Ballistic Spin Field-Effect Transistors Built on Silicon Fins

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1. Introduction

The outstanding increase of computational power of integrated circuits is supported by the continuing miniaturization of semiconductor devices' feature size. With scaling approaching its fundamental limits, however, the semiconductor industry is facing the necessity for new engineering solutions and innovative techniques to improve MOSFET performance. Using spin as an additional degree of freedom is a promising way for future nanoelectronic devices in both memory [1] and logic [2] applications. Silicon, the main element of microelectronics, possesses several properties attractive for spintronics: it is composed of nuclei with predominantly zero spin and is characterized by small spin-orbit coupling. In experiments coherent spin transport through an undoped silicon wafer of $350\,\mu$m thickness was demonstrated [3]. Spin coherent propagation at such long distances makes the fabrication of spin-based switching devices in the near future quite likely.

2. Method and Results

We investigate the properties of ballistic fin-structured silicon spin field-effect transistors (SpinFETs). The original suggestion for the spin transistor by Datta and Das [4] employs the spin-orbit coupling for current modulation. The electric-field dependent spin-orbit coupling is assumed to be due to the geometry-induced breaking of the inversion symmetry (Rashba type). However, it was demonstrated recently [5,6] that the major contribution to the spin-orbit interaction in thin silicon films is due to the interface-induced inversion asymmetry (Dresselhaus type). The coefficient of the spin-orbit interaction in silicon heterostructures is a linear function of the electric field which opens the way to modulating the current by applying the gate voltage.

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].

In our studies silicon fins have a square cross-section with (001) horizontal faces. The parabolic band approximation becomes insufficient in thin and narrow silicon fins, where an accurate description of the conduction band based on the **k·p** model [8] is necessary. This leads to a subband shape being dependant on the fin height and thickness. Fig.1 demonstrates the dependence of the subband minima as function of the fin thickness t. The fin orientation is along [110] direction. The dependence of the splitting between the unprimed subbands with decreasing t, which are perfectly degenerate in the effective mass approximation, is clearly seen. The value of the valley splitting is in good agreement with recent results from density-functional calculations [9] (Fig.2). Splitting between the valleys in a [100] fin can be ignored [9]. In contrast, the dependence of the effective mass of the ground subband in [100] fins on t is more pronounced as compared to [110] fins. Results of the density-functional calculations confirm the mass dependences obtained from the **k·p** model (Fig.3).

To form the SpinFET we sandwich the silicon fin between two ferromagnetic metallic contacts. The degree of the spin polarization in each contact is $0<P<1$. The contacts can be in either parallel or anti-parallel configuration. The carriers in the contacts are characterized by the effective mass m_F and the Fermi-energy E_F. Following [10], delta-function barriers at the interfaces between the contacts and the channel of the strength $z = 2m_F U / \hbar^2 k_F$ are introduced. Contrary to [10], the spin-orbit interaction is taken into account in the Dresselhaus form [5-6]. We study the conductance G through the system for parallel and anti-parallel configurations of the contacts. Fig.4 shows the dependence of TMR=$(G_{\uparrow\uparrow} - G_{\uparrow\downarrow}) / G_{\uparrow\downarrow}$ for [100] and [110] oriented fins with t=1.5nm on the value of spin-orbit interaction. Fins of [100] orientation display stronger dependence on β and are thus preferred for practical realizations of silicon SpinFETs. Because of the Dresselhaus form of the spin-orbit interaction, the TMR of [110] fins is most affected by the magnetic field along the transport direction (Fig.5), while the magnetic field orthogonal to the transport direction influences the TMR of [100] fins (Fig.6). Again, the TMR in [100] fins is most modified (Fig.6) by the external magnetic field, which provides an additional option to tune the performance of the silicon SpinFET.

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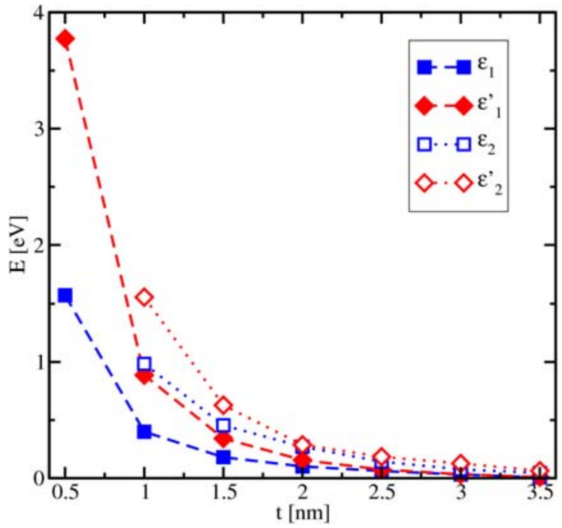

Fig.1: *Subband minima as a function of [110] fin thickness t.*

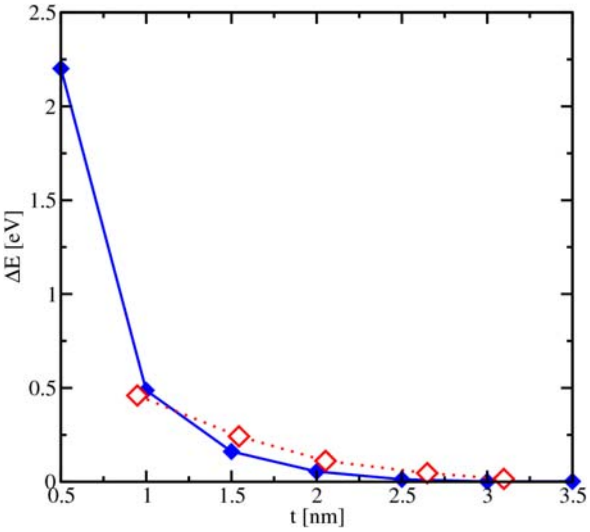

Fig.2: *Valley splitting in a [110] fin as a function of t. Open symbols are from [9].*

