Sains Malaysiana 42(2)(2013): 205–211

Current and Conductance Modulation at Elevated Temperature in Silicon and InAs-based Spin Field-Effect Transistors

(Modulasi Arus dan Konduktans pada Suhu Tinggi dalam Transistor Silikon dan InAs Berasaskan Spin Kesan Medan)

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ABSTRACT

Spin field-effect transistors (SpinFETs) are promising candidates for future integrated microelectronic circuits. A SpinFET is composed of two ferromagnetic contacts (source and drain), which sandwich a semiconductor channel. Current modulation is achieved by electrically tuning the gate voltage dependent strength of the spin-orbit interaction in the semiconductor region. We investigated the properties of SpinFETs for various parameters - the band mismatch, the barrier height between the contacts and the channel and the strength of the spin-orbit coupling, for various temperatures. We demonstrated that the creation of Schottky barriers between the channel and the contacts guarantees a pronounced modulation of the magnetoresistance sufficient to open a possibility to operate SpinFETs at room temperature. We also demonstrated that silicon fins with [100] orientation exhibit a stronger dependence on the value of the spin-orbit interaction and are thus preferable for practical realization of silicon-based SpinFETs.

Keywords: Spin field-effect transistor; spin-orbit interaction; temperature

ABSTRAK

Transistor spin kesan medan (SpinFETs) adalah calon yang menjanjikan masa depan mikroelektronik litar bersepadu. SpinFET terdiri daripada dua sentuhan feromagnetik (punca dan salir), antara saluran semikonduktor. Modulasi arus dicapai dengan pelarasan secara elektrik kekuatan voltan get bergantung bagi interaksi orbit putaran di rantau semikonduktor. Sifat SpinFETs bagi pelbagai parameter - ketidaksepadanan jalur, ketinggian sempadan di antara sentuhan dan saluran dan kekuatan gandingan putaran orbit untuk pelbagai suhu telah dikaji. Ditunjukkan bahawa pembentukan sempadan Schottky antara saluran dan sentuhan menjamin modulasi ketara magnetorintangan yang mencukupi untuk membuka kemungkinan untuk operasi SpinFETs pada suhu bilik. Ditunjukkan juga bahawa sirip silikon dengan [100] orientasi menunjukkan pergantungan yang kuat kepada nilai interaksi putaran orbit dan dengan itu lebih baik untuk realisasi praktikal SpinFETs berasaskan silikon.

Kata kunci: Interaksi spin-orbit; suhu; transistor spin kesan medan

INTRODUCTION

The significant progress in integrated circuits' performance has been supported by the miniaturization of the transistor feature size. With transistor scalability gradually slowing down new concepts have to be introduced in order to maintain a computational speed increase at reduced power consumption for future micro and nanoelectronic devices. A promising alternative to the charge degree of freedom currently used in MOSFET switches is to take into account the electron's spin degree of freedom. Employing spin as an additional degree of freedom is promising for boosting the efficiency of future low-power integrated circuits. Indeed, the spin of an electron can change its orientation to opposite very fast by consuming an amazingly small amount of energy.

The spin field-effect transistor (SpinFET) is a future semiconductor spintronic device potentially providing a performance superior to achieved in the present transistor technology. A SpinFET is composed of two ferromagnetic contacts (source and drain) connected to the semiconductor channel. A schematic illustration of the SpinFET is shown in Figure 1. The ferromagnetic source (drain) contact injects (detects) spin-polarized electrons to (from) the semiconductor region. Thus, ferromagnetic contacts act as polarizer and analyzer for the electron spin as described by Datta and Das (1990). Because of the non-zero spin-orbit interaction, the electron spin precesses during the propagation through the channel. Only the electrons with the spin aligned to the drain magnetization can leave the channel at the drain contact and contribute to the current. Current modulation is achieved by changing the strength of the spin-orbit interaction in the semiconductor region and thus the degree of the spin precession. The spin precession angle $\Delta\theta$ defined as the difference between the orientation of the spin of the electron at the end and at the beginning of the semiconductor region is (Sugahara & Nitta 2010):

