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Electrical transport in Mn-doped GaAs pn-diodes

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We have studied the effect of magnetic ordering on the electrical transport in magnetic GaAs diodes. The fabricated pn-junctions consist of Mn-doped ferromagnetic layers on top of non-magnetic semiconductor substrates. First the electrical and magnetic properties of the magnetic layers are investigated, which shows that the exchange interaction between the charge carriers and the localized magnetic moments of the Mn-atoms dominates the charge transport at temperatures close to the Curie temperature. In the Ga\textsubscript{1−x}Mn\textsubscript{x}As/GaAs-p\textsuperscript{+}/n\textsuperscript{+}-junctions having heavily doped p- and n-regions, the inter-band tunnelling current shows large dependence on the magnetic ordering. The spin-dependent tunnelling can be explained by a model, where the density of valence band states decreases due to the band splitting caused by the exchange interaction. From the measured decrease of the tunnelling current we estimated the value for the exchange parameter $J_{\text{exch}}^{\text{pd}} = 2.9$ eV. Various explanations for the absence of magnetoresistance in the magnetic diodes with lightly doped non-magnetic regions are discussed.

1 Introduction

Spintronics is an emerging field of micro- and nanoelectronics, where the electron spin in addition to its charge plays an important role [1, 2]. One of the major factors affecting the rapid progress in semiconductor spintronics during the last few years has been the discovery of ferromagnetism in conventional III–V compound semiconductors like GaAs, when heavily doped with magnetic ions such as manganese [3, 4]. These diluted magnetic semiconductors (DMS’s) have attracted considerable attention, because they hold promises of creating a new class of semiconductor devices with unprecedented functionality for electronics and photonics. The suggested applications [5] include, e.g., magnetic devices with gain, spin field effect transistors operating at low power levels and allowing, e.g., the software reprogramming of the microprocessor hardware during run time, spin valves, which would result in a fast non-volatile semiconductor memory, integrated magnetic/electronic/photonic devices (‘electromagnetism-on-a-chip’), and spin qubits for quantum computing.

Mn-doped GaAs has been the most studied DMS so far for obvious reasons: (Ga,Mn)As is compatible with the highly developed GaAs device technology, and the observed carrier induced ferromagnetism can be controlled by fabrication techniques in a straightforward manner. In addition to pure material

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research also some basic semiconductor devices such as pn-junctions [6–10] and resonant tunnelling
devices [11] have been fabricated and studied. The \( I-V \) characteristics and the light emitting properties
of those devices have been investigated, but typically the dependence of the charge transport on the mag-
netic properties of the devices has been omitted. Recently we have discussed briefly the properties of a
ferromagnetic tunnel diode made of Mn-doped GaAs [12].

In the present paper we study thoroughly the magnetotransport in GaAs-pn-diodes consisting of a Mn
doped ferromagnetic layer on top of a non-magnetic semiconductor substrate. Especially we are inter-
ested in the magnetic field dependence of the electrical transport, which has not been studied previously.
The ferromagnetic pn-diodes are studied for various dopant concentrations, which allows us to investi-
gate the magnetic diodes operating both in the ordinary diffusion and tunnelling modes.

The theory of magnetic pn-diodes has been developed by several groups [13–15]. In the present paper
we briefly discuss the most important features of the existing models, which then can be exploited in the
analysis of the experimental results. Especially, we add to the models the spin-dependent tunnelling
processes, which have been neglected in the previous models and which are important in the heavily
doped pn-diodes. A large magnetic field dependence in the \( I-V \) characteristics has been found in non-
magnetic tunnel diodes already decades ago [16–19]. However, this phenomenon, which is related to a
formation of the Landau levels in high mobility semiconductors, was observed only in tunnel diodes
made of small band-gap semiconductors such as InSb or PbTe, not in GaAs diodes. In addition, the phe-
nomenon is not associated with the magnetic ordering of the magnetic atoms, and therefore we do not
discuss it in the present paper.

2 Modelling of the magnetic diodes

In magnetic semiconductors the strong dependence of the electrical properties on the magnetic ordering
is caused by the exchange interaction between the charge carrier spin \( s \) and the total spin \( S_R \) of the local-
ized magnetic electrons at a lattice point \( R \):

\[
H_{\text{exch}} = - J_{\text{exch}} \sum_R \delta(r-R) S_R \cdot s(r),
\]

where \( J_{\text{exch}} \) is the parameter for the exchange interaction. This interaction results in a band splitting \( \Delta \)
between the spin-up and spin-down carriers:

\[
\Delta = x J_{\text{exch}} \langle S^z \rangle.
\]

Here \( x \) is the mole fraction of the magnetic ions, and \( x \langle S^z \rangle = \sum_R \langle S_R^z \rangle / N \) is the average spin polarization
of the magnetic ions \( (N \) is the number of unit cells).