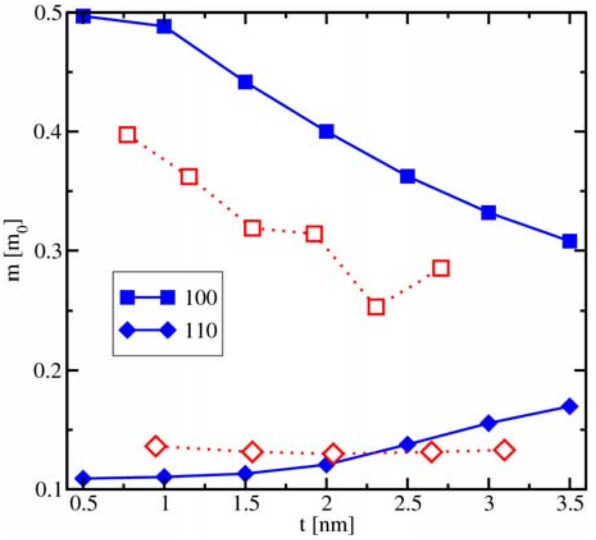

Fig.3: *Ground subband effective mass dependence on t in [100] and [110] fins. Open symbols are from [9].*

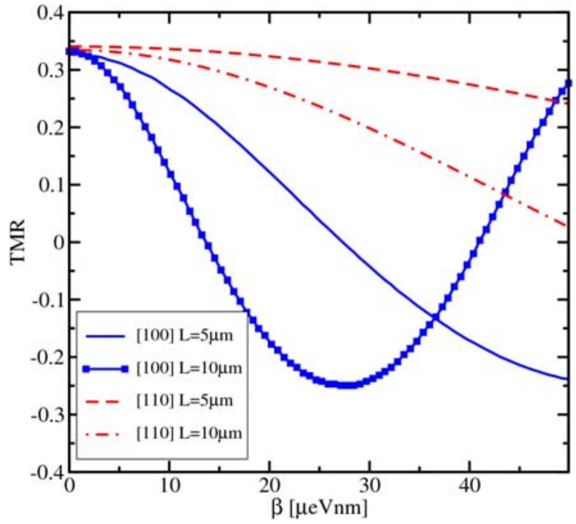

Fig.4: *TMR dependence on the value of the Dresselhaus spin-orbit interaction parameter for t=1.5nm, B=0T, P=0.4, z=5.*

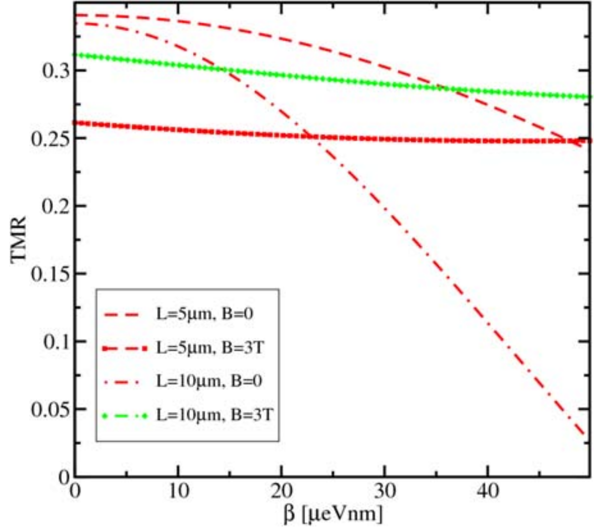

Fig.5: *The same as in Fig.4, for a [110] fin in a magnetic field parallel to the transport direction.*

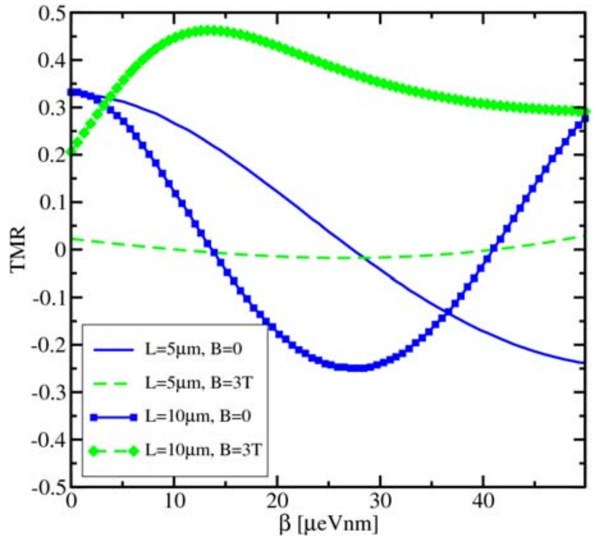

Fig.6: *The same as in Fig.4, for a [100] fin. The magnetic field is in [010] direction.*