



Research articles

Effects of temperature on the magnetic tunnel junctions with periodic grating barrier

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ABSTRACT

We have developed a tunneling theory to describe the temperature dependence of tunneling magnetoresistance (TMR) of the magnetic tunnel junctions (MTJs) with periodic grating barrier. Through the Patterson function approach, the theory can handle easily the influence of the lattice distortion of the barrier on the tunneling process of the electrons. The lattice distortion of the barrier is sensible to the temperature and can be quite easily weakened by the thermal relaxation of the strain, and thus the tunneling process of the electrons will be significantly altered with the variation of the temperature of the system. That is just the physical mechanism for the temperature dependence of the TMR. From it, we find two main results: 1. The decrease of TMR with rising temperature is mostly carried by a change in the antiparallel resistance (R_{AP}), and the parallel resistance (R_P) changes so little that it seems roughly constant, if compared to the R_{AP} . 2. For the annealed MTJ, the R_{AP} is significantly more sensitive to the strain than the R_P , and for non-annealed MTJ, both the R_P and R_{AP} are not sensitive to the strain. They are both in agreement with the experiments of the MgO-based MTJs. Other relevant properties are also discussed.

1. Introduction

Magnetic tunnel junctions (MTJs) have received considerable attention for many years. They can be applied to the promising spintronic devices such as high-density magnetic reading head [1]. Early experimental studies were confined to the MTJs with amorphous aluminum oxide (Al-O) barriers. In 2001, Butler et al. [2] predicted theoretically that, if single-crystal MgO is used as the MTJ barrier, the tunneling magnetoresistance (TMR) can reach a extremely high value. The prediction was verified soon by Parkin et al. [3] and Yuasa et al. [4]. Since then, the MgO-based MTJs have been widely investigated over the last decade [5–14]. One of the most important and distinguished properties of MgO-based MTJs is that the parallel resistance (R_P), the antiparallel resistance (R_{AP}), and the TMR all oscillate with the barrier thickness [4,11–14], which is radically different from the case of Al-O-based MTJs where no such oscillation is found. Those oscillations have already been well interpreted by the spintronic theory developed previously by us [15]. The theory is founded on the traditional optical scattering theory [16]. Within it, the barrier is treated as a diffraction grating with intralayer periodicity. It is found that the periodic grating can bring strong coherence to the tunneling electrons, the oscillations

being a natural result of this coherence. Besides the oscillations, the theory can also explain the puzzle why the TMR is still far away from infinity when the two electrodes are both half-metallic.

Experimentally, there is another important property for MgO-based MTJs, that is, the temperature dependences of the R_P , R_{AP} and TMR. It is found that, as usual, the TMR will decrease when the temperature of the system increases. However, the decrease of TMR with rising temperature is mostly carried by a change in the R_{AP} . The R_P changes so little that it seems roughly constant, if compared to the R_{AP} [3,17–25]. Theoretically, the modified version of the magnon excitation model [26] is at hand for the mechanism of the above temperature dependence. However, this model can not explain the TMR oscillation on the thickness of MgO barrier. Physically, that is because it does not include the effect of the periodicity of the single-crystal barrier which plays a key role in the scattering process when the electrons tunnel through the barrier. Based on this reason, we would like to extend our previous theory to interpret the temperature dependences of the R_P , R_{AP} and TMR of MgO-based MTJs.

As well known, the MgO-based MTJs are fabricated through epitaxial growth. Hence there will be lattice mismatch and interfacial defects between the barrier and its neighbouring layers. Obviously,

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both of them can cause some lattice distortion to the barrier. The influences of this lattice distortion have been investigated widely by the experiments [4,27,28]. In particular, Ref. [27] discovers that, if the MTJ is annealed, the R_{AP} will increase with raising of strain, which is much more sensitive than the R_P , and if it is non-annealed, the R_{AP} will unchange with the strain. In addition, Ref. [28] finds that the lattice distortion can modify the band gap of the MgO barrier. Based on those facts, we shall take into account the effect of the lattice distortion of the barrier upon the R_P , R_{AP} and TMR within the framework of our previous work. Our aim is to interpret theoretically the temperature dependences of the RP, RAP and TMR of MgO-based MTJs. As will be seen in the following, this effect can account for the temperature dependences of the R_P , R_{AP} and TMR of MgO-based MTJs.

