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Large magnetoresistance in a ferromagnetic GaMnAs/GaAs Zener diode

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Abstract. –We investigate spin-dependent interband tunnelling in a ferromagnetic (Ga, Mn)As/GaAs Zener diode. The ferromagnetic pn-junction is fabricated with a Mn-doped p-type GaAs layer on top of a nonmagnetic n-type GaAs substrate. When both sides of the junction are heavily doped, a large magnetic-field–dependent tunnelling effect can be seen at low temperatures in the measured current-voltage (I-V) characteristics. A model for the tunneling current in a ferromagnetic Zener diode is presented, and the observed effects are explained by the exchange interaction related splitting of the valence band states in (Ga, Mn)As. To our knowledge, this is the first time the effect of the band splitting and a large magnetoresistance related to the tunnelling processes have been observed experimentally in the I-V characteristics of a ferromagnetic Zener diode.

In semiconductor physics the spin degree of freedom usually is neglected due to the almost degenerate energies of the spin-up and spin-down states of the charge carriers. However, recent advances [1] in the fabrication of ferromagnetic semiconductor thin films based on the diluted magnetic III-V semiconductors such as Mn-doped GaAs have opened a route to semiconductor spintronics, where spin-dependent phenomena in electrical and optical properties may become the dominant ones. The strong exchange interaction between the carrier spins and the spins of the magnetic $3d^5$ electrons is manifested, *e.g.*, in a large splitting between the spin-up and spin-down band energies.

Some basic semiconductor device structures such as pn-junctions, light-emitting diodes [2–4], and resonant-tunnelling diodes [5] have been made of Mn-doped GaAs. The first ferromagnetic (Ga, Mn)As Zener diode was studied by Jonston-Halperin *et al.* [6], when they used the reverse biased diode as a spin emitter for a nonmagnetic quantum well. However, the

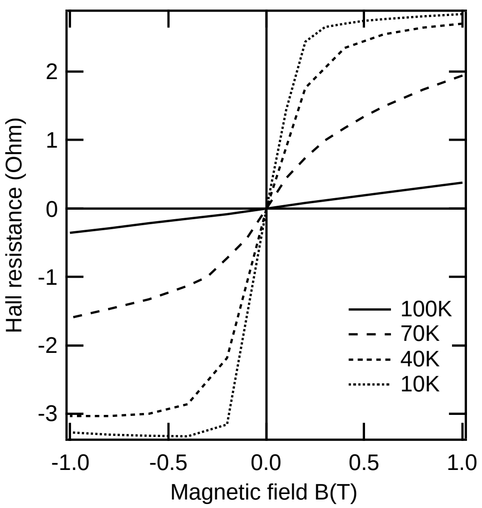

Fig. 1

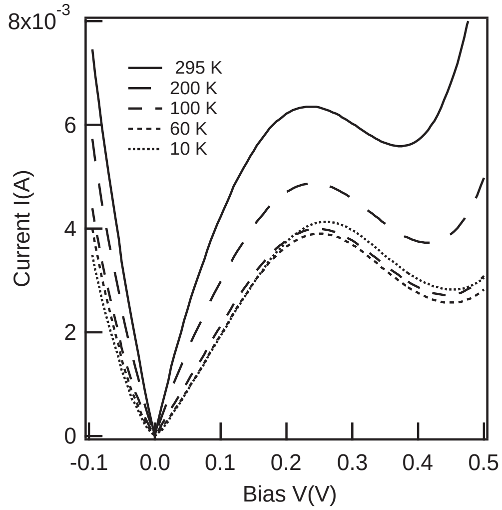

Fig. 2

Fig. 1 – Hall resistance *vs.* magnetic field in (Ga, Mn)As at various temperatures. Mn composition is $x = 0.04$.

