Hall effect and magnetoresistance in p-type ferromagnetic semiconductors

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Recent works aiming at understanding magnetotransport phenomena in ferromagnetic III-V and II-VI semiconductors are described. Theory of the anomalous Hall effect in p-type magnetic semiconductors is discussed, and the relative role of side-jump and skew-scattering mechanisms assessed for (Ga,Mn)As and (Zn,Mn)Te. It is emphasized that magnetotransport studies of ferromagnetic semiconductors in high magnetic fields make it possible to separate the contributions of the ordinary and anomalous Hall effects, to evaluate the role of the spins in carrier scattering and localization as well as to determine the participation ratio of the ferromagnetic phase near the metal-insulator transition. A sizable negative magnetoresistance in the regime of strong magnetic fields is assigned to the weak localization effect.

INTRODUCTION

The assessment of magnetic characteristics by means of magnetotransport studies is of particular importance in the case of thin films of diluted magnets, in which the magnitude of the total magnetic moment is typically small. For this reason, recent years have witnessed a renewed interest in the nature of the anomalous Hall effect (AHE) \[1,2,3,4,5\], which—if understood theoretically—can serve to determine the magnitude of magnetization. Also magnetoresistance, though less directly, provides information on the magnetism and on the interplay between electronic and magnetic degrees of freedom.

In this paper, we discuss selected magnetotransport properties of III-V and II-VI magnetic semiconductors containing Mn as the magnetic element. In particular, we show that the side-jump mechanism accounts for the magnitude of the anomalous Hall effect in both (Ga,Mn)As and (Zn,Mn)Te samples for which extensive experimental data are available. We emphasize, however, that the current theory of the effect requires further refinements. We also suggest that weak localization magnetoresistance may contribute to the increase of the hole conductivity in the limit of low temperatures \(T\) and high magnetic fields \(H\). Recent review papers \[6,7\] summarize rather thoroughly principal findings of previous comprehensive studies of these materials, which are not touched upon here.

HALL EFFECT IN FERROMAGNETIC SEMICONDUCTORS – THEORETICAL MODELS

The Hall resistance \(R_{\text{Hall}} \equiv \rho_{xy}/d\) of a film of the thickness \(d\) is empirically known to be a sum of ordinary and anomalous Hall terms in magnetic materials \[8,9,10,11,12\].

\[
R_{\text{Hall}} = R_0 \mu H/d + R_S \mu M/d. \tag{1}
\]

Here, \(R_0\) and \(R_S\) are the ordinary and anomalous Hall coefficients, respectively \((R_0 > 0\) for the holes), and \(M(T,H)\) is the component of the magnetization vector perpendicular to the sample surface. While the ordinary Hall effect serves to determine the carrier density, the anomalous Hall effect (known also as the extraordinary or spin Hall effect) provides valuable information on magnetic properties of thin films. The coefficient \(R_S\) is usually assumed to be proportional to \(R_{\text{sheet}}^\alpha\), where \(R_{\text{sheet}}(T,H)\) is the sheet resistance and the exponent \(\alpha\) depends on the mechanisms accounting for the AHE.

If the demagnetization effect were been dominating, \(R_S\) would be rather proportional to \(R_0\) than to \(R_{\text{sheet}}\). However, there is no demagnetization effect in the magnetic field perpendicular to the film surface, \(B = \mu_0 H\). Here, spin-orbit interactions control totally \(R_S\). In such a situation \(\alpha\) is either 1 or 2 depending on the origin of the effect: the skew-scattering mechanism, for which the Hall conductivity is proportional to momentum relaxation time \(\tau\), results in \(\alpha \approx 1\) \[3,6,13,14,15\]. From the theory point of view particularly interesting
is the side-jump mechanism. This is because in both weak and strong scattering limit, $\omega \tau \gg 1$ and $\omega \tau \ll 1$, where $\omega$ is the frequency of the electric field, the corresponding Hall conductivity $\sigma_{AH} = \frac{R_s M}{(R_{\text{sheet}} d)^2}$ does not depend explicitly on scattering efficiency but only on the band structure parameters $[3, 11, 12]$. Surprisingly, $\sigma_{AH}(\omega \tau \gg 1) = -\sigma_{AH}(\omega \tau \ll 1)$ according to these works.