2. Method

To begin with, let us consider a MTJ with a perfect single-crystal barrier. As in Ref. [15], we suppose that the atomic potential of the barrier is $v(\mathbf{r})$, and that the total number of the layers of the barrier is n . Then, the periodic potential $U(\mathbf{r})$ of the barrier can be written as

$$U(\mathbf{r}) = \sum_{l_3=0}^{n-1} \sum_{\mathbf{R}_h} v(\mathbf{r} - \mathbf{R}_h - l_3 \mathbf{a}_3), \quad (1)$$

where \mathbf{R}_h is a two-dimensional lattice vector of the barrier: $\mathbf{R}_h = l_1 \mathbf{a}_1 + l_2 \mathbf{a}_2$, with \mathbf{a}_1 and \mathbf{a}_2 being the primitive vectors of the atomic layers, and l_1 and l_2 the corresponding integers. The \mathbf{a}_3 is the third primitive vector of the barrier, with l_3 the corresponding integer. Letting $\mathbf{e}_z = \mathbf{a}_1 \times \mathbf{a}_2 / |\mathbf{a}_1 \times \mathbf{a}_2|$, we shall set \mathbf{e}_z pointing from the upper electrode to the lower one, which is antiparallel to the direction of the tunneling current. As pointed out in Ref. [15], it is just the periodicity of the potential of barrier that will cause strong effect of coherence to the electrons passing through it. The diagrammatic sketches of this physical picture have been shown in Figs. 1 and 6 of Ref. [15].

Now, let us consider the effect of the lattice distortion of the barrier. Physically, the periodic potential $U(\mathbf{r})$ of the barrier will be modified by the lattice distortion, as stated in Ref. [28]. In order to elucidate the effect of the distortion on the potential $U(\mathbf{r})$, we would employ the Patterson function approach, which is a standard and very powerful method for studying the diffraction by imperfect crystals [16]. Within the framework of two-beam approximation [15,16], this leads to that the Fourier transform $v(\mathbf{K}_h)$ of the atomic potential undergoes a modification as follows,

$$v(\mathbf{K}_h) = \left(1 + 2 \frac{\sigma}{1-\sigma} \cos(\mathbf{K}_h \cdot \boldsymbol{\alpha})\right) (1-\sigma) v_0(\mathbf{K}_h), \quad (2)$$

where \mathbf{K}_h is a planar vector reciprocal to the intralayer lattice vectors \mathbf{R}_h , σ is the defect concentration, $\boldsymbol{\alpha}$ represents the effect of strain of the

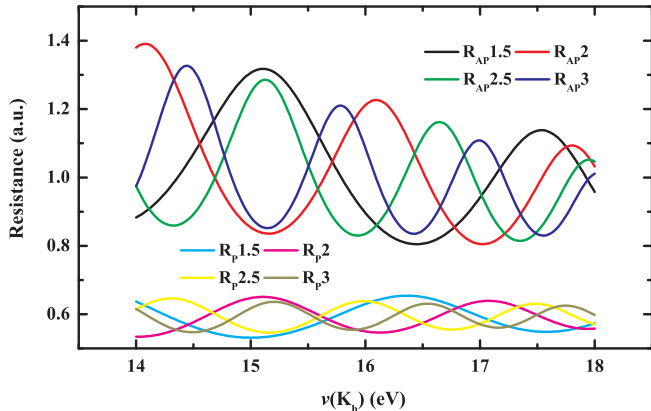


Fig. 1. R_P and R_{AP} as functions of $v(\mathbf{K}_h)$ under different barrier thickness $d = 1.5$ nm, 2 nm, 2.5 nm, and 3 nm.

barrier [16], and $v_0(\mathbf{K}_h)$ is the Fourier transform of the atomic potential of ideal perfect barrier,

$$v_0(\mathbf{K}_h) = \Omega^{-1} \int d\mathbf{r} v(\mathbf{r}) e^{-i\mathbf{K}_h \cdot \mathbf{r}}. \quad (3)$$

Here, Ω is the volume of the primitive cell of the barrier: $\Omega = (\mathbf{a}_1 \times \mathbf{a}_2) \cdot \mathbf{a}_3$.