The effect of the band splitting (2) on the band diagram of the magnetic pn-diode is shown in Fig. 1,
where \( \Delta_1 = x J_{\text{exch}}^\text{con} \langle S^z \rangle \) is the band splitting parameter for the conduction band, and \( \Delta_2 = x J_{\text{exch}}^\text{val} \langle S \rangle \) for the
valence band. The case (a) is valid in an ideal ferromagnetic pn-diode, where the magnetic region on the
p-side extends also to the depletion region \([-x_p, 0] \), and the possible band discontinuities at \( x = 0 \) have
been neglected. Figure 1(b) shows the effect of large band discontinuities on the band diagram, and, finally,
Fig. 1(c) shows the situation, where the ferromagnetism is carrier induced, and therefore there is
no magnetic ordering in the depletion region, and the band splitting occurs only in the neutral region
\( x < -x_p \) on the magnetic side of the junction.

In addition to the band splitting, the exchange interaction (1) also causes spin disorder scattering
[20–22] due to the spin fluctuations in the magnetic subsystem. The scattering rate is highest at temperatures
close to \( T_C \), and it is reduced in high magnetic fields leading to negative magnetoresistance. This
must be taken into account when considering the effect of the series resistance of the diodes on the \( I-V \)
characteristics of the magnetic pn-junctions.

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The total electrical current in a magnetic pn-diode is given by [15, 23]

\[ I_{\text{tot}} = I_{\text{diff}} + I_{\text{rec}} + I_{\text{tunn}} + I_X, \]

where \( I_{\text{diff}} \) is the diffusion current density, and \( I_{\text{rec}} \) is associated with the recombination processes in the depletion region. \( I_{\text{tunn}} \) describes the direct band-to-band tunnelling contribution, and \( I_X \) is the tunnelling current through defect states in the band gap.

When the band splitting (2) is taken into account, the standard Shockley model leads to the following expression for the diffusion current in the case of Fig. 1(a) [15]:

\[ I_{\text{diff}} = A q n_i^2 \left( \frac{D_n \alpha^4/2kT}{2L_n n_A^2} + \frac{D_p \alpha^4/2kT}{2L_p n_P N_A^2} + \frac{D_p}{I_p N_D} \right) \left( e^{(\beta R_{\text{ser}})/kT} - 1 \right). \]

Here \( A \) is the area of the diode, \( n_i \) is the intrinsic carrier concentration, \( D_n (D_p) \) is the carrier diffusion coefficient for the electrons (holes), \( L_n (L_p) \) is the diffusion length of the electrons (holes), and \( N_A (N_D) \) is the acceptor (donor) concentration. \( R_S \) is the series resistance of the diode, which may depend on the magnetic ordering, if the spin disorder scattering dominates the charge transport in the magnetic layer.

The band splitting parameter \( \Delta_1 \sim \langle S' (T, B) \rangle \) depends strongly on temperature \( T \) and magnetic field \( B \), and, therefore, the diffusion current model (4) predicts a large magnetoresistance at temperatures, where \( \Delta_1 \gg k_B T \), if \( I_{\text{diff}} \) is the dominant contribution to the total current, and if \( N_A \geq N_D \). The same prediction has been presented by Zutic et al. [13] in their model for magnetic diodes. However, if there is a large band discontinuity \( \Delta E_c \) in the depletion region, as shown in Fig. 1(b), the thermionic emission over the barrier \( \Delta E_c \) can dominate the current instead of \( I_{\text{diff}} \). This contribution does not depend on the band splitting, and, therefore, we do not expect large magnetoresistance in the case of Fig. 1(b). Also in the case of Fig. 1(c), where the magnetic ordering is missing completely in the depletion region due to the absence of charge carriers, the built-in potential over the depletion region does not depend on the band splitting, and, consequently, no large magnetoresistance is expected.
In the case of magnetic diodes the tunnelling contribution $I_{\text{tunn}}$ to the total current (3) becomes dependent on the magnetic ordering due to the effect of the band splitting on the density of states and due to the spin-dependence of the tunnelling probability. Figure 2 shows the band diagram in a heavily doped ferromagnetic tunnel diode. As the forward bias voltage over the diode increases, the electrons in the conduction band on the n-side may tunnel to the empty states in the valence band on the p-side, i.e., the tunnelling current vs. voltage probes the electronic states near the band edge on the ferromagnetic side of the pn-junction. Especially, the valence band splitting shown in Fig. 2 should have an effect on the $I-V$ characteristics of the ferromagnetic tunnel diode. This effect can be estimated from the standard tunnelling current expression [23] for the direct inter-band tunnelling processes:

