direction from the band to an ion only, independently on the spin direction. In this case the exchange constant was obtained in the form.

\[
J_{dd}^{hh}(R_{ij}) = -2V_{pd}^2\left[U_{\text{eff}}^{-1}\left(E_v - \varepsilon_d - U_{\text{eff}}\right)^2 - \left(E_v - \varepsilon_d - U_{\text{eff}}\right)^3\right]f(r) \tag{17}
\]

\[
J_{dd}^{hh}(R_{ij}) = -2V_{pd}^2\left[U_{\text{eff}}^{-1}\left(E_v - \varepsilon_d - U_{\text{eff}}\right)^2 - \left(E_v - \varepsilon_d - U_{\text{eff}}\right)^3\right]f(r) \tag{17}
\]

\[
\gamma_N = \frac{V_{pd}^2}{\Omega\left(S + \frac{1}{2}\right)}\left[\frac{1}{E_{N+l}^{S+1/2} - \varepsilon_p - E_N^S} - \frac{1}{E_{N+l}^{S-l/2} - \varepsilon_p - E_N^S}\right] \tag{18}\]
The second term in (18) is smaller in comparison with the first one, thus the exchange constant is positive giving ferromagnetic properties of the system. The free Cr$^{2+}$ ion has $N = 4$ electrons on $d$ shell. The ground state is a triplet state $T_2$. One state among the one electron $t_{2g}$ states is empty. In this case the kinetic exchange Hamiltonian between $d$ electrons and $p$ ($\Gamma_8$) band electrons is [22].

$$H_{ex} = \left( \frac{1}{\Omega} \right) \left( C_N - B_N \right) \cdot \vec{J} \pm \left( C_N + B_N \right) \cdot \left( \vec{J} + \left[ \hat{H}_Q - \vec{L} \cdot \vec{J} + \hat{\Omega} \right] \right) \cdot \vec{S} + D_N \left( \hat{H}_Q - \vec{L} \cdot \vec{J} \right)$$  \hspace{1cm} (19)

The constants $B_N$, $C_N$, $D_N$ (corresponding to the constants $\beta_N$, $\gamma_N$, $\delta_N$ in notation of the paper [24]) and the operator $\hat{H}_Q$ are:

$$B_N = \beta_N = \left( \frac{V^2}{2S} \right) \left[ \left( E_N^S - E_{N-i}^{S-j/2} - \epsilon_p \right)^{\dagger} + \left( E_N^S + \epsilon_p - E_{N+i}^{S-j/2} \right)^{\dagger} \right]$$  \hspace{1cm} (20)

$$C_N = -\gamma_N = \frac{V^2}{2S + 1} \left[ \left( E_N^S + \epsilon_p - E_{N+i}^{S-j/2} \right)^{\dagger} - \left( E_N^S + \epsilon_p - E_{N+i}^{S-j/2} \right)^{\dagger} \right]$$  \hspace{1cm} (21)

$$D_N = \delta_N = (S + 1)C_N + SB_N$$  \hspace{1cm} (22)

$$\hat{H}_Q = \left( \vec{L} \cdot \vec{J} \right)^2 + \frac{1}{2} \vec{L} \cdot \vec{J} - \frac{1}{3} l(l+1)j(j+1)$$  \hspace{1cm} (23)

The parameters $B_N$, $C_N$, $D_N$ depends on Parmenter parameters $\epsilon_d - \epsilon_p$, on the energy $U'$ and $J$ as well as on the hybridization constant $V$. The $E_N^S$ denotes energy of the unperturbed $d$ shell with $N$ electrons and total spin $S$.