With regard to the strain α , Ref. [29] has studied it both experimentally and theoretically on some oxide heterostructures, it is found that, within the low temperature region, the strain decreases linearly with temperature T as follows,

$$\alpha = \alpha_0 \left(1 - \frac{T}{T_c}\right), \quad T < T_c, \quad (4)$$

where α_0 is the strain of the oxide film at zero temperature, and T_c is the recovery temperature above which the strain disappears. Generally, T_c is around 800 K. As pointed in Ref. [29], this result can be applied to other oxide heterostructures. Therefore, we would like to employ it to handle the strain of MgO barrier. As to the defect concentration σ , it should be independent of the temperature because the energy to excite defects within a lattice is too high.

Combining the Eqs. (2) and (4) above, we obtain

$$v(\mathbf{K}_h) = \left[1 + 2 \frac{\sigma}{1-\sigma} \cos\left(\mathbf{K}_h \cdot \boldsymbol{\alpha}_0 \left(1 - \frac{T}{T_c}\right)\right)\right] (1-\sigma) v_0(\mathbf{K}_h). \quad (5)$$

This equation builds the relationship between the Fourier transform $v(\mathbf{K}_h)$ of the atomic potential of realistic imperfect barrier and the temperature T .

Now, according to Ref. [15], the transmission coefficient for the channel of the spin-up to spin-up tunneling reads as follows,

$$T_{\uparrow\uparrow}(\mathbf{k}) = \frac{1}{8k_z} \{ p_+^z e^{i[p_+^z - (p_+^z)^*]d} + p_-^z e^{i[p_-^z - (p_-^z)^*]d} + q_+^z e^{i[q_+^z - (q_+^z)^*]d} + q_-^z e^{i[q_-^z - (q_-^z)^*]d} + [p_+^z e^{i[p_+^z - (p_+^z)^*]d} + p_-^z e^{i[p_-^z - (p_-^z)^*]d} - q_+^z e^{i[q_+^z - (q_+^z)^*]d} - q_-^z e^{i[q_-^z - (q_-^z)^*]d}] + \text{c. c.} \} \quad (6)$$

where \mathbf{k} is the incident wave vector of tunneling electrons, and k_z its z -component, d is the thickness of MgO barrier, and

$$p_{\pm}^z = [\mathbf{k}^2 - \mathbf{k}_h^2 \pm 2m\hbar^{-2} v(\mathbf{K}_h)]^{1/2}, \quad (7a)$$

$$q_{\pm}^z = [\mathbf{k}^2 - (\mathbf{k}_h + \mathbf{K}_h)^2 \pm 2m\hbar^{-2} v(\mathbf{K}_h)]^{1/2}. \quad (7b)$$

Here, \mathbf{k}_h is the planar component of \mathbf{k} . Since $v(\mathbf{K}_h)$ is a function of T now, the transmission coefficient $T_{\uparrow\uparrow}(\mathbf{k})$ will also be a function of T . That is to say, the tunneling process will vary with temperature.

From $T_{\uparrow\uparrow}$, the conductance $G_{\uparrow\uparrow}$ for the channel of the spin-up to spin-up tunneling can be obtained as follows,

$$G_{\uparrow\uparrow} = \frac{e^2}{16\pi^3\hbar} \int_0^{\pi/2} d\theta \int_0^{2\pi} d\varphi k_{F\uparrow}^2 \sin(2\theta) T_{\uparrow\uparrow}(k_{F\uparrow}, \theta, \varphi), \quad (8)$$

where e denotes the electron charge, θ the angle between \mathbf{k} and \mathbf{e}_z , φ the angle between \mathbf{k}_h and \mathbf{a}_1 , and $k_{F\uparrow}$ the Fermi wave vector of the spin-up electrons. Here, we have ignored the effect of temperature on the Fermi–Dirac distribution of the electrons of ferromagnetic electrodes, which is fairly weak in the present case because $T \leq 400$ K $\ll T_F$ where $T_F > 10^4$ K is the Fermi temperature for either of the electrodes. Since $T_{\uparrow\uparrow}$ is a function of T , the above equation shows that $G_{\uparrow\uparrow}$ will depend on the temperature, too.