For both skew-scattering and side-jump mechanisms, the overall magnitude of the anomalous Hall resistance depends on the strength of the spin-orbit interaction and spin polarization of the carriers at the Fermi surface. Accordingly, at given magnetization $M$, the effect is expected to be much stronger for the holes than for the electrons in tetrahedrally coordinated semiconductors. For the carrier-mediated ferromagnetism, the latter is proportional to the exchange coupling of the carriers to the spins, and varies – not necessarily linearly – with the magnitude of spin magnetization $M$. Additionally, the skew-scattering contribution depends on the asymmetry of scattering rates for particular spin subbands, an effect which can depend on $M$ in a highly nontrivial way. Importantly, the sign of either of the two contributions can be positive or negative depending on a subtle interplay between the orientations of orbital and spin momenta as well as on the character (repulsive vs. attractive) of scattering potentials.

We presume that general theory of the AHE effect in semiconductors $[11, 12]$ gives correctly the ratio of side-jump and skew-scattering mechanisms, also in the case of p-type semiconductors. If scattering by ionized impurities dominates, this ratio is then given by $[10, 12, 13]$

$$\frac{\sigma_{AH}^{s_j}}{\sigma_{AH}^{s_j}} = \pm f(\xi)(N_A + N_D)/(pr_s k_F \ell),$$

where the positive sign corresponds to the weak scattering limit. Here, $f(\xi) \approx 10$ is a function that depends weakly on the screening dimensionless parameter $\xi$; $(N_A + N_D)/p$ is the ratio of the ionized impurity and carrier concentrations; $r_s$ is the average distance between the carriers in the units of the effective Bohr radius, and $\ell$ is the mean free path. Similarly, for spin-independent scattering by short range potentials, $V(r) = V\delta(r - r_i)$ $[11]$.

$$\frac{\sigma_{AH}^{s_j}}{\sigma_{AH}^{s_j}} = \pm 3/[\pi V \rho(\varepsilon_F) k_F \ell],$$

where the negative sign corresponds to the weak scattering limit and $\rho(\varepsilon_F)$ is the density of states at the Fermi level. Of course, the overall sign depends on the sign of the scattering potential $V$.

In order to find out which of the two AHE mechanisms operates predominantly in p-type tetrahedrally coordinated ferromagnetic semiconductors, we note that scattering by ionized impurities appears to dominate in these heavily doped and compensated materials. This scattering mechanism, together with alloy and spin disorder scattering, limits presumably the hole mobility and leads ultimately to the metal-to-insulator transition (MIT). Since at the MIT $r_s \approx 2$ and $k_F \ell \approx 1$ we expect from Eq. 2 that as long as the holes remain close to the localization boundary the side-jump mechanism accounts for the AHE. It would be interesting on know how quantum localization corrections affect the anomalous Hall conductivity as well as how to extend theory towards the insulator side of the MIT. A work in this direction has recently been reported $[14]$.

Recently, Jungwirth et al. $[4]$ developed a theory of the AHE in p-type zinc-blende magnetic semiconductors, and presented numerical results for the case of (Ga,Mn)As, (In,Mn)As, and (Al,Mn)As. The employed formula for $\sigma_{AH}$ corresponds to that given earlier $[3, 11, 12]$ for the side-jump mechanism in the weak scattering limit. For the hole concentration $p$ such that the Fermi energy is much smaller than the spin-orbit splitting $\Delta_0$, but larger than the exchange splitting $h$ between the majority $j_z = -3/2$ and minority $j_z = +3/2$ bands at $k = 0$, $\Delta_0 \gg |\varepsilon_F| \gg h$, Jungwirth et al. $[4]$ predict within the $4 \times 4$ spherical Luttinger model

$$\sigma_{AH}^{s_j} = e^2 h m_{hh}/[4\pi^2 \hbar^3 (3\pi p)^{1/3}].$$

Here the heavy hole mass $m_{hh}$ is assumed to be much larger than the light hole mass $m_{lh}$, whereas $\sigma_{AH}^{s_j}$ becomes by the factor of $2^{4/3}$ greater in the opposite limit $m_{hh} = m_{lh}$. In the range $h \ll |\varepsilon_F| \ll \Delta_0$, the determined value of $\sigma_{AH}^{s_j}$ is positive, that is the coefficients of the normal and anomalous Hall effects are expected to have the same sign. However, if the Fermi level were approached the split-off $\Gamma_7$ band, a change of sign would occur.

