An InAs-Based Spin Field-Effect Transistor: A Path to Room Temperature Operation

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Novel microelectronic devices have to be smaller and faster than the traditional ones and be more efficient in order to reduce power consumption of future integrated electronic circuits. A promising alternative to the charge degree of freedom currently used in MOSFET switches is to take into account the spin degree of freedom. The spin of an electron can change its orientation to opposite very fast by using an amazingly small amount of energy, which offers a unique opportunity to reduce the power per operation in semiconductor logics.

The spin field-effect transistor (SpinFET) is a future semiconductor spintronic device promising to achieve outstanding device and circuit performance superior to that of the present transistor technology. A SpinFET is a three-terminal device composed of source and drain contacts made from ferromagnetic materials and a semiconductor region sandwiched between the contacts. Spin-polarized electrons injected in the semiconductor region begin to precess in the effective magnetic field created by the spin-orbit interaction. At the end of the semiconductor channel spins are aligned along an axis which forms an angle with the magnetic polarization of the drain contact. The magnitude of this angle depends on the strength of the spin-orbit interaction α_R. By modifying this strength one can adjust the spin orientation at the end of the semiconductor region. This allows manipulation of the current in the device through the influence of the mutual orientation of spins and the drain contact on resistance known as the giant magnetoresistance effect. Thus, current modulation is achieved by electrically tuning the gate voltage dependent strength of the spin-orbit interaction in the semiconductor region [1], [2].

We investigate the properties of a SpinFET based on InAs. This material is characterized by strong spin-orbit interaction [3]. We use the model of a SpinFET introduced in [3], [4]. First we compute the magnetoresistance ratio (TMR) defined as TMR = $(G_{\uparrow\uparrow} - G_{\uparrow\downarrow})/G_{\uparrow\downarrow}$, where $G_{\uparrow\uparrow}$ and $G_{\uparrow\downarrow}$ are the conductances for the parallel and anti-parallel orientation of the source and the drain contacts, respectively. In the corresponding parameter range we reproduced the zero-temperature results [3]. Figure 1 and Figure 2 demonstrate the oscillations of the TMR at zero temperature for two intervals of values of the conduction band mismatch between the ferromagnetic contacts and the channel δE_c. Contrary to the recently studied short-channel Si-based SpinFET [5], [6], the amplitude of the magnetoresistance oscillations depends strongly on α_R, although the strength of the spin-orbit interaction does not influence the period of oscillations. At fixed channel length the period of the oscillations slightly increases, while the range of δE_c shifts to smaller values.

Figure 3 shows the dependence of the TMR on the value of the band mismatch δE_c for several temperatures. The amplitude of the oscillations of the TMR seen in Figure 1 and Figure 2 is considerably reduced at elevated temperatures. However, the TMR modulation as a function of the band mismatch does not vanish completely. Hence, the current in the SpinFET can be controlled by adjusting the value of the band mismatch. However, in order to operate it successfully the value of the band mismatch must vary in a wide range.

Another option to proceed to higher temperatures is to boost the value of the TMR by exploiting at the same time its dependence on α_R. Following [3] and [4] we introduce the Schottky barriers with the strength $z=2m_fU/\hbar^2k_F$ at the interfaces between the contact and the channel. Figure 4 illustrates the corresponding change. As the barriers become stronger the quantization of the energy in the semiconductor channel becomes more pronounced. The energy quantization is responsible for the appearance of the sharp peaks on the TMR dependence on δE_c clearly seen in Figure 4. An excellent feature following from Figure 4 is that the TMR value remains positive in a broad range of δE_c. Most importantly, the sign and the values of the TMR depend on the strength of the spin-orbit interaction. It then follows that in the presence of the barriers between the contact and the channel the values of the TMR must depend on the strength of the spin-orbit interaction controlled by the gate voltage at elevated temperatures as well. We next generalize the consideration [3], [4] to finite temperatures.