The exchange Hamiltonian $H_{ex}$ (19) depends on the orbital momentum $\vec{L}$ of the ground state of the ion, contrary to the Hamiltonian (14)

$$H_{ex} = \left( \frac{1}{\Omega} \right) 2B_N \vec{S} \vec{J}$$  \hspace{1cm} (24)

derived for Mn ions. Therefore the system is sensitive to a perturbation which can lift the degeneracy of the ground state such as Jahn-Teller distortion, external magnetic field, or spin-orbit coupling. In the II-VI DMS with Cr$^{2+}$ ions the tetragonal Jahn-Teller distortion is static and very strong [25, 26]. In this case the exchange Hamiltonian has form [22]:

a) for a distortion in the [001] direction

$$H_{ex} = \frac{1}{6} xN_0 \delta_j \left( \frac{5}{4} - J_z^2 \right) + \frac{1}{3} xN_0 \left< S_z \right> J_z \left[ \beta_n \left( \frac{5}{4} - J_z^2 \right) - \gamma_n \left( \frac{9}{4} - J_z^2 \right) \right]$$  \hspace{1cm} (25)

b) for uniform distortion in three equivalent {001} directions
The second Hamiltonian is of the Heisenberg-like form with exchange constant proportional to $(2\beta_4 + \gamma_4)$. Thus the sign of this constant follows from the contributions of both values $\beta_4$ and $\gamma_4$. However, there are several experiments [27] pointed that the origin of ferromagnetic type of Cr based DMS follows from the position of the donor Cr$^{2+}/3+$ level which is near the top of the valence band as it is schematically drawn in Fig. 4. We note in Fig.4 that the donor levels of Cr impurity is almost at the valence band maximum in two cases: of ZnTe and CdTe crystals. Blinowski and Kacman [21, 28] show that, in principle, the sign of $\beta$ is determined by the energy $e_1$ of charge transfer from Cr$^{2+}$ ion to the valence band. The $\beta$ should be positive if this energy is negative. This conclusion is in good agreement with Kanamori model of the energy levels of Cr$^{2+}$ in ZnS, ZnSe, ZnTe [29] as well as with experimental results of Mac et al [27].

Table 1. Values of the p-d exchange interaction constants in Cr based DMS.

| Material | $N_0\alpha$ (eV) | $N_0\beta$ (eV) |
|----------|------------------|-----------------|
| Cd$_{1-x}$Cr$_x$S | - | 0.22 ± 0.02 [30] |
| Cd$_{1-x}$Cr$_x$Se | - | 0.48 ± 0.05 [31] |
| Cd$_{1-x}$Cr$_x$Te | - | 0.62 [27] |
| Zn$_{1-x}$Cr$_x$S | - | 0.95 [27] |
| Zn$_{1-x}$Cr$_x$Se | - | 4.25 [27] |
| Zn$_{1-x}$Cr$_x$Te | - | 0.93 [27] |

Fig. 4 Approximate energy levels position of Cr and Mn ions in Cr$^{2+}/3+$, Mn$^{2+/3+}$ (lower levels) and Cr$^{1+/2+}$, Mn$^{1+/2+}$ (upper levels) charge states. The diagram is constructed basing on the data given in [32] and [33].

The ferromagnetic p-d exchange interaction of Cr ions in Zn-chalcogenides has been experimentally studied in several papers of Mac, Twardowski at al [27, 31, 34, 35]. The values of p–d exchange constants in such materials are collected in Table 1.
4. EPR measurements in CdCrTe

The measurements were carried out on Cd\textsubscript{1-x}Cr\textsubscript{x}Te sample. The sample was prepared by synthesis of the CdTe and Cr\textsubscript{2}Te\textsubscript{3} components with the nominal Cr concentration x = 5%. The liquid high temperature synthesis was carried out in quartz ampoule at temperature 1300\degree C. The concentration of Cr in the ingot obtained was measured by XRF method and was x = 0.02. The EPR studies were carried out on X-band spectrometer in high temperature regime of 290 - 380K. The set of EPR spectra obtained at various temperatures are collected in Fig. 5a.

![Fig. 5. EPR spectra of CdCrTe DMS (a), Temperature dependence of the EPR lines width (b).](image)

The spectrum consists of one broad line with resonance field at 260 – 320 mT depending on temperature. The shape of the line at two different temperatures are presented in Fig. 6a and b. The shape was adjusted to the Lorentz function. The good agreement with this function is visible. The width of the lines was derived from the theoretical adjustment.