We have derived $\sigma_{AH}^{s_j}$ from Chazalviel’s formula $[12]$ in the weak scattering limit (which is equivalent to Eq. 4 of Jungwirth et al. $[4]$), employing the known form of the heavy hole Bloch wave functions $u_{k,j_z}$. Neglecting a small effect of the spin splitting on the heavy hole wave functions, we find $\sigma_{AH}^{s_j}$ to be given by the right hand side of Eq. 4 multiplied by the factor $(16/9)\ln 2 - 1/6 \approx 1.066$.

Obviously, the presence of the AHE makes a meaningful determination of the carrier type and density difficult in ferromagnetic semiconductors. Usually, the ordinary Hall effect dominates only in rather high magnetic fields or at temperatures several times larger than $T_C$. It appears, therefore, that a careful experimental and theoretical examination of the resistivity tensor in wide field and temperature ranges is necessary to separate characteristics of the spin and carrier subsystems.
70% of them must have been compensated by donors. If as acceptors in the metallic sample described above, the average hole concentration is \( p = 3.5 \times 10^{20} \text{ cm}^{-3} \), about 30% of the Mn concentration. A similar value of the hole concentration, which is almost independent of \( x \), has been obtained from the Seebeck coefficient assuming a simple model of the valence band [17]. If all Mn centers are acting as acceptors in the metallic sample described above, 70% of them must have been compensated by donors.

The most natural candidates for these donors are As antisite defects, which act as deep donors in GaAs. Accordingly, (Ga,Mn)As should become insulating at room temperature when the density of As antisites exceeds the density of shallow acceptors. Because the magnitudes of these densities are comparable and moreover fluctuate from run to run depending on subtleties of the growth conditions, we expect the overcompensation to occur occasionally. However, no such ‘overcompensated’ sample has been obtained so far. This seems to call for mechanisms controlling the upper limit of the excess As concentration and/or leading to selfcompensation of Mn but not to overcompensation. One candidate for the latter might be the Mn interstitial, which acts as the relevant compensating donor according to first principles calculations [18] and recent channeling studies [19].

Figures 2 and 3 present a comparison of the Hall resistance \( R_{Hall} \) at 50 mK in the field range of 22–27 T on the sample with \( x = 0.053 \) revealed that the conduction is p-type, consistent with the acceptor character of Mn, as shown in Fig. 1 [10]. The determined hole concentration is \( p = 3.5 \times 10^{20} \text{ cm}^{-3} \), about 30% of the Mn concentration. A similar value of the hole concentration, which is almost independent of \( x \), has been obtained from the Seebeck coefficient assuming a simple model of the valence band [17]. If all Mn centers are acting as acceptors in the metallic sample described above, 70% of them must have been compensated by donors.
played field and temperature range. If $R_{\text{sheet}}$ depends on temperature, a comparison of magnetization and magnetotransport data can serve to identify whether the skew-scattering or side-jump mechanism dominates. In particular, since $R_{\text{Hall}}/R_{\text{sheet}}^\alpha \sim M$, Arrott’s plots can be employed to determine the temperature dependence of spontaneous magnetization $M_S(T) = M(T, 0)$. As shown in Fig. 2, the temperature dependence of $M_S$ determined by the magnetotransport measurements assuming $\alpha = 1$ can be fitted rather well by the mean-field Brillouin function \[ V \]. A different temperature dependence stems from direct magnetization measurements in a SQUID magnetometer presented in Fig. 3 for the same sample \[ W \]. Owing to an increase of $R_{\text{sheet}}$ with temperature in this sample, $M_S(T)$ determined by the two methods can be made somewhat closer by choosing $\alpha = 2$. This may indicate that the side-jump mechanism dominates. The dependence $M_S(T)$ determined by the SQUID measurements cannot be fitted by a simple Brillouin function, $M_S(T)/M_S(0) = 1 - (T/T_c)\gamma$, where $\gamma = 5/2$. Actually, a less convex dependence, $n < 5/2$, is expected even within the MFA in magnetic semiconductors \[ X \].

The findings presented above have been exploited by Jungwirth et al. \[ Y \] to test their theory of the AHE. The results of such a comparison are shown in Fig. 4 \[ Z \]. There is a good agreement between the theoretical and experimental magnitude of the Hall conductivity. Importantly, no significant contribution from the skew-scattering is expected for the (Ga,Mn)As sample in question, for which, according to Figs. 1-3, $(N_A + N_D)/p \approx 5$, $r_s \approx 1.1$, and $k_F \ell \approx 0.8$, so that $\sigma_{AH}^{\sigma} \approx \sigma_{AH}^\sigma \approx 57$. Finally, we note that the sign of the effect indicates that weak scattering limit $\omega \tau \gg 1$ is appropriate in the case under consideration. Obviously, however, further works are necessary to elucidate the role of intra- and inter-subband scattering processes in the physics of the side-jump mechanism.

