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<th>Tunneling magnetoresistance in Fe3Si/MgO/Fe3Si(001) magnetic tunnel junctions</th>
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<td>Author(s)</td>
<td>Tao, LL; Liang, SH; Liu, DP; Wei, HX; Wang, J; Han, XF</td>
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Tunneling magnetoresistance in Fe$_3$Si/MgO/Fe$_3$Si(001) magnetic tunnel junctions

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We present a theoretical study of the tunneling magnetoresistance (TMR) and spin-polarized transport in Fe$_3$Si/MgO/Fe$_3$Si(001) magnetic tunnel junction (MTJ). It is found that the spin-polarized conductance and bias-dependent TMR ratios are rather sensitive to the structure of Fe$_3$Si electrode. From the symmetry analysis of the band structures, we found that there is no spin-polarized $\Delta_1$ symmetry bands crossing the Fermi level for the cubic Fe$_3$Si. In contrast, the tetragonal Fe$_3$Si driven by in-plane strain reveals half-metal nature in terms of $\Delta_1$ state. The giant TMR ratios are predicted for both MTJs with cubic and tetragonal Fe$_3$Si electrodes under zero bias. However, the giant TMR ratio resulting from interface resonant transmission for the former decreases rapidly with the bias. For the latter, the giant TMR ratio can maintain up to larger bias due to coherent transmission through the majority-spin $\Delta_1$ channel.

The phenomenon of tunnel magnetoresistance (TMR) observed in magnetic tunnel junctions (MTJs) has been extensively investigated for decades, due to its rich physics and potential application in spintronic devices. MTJ devices have several designs including the in-plane MTJ and perpendicular MTJ (p-MTJ), depending on the ferromagnetic electrodes possessing an in-plane or perpendicular magnetic easy axis. The room-temperature TMR ratio in excess of 600% has been achieved in the MgO-based in-plane MTJ after the prediction of first-principles calculation. The p-MTJ can be used for current-induced magnetization switching using spin-transfer torque (STT) effect and has several advantages such as higher thermal stability and lower switching current density as compared with in-plane MTJ, which are favorable in the applications for STT-based magnetic random access memory (STT-MRAM). The critical switching current density $J_c$ and thermal stability are the two key parameters characterizing the performance of the p-MTJ while maintaining the high TMR ratio. $J_c$ is proportional to the Gilbert damping constant $\alpha$ and saturation magnetization $M_s$ as $J_c \propto \alpha M_s$. In this regard, Fe$_3$Si with uniaxial magnetic anisotropy is a promising candidate as a ferromagnetic electrode of p-MTJ due to its lower $M_s$ and smaller $\alpha$ than that of NiFe (Py) or CoFe alloy, and thus possibly achieving lower $J_c$. In addition, the high Curie temperature of $\sim 800$ K as well as high spin polarization of $\sim 45\%$ makes Fe$_3$Si a better material as ferromagnetic electrodes of spintronic devices. Very recently, Fe$_3$Si has been explored as ferromagnetic electrode for the MTJ using amorphous Al-O barrier, and the room-temperature TMR ratio of $\sim 20\%$ has been observed. Moreover, Fe$_3$Si was found to have an out-of-plane magnetization easy axis on MgO(001) substrate, which favors the thermal stability of p-MTJ required for data non-volatility.

Besides switching current density and thermal stability, another important device merit of a MTJ is the TMR ratio. A natural question to ask is whether the MTJs with Fe$_3$Si electrode can yield giant TMR ratio. To answer this question, we have carried out a theoretical study on the quantum transport in a Fe$_3$Si/MgO/Fe$_3$Si MTJ with two structures of Fe$_3$Si electrode. Our results show that for the MTJ with cubic Fe$_3$Si electrode, the zero-bias TMR ratio reaches 5000%. However, the giant TMR ratio decreases rapidly as the bias is turned on. In contrast, for the MTJ with tetragonal Fe$_3$Si electrode driven by in-plane strain, the zero-bias TMR ratio can reach 2000%. Importantly, this giant TMR ratio can sustain much larger bias. Analysis of symmetry-resolved band structures, electronic structures and transport in momentum space provide clear understanding of these results.