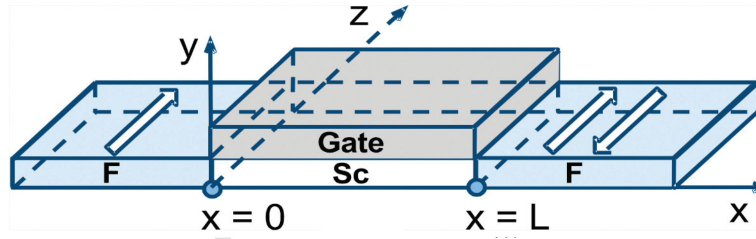

FIGURE 1. Schematic illustration of the spin field-effect transistor

$$\Delta\theta = \frac{2\alpha_R m^*}{\hbar^2} L, \quad (1)$$

where α_R is the strength of the Rashba spin-orbit interaction, m^* is the effective mass of the electron, $\hbar$ is the reduced Planck constant and L is the length of the semiconductor channel. In the absence of the spin-orbit interaction, electrons propagate with the conserved orientation of the spin up to the spin relaxation distance which is determined by the properties of the material. The strength of the spin-orbit interaction determines minimum length of the semiconductor channel that will be sufficient to change orientation of the spin to the opposite. In case of the materials with strong spin-orbit interaction such as InAs, the semiconductor channel will be shorter than the weak spin-orbit interaction material such as silicon. However, the semiconductor channel should be shorter than the spin relaxation length specific to the material.

Silicon is the main element of the present microelectronics and utilizing silicon in future devices is preferred. Silicon possesses several properties attractive for spin-driven applications: it is composed of nuclei with predominantly zero spin and is characterized by small spin-orbit interaction. Because of that, the spin relaxation in silicon is relatively weak, which results in large spin life time (Cheng et al. 2010; Dash et al. 2011). In experiments, coherent spin propagation through an undoped silicon wafer of 350 μm thickness was demonstrated (Huang et al. 2007). Coherent spin propagation over such long distances makes the fabrication of spin-based switching devices in the near future likely increasing (Inokuchi et al. 2012; Jansen 2012).

The two dominant mechanisms of the spin-orbit interaction in the III-V semiconductor heterostructures are of Rashba and Dresselhaus types. The Rashba type of the spin-orbit interaction is due to the structural asymmetry (Rashba 1960) and the Dresselhaus type of the spin-orbit interaction is caused by the absence of bulk inversion symmetry (Dresselhaus 1955). The effective Hamiltonian of the spin-orbit interaction due to the structural-induced inversion asymmetry (Rashba type) along the z-axis is usually consider in the form:

$$H_R = \frac{\alpha_R}{\hbar}(p_x\sigma_y - p_y\sigma_x), \quad (2)$$

where α_R is the effective electric field-dependent parameter of the spin-orbit interaction, $p_{x(y)}$ is the electron momentum projection, σ_x and σ_y are the Pauli matrices. As silicon is characterized by weak spin-orbit interaction, it was not consider as a candidate for the SpinFET channel material. Recently, however, it was shown (Nestoklon et al. 2008; Prada et al. 2011) that thin silicon films inside SiGe/Si/SiGe structures may have relatively large values of spin-orbit interaction. Interestingly, the strength of the Rashba spin-orbit interaction is weak and is approximately ten times smaller than the value of the dominant contribution which is of a Dresselhaus type with a corresponding effective Hamiltonian in the form:

$$H_D = \frac{\beta}{\hbar}(p_x\sigma_x - p_y\sigma_y). \quad (3)$$

This major contribution to the spin-orbit interaction is due to interfacial disorder induced inversion symmetry breaking and its strength depends almost linearly on the effective electric field (Prada et al. 2011). For a built-in field 50 kV/cm, the strength of the Dresselhaus spin-orbit interaction is found to be $\beta \approx 2$ μeVnm, which is in agreement with the value reported experimentally (Wilamovsky & Jantsch 2004), while $\alpha_R \approx 0.1$ μeVnm. This value of the spin-orbit interaction in confined silicon systems is sufficient for their applications as SpinFET channels.

The stronger spin-orbit interaction leads to an increased spin relaxation. The D'yakonov-Perel' mechanism is the main spin relaxation mechanism in systems, where the electron dispersion curves for the two spin projections are non-degenerate. In quasi-one-dimensional electron structures, however, a suppression of the spin relaxation mechanism is expected (Bournel et al. 1998). Indeed, in case of elastic scattering only back-scattering is allowed. Reversal of the electron momentum results in the inversion of the effective magnetic field direction. Therefore, the precession angle does not depend on the number of scattering events along the carrier trajectory in the channel but is a function of the channel length only. Thus, the spin-independent elastic scattering does not result in additional spin decoherence. In the presence of an external magnetic field, however, spin-flip processes become possible and the Elliott-Yafet spin relaxation mechanism is likely activated (Cahay & Bandyopadhyay 2004).