$$I_{\text{tunn}} = AC \sum_{\sigma} \int \frac{E_c(n)}{E_v(p)} T_{\sigma}(E) \left( f_c(E) - f_v(E) \right) D_c(E) D_v(E) \, dE,$$

where $C$ is a constant, and $E_c(n)$ and $E_v(p)$ are the band edges of the conduction band on the n-side and the valence band on the p-side, respectively. $T_{\sigma}(E)$ is the spin-dependent tunnelling probability, $f_c(E)$ and $f_v(E)$ are the Fermi–Dirac distribution functions, and $D_c(E)$ and $D_v(E)$ are the densities of state for the conduction and valence bands, respectively:

$$D_c(E) = \frac{M_c m_{hc}^3 \sqrt{2}}{\pi^2 \hbar^3} (E - E_c)^{3/2},$$

$$D_v^\sigma(E) = \frac{1}{2} \frac{m_v^\sigma \sqrt{2}}{\pi^2 \hbar^3} \left[ E_v - E - \frac{\Delta_v}{2} \left( \delta_{\uparrow\uparrow} - \delta_{\downarrow\downarrow} \right) \right]^0.$$

Here $M_c$ is the number of equivalent minima in the conduction band, and $m_{hc}(m_v)$ is the density of state effective mass for the electrons (holes). In (7) we have taken into account the ferromagnetism on the p-side and the consequent valence band splitting (2). The parameters $p_1$ and $p_2$ have the value 1/2 in the case of parabolic bands [23]. However, in heavily doped disordered semiconductors with tail states at energies close to the band edges $E_c$ and $E_v$, the parameters $p_1$ and $p_2$ may have values larger than 1/2.

The tunnelling probability depends exponentially on the height of the tunnelling barrier [23] $E^\sigma$:

$$T_{\sigma}(E) = \exp \left[ -A_{\sigma}(E^\sigma)^{3/2} - A_{\perp}E_{\perp} \right],$$

where $A_{\sigma} = \pi \sqrt{m_e^w/(2\sqrt{2}qF)}$, $m_e^w$ is the electron–hole reduced mass, $F$ is the electric field in the depletion region, $A_{\perp} = 3\pi \sqrt{m_h^w E^w/(4\sqrt{2}qF)}$, $E^w$ is the forbidden band gap, and $E_{\perp}$ is the energy associated with the transverse momentum. The band splitting (2) results in the spin-dependence of the tunnelling.
probability, since now the tunnelling barrier depends on the spin-polarization as

\[ E_n^\sigma = E_\sigma + \frac{A}{2} (\delta_{\sigma_1} - \delta_{\sigma_0}) . \]  

(9)

We can expand (8) as a Taylor series by substituting (9) into (8) and considering \( \Delta \) as a small parameter as compared to \( E_\sigma \):

\[ T_\sigma(E) = e^{-\frac{3AE_\sigma^{3/2}\Delta}{4E_\sigma}} \left[ 1 - \frac{3AE_\sigma^{3/2}\Delta}{4E_\sigma} (\delta_{\sigma_1} - \delta_{\sigma_0}) + \frac{3}{32} \left( \frac{\Delta}{E_\sigma} \right)^2 AE_\sigma^{3/2} + \ldots \right] . \]  

(10)

Furthermore, we can estimate the relative change in \( T(E) \) (and in the current \( I \)) from (10):

\[ \frac{\Delta T}{T} = \left[ \frac{1}{2} (T_\sigma(\Delta > 0) + T_\sigma(\Delta > 0)) - \frac{1}{2} (T_\sigma(\Delta = 0) + T_\sigma(\Delta = 0)) \right] / \frac{1}{2} [T_\sigma(\Delta = 0) + T_\sigma(\Delta = 0)] 
\approx - \frac{3\pi \sqrt{m^*}}{64 \sqrt{2\hbar F}} \left( \frac{\Delta}{E_\sigma} \right)^2 . \]  

(11)

By using typical values for the parameters in Mn-doped GaAs, \( \Delta^{mn} = 0.025 \) eV \([24]\), \( E_\sigma = 1.4 \) eV, \( F = 10^7 \) V/cm, and \( m^* = 0.5m_0 \), we can estimate from (11), that the change in the tunnelling current due to the change in the tunnelling probability is negligible (<0.1%).