Our quantum transport calculation is based on Nonequilibrium Green’s Function-density functional theory (NEGF-DFT) method that combines real-space DFT with the Keldysh NEGF formalism, as implemented in Nanodcal package. For more technical details, we refer interested readers to the original literature. The spin-polarized conductance $G_\sigma$ is given by Landauer–Büttiker formula

$$G_\sigma = \frac{e^2}{h} \sum_{k_\perp} T_{\sigma}(k_\perp, E_F),$$

where $T_{\sigma}(k_\perp, E_F)$ is the transmission coefficient at the Fermi level $E_F$ with spin $\sigma = \uparrow, \downarrow$ and transverse Bloch wave vector $k_\perp = (k_x, k_y)$ due to the transverse periodicity, $e$ the electron charge, and $h$ the Planck’s constant. We used a $10 \times 10 k_\perp$ mesh to converge the density matrix and a $400 \times 400 k_\perp$ mesh for evaluating transmission coefficients of all spin channels. The valence electrons are treated by

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linear combination of atomic orbital basis with double-$\zeta$ plus polarization basis for all the atoms. The local density approximation as parameterized by Perdew and Zunger is used for the exchange-correlation potential.\(^{15}\)

The MTJ device model investigated in this work is a two-probe tunnel junction, consisting of two semi-infinite Fe\(_3\)Si electrodes sandwiching several monolayers (ML) of MgO barriers as shown in Fig. 1. The atomic structures of central region are fully relaxed using the DFT based VASP electronic package.\(^{16}\) The in-plane lattice constant of the junction is fixed at 3.997 Å, corresponding to $\sqrt{2}/\sqrt{2}$ of experimental value (5.653 Å) of Fe\(_3\)Si. Thus, the lattice mismatch between Fe\(_3\)Si(001) and MgO(001) (4.21 Å) rotated by 45° is about 5%. The optimized Fe-O distance is found to be 2.191 Å. Note that there are two different terminations due to the layered structure of Fe\(_3\)Si. The Fe termination is verified to be more stable than FeSi termination by performing the cohesive energies calculations. Thus, the Fe termination is considered in the present work. All the MgO barriers are fixed at 5 ML in the rest of the paper.

It is known that TMR ratio is a key parameter characterizing performance of MTJs. The optimistic TMR ratio is defined as $TMR = (G_P - G_{AP})/G_{AP}$, with $G_P$ and $G_{AP}$ being the total conductance for the magnetizations of two electrodes with parallel (PC) and anti-parallel configurations (APC), respectively. The calculated spin-polarized conductance and TMR ratios for a number of different MTJ models are reported in Table I. All the relevant results for Fe/MgO/Fe(001) are also presented for comparison. We find that TMR ratio of Fe/MgO/Fe is around 3000%, which is in good agreement with that of Ref. 17. The giant TMR ratio in Fe/MgO/Fe originates from $\Delta_1$ spin-filtering effect, as explained clearly in Refs. 3 and 4. Namely, incident Bloch wave functions from electrode will decay at symmetry-dependent rates through MgO barrier and the state with $\Delta_1$ symmetry decays most slowly when compared with other states. Moreover, for bcc Fe, the $\Delta_1$ band exists only in majority-spin channel at the Fermi level. Thus, a large conductance difference between PC and APC is obtained giving rise to the giant TMR ratio. The TMR ratio for the Fe\(_3\)Si/MgO/Fe\(_3\)Si is very large, reaching $\sim$5000%, which is larger than that of Fe/MgO/Fe. It is interesting and instructive to make a comparison between the $G_P^{\uparrow}$ and $G_P^{\downarrow}$. First of all, $G_P^{\uparrow}$ is larger than $G_P^{\downarrow}$ for Fe/MgO/Fe due to the contribution of the slowly decaying $\Delta_1$ state. This is in sharp contrast to the case of Fe\(_3\)Si/MgO/Fe\(_3\)Si for which $G_P^{\downarrow}$ plays a dominant role in all spin channels. As Table I shows, $G_P^{\downarrow}$ is about two orders of magnitude larger than that of other spin channels.