In order to calculate the dependence of the transport properties on the spin-orbit interaction, we need the electron eigenfunctions in the ferromagnetic and the

semiconductor regions. We are looking for a wave function in the left contact in the following form:

$$\Psi_L(x) = (e^{ik_\uparrow x} + R_\uparrow e^{-ik_\uparrow x})\begin{pmatrix}1\\0\end{pmatrix} + R_\downarrow e^{-k_\downarrow x}\begin{pmatrix}0\\1\end{pmatrix}, \quad (4)$$

$$\Psi_L(x) = R_\uparrow e^{-ik_\uparrow x}\begin{pmatrix}1\\0\end{pmatrix} + (e^{ik_\downarrow x} + R_\downarrow e^{-k_\downarrow x})\begin{pmatrix}0\\1\end{pmatrix}, \quad (5)$$

where (4) corresponds to the incoming spin-up electrons and (5) to the incoming spin-down electrons, respectively, $k_{\uparrow(\downarrow)} = \sqrt{2m_f^*(E \pm h_0)/\hbar^2}$ is the wave vector of the spin-up (spin-down) electrons, and $R_{\uparrow(\downarrow)}$ is the amplitude of the reflected wave. For the right contact the wave function is given by:

$$\Psi_R(x) = C_\uparrow e^{-ik_\uparrow x}\begin{pmatrix}1\\0\end{pmatrix} + C_\downarrow e^{k_\downarrow x}\begin{pmatrix}0\\1\end{pmatrix}. \quad (5)$$

For the semiconductor region the wave function can be written as:

$$\Psi_S(x) = A_+ e^{ik_{x1}^{(+)}x}\begin{pmatrix}k_1\\1\end{pmatrix} + B_+ e^{ik_{x2}^{(+)}x}\begin{pmatrix}k_2\\1\end{pmatrix} + A_- e^{ik_{x1}^{(-)}x}\begin{pmatrix}k_3\\-1\end{pmatrix} + B_- e^{ik_{x2}^{(-)}x}\begin{pmatrix}k_4\\-1\end{pmatrix}, \quad (7)$$

where $k_{x1(x2)}^{(+)}$ and $k_{x1(x2)}^{(-)}$ are the wave vectors obtained by solving the equations:

$$\frac{\hbar^2 k^2}{2m_s^*} + \delta E_c \pm \sqrt{\left(\frac{Bg\mu_B\cos(\gamma)}{2}\right)^2 + \left(\frac{Bg\mu_B\sin(\gamma)}{2} - \beta k\right)^2} = E, \quad (8)$$

The coefficients k_i, i = 1, …, 4 depend on the external magnetic field and β:

$$k_1 = -\frac{i\left(Bg\mu_B\sin(\gamma) - 2\beta k_{x1}^{(+)}\right) - Bg\mu_B\cos(\gamma)}{2\sqrt{\left(\frac{Bg\mu_B\cos(\gamma)}{2}\right)^2 + \left(\frac{Bg\mu_B\sin(\gamma)}{2} - \beta k_{x1}^{(+)}\right)^2}}, \quad (9)$$

$$k_2 = -\frac{i\left(Bg\mu_B\sin(\gamma) - 2\beta k_{x2}^{(+)}\right) - Bg\mu_B\cos(\gamma)}{2\sqrt{\left(\frac{Bg\mu_B\cos(\gamma)}{2}\right)^2 + \left(\frac{Bg\mu_B\sin(\gamma)}{2} - \beta k_{x2}^{(+)}\right)^2}}, \quad (10)$$

$$k_3 = -\frac{i\left(Bg\mu_B\sin(\gamma) - 2\beta k_{x1}^{(-)}\right) - Bg\mu_B\cos(\gamma)}{2\sqrt{\left(\frac{Bg\mu_B\cos(\gamma)}{2}\right)^2 + \left(\frac{Bg\mu_B\sin(\gamma)}{2} - \beta k_{x1}^{(-)}\right)^2}}, \quad (11)$$

$$k_4 = -\frac{i\left(Bg\mu_B\sin(\gamma) - 2\beta k_{x2}^{(-)}\right) - Bg\mu_B\cos(\gamma)}{2\sqrt{\left(\frac{Bg\mu_B\cos(\gamma)}{2}\right)^2 + \left(\frac{Bg\mu_B\sin(\gamma)}{2} - \beta k_{x2}^{(-)}\right)^2}}. \quad (12)$$