It is important to note that there exist several reasons causing that the Hall effect and direct magnetometry can provide different information on magnetization. Indeed, contrary to the standard magnetometry, the AHE does not provide information about the magnetization of the whole samples but only about its value in regions visited by the carriers. Near the metal-insulator boundary, especially when the compensation is appreciable, the carrier distribution is highly non-uniform. In the regions visited by the carriers the ferromagnetic interactions are
strong, whereas the remaining regions may remain paramagnetic. Under such conditions, magnetotransport and direct magnetic measurements will provide different magnetization values. In particular, $M_S$ at $T \to 0$, as seen by a direct magnetometry, can be much lower than that expected for a given value of the magnetic ion concentration. High magnetic fields are then necessary to magnetize all localized spins. The corresponding field magnitude is expected to grow with the temperature and strength of antiferromagnetic interactions that dominate in the absence of the holes.

Finally, we note that no clear indication of the presence of MnAs clusters has been observed in the transport studies, even in the cases, where direct magnetization measurements detect their presence. One of possibilities is that the Schottky barrier formation around the MnAs clusters prevents their interaction with the carriers. Conversely, the presence of a clear influence of the magnetic subsystem onto transport properties (colossal magnetoresistance, anomalous Hall effect) can be taken as an evidence for the mutual interactions of the spins and the carriers. Such interactions are behind virtually all proposed applications of magnetic semiconductors.

**EXPERIMENTAL RESULTS: (ZN,MN)Te**

Figure 5 shows the Hall resistivity $R_{\text{Hall}}$ measured at various temperatures for the highly doped $\text{Zn}_{0.981}\text{Mn}_{0.019}\text{Te}:\text{N}$ sample. The quoted hole concentration is deduced from the slope of the room temperature Hall resistance. The dependence $R_{\text{Hall}}$ is linear in the magnetic field and temperature independent down to 150 K. In the case of the p-ZnTe sample, this normal Hall effect $R_{\text{Hall}}$, linear in the field $H$ and temperature independent, is observed down to 1.6 K. By contrast, in the case of p-$\text{Zn}_{1-x}\text{Mn}_x\text{Te}$, when decreasing the temperature below 100 K, one observes first an increase of the slope of the Hall resistance, and then a strong non-linearity, which point to the presence of the anomalous Hall effect.

As expected, no anomalous Hall effect has been detected in wide-gap n-type II-VI DMS [24]. At low temperature and high field, the Mn or the hole spin polarization saturate, and then the Hall resistivity exhibits again a linear dependence on the applied field, with the same slope as at room temperature. Thus, while the spin-dependent component is too large to allow us to determine the hole density at low temperatures and in small fields, due to low $T_C$, its magnitude becomes negligibly small at room temperature, or at low-temperature in high fields. For these two cases, the slope of the Hall resistance was found to be identical, giving unambiguously the value of the hole density.

In the case of less doped samples, it was possible to measure the Hall resistivity down to typically 10 K, with the same conclusions, i.e., (i) the normal Hall effect dominates at temperatures above 150 K; (ii) the Hall resistivity varies linearly with the magnetic field at low temperature in sufficiently large magnetic fields, and (iii) a strong spin-dependent component appears at weak magnetic fields and at low temperatures, though its accurate determination in this region is hampered by the large value of the resistance and a strong magnetoresistance. As mentioned above, the Hall resistance provides direct information on the degree of spin polarization $\mathcal{P}$ of the carrier liquid.

In Fig. 6, $\rho_{yx}/\rho_{xx} - \mu B$, i.e., the spin dependent Hall angle, is compared to the magnetization measured in a vibrating sample magnetometer [23]. The normal Hall angle $\mu B = \mu \mu_B H$ was subtracted assuming a constant hole mobility $\mu$ i.e., assigning the conductivity changes entirely to variations in the hole concentration. This assumption is not crucial for the present highly doped sample, but it proves to be less satisfactory for the less doped samples. As shown in Fig. 6, a reasonable agreement is found by taking,

$$\rho_{yx}/\rho_{xx} = \mu B + \Theta M/M_S, \tag{5}$$

where $M_S$ is the saturation value of magnetization and $\Theta = 0.04$ is the adjustable parameter. For the sample in question, the maximum value of hole polarization, $(\rho_{pp} - \rho_{down})/(\rho_{pp} + \rho_{down})$, has been estimated to be of the order of 10% [23].

