Magnetotransport in ferromagnetic Schottky diodes made of Mn-doped GaAs

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Abstract. The Mn-doped GaAs thin films were grown on p-type GaAs substrates by using Molecular Beam Epitaxy technique. The Schottky contacts on top of the (Ga,Mn)As layer were made of Pt metal. In contrast to the non-magnetic GaAs Schottky diodes, a large negative magnetoresistance (MR) in the dc current was observed in the magnetic diodes at low temperatures. The contributions to the observed MR effects from the spin dependent tunnelling through the thin Schottky barrier and the negative MR of the semiconducting layer are discussed in detail.

1. Introduction
Diluted magnetic III-V semiconductors (DMS’s) [1,2] have attracted considerable attention, because they hold promises of creating a new class of spintronic devices. 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 the present paper we discuss the magnetotransport properties of a magnetic Schottky diode made of the magnetic semiconductor (Ga,Mn)As. To our knowledge, this is the first time a rectifying Schottky barrier has been fabricated successfully on a ferromagnetic Mn-doped p-type GaAs.

2. Modelling of the magnetic Schottky diode
In magnetic semiconductors a strong dependence of the electrical properties on the magnetic ordering is caused by the exchange interaction between the charge carrier spin and the total spin of the localized magnetic electrons, which gives rise to a giant Zeeman splitting \( \Delta E(T,B) = x J_{\text{exch}} \langle S(T,B) \rangle \) of the conduction and valence bands. Here \( x \) is the mole fraction of the magnetic ions, and \( \langle S(T,B) \rangle \) is the average temperature and magnetic field dependent spin polarization of the magnetic ions. The effect of the band splitting \( \Delta E \) on the band diagram of the magnetic Schottky diode is shown in figure 1(a), where it was assumed that the ferromagnetic region extends to the depletion region of the diode. However, in Mn-doped GaAs the ferromagnetic ordering is a carrier-induced effect [2], and it is unlikely that the ferromagnetic region could extend over the whole depletion region, when there are no
charge carriers, excluding a short distance (denoted by $\Delta d$ in figure 1 (b)) close to the boundary between the neutral region and the depletion region. Therefore, the situation depicted in figure 1 (b) could be more realistic.

We have modelled recently [3] the ideal ferromagnetic Schottky diode in the case of figure 1(a) based on a standard thermionic emission theory. If the series resistance $R_S$ due to the semiconductor is taken into account, the current-voltage relation is given by

$$J = \left(\frac{4\pi q m^* k_B}{h^3}\right) T^2 e^{-q\phi_0/k_BT} \cosh \left(\frac{\Delta E}{2k_BT}\right) [e^{qV/k_BT-qdR_S/k_BT-1} - 1]$$  \hspace{1cm} (2)$$

where $q\phi_0$ is the barrier height before the band splitting, and $I=AJ$ is the total current through the diode having a cross section $A$. Since $\Delta E$ depends strongly on external magnetic field, the model (2) predicts a large negative magnetoresistance (MR) at temperatures $k_BT<\Delta E$.

In the case of figure 1 (b) the ferromagnetic region extends only a narrow distance $\Delta d$ to the depletion region. However, also in this case the junction can rectify the current, if the Fermi level is very close to the band edge, and the current flow is dominated by the tunnelling of the charge carriers through the potential barrier. Since the tunnelling current depends exponentially on the barrier height $q\phi_0$ and width $d$, $J_T \propto \exp\left(-d\sqrt{2m^* q\phi_0 / h^2}\right)$, we can estimate from figure 1 (b) that the relative change of the tunnelling current due to the band splitting is given by

$$\Delta J_T / J_T \approx \exp\left(\Delta d \sqrt{2m^* q\phi_0 / h^2}\right) - 1$$ \hspace{1cm} (3)$$

where the shortening of the barrier width due to the band splitting can be estimated as $\Delta d / d \approx \Delta E / q\phi_0$. Also in this case a large negative MR is expected.

Finally we should notice, that via the series resistance $R_S$ in (2) the magnetoresistance of the semiconductor layer may have an effect on the voltage distribution within the diode structure in the studies of the magnetic field dependence of the $I$-$V$ characteristics.

When the Mn doping concentration increases in GaAs, a transition from an insulating (or semiconducting) to a metallic behaviour occurs [4]. The energy level $E_m$ separating the localized states from the extended states is called the “mobility edge”. Oiwa et al. [5] have proposed that in the ferromagnetic semiconductors there is a small magnetic contribution to $E_m$ due to the spin disorder,
which then vanishes at low temperatures well below \( T_c \) due to the magnetic ordering. Since the band splitting \( \Delta E \sim \langle S^z \rangle \), we can model the magnetization dependent mobility edge as

\[
E_{\text{m}}(T, B) = E_{\text{m}} - \alpha \Delta E(T, B),
\]

where \( \alpha \ll 1 \). In the vicinity of the M-I transition the charge transport in heavily Mn-doped GaAs can be described by the Dubson-Holcomb (DH) model [6], and the resistivity is then given by

\[
\rho(T, B) = \frac{1}{\ln\left(1 + e^{\frac{E_{\text{F}}(x, x) - E_{\text{F}}}{e T}}\right)}.
\]