Fig. 2 – I-V characteristics of a ferromagnetic Zener diode at various temperatures ($B = 0\,\mathrm{T}$).

magnetic-field and temperature dependences of the tunnelling current in the case of a forward bias were not investigated. In the present paper we study the interband tunneling in ferromagnetic (Ga, Mn)As/GaAs pn-junctions. Especially, we are interested in the forward biased Zener diode, since it allows us to perform tunnelling spectroscopy of the electronic states on the ferromagnetic side of the junction. Simply by measuring the current-voltage characteristics as a function of temperature in various magnetic fields we can study the tunnelling processes from the nonmagnetic n-type layer to the ferromagnetic p-type layer, which gives us information on the spin-dependent electronic states in the ferromagnetic layer.

Homogeneous ferromagnetic $Ga_{1-x}Mn_xAs$ thin films with good crystal quality were fabricated by using low-temperature (200–300 °C) molecular-beam epitaxy (MBE) following the procedure described in ref. [7]. Our heavily Mn-doped (Ga, Mn)As layers were grown on semi-insulating GaAs (100) substrates in a VG100H MBE system. Possible oxides on the substrate surface were removed at 600 °C under an As_4 overpressure. 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. Various $Ga_{1-x}Mn_xAs$ thin films with Mn mole fraction x varying from 0.02 to 0.05 were grown at a growth rate $0.5\,\mu$m/h. However, a clear indication of ferromagnetism with reasonably high Curie temperatures (50–70 K) was observed only, when x was within a rather narrow range from $x = 0.04$ to $x = 0.05$. The final thickness of the films was $1\,\mu$m. Finally, the ohmic Pt/Ni/Pt/Au (50 Å/200 Å/200 Å/1000 Å) 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. In the Hall effect measurements the magnetic field (up to 1.3 T) was applied perpendicular to the sample plane.

In our Zener diode structures on top of the n-type GaAs substrate having a dopant concentration (Si) of $10^{18}\,\mathrm{cm}^{-3}$, there is an n^+-layer with a dopant concentration (Si) of $5\cdot10^{18}\,\mathrm{cm}^{-3}$

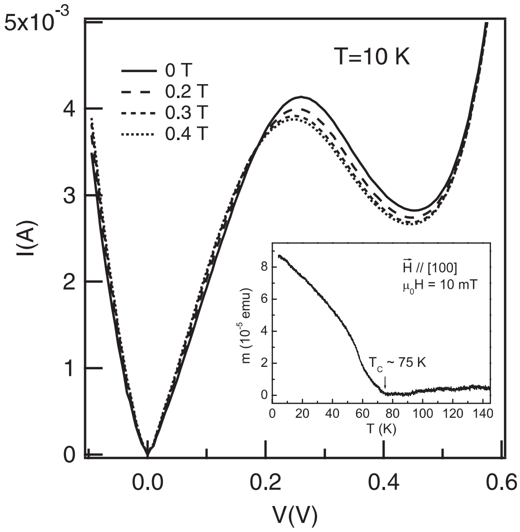

Fig. 3

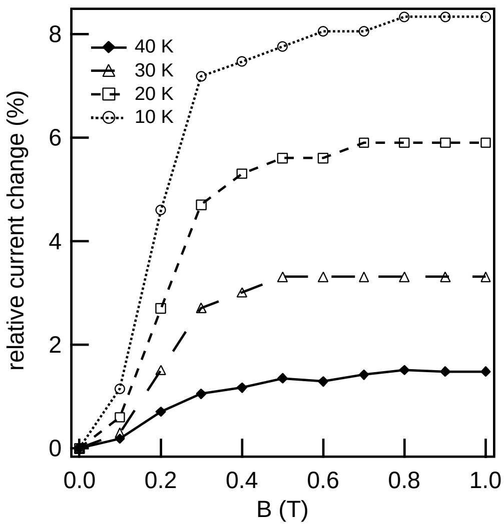

Fig. 4

Fig. 3 – Measured *I-V* characteristics for a ferromagnetic Zener diode at $T = 10\,\mathrm{K} < T_\mathrm{C}$ in various magnetic fields. The inset shows the magnetic moment m *vs.* temperature T in the (Ga, Mn)As/GaAs diode measured by using a vibrating sample magnetometer at $\mu_0 H = 10\,\mathrm{mT}$; T_C is the Curie temperature.

