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Magnetotransport in Ferromagnetic (Ga, Mn)As and (Ga, Mn)N Pn-Diodes

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GaAs and GaN pn-junctions are fabricated with Mn-doped ferromagnetic layers on top of nonmagnetic substrates. In the case of heavily doped (Ga,Mn)As/GaAs $p^{++}n^{++}$ -junctions (Zener diodes) the tunneling current becomes magnetic field dependent at low temperatures. This can be explained by a model based on the valence band splitting due to the exchange interaction between the hole spins and the localized spins of the Mn atoms. In the pn-junctions with more lightly doped nonmagnetic regions in the (Ga, Mn)N and (Ga, Mn)As diodes, no magnetic field dependence in the I - V characteristics is observed, probably due the absence of ferromagnetism in the depletion region of the p^+n -junctions.

Index Terms—Magnetic semiconductors, magnetoresistance, spin-dependent tunneling.

I. INTRODUCTION

ALMOST all the commercial applications in spintronics are based on ferromagnetic properties of the metallic thin films [1]. However, the new ferromagnetic semiconductors such as Mn-doped GaAs and GaN could offer many advantages compared to metals, e.g., an easier integration to conventional microelectronics [2].

Some simple devices such as light-emitting diodes [3]–[6], resonant tunneling diodes [7] and Zener diodes [8], [9] have already been fabricated of Mn-doped GaAs. However, due to the low Curie temperature T_C , all these magnetic devices operate only at low temperatures. In Mn-doped GaN, the measured T_C 's are even well above 300 K [10], which gives hope of a room-temperature spintronics based on semiconductors. However, so far only a few (Ga, Mn)N devices have been fabricated [11], [12]. In the present paper, we investigate the electrical and magnetic properties of Mn-doped GaAs and GaN pn-diodes. Especially, we are interested in the spin-dependent tunneling in the p^{++} -(Ga, Mn)As/ n^{++} -GaAs Zener diode.

II. SAMPLE FABRICATION

The (Ga, Mn)As and (Ga, Mn)N pn-diodes were fabricated by using molecular beam epitaxy (MBE). The structure of the tunneling GaAs diodes is shown in Fig. 1. First, a heavily doped n^+ -GaAs layer (0.25 μm) was grown on top of an n-type (10^{18} cm^{-3}) GaAs substrate. After that, a 0.5- μm -thick magnetic Mn doped GaAs layer was grown by MBE. The mole fraction of Mn was varied between 2% and 5%. Since Mn acts as an acceptor, the top layer in GaAs is of p-type. The growth temperature was only 230 °C in order to inhibit the formation of second phases and segregation of Mn at the surface. Finally, the ohmic Pt/Ni/Pt/Au (50 Å/200 Å/200 Å/1000 Å) and Au/Ge/Ni/Au (200 Å/300 Å/300 Å/400 Å) contacts were evaporated by

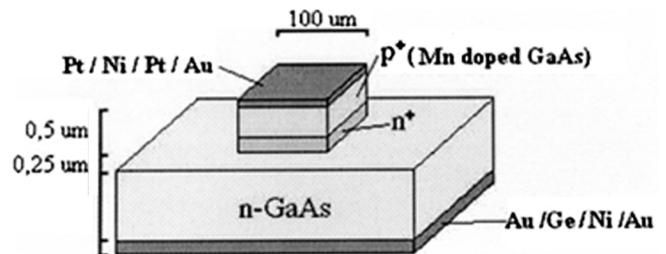


Fig. 1. Structure of a magnetic GaAs/GaAs:Mn tunneling diode.

using an electron-beam evaporator. The structure of (Ga, Mn)N pn-diode was similar, except that the ferromagnetic Mn-doped region, which was made by using solid state diffusion [13], turned out to be of n-type.

III. THEORY

According to a model [14] for an ideal magnetic diode consisting of a pn-junction made of ferromagnetic and nonmagnetic semiconductors, a large magnetoresistance effect should appear at low temperatures due to the giant Zeeman splitting of the bands states even in the depletion region of the pn-junction. However, in Mn-doped GaAs, the ferromagnetism is charge carrier-mediated [15], and, therefore, the presence of magnetic ordering in the depletion region is questionable. This problem can be circumvented, if the both sides of the pn-junction are heavily doped, and tunneling processes through the depletion region dominate the charge transport. The tunneling current [16] depends on the product between the density of states of the valence band $D_V^\sigma(E)$ and the tunneling probability $T_\sigma(E)$, which both become spin-dependent in the case of the magnetic tunneling diode (σ is the spin index). In the presence of the ferromagnetic ordering in magnetic semiconductors a band splitting to spin-up and spin-down states occurs due to a strong exchange interaction between the carrier spins and the spins of the localized magnetic electrons of the Mn ions. Considering the band splitting Δ_1 for the valence band as a small parameter and assuming a parabolic

band, we can expand $D_V(E \pm \Delta_1)$ as a Taylor series, and we get the following estimate for the relative change due to the band splitting:

$$\begin{aligned} \Delta D_V/D_V &= [D_V(\Delta_1 > 0) - D_V(\Delta_1 = 0)]/D_V(\Delta_1 = 0) \\ &\approx -\frac{\Delta_1^2}{32(E_V - E_F)^2} \end{aligned} \quad (1)$$

where $E_V - E_F$ is the energy difference between the valence band edge and the Fermi energy. In the same way, a contribution from the relative change of the tunneling probability due to a change in the height of the tunneling barrier can be estimated, as follows:

$$\begin{aligned} \Delta T/T &= [T(\Delta_2 > 0) - T(\Delta_2 = 0)]/T(\Delta_2 = 0) \\ &\approx -\frac{3\pi\sqrt{m^*}}{64\sqrt{2}q\hbar F} \left(\frac{\Delta_2}{E_g^0}\right)^2 \end{aligned} \quad (2)$$

where m^* is the reduced effective mass, F the electric field in the depletion region, E_g^0 the bandgap before the conduction band splitting given by Δ_2 . By using the values $E_V - E_F = 0.2$ eV, $\Delta_1 = 0.2$ eV, $\Delta_2 = 0.025$ eV, $F = 10^6$ V/cm, $E_g^0 = 1.4$ eV, and $m^* = 0.5m_0$, which are typical for Mn-doped GaAs tunneling diode, we can estimate the contributions from (1) and (2): $\Delta D_V/D_V \approx 3\%$ and $\Delta T/T < 0.1\%$. Therefore, our conclusion is that, due to the ferromagnetic ordering, the tunneling current in a magnetic Zener diode should decrease mainly due to the decrease of the density of valence band states caused by the band splitting.

A decrease in the tunneling current due to the formation of the Landau levels in the high magnetic fields has been observed previously in nonmagnetic Zener diodes made of small bandgap and high mobility semiconductors such as InSb [17], [18]. However, the effect was never observed in GaAs having a much larger bandgap and smaller mobility in the heavily doped p- and n-regions, so that the necessary condition $\mu B > 1$ (μ is the mobility) for the Landau level formation never fulfills.

IV. RESULTS AND DISCUSSION

The direct magnetization measurements were performed in order to confirm that the (Ga, Mn)As and (Ga, Mn)N layers are ferromagnetic. The observed Curie temperatures were in the range 40–70 K in Mn-doped GaAs and about 330 K in Mn-doped GaN (the details of the characterization of Mn-doped GaN have been published elsewhere [13]).

The measured I - V characteristics of the p^+- (Ga, Mn)As/n-GaAs diode at various temperatures are shown in Fig. 2. No magnetic-field dependence in the current could be observed, if the n-side of the junction was lightly doped ($N_D < 10^{19}$ cm $^{-3}$). The same result was observed also in the (Ga, Mn)N pn-diodes, Fig. 3. We believe that the absence of magnetoresistance in the diodes having lightly doped nonmagnetic regions is mainly due to the absence of ferromagnetism in the depletion region of the diodes. Consequently, no changes in the electronic states inside the depletion region occur due to magnetic ordering, and—according to the model [14]—no magnetoresistance is observed. Also, since $N_D \ll N_A$, the nonmagnetic side of the junction

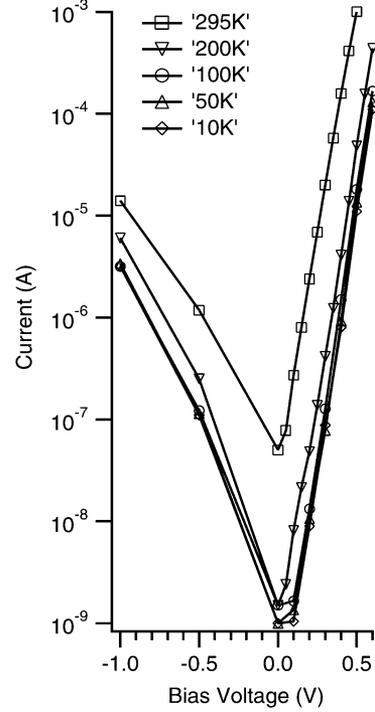


Fig. 2. Current in a GaAs/GaAs:Mn pn-diode as a function of bias voltage at various temperatures.

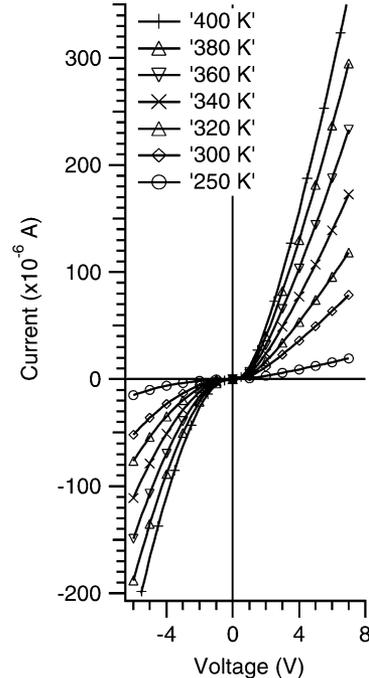


Fig. 3. Current in GaN:Mn/GaN pn-diode as a function of bias voltage at various temperatures.

dominates the current, and it may further reduce the magnetoresistance effect in these diodes.