Now we can estimate the negative magnetoresistance:

\[
\Delta \rho_{\text{DH}} / \rho_{\text{DH}} \approx -\alpha \left[ \Delta E(T, B \neq 0) - \Delta E(T, B = 0) \right] / k_B T.
\]

Finally, if \( E_F < E_{\text{m}} \), a variable range hopping (VRH) conduction within the localized states also leads to a negative MR, \( \rho(B) = \rho_0 \exp\left(-\gamma B^{1/3}\right) \), where \( \gamma \) is a constant. Experimentally the VRH and DH contributions to MR can be distinguished based on different magnetic field dependences in high magnetic fields.

3. Experimental
Homogeneous ferromagnetic Ga\(_{1-x}\)Mn\(_x\)As \((x=0.01-0.05)\) thin films with good crystal quality can be fabricated by using a low temperature (200-300 °C) molecular beam epitaxy (MBE) [2]. Various Ga\(_{1-x}\)Mn\(_x\)As thin films with Mn mole fraction \( x \) varying from 0.02 to 0.05 were grown in our VG100H MBE system. The Schottky contacts on top of the (Ga,Mn)As layer were made of Pt metal by using an e-beam evaporation. The ohmic contacts on the backside were made of an Au/Ge/Ni alloy. For comparison, we also fabricated non-magnetic GaAs Schottky diodes, where, instead of the Mn doping, beryllium was used as a p-type dopant. In the characterization of the Schottky diodes first the magnetotransport properties of the Mn-doped layer without a Schottky contact were studied by performing resistivity, magnetoresistance (MR), and Hall measurements.

4. Results and discussion
The ferromagnetic behaviour of our Ga\(_{1-x}\)Mn\(_x\)As samples with Curie temperatures varying from 30 to 70 K, when \( x \) increased from 0.03 to 0.04, was verified by direct magnetization measurements. MR was measured at various temperatures in magnetic fields up to 4 T. The negative MR increased with decreasing \( T \) and it was as large as -80 % at low temperatures \( T<10\)K. The negative MR can be explained by VRH or DH models: In the DH model even a small value of \( \alpha[\Delta E(B>0) - \Delta E(B=0)] \approx 2 \) meV at \( T=10\)K and \( B=1\)T is enough to explain the measured order of magnitude of the negative MR. Also the observed increase in MR with decreasing temperature is in agreement with the DH model. However, there was no saturation of the MR in fields \( B > 1\)T, which makes the VRH model more plausible.

![Figure 2](image-url)  
**Figure 2.** Measured I-V characteristics in a magnetic Schottky diode at various temperatures (B=0T)

Figure 2 shows the measured I-V characteristics of the magnetic Schottky diode at various temperatures. The rectifying properties are clearly seen: The rectifying ratio at 0.5 V is about \( 10^2 \).
negative MR about 30% at \( T=8 \)K can be seen, which was not found in our non-magnetic Schottky diodes. An interesting finding is a decrease of MR with increasing voltage at low bias voltages, figure 4, before the strong increase starts at higher voltages.

The both models (2) and (3), where the current depends exponentially on the band splitting parameter \( \Delta(T, B) \), predict a giant negative MR, especially at temperatures close to the Curie temperature. This is not observed in our measured results. On the other hand, if we assume that the saturation current \( I_s \) in (2) does not depend on magnetic field, where as the series resistance \( R_s \) does, we get a nice fit of the model (2) to the experimental results, as shown in figure 3. A fitting parameter \( \Delta R_s/R_s = -26 \% \) at \( B=1 \)T was used in the calculations. This value is closed to measured negative MR value in our Mn doped GaAs layers at low temperatures. However, we cannot rule out completely a contribution from the magnetization dependent tunnelling current (3). Especially, the anomalous voltage dependent MR shown in figure 4 at low voltages may be related to a change from a tunnelling current dominating MR at low voltages to the MR due to the \( B \)-dependent series resistance at higher voltages.

![Figure 3](image1.png)

**Figure 3.** Effect of the external magnetic field on the \( I-V \) characteristics of a magnetic Schottky diode at \( T=8 \)K. The dots are the results calculated by the series resistance model (2) \( B=0 \)T and \( B=1 \)T.

![Figure 4](image2.png)

**Figure 4.** Magnetoresistance \( [I(B=1T)-I(0)]/I(0) ] \) vs. bias voltage at \( T=8 \)K.

5. Conclusion

To conclude we can state, that the most probable explanation for the observed large MR in the ferromagnetic Schottky diode at low temperatures is the large negative MR of the Mn-doped GaAs layer in the diode. The reason for the observed anomalous voltage dependence at low voltages remains uncertain to some extent.

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