Fig. 4 – Relative change of the tunneling current *vs.* magnetic field at $V = 350\,\mathrm{mV}$ and at various temperatures in a ferromagnetic Zener diode. The relative current change is defined as an absolute value of $(I(B) - I(0))/I(0)$.

and a thickness of $0.25\,\mu$m. Above the n^+-layer there is a $0.5\,\mu$m thick Mn-doped p^+-layer. The ohmic contacts in the n-type substrate were made by using an Au/Ge/Ni/Au metallization. The ferromagnetism in the grown (Ga, Mn)As layers and diodes was confirmed both by measuring the anomalous Hall effect *vs.* magnetic field at various temperatures (fig. 1) and by a direct magnetization measurement by using a vibrating sample magnetometer in a magnetic field of 10 mT applied in-plane along the [100] axis (see the inset of fig. 3). In the measurements of the *I-V* characteristics of the Zener diode the external magnetic field was applied parallel to the plane of the pn-junction.

Figure 2 shows the measured *I-V* characteristics of a ferromagnetic Zener diode at various temperatures in zero magnetic field. The typical negative resistance region due to the interband tunnelling is clearly shown in fig. 2. At high temperatures the current is strongly temperature dependent, especially at high bias voltages, but below 100 K the T-dependence becomes much weaker in the whole voltage range.

At low temperatures below the Curie temperature (75 K) the tunnelling current in our Zener diodes becomes strongly magnetic-field dependent, as shown in figs. 3 and 4. The relative change is as large as 6% when changing the field, *e.g.*, from 0.1 T to 0.3 T. The change is largest in the tunnelling region in the forward voltage range 150–450 mV. The observed magnetoresistance decreases rapidly with increasing temperature, and at high temperatures the relative change in the current is below 0.1%. The saturating relative change of the current in fig. 2 shows the same magnetic-field dependence as the anomalous Hall effect at low temperatures (fig. 1), indicating clearly that the effect is magnetization dependent. When changing the direction of the applied magnetic field in the plane of the pn-junction, *e.g.*, from

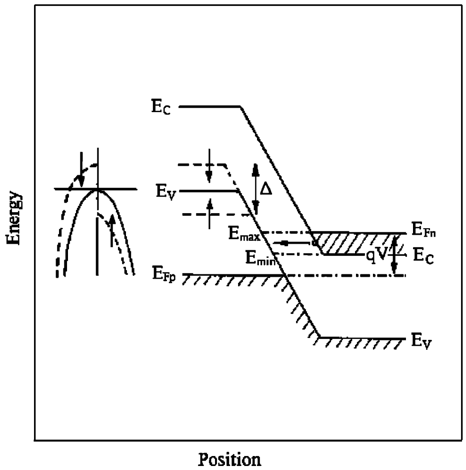

Fig. 5

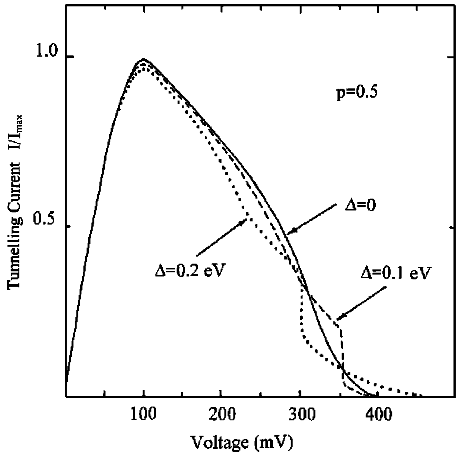

Fig. 6

Fig. 5 – Schematic energy band diagram *vs.* position for a ferromagnetic Zener diode, when the n-side is nonmagnetic GaAs and p-side is ferromagnetic Mn-doped GaAs. E_{Fp} and E_{Fn} are the quasi-Fermi levels on the p- and n-sides, respectively. The dashed lines represent the spin-polarized valence band edges, when the band splitting energy $\Delta > 0$. V is the applied voltage. $E_{\min}$ and $E_{\max}$ determine the energy range for the band energy overlap between the conduction band on the n-side and valence band on the p-side.

