Modeling Spintronic Effects in Silicon

Dmitry Osintsev, Viktor Sverdlov, and Siegfried Selberherr

Institute for Microelectronics, TU Wien, Gußhausstraße 27-29, A-1040 Wien, Austria
{Osintsev|Sverdlov|Selberherr}@iue.tuwien.ac.at

1. Introduction

The electron spin can change its orientation to opposite very fast by utilizing an amazingly small amount of energy, which offers a unique opportunity to reduce the power per operation in semiconductor logic devices. The spin field-effect transistor (SpinFET) is a switch which employs the spin properties of electrons. The SpinFET is composed of a semiconductor channel region sandwiched between the two ferromagnetic contacts, source and drain (Fig.1). The source contact injects spin-polarized electrons in the semiconductor region. The gate-voltage-dependent spin-orbit interaction in the channel is used to modulate the current through the SpinFET [1]. It causes the electron spin to precess during the electron propagation through the channel. Only the electrons with their spin aligned to the drain contact magnetization can leave the channel through the drain contact, thus contributing to the current. The spin-orbit interaction is controlled electrically by applying an external gate voltage.

2. Model and Results

To calculate the transport properties of the ballistic spin field-effect transistor schematically shown in Fig.1 we consider the Hamiltonian in the ferromagnetic regions in the following form [2], [3]:

$$\begin{aligned} H &= \frac{p_x^2}{2m_f^*} + h_0\sigma_z, \quad x<0, \\ H &= \frac{p_x^2}{2m_f^*} \pm h_0\sigma_z, \quad x>L, \end{aligned} \tag{1}$$

where m^*_f is the effective mass in the contacts, $h_0=2PE_F/(P^2+1)$ is the exchange splitting energy with P defined as the spin polarization in the ferromagnetic regions, E_F is the Fermi energy, and σ_z is the Pauli matrix; ± in (1) stands for the parallel (P) and anti-parallel (AP) configuration of the contact magnetization. The effective Hamiltonian in the channel is [2]

$$H = \frac{p_x^2}{2m_s^*} + \delta E_c + \frac{\beta}{\hbar}(p_x\sigma_x - p_y\sigma_y) + \frac{1}{2}g\mu_B B\sigma^* \tag{2}$$

Here m^*_s is the subband effective mass, δE_c is the band mismatch between the ferromagnetic and the semiconductor region, g is the Landé factor, μ_B is the Bohr magneton, B is the magnetic field, and $\sigma^* \equiv \sigma_x\cos\gamma + \sigma_y\sin\gamma$ with γ defined as the angle between the magnetic field and the transport direction. As it was recently demonstrated [4], [5], the major contribution to the spin-orbit interaction in thin silicon films is due to the interface-induced inversion asymmetry and is mathematically equivalent to the linear Dresselhaus term. The coefficient β of the spin-orbit interaction in silicon heterostructures is a linear function of the gate voltage, which is the key for the current modulation in the channel (Fig.1): it causes the electron spin to precess during the propagation through the channel. Fig. 2 shows the modulation of the tunnel magneto-resistance $TMR \equiv \frac{G^P - G^{AP}}{G^{AP}}$ defined by the channel conductances in P/AP configuration of the relative source/drain magnetizations on the strength of the spin-orbit interaction β in silicon channels of different length. As the length of the channel decreases, the period of the TMR modulation increases. L=4μm is sufficient to observe half of the oscillation and thus to modulate the TMR by adjusting the strength of the spin-orbit interaction. To facilitate the spin injection into silicon delta-function barriers of strength $z = 2m_F U/\hbar^2 k_F$ are introduced. As shown in Fig.3, increasing the barrier leads to a more pronounced TMR modulation as a function of β. Fig.4 shows oscillations of the TMR on the value of the bandgap mismatch δE_c. The period of the oscillations is inversely proportional to the length of the channel. Temperature exerts a significant influence on the oscillatory amplitude as shown in Fig.5. For L = 0.2μm the oscillatory behavior of the TMR completely vanishes for T = 50K. The reason is a relatively short period of the TMR oscillation with respect to δE_c shown in Fig.4. For longer channels the period becomes even shorter, hence the shorter channels are needed to preserve the TMR modulation at higher temperatures as a function of δE_c. A different option to proceed to room temperature operation is to increase the channel length. Fig.6 shows a possibility to modulate the TMR by changing the value of β even at room temperature, however, the channel length should be a few micrometers for the parameters specified [6]. The non-zero spin-orbit interaction leads to an increased spin relaxation. In quasi-one-dimensional electron structures, however, a suppression of the spin relaxation was predicted [7].