Another factor, which may result in a larger magnetic-field dependence of the tunnelling current, is a change in the density of states \( v(D) \) due to the band splitting (2). We can expand (7) as a Taylor series by considering now the valence band splitting parameter as a small parameter, and by using the expansion \( (1 + x)^p = 1 + px + p(p - 1) x^{p/2} \). When \( E_\sigma - E > \Delta/2 \) we get

\[ D^\sigma(D) = \frac{m^*}{\pi\hbar^2} \left[ E_\sigma - E - \frac{\Delta}{2} (\delta_{\sigma_1} - \delta_{\sigma_0}) \right]^p \approx D_1 \left[ E_\sigma - E - \frac{\Delta}{2} (\delta_{\sigma_1} - \delta_{\sigma_0}) \right]^p \]

\[ = D_1 \left( E_\sigma - E \right)^p \left[ 1 - \frac{\Delta_1 (\delta_{\sigma_1} - \delta_{\sigma_0})}{2(E_\sigma - E)} \right]^p \]

\[ = D_1 \left( E_\sigma - E \right)^p \left[ 1 - \frac{p_1 \Delta_1 (\delta_{\sigma_1} - \delta_{\sigma_0})}{2(E_\sigma - E)} + \frac{p_1(p_1 - 1)}{2} \left( \frac{\Delta_1}{2(E_\sigma - E)} \right)^2 \right] . \]  

(12)

By using this expansion we can estimate the relative change in the density of states due to the band splitting, and it is given by

\[ \frac{\Delta D^\sigma}{D^\sigma} = \left[ D_1^\sigma(E) + D_1^\sigma(E) - 2D_1^\sigma(E_\sigma - E)^p - 2D_1^\sigma(E_\sigma - E)^p \right] / 2D_1^\sigma(E_\sigma - E)^p \approx \frac{p_1(p_1 - 1)}{2} \left( \frac{\Delta_1/2}{E_\sigma - E} \right)^2 . \]  

(13)

We see from (13), that in the case of the parabolic band \( p_1 = 1/2 \) the density of states decreases, \( \Delta D^\sigma/D^\sigma < 0 \), when \( \Delta_1 \neq 0 \). By using the parameter values \( \Delta_1 = 0.2 \) eV \([24]\), \( p_1 = 1/2 \), and \( E_\sigma - E_\sigma = 0.2 \) eV, we get from (13) an estimate \( \Delta D^\sigma/D^\sigma = -3\% \) for the maximum change due to the band splitting, which is much larger than the previous estimate for the change in the tunnelling probability.

The effect of the magnetic ordering on the tunnelling current in a ferromagnetic tunnel diode can be calculated more reliably from the current expression (5) by performing the numerical integration over the overlapping band states in the case of Fig. 2. Figure 3 shows the calculated \( I \sim V \) characteristics in the cases \( p_2 = 1/2 \) and \( p_2 = 3/2 \), when only the inter-band tunnelling is taken into account. Here we used the
Fig. 3 Calculated $I–V$ characteristics in a ferromagnetic tunnel diode in the case (a) $p_2 = 1/2$, and (b) $p_2 = 3/2$. The solid curves show the tunnelling currents when there is no band splitting, $\Delta = 0$, and the dashed and dotted curves show the results in the cases $\Delta = 0.1$ eV and $\Delta = 0.2$ eV, respectively.

following material parameters valid in heavily Mn-doped GaAs: $V_{bg} = E_c = 1.4$ eV, $E_{bg} - E_c = 0.1$ eV, and $E_s - E_{bg} = 0.3$ eV. Furthermore, we replaced the Fermi–Dirac distribution functions by Heaviside’s step functions, which is a good approximation at low temperatures. The solid curves in Fig. 3 show the calculated tunnelling current vs. bias voltage in the case when there is no band splitting, i.e., $\Delta = 0$. In high magnetic fields or below Curie temperature $\Delta$ is non-zero, and the dashed and dash-dotted curves in Fig. 3 show the effect of the band splitting on the tunnelling current in the cases $\Delta = 0.1$ eV and $\Delta = 0.2$ eV, respectively. In the case $p_2 = 1/2$ (Fig. 3(a)) the calculated current decreases due to the band splitting, which is in accordance with the previous approximate result (13). Also the calculated maximum decrease $\Delta I_{tunn}/I_{tunn} = -5\%$ at the peak voltage is close to the previous value $-3\%$ estimated from (13). In the case $p_2 = 3/2$ in Fig. 3(b) the calculated tunnelling current increases due to the band splitting, which is again in agreement with the approximate expression (13) ($\Delta D > 0$, when $p_2 > 1$).

To complete the modelling of the magnetic diodes we state that the last term $I_x$ in the diode current (3) describes the temperature-independent excess current [23] associated with impurity states in the forbidden band gap, and it is given by

$$I_x = A I_v \exp \left[ \frac{4}{3} \left( \frac{m^*}{N^*} \right)^{1/2} (V - R_s I_{tunn} - V_c) \right],$$

(14)

where $I_v$ is the current at a valley voltage $V_c$, and $N^* = N_x N_{bg} / (N_x + N_{bg})$. The excess current (14) may become the dominant contribution in (3) at low temperatures and at high bias voltages, where the diffusion current and the direct inter-band tunnelling current are small. Experimentally $I_x$ can be distinguished from the diffusion current by the different temperature dependence: The diffusion current (4) depends exponentially on temperature, whereas (14) is almost $T$-independent.

