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Semimagnetic resonant tunneling diodes for electron spin manipulation

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Abstract. Recently, efficient electrical injection of spin polarized electrons into GaAs has been accomplished by using a semimagnetic II–VI single layer, namely BeMnZnSe, as a spin aligner [1]. In such spin aligner materials, the orientation of the electron spins can only be controlled by varying the magnetic field. Here, we introduce an approach aiming at manipulating spins by an external voltage. For that we developed BeTe/ZnMnSe/BeTe semimagnetic resonant tunneling diodes as a spin injector into nonmagnetic III–V material. By changing the resonance condition from a spin-up to spin-down Zeeman level, it should be possible to actually switch from one spin orientation to the other. An AlGaAs/GaAs/AlGaAs p-i-n Light Emitting Diode was used to detect the efficiency of the spin injection, because the circular polarization of the electroluminescence is a direct measure of the spin polarization of the injected electron current. Although no spin-splitting of the bound electron states in the ZnMnSe quantum well could be observed in current-voltage-measurements, electroluminescence from the LED revealed a high circular polarization of up to 70%, indicating a strongly spin-polarized electron current. The use of a semimagnetic RTD as a spin-switch device would represent a further important step towards spin manipulation in semiconductors.

Introduction

Until today, common electronic devices are operated with the charge of the electrons only. But electrons also carry spin, and since several years theory predicts immense advantages, if one could employ this attribute in electronic devices. In spite of great efforts dedicated to the development of such spin-coherent electronics, very basic problems seem to oppose a real breakthrough in this field. One major task is to find an efficient spin injector. Much work focused on utilizing ferromagnetic metallic contacts, but it proved extremely difficult to show spin injection into a semiconductor material. Only very small effects of spin-polarized injection from a NiFe contact have been reported until today [2, 3] (0.9% and 0.2% resistance change, respectively). Therefore more attention is recently being paid to another set of materials, i.e. diluted magnetic semiconductors, and very promising results have already been reported. Recently, we have been able to demonstrate a very efficient spin injection into non-magnetic GaAs via a single layer of the semimagnetic II–VI material BeMnZnSe [1]. A spin polarization of close to 100% in the BeMnZnSe together with a high quality II–VI/III–V interface and a small conduction band offset in that system are the prerequisites for efficient spin injection. In fact it has been shown theoretically that a spin polarization of less than 100%, as is the case for ferromagnetic metal contacts, will result in a very small degree of spin injection into a non-magnetic semiconductor [4]. A major limitation of this simple spin aligner approach, however, is that the spin orientation of the injected electron current can only be changed by reversing the magnetic field, which is a slow and dissipative process.

Here we report on the development of BeTe-ZnMnSe-BeTe resonant tunneling diodes, aiming at the fabrication of a voltage operated spin-switch device. The incorporation of

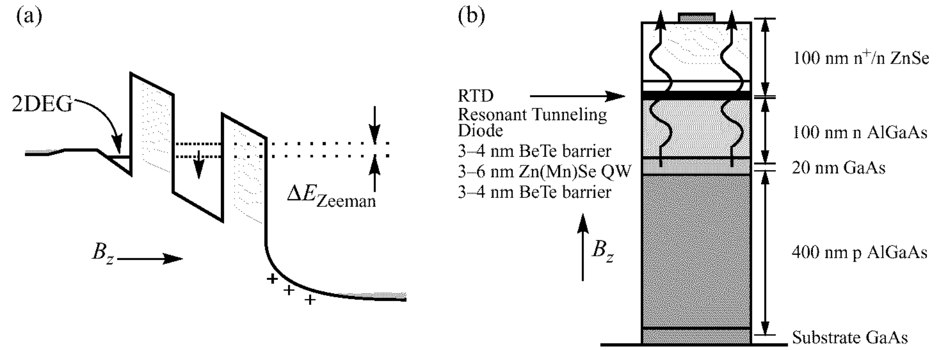

Fig. 1. (a) Band structure of a Resonant Tunneling Diode in an external magnetic field in resonance with the spin down subband level and (b) General structure (sideview) of a LED+RTD device.

the magnetic Mn ions (with their magnetic moment arising from the half-filled d-shell) into ZnSe presents a semimagnetic system with a well known magnetic behaviour. Most significantly, the sp-d exchange interaction between the Mn ion spins and carrier spins leads to a giant effective g-factor of up to 100, and hence a large Zeeman-splitting in external magnetic fields [5]. Using ZnMnSe in the quantum well of a double barrier RTD and applying an external magnetic field therefore results in a splitting of every subband into two spin-split bands, each corresponding to one spin component (Fig. 1(a)). Theoretical considerations using the Transfer-Matrix-Method predict a spin-dependent transmission coefficient, leading to a spin polarized tunneling current [6]. Consequently, the orientation of the spin-polarization should be tunable by the voltage applied across the RTD.