Figure 5 displays the TMR dependence on the strength of the spin-orbit interaction at different temperatures. The TMR modulation is preserved at elevated temperatures, thus opening a practical possibility to control the TMR by changing the value of α_R even at room temperature.

Finally, the current dependences on the drain-source voltage are shown in Figure 6 for parallel and antiparallel configurations of the contact magnetization, for several temperatures. At low temperature a step-like behavior at low voltages is observed due to the resonances created by the Schottky barriers at the interfaces between the contact and the channel. The current values for the parallel configuration of the contacts' magnetization is about two times larger compared to that of currents for the antiparallel configuration. This difference remains even at room temperature and is preserved for the currents at saturation as seen in Figure 6. Therefore, analogously to the TMR, the current in the SpinFET can be modulated by modifying the strength of the spin-orbit interaction at room temperature, provided the channel length is shorter than the characteristic spin relaxation length.

References

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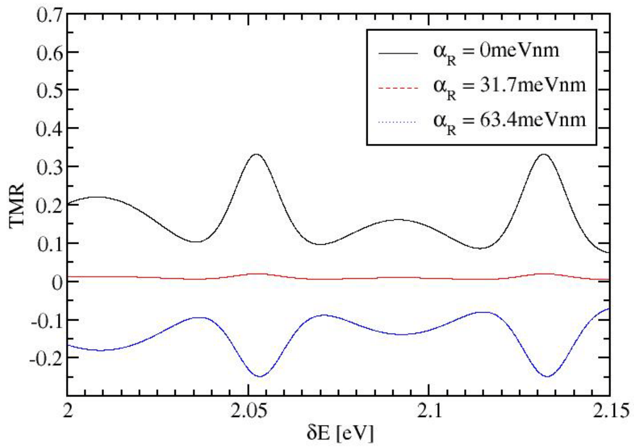

Fig. 1: T*MR dependence on the value of the* δE_c *for the Fermi energy* $E_F = 2.47eV$*, length* $L = 0.05\mu m$*, and polarization* $P = 0.5$*.*

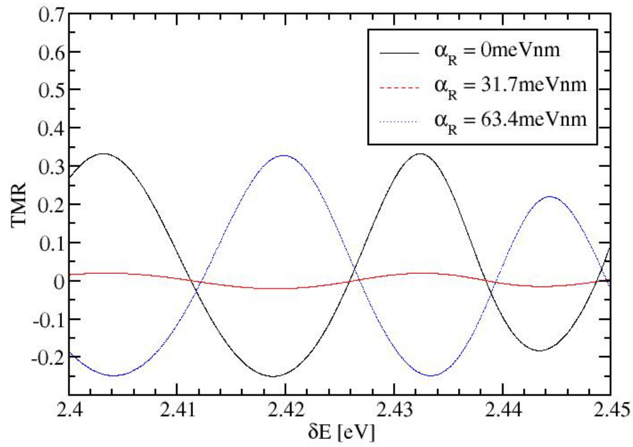

Fig. 2: *TMR dependence on the value of the* δE_c *for* $E_F = 2.47eV$*,* $L = 0.05\mu m$*,* $z = 0$*,* $P = 0.5$*.*

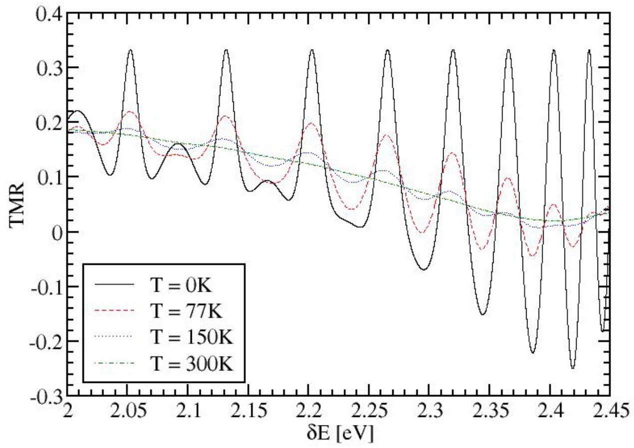

Fig. 3: T*MR dependence on the value of the* δE_c *for* $E_F = 2.47eV$*,* $L = 0.05\mu m$*,* $z = 0$*,* $P = 0.5$*.*