To understand the different conductance and TMR ratios presented above, we now examine transmission coefficients in the two-dimensional Brillouin zone (BZ), as plotted in Fig. 2. First, for Fe/MgO/Fe, the majority-spin in PC has a circular peak centered at $k_1 = (0, 0)$ due to the slow decay through $\Delta_1$ state, whereas the minority-spin is characterized by sharp peaks-called hot spots, originating from resonant transmission through interface resonant states (IRSs).\(^{18}\) In contrast, in the case of Fe\(_3\)Si/MgO/Fe\(_3\)Si, both the majority- and minority-spin in PC has negligible transmittance around the center of BZ, suggesting that there is no incoming $\Delta_1$ Bloch states from Fe\(_3\)Si electrode. This can be confirmed from the symmetry-resolved band structures of bulk Fe\(_3\)Si, as plotted in Figs. 3(a) and 3(b). The bands have $C_{6v}$ symmetry along the $\Delta$ direction ($T$-$X$). It is found only doubly degenerate $\Delta_2$ (pd) band crosses the Fermi level $E_F$ for majority-spin, while both $\Delta_2$ and $\Delta_3$ (d) bands cross $E_F$ for minority-spin. On the other hand, the $\Delta_1$ (spd) band for majority-spin locates at about 0.2 eV above $E_F$. There are two $\Delta_1$ bands above $E_F$ for minority-spin; one localizes around 0.9 eV and the other positions at 1.6 eV. Second, the resonance transmission peaks for minority-spin in PC can be distinctly suppressed by breaking the symmetry of MTJs,\(^{19}\) e.g., by the interface oxidation or applied bias. To support this point, we constructed an asymmetric MTJ with one ML Fe 50% oxidized at one interface, namely Fe\(_3\)Si/FeO/MgO/Fe\(_3\)Si. As can be seen from Table I, the TMR reduces drastically from $\sim$5000% to $\sim$700% caused by the significant reduction of $G_P^{\downarrow}$. Because in the case of symmetric MTJ, the localized interface states on the two Fe\(_3\)Si/MgO interfaces are at identical energies and when they align in energy, resonance transmission occurs. However, in the case of asymmetric MTJs, the two interface states are separated with an energy. Thus, resonance transmission is destroyed due to the mismatching of the two interface states. It can be further confirmed by the local density of states (LDOS) of an Fe atom at the interface shown in Fig. 4(a). For the symmetric MTJ, the minority-spin DOS shows a clear peak at around $E_F$, which can be attributed to the existence of interfacial states; on the contrary, there is no minority-spin DOS peak around $E_F$ for the Fe atom in FeO

<table>
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<tr>
<th>Structure</th>
<th>$G_P^{\uparrow}$</th>
<th>$G_P^{\downarrow}$</th>
<th>$G_{AP}^{\uparrow}$</th>
<th>$G_{AP}^{\downarrow}$</th>
<th>TMR (%)</th>
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<td>8.78 x 10^{-7}</td>
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<td>750</td>
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<td>T-Fe(_3)Si/MgO/T-Fe(_3)Si</td>
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<td>2.01 x 10^{-4}</td>
<td>2.71 x 10^{-5}</td>
<td>2.65 x 10^{-5}</td>
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layer. Fig. 4(b) plots the TMR ratio of Fe$_3$Si/MgO/Fe$_3$Si (blue circles) versus the bias. Note that in this condition the TMR ratio is defined as 
\[ \text{TMR} = \frac{I_P - I_{AP}}{I_P} \] 
with \( I_P \) (\( I_{AP} \)) being the total current for MTJ in PC (APC). We define the zero-bias TMR ratio using transmission coefficients. We see that the TMR ratio decreases very quickly with increasing the bias and drops to around 100% at a bias of 50 mV. This is because a small bias separates the two interface states and, in consequence, suppresses the minority-spin resonance transmission in PC which is directly related to \( I_P \). For MTJ-device application, output voltage \( V_{out} \) is another important parameter to characterize the magnitude of the output signal modulation. \( V_{out} \) is defined as \( V_{out} = V_b (G_P - G_{AP}) / G_P \), where \( V_b \) is the applied bias. As plotted in the inset of Fig. 4(b) (blue circles), \( V_{out} \) increases roughly linearly with increasing \( V_b \) and then drops at around 40 mV due to the strong suppression of TMR ratio by bias.

To summarize, the giant TMR ratio of Fe$_3$Si/MgO/Fe$_3$Si decreases quickly with bias, which is detrimental to the output voltage \( V_{out} \). This is the result of a strong suppression of resonant transmission through IRSs by bias. On the other hand, \( \Delta_1 \) coherent transmission through MgO barrier is less affected by small bias in compared with IRSs. Thus, it is favorable to \( V_{out} \) to achieve \( \Delta_1 \) coherent transmission in Fe$_3$Si/MgO/Fe$_3$Si. We found that a slight in-plane compressive strain can drive the majority-spin \( \Delta_1 \) band of Fe$_3$Si crossing \( E_F \). We calculated the band structures of tetragonal Fe$_3$Si for a number of \( c/a \) ratios, where \( c \) and \( a \) are out-of-plane and in-plane lattice constants, respectively. Here, \( c/a \)

FIG. 2. Spin- and \( k_\parallel \)-resolved transmission coefficients for ((a)-(c)) Fe/MgO/Fe, ((d)-(f)) Fe$_3$Si/MgO/Fe$_3$Si and ((g)-(i)) T-Fe$_3$Si/MgO/T-Fe$_3$Si at the Fermi level. Panels from left to right are (a), (d), (g) for majority-to-majority and (b), (e), (h) for minority-to-minority in PC; (c), (f), (i) for majority-to-minority or minority-to-majority in APC.