3 Experimental

3.1 Mn-doped GaAs thin films

Homogeneous ferromagnetic Ga$_{1-x}$Mn$_x$As ($x = 0.01–0.09$) thin films with good crystal quality can be fabricated by using a low temperature (200–300 °C) molecular beam epitaxy (MBE) [4]. For the study of the magnetic and electrical properties of the heavily Mn-doped (Ga,Mn)As layers with various Mn content grown on semi-insulating GaAs(100) substrates in our VG100H MBE system. After a standard chemical cleaning the substrate was glued with In on a Mo holder by In and loaded in a high vacuum chamber. Possible oxides on the substrate surface were removed at 600 °C under an As$_4$ overpressure.
First a 50 nm thick undoped GaAs layer was grown at 580 °C by using an As$_4$/Ga ratio of 10. In order to overcome the low solubility of Mn in GaAs and to suppress the surface segregation of Mn and the formation of the MnAs second phase during the growth, the growth temperature was lowered to 230 °C, and the As$_4$/Ga ratio was reduced to 3. Various Ga$_{1-x}$Mn$_x$As thin films with Mn mole fraction $x$ varying from 0.02 to 0.05 were grown at a growth rate 0.5 μm/h. However, a clear indication of ferromagnetism with reasonably high Curie temperatures (see below) was observed in our samples only when $x$ was within a rather narrow range from $x = 0.03$ to $x = 0.05$. The final thickness of the films was 1 μm. The crystal quality was controlled during the growth by using Reflection High Energy Electron Diffraction (RHEED). Finally, the samples were cut into pieces having an area of 10 × 10 mm$^2$, and the ohmic Pt/Ni/Pt/Au contacts to the p$^+$-layer were made by using an e-beam vacuum evaporation technique. The resistivity and the Hall effect were measured in the temperature range 10–300 K by using a Van der Pauw configuration for the contacts. For the Hall effect measurements the magnetic field (up to 1.3 T) was applied perpendicular to the sample plane. Direct magnetization measurements were carried out by using a vibrating sample magnetometer in a magnetic field of 10 mT applied in-plane along the [100] axis.

### 3.2 Mn-doped GaAs pn-junctions

After verification that our Mn-doped GaAs thin films are ferromagnetic (see below), pn-junctions and tunnel diode structures shown in Fig. 4 were fabricated. On top of the n-type GaAs substrate having a dopant concentration (Si) of $10^{18}$ cm$^{-3}$, there is an n-layer with a dopant concentration (Si) of $10^{17}$ cm$^{-3}$ and a thickness of 0.25 μm. In the tunnel diode structure the n$^+$-layer was more heavily doped having a concentration of $10^{19}$ cm$^{-3}$. Above the n$^+$-layer there is a 0.5 μm thick Mn-doped p$^+$-layer (Fig. 4(a)). The ohmic contact in the n-type substrate was made by using an Au/Ge/Ni/Au metallization. In the measurements of the $I$–$V$ characteristics of the magnetic diodes the external magnetic field was applied parallel to the plane of the pn-junction. For some diodes the ferromagnetism was verified by direct magnetization measurements.

### 4 Results and discussion

#### 4.1 Mn-doped GaAs thin films

Ferromagnetic ordering is clearly manifested in the electrical properties of the Mn-doped GaAs layers, as shown in Figs. 5 and 6, which present the measured resistivity $\rho$ vs. temperature and Hall resistivity $\rho_{\text{Hall}}$ vs. magnetic field, respectively, in Ga$_{1-x}$Mn$_x$As for various Mn mole fractions $x$. The solid curves in Fig. 5 show the calculated $\rho$ vs. $T$, when a model is used, which combines the spin disorder scattering model (4) with a Dubson–Holcomb (DH)-model [25] for electrical transport in heavily doped semicon-
Fig. 5  (a) Resistivity vs. temperature in Ga$_{1-x}$Mn$_x$As layers with the room temperature hole concentrations $5.6 \times 10^{19}$ cm$^{-3}$, $7.0 \times 10^{19}$ cm$^{-3}$, and $1.7 \times 10^{20}$ cm$^{-3}$ (from top to the bottom). The solid curves have been calculated by combining the spin disorder scattering model with a Dubson–Holcomb-model [25] for disordered semiconductors near the metal-semiconductor transition. The inset shows the lowest curve in more detail.  (b) Magnetoresistance $\frac{\rho(B) - \rho(0)}{\rho(0)}$ vs. magnetic field at various temperatures in Ga$_{1-x}$Mn$_x$As with $x = 0.04$.