However, if also the n-side is heavily doped, the pn-diode changes to a tunnelling or Zener diode, as shown in Fig. 4, and according to the theory presented in Section III, the tunneling current should show a large magnetic field dependence. Indeed, at low temperatures large magnetoresistance was observed in

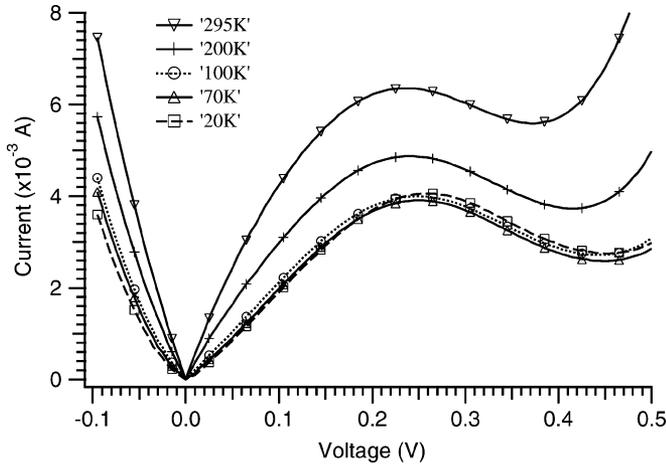


Fig. 4. Current in GaAs/GaAs:Mn tunneling diode as a function of bias voltage at various temperatures.

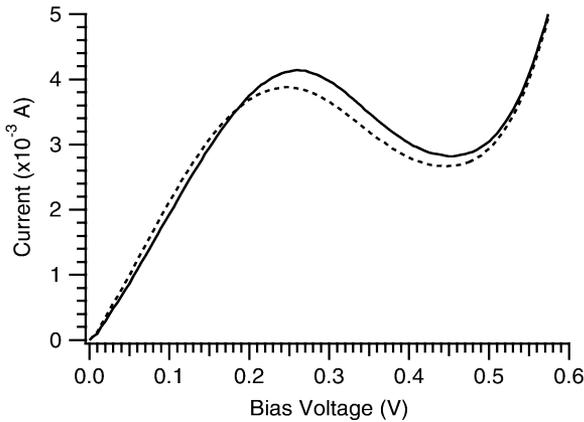


Fig. 5. Current in GaAs/GaAs:Mn tunneling diode as a function of bias voltage without (solid line) and with 1T magnetic field (dashed line) at 10 K.

the I - V characteristics, as shown Fig. 5. At higher bias voltages, no magnetic-field dependence can be observed, probably due to the fact that in this voltage range, the magnetic-field-independent contributions, i.e., the excess and the normal diffusion currents dominate. The large magnetoresistance in the tunneling region can be seen more clearly in Fig. 6, where the absolute current change as a function of magnetic field is shown at various temperatures. The observed maximum decrease $\approx 6\%$ (Fig. 5) in the tunneling current due to the applied magnetic field is on the same order of magnitude as the value $\approx 3\%$ calculated above from (1). The increase of the tunneling current at low bias (see Figs. 5 and 6) may be due to the negative magnetoresistance of the series resistance of the Mn-doped layer in the diode structure, which shifts the I - V characteristics to lower voltages.

To conclude, we can state that we have observed a large magnetoresistance in the (Ga, Mn)As/GaAs Zener diodes, where the both sides of the junction were heavily doped. However, no magnetic field dependence was observed in the I - V characteristics of the ferromagnetic GaAs and GaN pn-diodes with a more lightly doped nonmagnetic side.

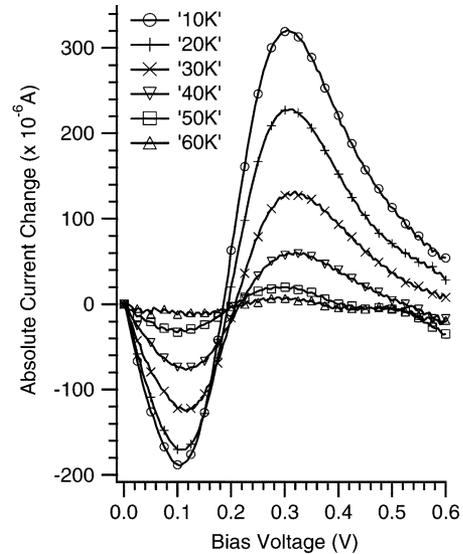


Fig. 6. Absolute current change in a tunnelling diode as a function of bias voltage. The absolute current change is defined as the current at zero field minus the current in a magnetic field of 1T.

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