We note that similarly to the case of (Ga,Mn)As, the sign and magnitude of the anomalous Hall coefficient suggests that the side jump mechanism in the weak scattering limit is involved. We evaluate $\Theta$ theoretically from
carrier concentration. Since the magnetic field orders the spins, negative magnetoresistance occurs, sometimes leading to the field-induced insulator-to-metal transition\cite{23, 24}. Deeply in the metallic phase, virtually all spins contribute to the ferromagnetic ordering. Critical scattering and the associated negative magnetoresistance are then observed\cite{14}. However, as shown in Fig. 1, the negative magnetoresistance hardly saturates, even in the extremely strong magnetic fields. In order to explain this observation we note that the giant splitting of the valence band makes both spin-disorder and spin-orbit scattering relatively inefficient. Under such conditions, weak localization magnetoresistance can show up at low temperatures, where inelastic scattering ceases to operate. According to Kawabata\cite{22},

$$
\Delta \rho / \rho = -n_e e^2 C_\rho (e B / h)^{1/2} / (2 \pi^2 h),
$$

where $C_\rho \approx 0.605$ and $1/2 \leq n_e \leq 2$ depending on whether one or all four hole subbands contribute to the charge transport. For the sample in question the above formula gives $\Delta \rho / \rho = -0.1$ for $n_e = 1$ and 25 T, the value consistent with the experimental results in Fig. 1. Since the negative magnetoresistance takes over above $B_0 \approx 1$ T, we can evaluate a lower limit for the spin-flip scattering time\cite{23, 24, 30}, $\tau_s > m * / (e B k_F \ell) \approx 5$ ps for $m* = 0.7 m_o$ and $k_F \ell = 0.8$.

**SUMMARY**

Experimental results discussed above demonstrate the critical importance of the Hall effect in the assessment of the magnetic properties of III-V ferromagnetic semiconductors. Furthermore, they suggest that the side-jump mechanisms gives the dominant contribution for metallic samples, in which a comparison between theoretical expectations and experimental results is possible. Importantly, the theory discussed here explains the sign of the effect and, together with the results obtained by Jungwirth\textit{et al.}\cite{5}, explains the magnitude of the Hall conductance.

Importantly, such studies can also serve to detect a participation of the double exchange mechanism in the spin-spin interactions. This is because, the spin excitations associated with this coupling produce a strong temperature dependence of $R_S$ near $T_C$\cite{5}. We take the absence of a strong temperature dependence of $R_S$ near $T_C$ as an evidence for the minor importance of the double exchange in the studied systems. Conversely, a good agreement between the measured and calculated Hall coefficients, if confirmed by further investigations, will constitute an important support for basic assumptions behind the Zener model\cite{22} of ferromagnetism in this class of ferromagnetic semiconductors.

Furthermore, the accumulated information on magnetoresistance points to significance of the spin-disorder

FIG. 6: Comparison of the normalized anomalous Hall effect (lines) with the normalized magnetization $M/M_S$ (crosses); from top to bottom: 1.7, 2.8, 4.2, 7, 10, 30, and 50 K; the data are shifted for clarity (after\cite{23}).

Eq. 4 by adopting parameters suitable for the sample in question, $m_{th} = 0.6m_o$, $\rho_{xx} = 5 \times 10^{-3}$ $\Omega$cm and the saturation value of the splitting $h = 41$ meV. This leads to $\sigma_{AH}^2 = 13.1$ ($\Omega$cm)$^{-1}$ and $\Theta^{2j} = 0.065$, in a reasonable agreement with the experimental value $\Theta = 0.04$. Since a contribution from the light hole band will enhance the theoretical value, we conclude that the present theory describes the anomalous hole effect within the factor of about two. We note also that in contrast to earlier suggestions\cite{23}, not skew-scattering but the side-jump mechanism appears to give the dominant contribution to the AHE in p-(Zn,Mn)Te. However, as mentioned above, further theoretical work is needed to assess the role of hole scattering.