The reflection and transmission coefficients are determined by applying the standard boundary conditions at the ferromagnet/semiconductor interfaces. We compute the current through the device as (Osintsev et al. 2011):

$$I^{P(AP)}(V) = \frac{e}{h}\int_{\delta E_c}^{\infty}\left[T_\uparrow^{P(AP)}(E) + T_\downarrow^{P(AP)}(E)\right] \left\{\frac{1}{1+e^{\frac{E-E_F}{k_BT}}} - \frac{1}{1+e^{\frac{E-E_F+eV}{k_BT}}}\right\}dE, \quad (13)$$

where k_B is the Boltzmann constant, T is the temperature and V is the voltage. The spin-up $(T_\uparrow^P)$ and spin-down $(T_\downarrow^P)$ transmission probability for the parallel configuration of the contact magnetization is defined as:

$$T_\uparrow^P = |C_\uparrow|^2 + \frac{k_\downarrow}{k_\uparrow}|C_\downarrow|^2, \quad (14)$$

$$T_\downarrow^P = \frac{k_\uparrow}{k_\downarrow}|C_\uparrow|^2 + |C_\downarrow|^2. \quad (15)$$

For the anti-parallel configuration of contact magnetization the transmission probability is obtained in a similar fashion. The conductance is defined as:

$$G^{P(AP)} = \lim_{V\to 0}\frac{I^{P(AP)}}{V}. \quad (16)$$

In the limit of low temperatures, the conductance must coincide with the one obtained from the Laudauer-Büttiker (Büttiker 1986; Landauer 1957) formula,

$$G^{P(AP)} = \frac{e^2}{h}\left(T_\uparrow^{P(AP)}(E_F) + T_\downarrow^{P(AP)}(E_F)\right). \quad (17)$$

Finally, the magnetoresistance (TMR) is computed as,

$$\text{TMR} \equiv \frac{G^P - G^{AP}}{G^{AP}}. \quad (18)$$

Results and Discussion

In our calculations we used InAs which is characterized by strong value of the spin-orbit interaction and silicon. For all calculations for the InAs semiconductor channel, we assume effective mass of electrons in the ferromagnetic regions to be equal to the electron rest mass and for the semiconductor region to be equal 0.036 of the electron rest mass. Figure 2 shows the dependence of the TMR on the value of the band mismatch δE_C between the ferromagnetic contacts and the semiconductor channel. The TMR oscillates between positive and negative values. The amplitude of the oscillations in the positive plane across the TMR axis is equal to 1, which means (according to (18)) that the conductance in the parallel configuration is twice as large as the conductance in the anti-parallel configuration of the contact magnetizations. This value is enough to modulate the current in the SpinFET transistor, however this results was obtained for the temperature $T = 0K$. As the length of the semiconductor channel decreases, the period of the oscillations increases. The period of the TMR oscillations is inverse proportional to the length of the semiconductor

