Magnetic GaAs resonant tunnelling diodes with a Mn-doped emitter

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We have fabricated ferromagnetic resonant tunnelling diodes (FRTD’s) based on the AlAs/GaAs/AlAs quantum wells and the p-type Mn-doped GaAs emitter layers. At low temperatures a large magnetic field dependence of the tunnelling current appears in the magnetic RTD’s in rather low fields (B < 1T), which is not found in nonmagnetic RTD’s. The observed decrease of current in the case of the metallic ferromagnetic emitters is explained by a tunnelling anisotropic magnetoresistance effect.

1. Introduction

Spintronic devices are hoped to provide low power alternatives for conventional microelectronics. The interest in semiconductor spintronics increased rapidly after the discovery of ferromagnetism in III-V compound semiconductors such as Mn-doped GaAs [1,2]. Ever since the spin-dependent tunnelling has been a topic of intensive research, both in ferromagnetic spin Zener-Esaki-tunnel diodes [3] and ferromagnetic resonant tunnelling diodes (FRTD’s) [4]. In the FRTD a spontaneous band splitting has been observed in the I-V characteristics of the diode [4]. In the present paper we carry out a comparative study between the magnetic and non-magnetic resonant tunnelling diodes (RTD’s) made of p-type GaAs and insulating AlAs thin films. Especially, we are interested in the magnetic field dependence of the I-V characteristics.

2. Experimental

The magnetic RTD structures, which were studied in the present work and which are shown schematically in figure 1, were grown by using both molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy deposition (MOVPE) growth techniques. First, a quantum well structure was grown by using MOVPE. The substrate was a non-magnetic p⁺-GaAs having a carrier concentration \( p = 1.3 \times 10^{19} \text{cm}^{-3} \). Then a p-type GaAs buffer layer was grown having the thickness of 100nm and \( p = 5 \times 10^{19} \text{cm}^{-3} \). On top of the buffer layer a thin (5 nm) undoped additional GaAs buffer layer was grown. The quantum well consists of undoped GaAs between two undoped AlAs barriers, all layers being 5 nm thick. Finally, a 500 nm thick Mn-doped magnetic GaAs layer was grown by using MBE at low temperatures \( T = 230 \text{ °C} \).

The fabrication of the final diode structures started with a lift-off process for a front metal contact consisting of 5/10/100 nm thick Au/Ti/Au layers, respectively, made by an e-beam evaporation technique. Then a 600 nm deep mesa was etched by using a \( \text{H}_2\text{O}_2/\text{citric acid} \). The thickness of the evaporated contact metals was increased by electroplating a 50 μm thick copper layer on top of the Au/Ti/Au contacts. We also fabricated non-magnetic reference RTD’s without Mn-doping, having...
otherwise the same parameters as the magnetic RTD's. Magnetotransport properties of the Mn-doped GaAs layers were measured by using a Van der Pauw configuration for the contacts. A magnetic field $B$ (up to 1.3 T) was applied perpendicular to the sample plane, as also in the measurements of the $I$-$V$ characteristics of the RTD's.

![Figure 1](image1.png)

Figure 1. Schematic structure of the fabricated magnetic RTD. The area of the mesa structure is 100 μm times 100 μm.

3. 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 both based on the observation of the anomalous Hall effect and the direct magnetization measurements. A M-I transition was observed when the Mn content increased from $x<$0.035 to $x\geq0.04$, i.e., the strongly temperature-dependent resistivity at low temperatures changed to a metallic or $T$-independent resistivity with increasing $x$. In the semiconducting samples with $x<0.035$ a large magnetoresistance (MR) (up to 40 % in $B=1$T) was observed at low temperatures $T<20$K. In the metallic samples MR was smaller with a maximum value $\approx3\%$ in $B=1$T at the Curie temperature $T_C \approx 50$K.

Figure 2 shows the measured $I$-$V$ characteristics of the non-magnetic RTD. The first three resonant peaks corresponding to the quantized HH1, LH1 and HH2 energy levels in the AlAs/GaAs/AlAs quantum well [5], are shown clearly at both bias voltage polarities. The inset shows that in the non-magnetic RTD the magnetic field-dependence of the tunnelling current is minor.

![Figure 2](image2.png)

Figure 2. $I$-$V$ characteristics of a non-magnetic GaAs RTD at 8 K. The inset shows the effect of the magnetic field on the HH2-resonant peak.