The other three conductances, $G_{\uparrow\downarrow}$, $G_{\downarrow\uparrow}$, and $G_{\downarrow\downarrow}$, can be obtained similarly. With them, one can get $G_P = G_{\uparrow\uparrow} + G_{\downarrow\downarrow}$, $G_{AP} = G_{\uparrow\downarrow} + G_{\downarrow\uparrow}$, $R_P = G_P^{-1}$, $R_{AP} = G_{AP}^{-1}$, and $\text{TMR} = G_P / G_{AP} - 1 = R_{AP} / R_P - 1$.

Likewise, $G_{\uparrow\downarrow}$, $G_{\downarrow\uparrow}$, and $G_{\downarrow\downarrow}$ will also depend on the temperature of the system. Physically, that arises from the fact that $v(\mathbf{K}_h)$ varies with temperature, as shown in Eq. (5). In a word, the four conductances, $G_{\uparrow\uparrow}$, $G_{\uparrow\downarrow}$, $G_{\downarrow\uparrow}$, and $G_{\downarrow\downarrow}$, as well as the TMR will all change with the

variation of temperature T .

The rest calculations are analogous to the Ref. [15]. The parameters of the ferromagnetic electrodes are chosen as follows: the chemical potential μ is 11 eV, the half of the exchange splitting Δ for the ferromagnetic electrodes is 10 eV, and the Fourier transform of the atomic potential of the ideal perfect barrier $v_0(\mathbf{K}_h)$ is set to be 15.3 eV.

3. Results and discussions

As a preparatory step to the effects of temperature on the MgO-based MTJs, we shall first study the dependences of R_p and R_{AP} on $v(\mathbf{K}_h)$. The results are shown in Fig. 1 where the thickness of the barrier varies from 1.5 nm to 3 nm. Obviously, both the R_p and R_{AP} oscillate with $v(\mathbf{K}_h)$. As pointed out in Ref. [15], that originates from the interference among the diffracted waves. In addition, Fig. 1 shows that the amplitude of R_{AP} is much larger than that of R_p . It can be understood as follows: As stated in Ref. [15], there exist two kinds of integral regions for the transmission coefficients, for the one of them, the transmission coefficients contain oscillating term, for the other, they do not. Only when both p_+^z and p_-^z are real or both q_+^z and q_-^z are real there can arise oscillating term. For the channel T_{11} , the integral region where the transmission coefficient contains oscillating term is more extensive than the other three channels. It leads to that R_{AP} oscillates more strongly than R_p . At last, it can be seen from Fig. 1 that, the thicker the width of barrier, the shorter the period of the oscillation. Eq. (6) indicates that when the width d of the barrier gets thicker, the frequency of T_{11} with respect to $p_+^z - p_-^z$ and $q_+^z - q_-^z$ will become larger. At the same time, it is easy to know from Eq. (7) that both the $p_+^z - p_-^z$ and $q_+^z - q_-^z$ are monotone increasing functions of $v(\mathbf{K}_h)$. Therefore, the thicker the width d of the barrier, the larger the frequencies of R_p and R_{AP} with respect to the variable $v(\mathbf{K}_h)$.

Based on those results, the effects of temperature on the MgO-based MTJs can be explained as follows. From Eq. (5), it can be found that $v(\mathbf{K}_h)$ oscillates with temperature T . Since both R_p and R_{AP} oscillate with $v(\mathbf{K}_h)$, as stated above, they will also oscillate with temperature T . In addition, the amplitude of R_{AP} will be much stronger than that of R_p , that is because R_{AP} shows stronger oscillations with regard to $v(\mathbf{K}_h)$ than R_p . This accounts for the physical mechanism of the effects of temperature on the MTJ.

In the following, we shall try to use this mechanism to explain in detail the experimental results of the MTJ.