ductors. In the DH-model the $T$-dependence of the resistivity is given by

$$
\rho_{300}(T) = \rho_{300\text{K}} \left( \frac{300 \text{ K}}{T} \right)^{\frac{1}{4}} \ln \left[ 1 + \exp \left( \frac{E_m - E_f}{k_b T} \right) \right],
$$

where $E_m$ is the mobility edge in a disordered semiconductor. In the calculations we used the following values for the material parameters: $J_{\text{exch}}^{\text{m}} = 2.4$ eV [24], lattice constant $a_0 = 5.65$ Å, and $m^* = 0.5m_0$ (heavy holes). The other parameters such as $\rho_{300\text{K}}$, $T_C$, and the total hole concentration were obtained from the experimental results. The only actual fitting parameter, which could be varied freely, was $E_m - E_f$. It varied from $-0.2$ meV (the uppermost curve in Fig. 5(a)) to $6.5$ meV (the lowest curve in Fig. 5(a)) in agreement with the observed change from the semiconducting behaviour to the metallic conduction with increasing $x$. The measured magnetoresistance $\frac{\rho(B) - \rho(0)}{\rho(0)}$ in Fig. 5(b) is also in good agreement with the spin disorder scattering model [20–22].

Fig. 6  Hall resistivity vs. magnetic field at various temperatures in Ga$_{1-x}$Mn$_x$As with (a) $x = 0.04$ and (b) $x = 0.05$. 

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The observed resistivity peaks in Fig. 5(a) give estimates for the Curie temperatures of the samples, according to the spin disorder scattering model. A more accurate estimation for $T_c$ can be obtained from the measured Hall resistance in Fig. 6. In ferromagnetic conductors an anomalous Hall effect (AHE) may appear, which depends on the average magnetization $M$ of the conductor. Since $M$ is a saturating function of the magnetic field $B$, the AHE causes a non-linear $B$-dependence, in contrast to the linear dependence in the non-magnetic conductors. Indeed, in our most heavily doped samples the $B$-dependence becomes non-linear at temperatures below the Curie temperature, as shown in Fig. 6. From the magnetization dependent part of the measured $\rho_{\text{Hall}}$ we can estimate the Curie temperatures $T_c = 30 – 50$ K, when $x$ varies from 0.03 to 0.05, in agreement with the estimates based on the resistivity peaks in Fig. 5(a). Finally, the ferromagnetism in our Mn-doped GaAs layers was verified by direct magnetization measurements, as shown in Fig. 7. The magnetization was measured in a tunnel diode structure after the metallization.

4.2 Mn-doped GaAs pn-diodes

Figure 8 shows the $T$-dependence of the measured $I$–$V$ characteristics in a magnetic p’-n-(Ga,Mn)As/GaAs-diode having a lightly doped ($N_D = 10^{17}$ cm$^{-3}$) non-magnetic n-type layer. The strong $T$-dependence at high temperatures vanishes at $T < 100$ K. This behaviour, which is similar to the one reported previously by Arata et al. [8], could be related to the excess current (14): At low temperatures the $T$-dependent diffusion current (4) is much smaller than the $T$-independent excess current. In the diode of Fig. 8 we did not find any magnetoresistance in the whole temperature range $T = 8 – 300$ K. Based on the models discussed in Section 2 there are several possible reasons for the absence of magnetoresistance:

(i) In the case $N_D \ll N_A$, the lightly doped non-magnetic side of the pn-junction dominates the current (6), and, therefore, the current does not depend on the band splitting $\Delta_1$.

(ii) The exchange parameter $J_{\text{exch}}^{\text{sd}}$ for the conduction electrons, and consequently also the band splitting $\Delta_1 \sim J_{\text{exch}}^{\text{sd}}$, are small compared to thermal energy even at low temperatures, $\Delta_1 \leq k_B T$.

(iii) The band discontinuity $\Delta E_c$ (see Fig. 1(b)) is so large that the current flows via a thermionic emission over the barrier, which does not depend on the magnetic field $B$.

(iv) The charge carrier mediated ferromagnetism is absent in the depletion region of the diode (see Fig. 1(c)), and consequently the built-in potential of the diode does not depend on $B$. Also the recombination current $I_{\text{rec}}$ does not depend on $B$, if the whole depletion region is non-magnetic [15].

(v) The excess current, which does not depend on magnetic field, dominates at low temperatures.