Experimental details

The AlGaAs-GaAs p-i-n LED structures have been grown in a separate III–V MBE reactor, using Be and Si as dopants. The BeTe/Zn(Mn)Se Resonant Tunneling Diodes were then grown directly onto the LED in a neighbored II–VI reactor, being transferred through a UHV transfer system to avoid any surface contamination. Figure 1(b) shows the general setup of such a structure. Flux calibration was done by the RHEED oscillation technique and the lasting and very pronounced RHEED oscillations were an indication for the high quality of the growth and a very low density of extended defects at the II–VI/III–V interface, as has been shown earlier for the BeTe growth start on GaAs [7].

First we have investigated electron transport in the BeTe/Zn(Mn)Se RTDs by means of electrical methods and standard dc measurements were done to record their I/V characteristics. The heteropair ZnSe and BeTe is characterized by a type II band alignement with extremely high band-offsets of 2.3 eV in the conduction band and 0.9 eV in the valence band, which enabled us to study up to four clearly separated resonances with high peak to valley ratios(PVR) and additional features such as LO-phonon assisted tunneling [8]. A giant electro-optical anisotropy of the spatially indirect transition from the ZnSe conduction band into the BeTe barriers has been interpreted in terms of quantum-confined Pockels-Effect, providing further proof for the high structural quality of the samples, in particular of the BeTe/ZnSe interfaces [9]. The next step was to use combined electro-optical methods to learn more about the LED-RTDs, by analyzing the LED electroluminescence in Faraday geometry with a conventional CCD camera.

Results and discussion

The resonance peaks in the I/V characteristics of the semimagnetic LED-RTDs showed no direct indication of Zeeman splitting in external magnetic fields, which is consistent with the results of Keim *et al*[10]. This could be due to the existence of a lateral fluctuation of the band offset because of "ZnTe" and "BeSe" terminated interfaces, leading to a broadening of the bound electron states in the quantum well. Another reason could be a dominating non-coherent, sequential tunneling current, leading to an efficient thermalization of carriers into the lower Zeeman level. In contrast to I/V, the polarization behaviour of the LED under electrical injection through the RTD shows a large effect of the semimagnetic quantum well: We found a very high degree of circular polarization of the emitted light, which is a direct measure of the spin-polarization of the injected electron current, since the recombination of the electrons with the split-off hh band in the non-magnetic GaAs qw follows the relevant selection rule $\Delta m_j = \pm 1$. In fact no lh transition has been observed in the samples. Figure 2(a) shows the magnetic field dependence of the circular polarization for a RTD with 10% Mn in the qw and the corresponding non-magnetic reference structure at 1.6 K and an applied voltage of 1.9 V. While the magnetic sample reveals a polarization of up to 70%, the non-magnetic reference emits almost unpolarized light, and its small polarization is due to the intrinsic g factor of the GaAs qw. The increase and consequent saturation of the polarization of the magnetic RTD with increasing magnetic field can be theoretically accounted for by considering the typical behaviour of the Zeeman splitting in diluted magnetic semiconductors. This is an important indication that the subbands in the RTD really split in magnetic fields, although this could not be observed in pure electrical measurements. We also examined the behaviour of the polarization degree with respect to the applied voltage, especially around the first resonance in the I/V characteristic of the RTD. Such a result is shown in Fig. 2(b) for a fixed magnetic field of 5.5 T. Around the first resonance, the spin polarization is sharply decreasing from 80% down to 60%. Presently its unclear whether the decrease in polarization with increasing bias voltage is due to the expected resonance effects, or just due to a heating of the Mn system at higher currents, leading to a smaller spin polarization. Even though no clear effect of the 2 Zeeman resonances could be detected at the present stage, semimagnetic BeTe/ZnMnSe RTD obviously

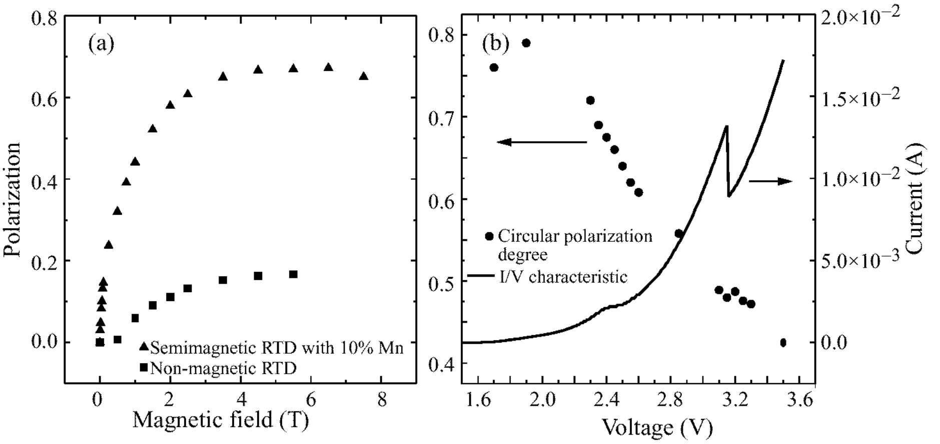

Fig. 2. (a) Circular polarization vs magnetic field and (b) circular polarization and current vs voltage.

presents a very efficient spin injector into non-magnetic GaAs. Further work has to be done in order to optimize the resonant tunneling structures.

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