**MAGNETORESISTANCE**

There is a number of effects that can produce a sizable magnetoresistance in magnetic semiconductors, especially at the localization boundary\cite{26}. In particular, spin disorder scattering shifts the MIT towards higher
scattering as well as reveal various effects associated with the interplay between spin and localization phenomena, specific to doped diluted magnetic semiconductors in the vicinity of the metal-insulator transition.

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[1] J.E. Hirsch, Phys. Rev. Lett. 83 (1999) 3737.
[2] Jinwu Ye, Yong Baek Kim, A.J. Millis, B.I. Shraiman, P. Majumdar, and Z. Téšanović, Phys. Rev. Lett. 83 (1999) 3737.
[3] S. Zhang, Phys. Rev. Lett. 85 (2000) 393.
[4] A. Crépieux and P. Bruno, Phys. Rev. B 64 (2001) 014416.
[5] T. Jungwirth, Qian Niu, and A.H. MacDonald, Phys. Rev. Lett. 88 (2002) 207208.
[6] H. Ohno and F. Matsukura, Solid State Commun. 117 (2001) 179.
[7] T. Dietl, Semicond. Sci. Technol. 17 (2002) 377.
[8] L. Berger and G. Bergmann, in: The Hall Effect and Its Applications, eds. L. Chien and C. R. Westgate (Plenum, New York, 1980).
[9] J.M. Luttinger, Phys. Rev. 112 (1958) 739.
[10] P. Leroux-Hugon and A. Ghazali, J. Phys. C 5 (1972) 1072.
[11] P. Nozières and C. Lewiner, J. de Physique 34 (1973) 901.
[12] J.-N. Chazalviel, Phys. Rev. B 11 (1975) 3918.
[13] J.-N. Chazalviel, Phys. Rev. B 10 (1974) 3018.
[14] V.K. Dugaev, A. Crépieux, and P. Bruno, cond-mat/0103182.
[15] W. Szymańska and T. Dietl, J. Phys. Chem. Solids 39 (1978) 1025.
[16] T. Omiya, F. Matsukura, T. Dietl, Y. Ohno, T. Sakon, M. Motokawa, and H. Ohno, Physica E 7 (2000) 976.
[17] V. Osinnyi, A. Jedrzejczak, M. Arciszewska, W. Dobrowolski, T. Story, and J. Sadowski, Acta Phys. Polon. A 100 (2001) 327.
[18] J. Mašek, J. and F. Máča, Acta Phys. Polon. A 100 (2001) 319; Phys. Rev. B 65 (2002) 235209.
[19] K.M. Yu, W. Wałukiewicz, T. Wojtowicz, I. Kuryliszyn, X. Liu, Y. Sasaki, and J. K. Furdyna, Phys. Rev. B 65 (2002) 201303(R).
[20] F. Matsukura, H. Ohno, A. Shen and Y. Sugawara, Phys. Rev. B 57 (1998) R2037.
[21] T. Dietl, H. Ohno, and F. Matsukura, Phys. Rev. B 63 (2001) 195205.
[22] T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science 287 (2000) 1019.
[23] D. Ferrand, J. Cibert, A. Wasiele, C. Bourgognon, S. Tatarenko, G. Fishman, S. Koleński, J. Jaroszyński, T. Dietl, B. Barbara, and D. Dufeu, J. Appl. Phys. (2000) 5461.
[24] Y. Shapira, N.F. Oliveira Jr., D.H. Ridges, R. Kershaw, K. Dwight, and A. Wold, Phys. Rev. B 34 (1986) 4187.
[25] D. Ferrand, J. Cibert, A. Wasiele, C. Bourgognon, S. Tatarenko, G. Fishman, T. Andrearczyk, J. Jaroszyński, S. Koleński, T. Dietl, B. Barbara, and D. Dufeu, Phys. Rev. B 63 (2001) 085201.
[26] T. Dietl, in Handbook on Semiconductors vol. 3B ed. T.S. Moss (Amsterdam: Elsevier) p. 1251.
[27] S. Katsumoto, A. Oiwa, Y. Iye, H. Ohno, F. Matsukura, A. Shen, and Y. Sugawara, phys. status solidi (b) 205 (1998) 115.
[28] A. Kawabata, Solid State Commun. 34 (1980) 432.
[29] Y. Ono and J. Kossut, J. Phys. Soc. Jpn. 53, 1128 (1984).
[30] M. Sawicki, T. Dietl, J. Kossut, J. Igalson, T. Wojtowicz, and W. Plesiewicz, Phys. Rev. Lett. 56, 508 (1986).