![Figure 3](image3.png)

Figure 3. (a) and (b) $I$-$V$ characteristics of a FRTD with a semiconducting (Ga,Mn)As emitter at various temperatures for the first two peaks. (c) and (d) Conductance $dI/dV$ vs. negative bias voltage at various temperatures for the first two peaks ($B=0$T in all cases)
Figures 3 (a)-(d) show the $I$-$V$ characteristics and the conductance $dI/dV$ vs. negative bias voltage, respectively, at various temperatures for a FRTD with an Mn-doped emitter on the insulating (or semiconducting) side of the M-I transition. The first two peaks start to show up at temperatures below 90 K. An interesting phenomenon is the appearance of a double peak structure in the conductance curve in figures 3 (c) and 3 (d) at low temperatures around and below the Curie temperature. At the positive bias we could not observe resonant tunnelling in the case of the Mn-doped emitter.

Figures 4 (a) and (b) show the effect of the external magnetic field of 1T on the $I$-$V$ characteristics and the conductance vs. voltage, respectively, in the case of the semiconducting Mn-doped emitter at $T=8$K. There is a rather large shift of the peaks to more positive voltages due to the applied magnetic field.

![Figure 4. (a) Effect of an external magnetic field on the I-V characteristics of a FRTD with a semiconducting emitter at $T = 8$ K for negative bias voltages. (b) Effect of an external magnetic field on conductance $dI/dV$ vs. negative bias voltage at $T=8$K.](image)

In a theoretical model for the FRTD’s [6] it has been shown, that at the negative bias the effect of the ferromagnetic ordering on the $I$-$V$ characteristics is minor. Therefore, we do not believe, that the observed large shifts of the resonant peaks in figures 3 and 4 in the case of the semiconducting emitter are related to the band splitting and the spin-dependent tunnelling. Instead, we believe that these shifts result from the observed large negative MR of the Mn-doped layer, which causes a redistribution of the bias voltage inside the FRTD structure. The reason for not observing resonant tunnelling at the positive bias is probably related to the large Fermi energy of the heavily Mn-doped emitter, which deteriorates the resolution of the tunneling spectroscopy. At the negative bias the tunnelling occurs from a more lightly doped GaAs layer having a smaller Fermi energy, and the peaks can be seen.

The double peak structures in the measured conductance $dI/dV$ in figures 3 (c)-3(d) and 4 (b) are similar to the ones reported by Ohno et al.[4]. They interpreted the double peaks as a manifestation of a spontaneous valence band splitting due to the magnetic ordering. However, we challenge this interpretation in our FRTD’s, since the double peak structure appears at different temperatures for the peaks in figures. 3 (c) and 3(d). If the double peaks were related to the appearance of the spontaneous magnetization, they should appear at $T_C$. Furthermore, in the case of the first peak the double peak structure disappears at low temperatures. Also, in disagreement with the model [6], the observed voltage difference between the double peaks does not depend on temperature or the magnetic field. Finally, the double peak structure seems to be related to a kink – or a current shoulder- in the $I$-$V$ characteristics in the voltage region for the negative differential resistance. This shoulder is well known also in the non-magnetic RTD’s [7], and it is probably related to the extrinsic instability of the bias circuit due to the negative differential resistance. The kinks appear and disappear at different temperatures for different resonant peaks (figure 3), since the kinks depend on the LRC-bias circuit [7], and the values of the series resistances due to the RTD structure in the circuit depend on temperature and are different at different peaks.
Figure 5. $I-V$ characteristics of a FRTD with a metallic (Ga,Mn)As emitter at various temperatures. The inset shows the effect of the external magnetic field on the resonant peak HH2 at $T=8K$.

In the case of the metallic Mn-doped emitter the temperature and magnetic field dependences of the resonant peaks are much weaker than above (figures 5 and 6). Now the external magnetic field decreases the current. The magnetic field dependence in figure 6 is similar to the one in the magnetic spin Zener-Esaki diodes [3]. Recently this effect was interpreted as an evidence for the tunneling anisotropy magnetoresistance (TAMR) [8]. According to the TAMR model the change in the direction of the saturated magnetization causes the MR effect at low temperatures: The magnetization, which originally in the case of zero magnetic field lies along the easy axis in the plane of the Mn-doped GaAs thin film, is aligned in the direction of the applied perpendicular magnetic field, even if the magnetization is saturated. Therefore, the change in the tunnel current is now due to the dependence of the anisotropic density of states (DOS) of the valence band on the direction of the magnetization [8]. The calculated anisotropy in DOS for other magnetic tunnel junctions based on the III-V magnetic semiconductors is on the same order of magnitude, or even larger than the observed decrease of the current in figure 6.

4. Conclusion

In the case of the metallic Mn-doped emitter in the AlAs/GaAs RTD we interpret the observed magnetic field dependence of the resonant peaks as a manifestation of the tunnelling anisotropy magnetoresistance effect. On the other hand, with the semiconducting emitter the large magnetic field dependence of the series resistance in the GaMnAs layer seems mask the possible spin dependent tunnelling effects.

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