Fig. 6 – Calculated tunneling current *vs.* voltage in the case of direct band-to-band tunneling in a ferromagnetic Zener diode. The solid curve represents the tunnelling when no band splitting is present, $\Delta = 0$, and the dashed and dotted curves represent the cases $\Delta = 0.1\,\mathrm{eV}$ and $\Delta = 0.2\,\mathrm{eV}$, respectively.

$\langle 100 \rangle$ to $\langle 110 \rangle$, only minor changes ($< 0.1\%$) in the tunnelling current were observed.

The observed effects can be explained by applying a dc model for conventional tunnel diodes [8], if the effect of the valence band splitting $\Delta = xJ_{exch}\langle S^z \rangle$ due to the exchange interaction is taken into account. Here J_{exch} is the exchange interaction parameter for holes in the valence band, and $\langle S^z \rangle$ is the average spin polarization of the Mn-ions. Figure 5 shows schematically the energy band structure *vs.* position in a ferromagnetic tunnel diode under a bias voltage V. As the voltage increases electrons in the conduction band on the nonmagnetic n-side may tunnel to the empty states in the valence band of the ferromagnetic p-side. Therefore, the tunnelling current probes the valence band states near the band edge as a function of voltage. Especially, if the band splitting between the spin-up and spin-down states occurs ($\Delta > 0$), as shown in fig. 5, this splitting should be seen in the I-V characteristics.

The total diode current can be expressed as a sum of three terms [8], $J_{tot} = J_t + J_X + J_T$, where J_t is related to the direct tunnelling between the band states

$$J_t = C \sum_{\sigma} \int_{E_{\min}}^{E_{\max}} T(E) \big[f_C(E) - f_V^{\sigma}(E) \big] D_C(E) D_V^{\sigma}(E) \mathrm{d}E. \tag{1}$$

Here C is a constant, $\sigma(=\uparrow,\downarrow)$ the spin index for holes, $T(E)$ the tunneling probability, $f_C(E)$ and $f_V(E)$ are the occupation probabilities for the conduction and valence bands, respectively, and $D_C(E)$ and $D_V^{\sigma}(E)$ are the densities of states for the conduction and valence bands, respectively. Since the p-side is ferromagnetic, the density of states for the valence band depends on the band splitting Δ, and near the band edge it is given by

$$D_V^\sigma(E) \sim \left(E_V - E - \frac{\Delta}{2}(\delta_{\sigma\uparrow} - \delta_{\sigma\downarrow})\right)^p, \tag{2}$$

where E_V is the energy of the valence band edge, and p is an exponent, which determines the energy dependence of the density of states. In an ideal semiconductor with parabolic bands $p = 0.5$, but in a heavily doped semiconductor at energies close to the band edge p may be larger than unity. The integration limits $E_{\min}$ and $E_{\max}$ depend on the overlap between the occupied conduction band states on the n-side and the unoccupied valence band states on the p-side, as shown in fig. 5.

J_X is the temperature-independent excess current density related to the impurity states in the forbidden energy gap in the junction, and is given by

$$J_X = J_V \exp\left[A(V - V_V)\right], \tag{3}$$

where J_V is the valley current density at the valley voltage V_V, and A is a constant. J_T is the ordinary minority-carrier injection current and is given by

$$J_T \sim \exp[(qV - E_g)/k_B T]. \tag{4}$$

We observed that at low temperatures, where J_T is small, the excess and tunnelling currents dominate, and eqs. (3) and (4) explain the temperature independent *I*-*V* characteristics also at high bias voltages.