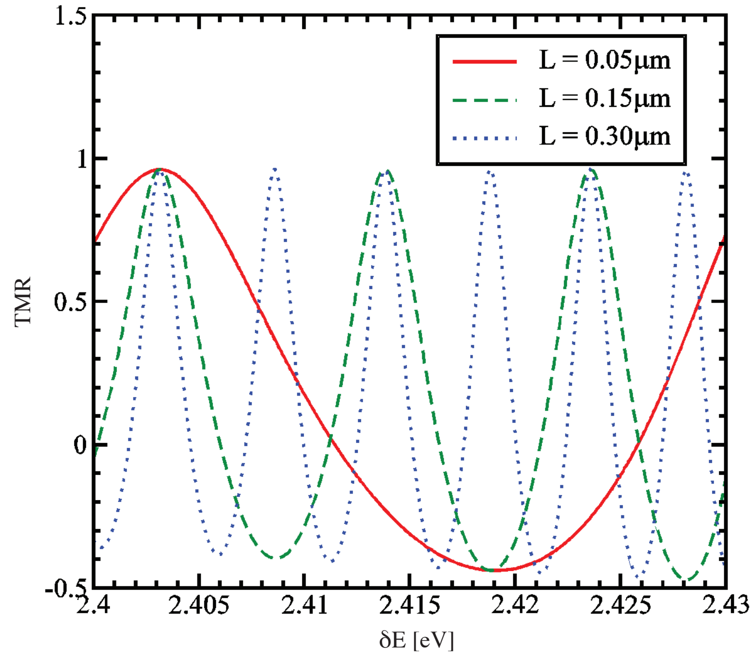

FIGURE 2. TMR dependence on the value of band mismatch δE_c, for $E_F = 2.47$ eV, $p = 0.7$, $\alpha_R = 0$ and $z = 0$

channel and to the square root of the effective mass of the electrons in the semiconductor region. Hence, the length of the semiconductor channel is the parameter to adjust in order to achieve better SpinFET characteristics at elevated temperatures.

Temperature exerts a significant influence on the device characteristics as shown in Figure 3. In order to create a SpinFET which will operate at room temperature, the TMR oscillations must have a period larger than $k_BT =$ 25 meV. The oscillations of the TMR must have pronounced amplitude in order to modulate the current through the transistor. Therefore, we have chosen parameters for the temperature analyses based on our previous findings.

Figure 3 shows the dependence of the TMR on the value of the band mismatch between the contacts and the semiconductor channel for three temperatures. For a channel length $L = 0.05$ μm the TMR oscillations are visible for $T = 77$K. For $T = 300$K the oscillations completely vanish. Hence, the channel length of 50 nm does not provide a sufficiently long period of the TMR oscillations in order to modulate the current in the SpinFET by adjusting the value of the band mismatch δE_C.

Following Jiang et al. (2010), delta-function-like Schottky barriers with a strength $z = 2m_fU/\hbar^2k_F$ at the interfaces between the contact and the channel are introduced. Figure 4 demonstrates the oscillations of the

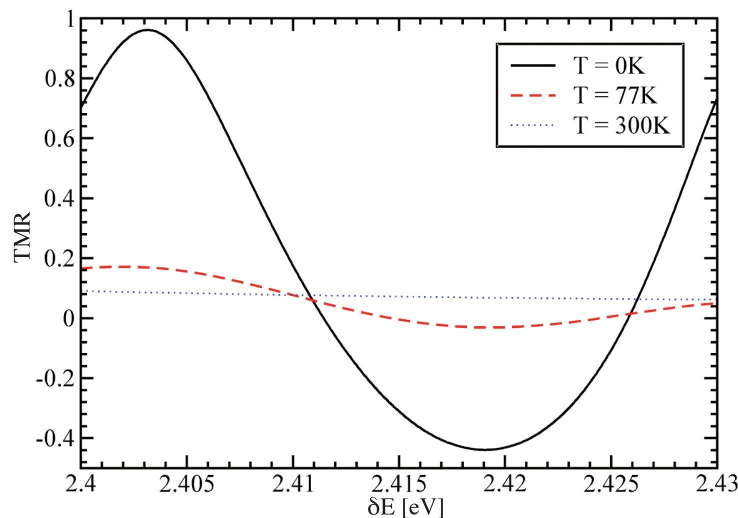

FIGURE 3. TMR dependence on the value of band mismatch δE_c, for $E_F = 2.47$ eV, $L = 0.05$ μm, $p = 0.7$, $\alpha_R = 0$ and $z = 0$ for several temperatures

TMR for different values of the spin-orbit interaction. The barriers separate the channel from the contacts, thus the semiconductor region becomes a quantum well. As the barrier becomes stronger the quantization of the energy in the semiconductor channel becomes more pronounced. The energy quantization is responsible for the appearance of the sharp features in the TMR dependence on δE_C clearly seen in Figure 4, in comparison with Figure 2 where the oscillations are smooth. Another excellent feature following from Figure 4 is that the range of the TMR values depends on the strength of the spin-orbit interaction in a broad range of δE_C. 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.