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References

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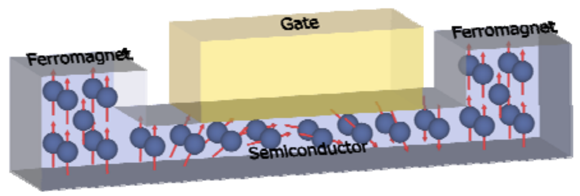

Fig.1: *Illustration of the Datta-Das spin field effect transistor. The spin-orbit interaction with the gate voltage dependent strength alters the spin polarization direction in the channel close to the ferromagnetic drain. Only electrons with the spin direction aligned to the drain magnetization contribute to the current.*

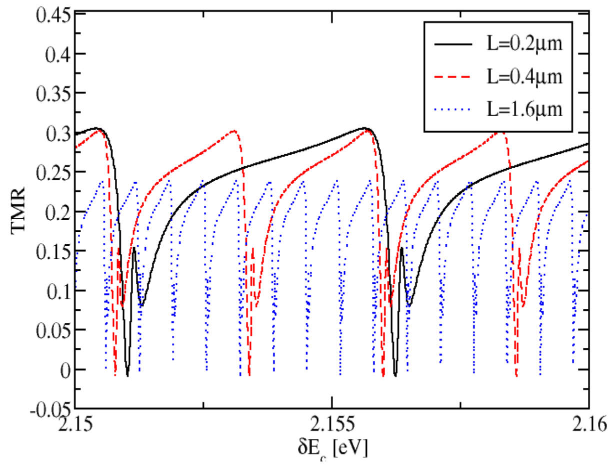

Fig.4: *TMR dependence on the conduction band mismatch for* z=3, β=42.3μeVnm.

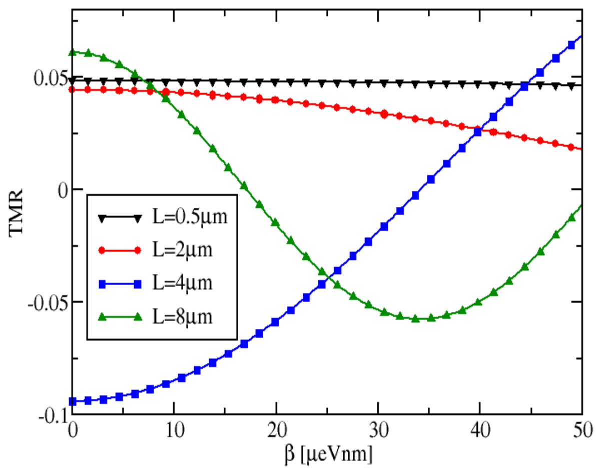

Fig.2: *TMR dependence on the value of the Dresselhaus spin-orbit interaction for* E_F=2.47eV, δE_c=2.154eV, z=1.

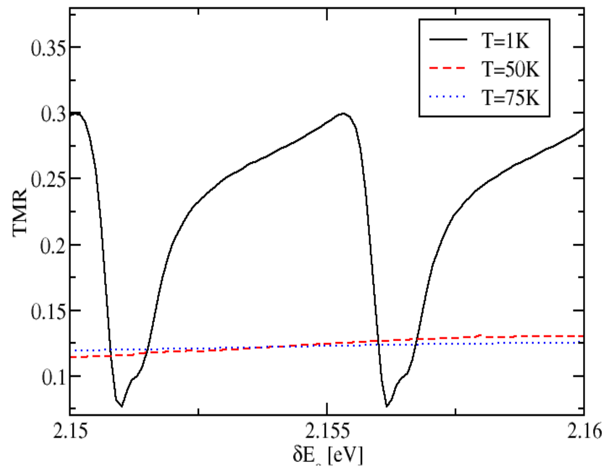

Fig.5: *TMR for different temperatures for the parameters from Fig.4, and* L=0.2μm, V=1meV.

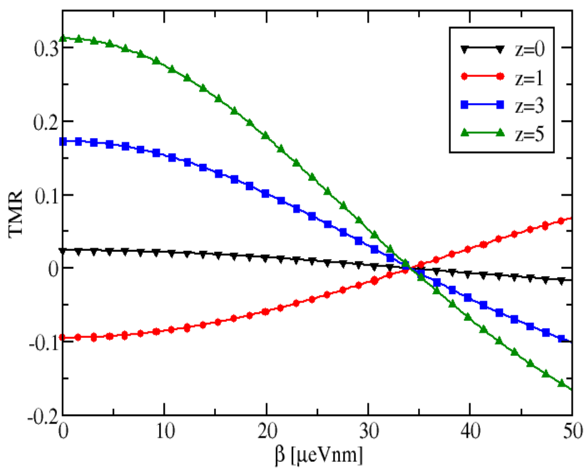

Fig.3: *TMR dependence on the spin-orbit interaction strength for* L=4μm.

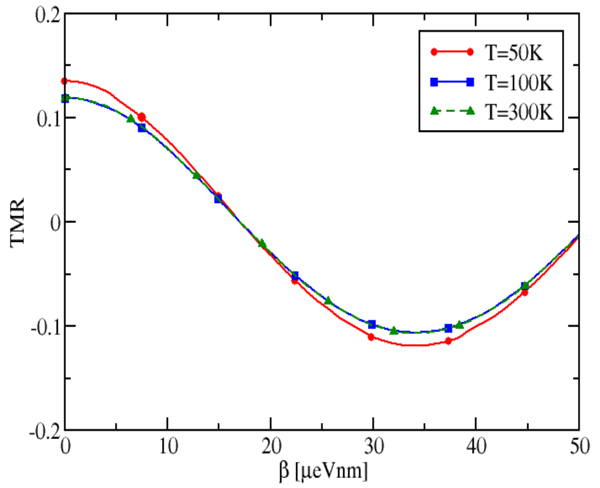

Fig.6: *TMR dependence on* β *for* L=8μm. *The other parameters are the same as in Fig.4.*