FIG. 3. Band structures of bulk ((a) and (b)) cubic Fe$_3$Si \((c/a = 1)\) and ((c) and (d)) tetragonal Fe$_3$Si \((c/a = 1.07)\). The Fermi level \( E_F \) has been aligned to zero.
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ratio is determined by keeping the volume of the Fe$_3$Si unit cell fixed, namely $a^2c = a'_0^2$ ($a'_0 = 5.653$ Å). It is found that the majority-spin $\Delta_1$ band crosses $E_F$, whereas minority-spin one does not when $c/a$ ratio excess 1.04 (1.3% strain). Figs. 3(c) and 3(d) plot the band structure of tetragonal Fe$_3$Si with $c/a = 1.07$. In this case, $a$ is chosen to be 3.905 Å, to model growth on the SrTiO$_3$(001) substrate, corresponding to 2.3% in-plane compressive strain. As expected, this new type of tetragonal Fe$_3$Si ($T$-Fe$_3$Si) reveals half-metal nature in terms of $\Delta_1$ state, which is rather similar to that of bcc Fe. Then we calculated the transmission coefficients for $T$-Fe$_3$Si/MgO/$T$-Fe$_3$Si MTJ. As shown in Figs. 2(g)–2(i), the majority-spin in PC shows the expected broad peak around the center of BZ, whereas for the minority-spin and for APC there are negligible transmittance in the BZ, except for some resonance peaks at special $k||$ points. This is quite similar to that of Fe/MgO/Fe. As a consequence, giant TMR ratio of $\sim 2000\%$ is predicted originating from the $\Delta_1$ spin-filtering effect, as reported in Table I. More importantly, as shown in Fig. 4(b) and as its inset, the giant TMR ratio decays much slower with bias and, even at 50 mV bias, the TMR ratio is still over 1500%. This is due to the coherent transmission through the majority-spin $\Delta_1$ channel, which is less affected by small bias when compared with IRSs. Thus, $V_{\text{out}}$ increases linearly with increasing $V_0$ and $V_{\text{out}}$ is almost 1.6 times larger than that of Fe$_3$Si/MgO/Fe$_3$Si at 50 mV bias. This $V_{\text{out}}$ difference will be expected to be further increased when the bias becomes larger.

In conclusion, we have calculated the TMR and spin-polarized transport in Fe$_3$Si/MgO/Fe$_3$Si(001) MTJs with two different Fe$_3$Si electrodes, i.e., cubic and tetragonal ones. Our results show that the giant TMR ratio for the former stems from the minority-spin interface resonant transmission, which can be dramatically reduced by breaking the symmetry of MTJs, e.g., by the interface oxidation or applied bias. For the latter, the tetragonal Fe$_3$Si reveals half-metal nature in terms of the $\Delta_1$ state. Giant TMR ratio is predicted capitalizing on $\Delta_1$ spin-filtering through MgO barrier and, more importantly, this giant TMR ratio drops much slower with bias in compared with former. Note that in real MTJs, the transport could be in either mixed ballistic and diffusive regime or diffuse regime due to the interface roughness and atom defects. Therefore, the TMR ratios might be smaller than the predicted values by taking into account of the diffuse scattering. Our studies provide some guidelines for achieving giant TMR ratio in Fe$_3$Si-based MTJ, which is a promising candidate as an MTJ element for designing STT-MRAM devices.

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$^{16}$G. Kresse and J. Furthmüller, Phys. Rev. B 54, 11169 (1996). The cut-off energy of 500 eV, Perdew-Burke-Ernzerhof generalized gradient approximation (GGA) for the exchange correlation functional, and Monkhorst-Pack grid of $10 \times 10 \times 1$ for k-point sampling were used. The atoms were

FIG. 4. (a) LDOS of an Fe atom at Fe$_3$Si/MgO, Fe$_3$Si/FeO/MgO interfaces; shaded plots are the LDOS of an Fe atom in the deep Fe layer, which is close to that of bulk. The majority- and minority-spin are plotted upward (positive) and downward (negative), respectively. (b) TMR ratios versus bias for Fe$_3$Si/MgO/Fe$_3$Si (blue circles) and T-Fe$_3$Si/MgO/T-Fe$_3$Si (red squares). Inset: Output voltage $V_{\text{out}}$ versus bias.
allowed to relax perpendicularly to the layers until the forces on each atom were smaller than 0.02 eV/Å.