Figure 5 displays the TMR dependence on the strength of the spin-orbit interaction at different temperatures. The

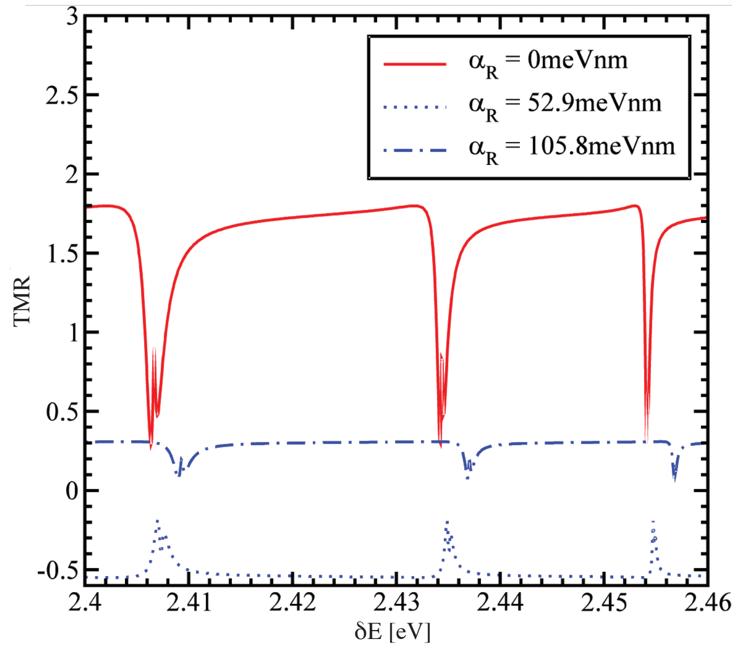

FIGURE 4. TMR dependence on the value of band mismatch δE_c, for $E_F = 2.47$ eV, $L = 0.05$ μm, $p = 0.7$, $T = 0$K and $z = 5$ for several values α_R of the spin-orbit interaction

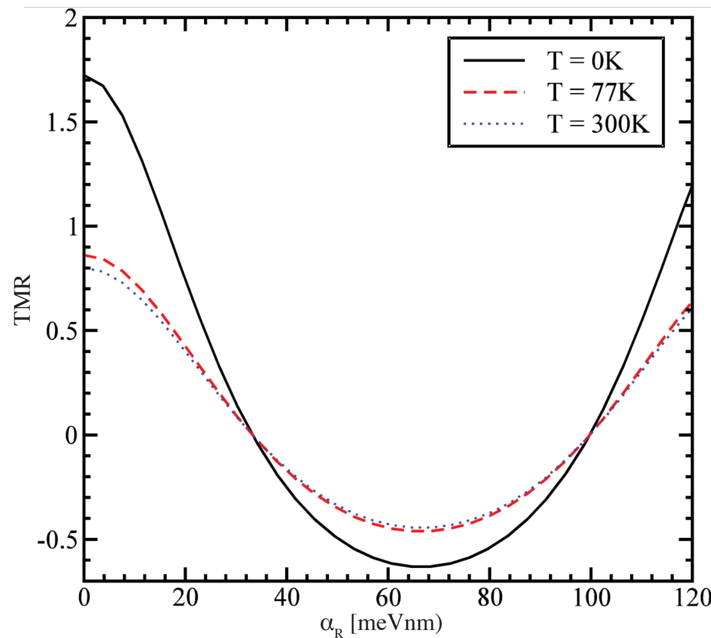

FIGURE 5. TMR dependence on the strength of spin-orbit interaction for $E_F = 2.47$ eV, $\delta E_c = 2.42$ eV, $L = 0.05$ μm, $p = 0.7$ and $z = 5$ for several temperatures

TMR modulation is preserved at elevated temperatures thus opening a practical possibility to modulate the TMR by changing the value of α_R even at room temperature.

We now consider square silicon fins of [100] and [110] orientations, with (001) horizontal faces. The spin-orbit interaction is treated in the Dresselhaus form (Prada et al. 2011). The dependence of the TMR on the spin-orbit interaction is shown in Figure 6. The wave vector $k_D = m_s\beta/\hbar^2$ determines the dependence of the TMR on the value of the strength of the Dresselhaus spin-orbit interaction. Fins with [100] orientation posses a larger subband effective mass (Tsuchiya et al. 2010) compared with [110] oriented fins. Therefore, a smaller variation of β is required in [100] oriented fins to achieve the same variation of k_D and thus the same variation of TMR.