![Fig 6 High temperature shape of the resonance lines of CdCrTe approximated with Lorentz function: T= 380K (a), T=360K (b).](image)

The temperature variation of the line width is presented in Fig. 5b. This dependence does not relate to that observed for Cd or Zn based antiferromagnetic DMS with Mn (e.g. Zn\textsubscript{1-x}Mn\textsubscript{x}S, Zn\textsubscript{1-x}Mn\textsubscript{x}Se, Zn\textsubscript{1-x}Mn\textsubscript{x}Te, Cd\textsubscript{1-x}Mn\textsubscript{x}S, Cd\textsubscript{1-x}Mn\textsubscript{x}Se, Cd\textsubscript{1-x}Mn\textsubscript{x}Te, [36]). For samples with Mn there is a dramatic broadening of the resonance at low temperatures and then the resonance narrows continuously as the temperature increases. Such a behaviour is typical for antiferromagnet DMS. In our sample we note (in Fig.5b) that the linewidth decreases starting from high temperature until...
temperature $T_{\text{min}} = 320\text{K}$ at which the linewidth takes minimal value. Below this temperature it increases with temperature decreasing. Such a behaviour was observed in studies of CMR manganites and is not fully understood. Huber et al [37] relates the EPR linewidth in LaMnO$_3$ to the interplay of crystal field anisotropy, Dzialozhinsky-Mariya (antisymmetric) exchange and anisotropic superexchange. Moreover, the same type of the temperature dependence of the EPR linewidth was observed by Story at al [38] in $\text{Pb}_{1-x}\text{Sn}_x\text{Mn}_x\text{Te}$ in the regime of high carrier concentration exceeding the value of threshold (see Fig.8 in [38]). However, in this paper this effect was attributed to the Korringa relaxation mechanism, where linear temperature dependence is expected in the high temperature regime. This mechanism was also addressed to interpretation of results of HgFeSe DMS [39].

In our material investigated the resonance field decreases strongly at temperatures $T < 300\text{K}$, the linewidth becomes large and the shape of lines is asymmetric considerably. Therefore at low temperatures the magnetic resonance of the material studied is addressed as ferromagnetic resonance (FMR). The properties of CdCrTe studies by FMR in low temperature regime 77-300K were presented in our previous paper [40].

5. Conclusions
Chromium based diluted magnetic semiconductors have been theoretically many years ago to reveal exceptional magnetic properties [28]. The theoretical models of the exchange interactions in DMS show that the unusual magnetic properties of Cd$_{1-x}$Cr$_x$Te arises from the strong Jahn-Teller distortion, from the position of donor Cr$^{2+}$ level, as well as from half occupation of $t_{2g}$ orbital of Cr$^{2+}$. These properties should lead to room temperature ferromagnetism in such materials. In the present paper the EPR measurements were carried out for Cr$_x$Cd$_{1-x}$Te crystal with a high concentration of Cr ions ($x$=0.02). Results presented in the paper, seem to correlate with the theoretical expectation. The shape of resonance line is Lorentzian. The temperature dependence of linewidth in high temperature regime (paramagnetic regime) differ considerably from that observed for Mn DMS. We observe broadening of the line with temperature instead the constant behaviour. Obtained minimum in the temperature dependence of the linewidth relates to the Curie temperature as in other ferromagnetic semiconductors. This temperature in our material is near room temperature. But the results do not explain which interaction is responsible for the observed phenomena. Further supplementary studies are necessary.