The calculated *I*-*V* characteristics for a ferromagnetic tunnel diode are presented in fig. 6 in the case $p = 0.5$. Here we used the following material parameters for (Ga, Mn)As: $m^* = 0.5m_0$, $E_g = 1.4\,\text{eV}$, $E_{Fn} - E_C = 0.1\,\text{eV}$, $E_V - E_{Fp} = 0.3\,\text{eV}$. We also assumed that temperature is so low that the Fermi-Dirac distribution functions could be approximated by step functions. The solid curve shows the tunnelling current as calculated from eq. (1), when there is no band splitting, $\Delta = 0$. Below Curie temperature or in high magnetic fields $\Delta > 0$, and the dashed and dotted curves show the effect of the band splittings $\Delta = 0.1\,\text{eV}$ and $\Delta = 0.2\,\text{eV}$, respectively, on the *I*-*V* characteristics. The calculated results indicate that in the case $p = 0.5$ the tunnelling current decreases due to the band splitting. This is due to fact that, according to eq. (2), the total density of states includes both the spin-up and spin-down states at Fermi energy and decreases due to the band splitting, when $p = 0.5$. This can be shown easily by expanding eq. (2) as a Taylor series with respect to the small parameter Δ, which yields for the change of the density of the valence band state as $D(\Delta = 0) - D(\Delta \neq 0) \sim p(p-1)$. This change is negative, when $p < 1$.

Since the band splitting $\Delta = xJ_{exch}\langle S^z(T, B)\rangle$ depends strongly on magnetic field at temperatures close to the Curie temperature, the calculated results point to a large magnetoresistance in the ferromagnetic Zener diode. This is in contrast to the behaviour of the conventional nonmagnetic Zener diodes, where the tunneling current depends only weakly on magnetic field. The calculated results of fig. 6 are in good agreement with the experimental results of fig. 3, where the measured current decreases due to the applied magnetic field. 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 tunneling current in the voltage range 300–400 mV, as shown by the kinks in fig. 4. However, this behaviour was not found in the experimental results, which we believe is due to the fact that in this voltage range the tail of the tunnelling current is much smaller than the excess current J_X, which does not depend on the magnetization.

According to the above model, in an ideal ferromagnet without magnetic domains, the effect of the magnetic field on the tunnelling current should be largest at temperatures close to T_C, where the change in magnetization due to the magnetic field is largest. However, in the experimental results shown in fig. 3 the change in current is largest at low temperatures well below T_C. We believe this is due to ferromagnetic domains, which in GaMnAs typically require a magnetic field $\geq 200\,\mathrm{mT}$ before the net magnetization approaches the saturation at $T \ll T_C$. Therefore the maximum change in the net magnetization from zero to the saturation magnetization due to the external magnetic field occurs at low temperatures well below T_C. The same explanation applies to the anomalous Hall resistance R_H *vs.* magnetic field shown in fig. 1, since in an ideal ferromagnet without domains also R_H should be nonzero even when $B = 0\,\mathrm{T}$, whereas the experimental results show a large increase in R_H from zero to a saturated value in low magnetic fields.

To conclude we can state that, to our knowledge, for the first time the effect of ferromagnetism has been observed experimentally in the *I-V* characteristics of the ferromagnetic Zener diode. It is manifested as a large magnetoresistance in the tunnelling current at low temperatures. The effect can be explained by applying a model, where the magnetic-field–dependent valence band splitting caused by the exchange interaction between carrier spins and the aligned magnetic moments of the Mn atoms reduces the density of states, and, consequently, the tunneling current. Therefore, the ferromagnetic Zener diode provides a simple device for tunnelling spectroscopy in heavily doped ferromagnetic semiconductors.

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