Finally, we extended the results obtained for InAs-based devices to silicon-based SpinFETs. Figure 7 shows that the TMR modulation as a function of the Dresselhaus

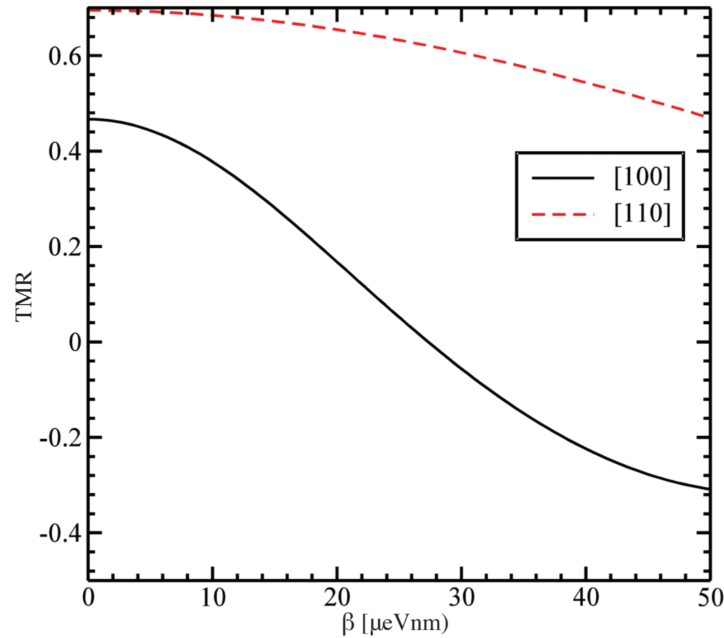

FIGURE 6. TMR dependence in a Si-based SpinFET on the value of the Dresselhaus spin-orbit interaction for $L = 5$ μm and $z = 2$

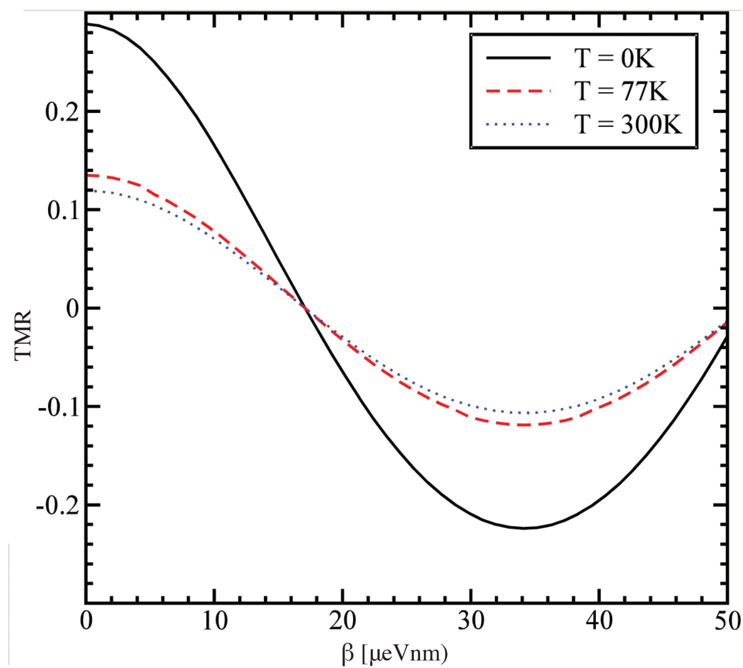

FIGURE 7. TMR dependence in a Si-based SpinFET on the value of the Dresselhaus spin-orbit interaction for $L = 8$ μm and $z = 3$

spin-orbit interaction for [100] silicon fins is preserved even at high temperatures. This opens the possibility to modulate current through a device by adjusting the value of β even at room temperature.

CONCLUSION

We investigated the transport properties of SpinFETs and show that devices can operate at room temperature by changing the strength of the spin-orbit interaction, if delta-function-like Schottky barriers are created between the contacts and the channel. We demonstrated that silicon fins of the [100] orientation are best suitable for practical realizations of silicon-based SpinFETs.

ACKNOWLEDGEMENT

This work was supported by the European Research Council through the grant #247056 MOSILSPIN.

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Received: 7 January 2012
Accepted: 21 May 2012