References
[1] Ohno H, Chiba D, Matsuokura F, Omiya T, Abe E, Dietl T, Ohno Y and Ohtani K 2000 *Nature* **408** 944
[2] Dobrowolski W, Kossut J and Story T 2003 *Handbook of Magnetic Materials* vol. 15, ed K H Bushow Amsterdam: Elsevier Science
[3] MacDonald A H, Schiffer P and Samarth N 2005 *Nature Materials* **4** 195
[4] Dietl T, Ohno H, Matsukura F, Cibert J and Ferrand D 2000 *Science* **30** 1019
[5] Dietl T, Ohno H and Matsukura F 2001 *Phys. Rev. B* **63** 195205
[6] Blinowski J, Kacman P and Majewski J A 1996 *Phys. Rev.* **53** 9524
[7] Wilamowski Z and Story T 1995 *Journal of Magnetism and Magnetic Materials* **140-144** 1731
[8] Dobrowolski W, Arciszewska M and Brodowska M 2006 *Sci. of Sintering* **38** 109
[9] Grodzicka E, Dobrowolski W, Story T, Wilamowski Z and Witkowska G 1996 *Cryst. Res. Technol.* **31** 651
[10] Story T, Wilamowski Z, Grodzicka E and Dobrowolski W 1995 *Acta Phys. Pol.* **87** 229
[11] Grodzicka E, Dobrowolski W, Kossut J, Story T and Witkowska B 1994 *J. of Crystal Growth* **138** 1034
[12] Ney A, Rajaram R, Kammermeier T, Ney V, Dhar S, Ploog K H and Parkin S S 2008 *J. Phys. Condens. Matter.* **20** 20
[13] Cui Y X, Medvedeva J E, Delley B and Freeman A J 2005 Phys. Rev. Lett. 95 256404.1
[14] Ko K Y and Blamire M G 2006 Appl. Phys. Lett. 88 1721101
[15] Saito H, Zayets V, Yamagata S and Ando K 2003 Phys. Rev. Lett. 116 207202
[16] Story T, Galazka R R, Frankel R B and Wolf P A 1986 Phys. Rev. Lett. 56 777
[17] Bhattarcharjee A K, Fishman G and Coqblin B 1983 Physica 449 117
[18] Dietl T 1981 Physics in High Magnetic Field, vol. 24 ed M Miura Berlin: Springer
[19] Larson B E, Haas K C, Ehrenreich H and Carlsson A E 1988 Phys. Rev. B 37 4137
[20] Kossut J 1976 Phys. Stat. Sol. (b) 78 537
[21] Blinowski J, Dietl T and Kacman P 1992 Acta Phys. Pol. 82 641
[22] Blinowski J and Kacman P 1992 Phys. Rev. B 46 12298
[23] Parmeuter R H 1973 Phys. Rev. B 8 1273
[24] Kacman P 2001 Semicond. Sci. Technol. 16 R25
[25] Vallin J T, Slack G A and Roberts S 1970 Phys. Rev. B 2 4313
[26] Vallin J T and Watkins D G 1974 Phys. Rev. B 9 2051
[27] Mac W, Twardowski A and Demianiuk M 1996 Phys. Rev. B 54 5528
[28] Blinowski J, Kacman P and Majewski J A 1995 Acta Phys. Pol. 88 683
[29] Kanamori J 1963 Progr. Theor. Phys. 30 275
[30] Twardowski A, Heiman D, Liu M T, Shapira Y and Demianiuk M 1996 Phys. Rev. B 53 10728
[31] Herbich M, Mac W, Twardowski A, Ando K, Shapira Y and Demianiuk M 1998 Phys. Rev. B 58 1912
[32] Langer J M and Heinrich H 1985 Phys. Rev. Lett. 55 1414
[33] Dietl T 1994 Handbook on Semiconductors vol. 3, ed T S Moss Amsterdam: Elsevier Science
[34] Mac W, Khoi Nguyen The, Twardowski A and Gaj J A 1993 Phys. Rev. Lett. 1a 2327
[35] Mac W, Twardowski A, Eggenkamp P J, Swagten H J, Shapira Y and Demianiuk M 1994 Phys. Rev. B 50 14144
[36] Kremer R E and Furdyna J K 1985 Phys. Rev. B 31 1
[37] Huber D L, Alejandro G, Causa M T, Prado F, Tovar M and Oseroff S B 1999 Phys. Rev. 60 12155
[38] Story T, Eggenkamp P J, Swuste C H, Swagten H J and de Jonge W J 1993 Phys. Rev. B 47 227
[39] Wilamowski Z, Mycielski A, Jantsch W and Hendorfer G 1988 Phys. Rev. B 38 3621
[40] Stefaniuk I, Bester M and Kuzma M 2008 J. of Physics: Conference Series 104 012010