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**Fig. 7** Magnetic moment vs. temperature in a Mn-doped GaAs tunnel diode structure measured by using a vibrating sample magnetometer at $B = 10$ mT. The inset shows the magnetic hysteresis of the Mn-doped layer of the diode structure measured at 10 K.
The explanation (i) can be ruled out, since even in the case \( N_A = N_D \), i.e., in our tunnel diodes (see below), we did not observe any \( B \)-dependence in the current at high bias voltages, where the diffusion current should dominate. Also the explanation (ii) is not probable, since the estimated value [24] for \( J_{\text{sd}} \) is about 0.2 eV, which would result in a band splitting \( \Delta E_{\text{sd}} = x J_{\text{sd}} \) at low temperatures. According to the studies carried out by Ohno et al. [26], a large band discontinuity occurs in the (Ga,Mn)As/GaAs interface: a value \( \Delta E_v \approx 0.2 \) eV has been estimated for the valence band edge. The value for the conduction band is unknown, but since the band gap of the Mn-doped GaAs is almost the same as in the undoped case [24], \( \Delta E_c \) must be much smaller than \( \Delta E_v \). Therefore, we do not consider the conduction band discontinuity, i.e., the explanation (iii), as the main reason for the absence of magnetoresistance. As a conclusion, we believe that the absence of ferromagnetism in the depletion region of the p n-diode explains the absence of magnetoresistance: According to the models in Section 2, all the possible current components, i.e., the excess current, the recombination current, and the diffusion current, become independent of the magnetic field, if there is no magnetic ordering and band splitting in the depletion region.

When the both sides of a (Ga,Mn)As/GaAs-p++n++-diode are heavily doped, we get a tunnel diode. Figure 9 shows the temperature dependence of the measured \( I-V \) characteristics in a ferromagnetic GaAs tunnel diode in zero magnetic field. The well-known [23] negative resistance region due to inter-band tunnelling is shown in Fig. 9 in the voltage range 0.2–0.4 V. At low temperatures \( T < 100 \) K the current becomes only weakly \( T \)-dependent, as shown more clearly in Fig. 10. This change in the \( T \)-dependence can be understood by the total current model (3), where the strongly \( T \)-dependent diffusion current (4) \( \sim \exp \left( \frac{(qV - E_c)}{k_B T} \right) \) and the recombination current \( I_{\text{rec}} \) dominate at high temperatures, whereas the \( T \)-independent tunnelling current (5) and the excess current (14) dominate at low temperatures \( T < 100 \) K. The slight increase of the measured tunnelling current in Figs. 9 and 10 in the voltage range 0.2–0.4 V at low temperatures remains unexplained.

In contrast to the p n-junction with slightly doped non-magnetic region discussed above, in the tunnel diode a large magnetoresistance is observed at low temperatures, as shown in Fig. 11. However, at high bias voltages, where the diffusion current (4) and the excess current (14) dominate, no magnetoresistance is observed at any temperature. This is in agreement with our observed results in p n-junction discussed above, where the diffusion current showed no magnetoresistive behaviour. The relative current change...
\( |I(B) - I(0)|/I(0)| \) saturates as the external magnetic field increases, as shown in Fig. 12. The measured maximum current decrease is 8% is on the same order of magnitude as the value 3% estimated from (13) and 5% calculated numerically from (5) and (7) in Section 2 with a parameter value \( \Delta_2 = 0.2 \text{ eV} \), Fig. 3. On the other hand, if we use \( \Delta_2 \) as a fitting parameter, we get from the calculated and measured current change an estimate for \( \Delta_2 = 0.36 \text{ eV} \), from which we get for the exchange parameter a value 2.9 \text{ eV} for \( x = 0.05 \) and \( S = 5/2 \). This value is between the previously reported values 2.4 \text{ eV} \ [24] and 3.3 \text{ eV} \ [28] obtained for \( J^{\text{exch}} \) from the optical and electrical measurements in Mn-doped GaAs, respectively.

![Fig. 9](image9.png) **Fig. 9** Measured \( I-V \) characteristics at various temperatures in a ferromagnetic (Ga,Mn)As/GaAs tunnel diode \( (B = 0 \text{ T}) \).

![Fig. 10](image10.png) **Fig. 10** Temperature dependence of the dc current in a GaAs tunnel diode at bias voltages \( V = 0.1 \text{ V}, V = 0.3 \text{ V} \) and \( V = 0.5 \text{ V} \).