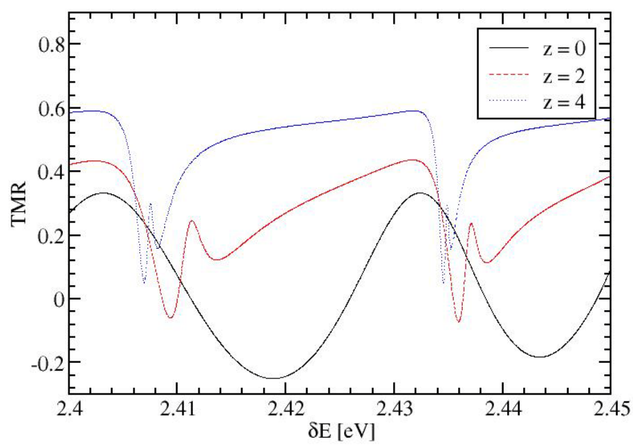

Fig. 4: T*MR dependence on the value of the* δE_c *for* $E_F = 2.47eV$*,* $L = 0.05\mu m$*,* $z = 0$*,* $P = 0.5$*.*

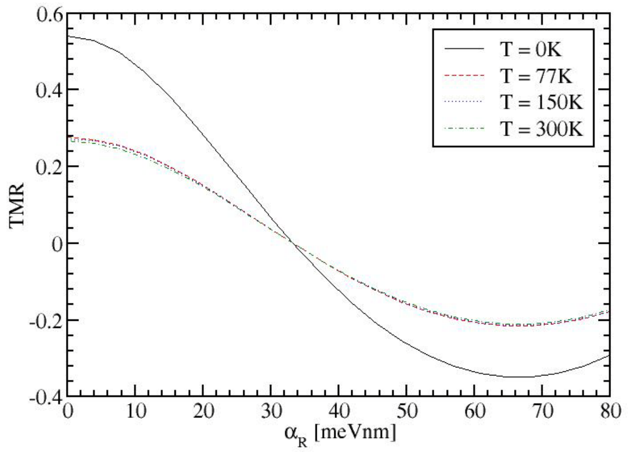

Fig. 5: *TMR dependence on the value of spin-orbit interaction for* $E_F = 2.47eV$*,* $L = 0.05\mu m$*,* $\delta E_c = 2.42eV$*,* $P = 0.5$*,* $z = 4$*.*

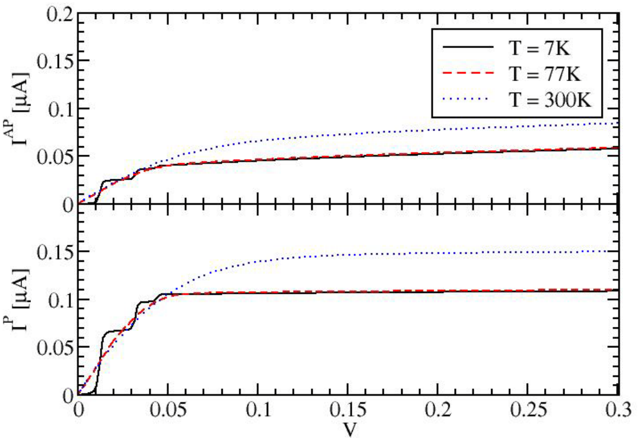

Fig. 6: *IV characteristics for antiparallel and parallel configurations of the contacts magnetization for* $E_F = 2.47eV$*,* $L = 0.05\mu m$*,* $\delta E_c = 2.42eV$*,* $\alpha_R = 0$*,* $P = 0.8$*,* $z = 5$*.*