![Fig. 11](image11.png) **Fig. 11** (a) Measured \( I-V \) characteristics in a (Ga,Mn)As/GaAs tunnel diode at \( T = 10 \text{ K} \) with and without magnetic field. (b) Measured \( I-V \) characteristics in the voltage region where the tunneling current dominates in various magnetic fields.
According to (13), the relative current change should saturate in high magnetic fields, since 

\[ \Delta I/I_{\text{num}} \sim n \Delta D_{\parallel}/D_{\parallel} \sim c^2 \left( \langle S^z \rangle \right)^2, \]

and \[ \langle S^z \rangle \] saturates with increasing \[ B \]. This is exactly the behaviour observed in Fig. 12. However, it differs strongly from the non-saturating \[ B \]-dependence \[ I/I_{\text{num}} \sim B^n \] with \[ n > 1 \] due to formation of the Landau levels, predicted by the magnetoresistance model [16–19] for the non-magnetic tunnel diodes made of high mobility, small band-gap semiconductors. Therefore, we conclude, that our observations in Fig. 12 are associated with the magnetic ordering in the Mn-doped GaAs layer, not with the formation of the Landau levels. In small magnetic fields the above relation \[ \Delta I/I_{\text{num}} \sim \left( \langle S^z \rangle \right)^2 \sim B^2 \] predicts a parabolic \[ B \]-dependence for the relative current change, which also is observed experimentally in Fig. 12 in the field range \[ B = 0–0.2 \, \text{T} \].

Figure 13 shows the bias voltage dependence of the current change \[ I(0) - I(B = 1 \, \text{T}) \] at various temperatures. We see that at low bias voltages \[ V < 0.2 \, \text{V} \] the applied magnetic field increases the current slightly. This behaviour remains unexplained to some extent. It could be related to a small negative magnetoresistance in the diode’s series resistance, which could cause a shift of the \[ I-V \] curve to lower voltages. However, it should cause a shift also at higher bias voltages \[ V > 0.5 \, \text{V} \], where we found no magnetoresistance (see Fig. 11), or only a slight change in the current, but in the opposite direction than at low voltages. Therefore, our conclusion is that the possible negative magnetoresistance of the series resistance cannot explain any of the observed changes in Figs. 11 and 13.

According to the model of the ferromagnetic tunnel diode presented in Section 2, in an ideal ferromagnet without magnetic domains, the effect of the external magnetic field on the tunnelling current should be largest at temperatures close to \[ T_c \], where the change in magnetization and in the band splitting is largest. However, in the measured results shown in Figs. 12 and 13 magnetoresistance is largest at low temperatures well below \[ T_c \]. We believe that this is due to ferromagnetic domains, which in (Ga,Mn)As typically require a magnetic field >200 mT before the net magnetization approaches the saturation at...
Therefore, the maximum change in the net magnetization from zero to the saturation due to the applied magnetic field occurs at low temperatures well below $T_c$.

To conclude the treatment of the Mn-doped GaAs diodes we can state that the calculated results in Fig. 3(a) describe well the measured decrease in the current in the tunnel diodes shown in Fig. 11. The calculated results indicate that the valence band splitting should be seen also as an excess structure in the $I–V$ characteristics in the tail of the tunnelling current in the voltage range 300–400 mV, as shown by the kinks in Fig. 3(a). However, this behaviour was not found in the experimental results, which we believe is due to the fact that in this voltage range the direct tunnelling current $I_{\text{tunn}}$ is much smaller than the excess current $I_{\text{x}}$, which does not depend on the magnetization. Also the kinks in the calculated $I–V$ characteristics in Fig. 3 appear only, if we assume a sharp edge of the band in an ideal semiconductor. However, in a heavily doped semiconductor the band edge may be smoothed due to disorder [27]. This is shown in the calculated results of Fig. 3, if we compare the cases $p_2 = 1/2$ and $p_2 = 3/2$: the latter case describes better the energy dependence of the band states in the tails of the band, and in this case the kinks due to the band splitting are much smaller than in the ideal case of Fig. 3 (a) with $p_2 = 1/2$. So, our conclusion is that since we observe experimentally a decrease of the current due to the band splitting, the density of states is described mainly by a parameter $p_2 < 1$ in (7), excluding the energies close to the band edge, where the tail states caused by the heavy doping could be described better by a parameter $p_2 > 1$.

5 Conclusions

We have shown that a large magnetoresistance in the magnetic GaAs pn-diodes can be found only in the cases, where the both sides of the pn-junction are heavily doped and the diode operates in the tunnelling mode. In these diodes a spin-dependent tunnelling current was observed, which was manifested as a large decrease of the current with increasing magnetic field at low temperatures. This could be explained by a model, where the exchange interaction induced band splitting and the consequent decrease of the density of states on the magnetic side of the junction cause the decrease in the tunnelling current. There are many possible reasons for the fact, that no magnetoresistance was observed in the magnetic diodes, if the diode operates in the ordinary diffusion/recombination mode. In the case of Mn-doped GaAs-pn-diodes, where the ferromagnetism is free carrier mediated, the most probable explanation is associated with the absence of ferromagnetic ordering in the depletion region of the diode, and therefore the magnetic-field induced band splitting on the magnetic side of the junction has no effect on the diode current.

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References