First, we would like to investigate the effect of the strain on R_p and R_{AP} . The theoretical results are depicted in Fig. 2 where $\mathbf{K}_h \cdot \alpha_0$ varies from $\pi/6$ to $\pi/2$, $\sigma = 0.08$, $T_c = 800$ K, and $d = 1.5$ nm. Fig. 2(a) shows the dependence of R_p and R_{AP} on the strain when $T = 10$ K. Clearly, both R_p and R_{AP} oscillate with $\mathbf{K}_h \cdot \alpha_0$ but the amplitude of R_{AP} is much larger than that of R_p . In order to interpret this result, we draw up Fig. 3 to demonstrate the dependence of $v(\mathbf{K}_h)$ on $\mathbf{K}_h \cdot \alpha_0$. It can be seen that $v(\mathbf{K}_h)$ decreases monotonously from 16.2 eV to 14.1 eV when $\mathbf{K}_h \cdot \alpha_0$ increases from $\pi/6$ to $\pi/2$. Combining Fig. 3 and Fig. 1, one can easily deduce that the amplitude of R_{AP} is much larger than that of R_p . As to the annealed MTJ of Ref. [27], it shows that the R_{AP} increases with raising of strain, that can be explained if the strain lies within the range from $\pi/6$ to 1.14 in Fig. 2(a). Of course, if the strain can exceed the region, the R_{AP} would be experimentally expected to decrease or even oscillate with raising of strain. On the other hand, if the MTJ is non-annealed, the barrier would be not well crystallized, the interference arising from the diffraction by the barrier will disappear. Therefore, the R_{AP} will unchange with the strain. In other words, the R_{AP} can not oscillate with the strain. As such, the theoretical results explain the experiments of Ref. [27]: For the annealed MTJ, the R_{AP} is significantly more sensitive to the strain than the R_p ; for non-annealed MTJ, both the R_p and R_{AP} are not sensitive to the strain. Fig. 2(b) displays the temperature dependence of R_p and R_{AP} under different strains. Evidently, both R_p and R_{AP} become more sensitive to the temperature when the strain goes larger. That can be easily understood from Eq. (5): The

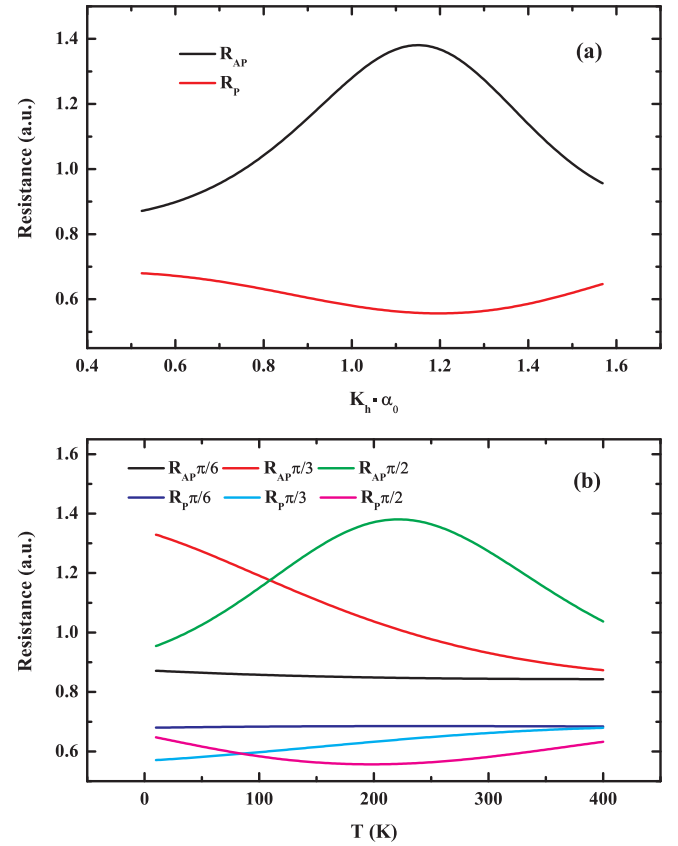


Fig. 2. (a) R_p and R_{AP} as functions of $\mathbf{K}_h \cdot \alpha_0$ at 10 K, (b) R_p and R_{AP} as functions of the temperature under different $\mathbf{K}_h \cdot \alpha_0 = \pi/6, \pi/3$, and $\pi/2$, where $\sigma = 0.08$, $T_c = 800$ K, and $d = 1.5$ nm.

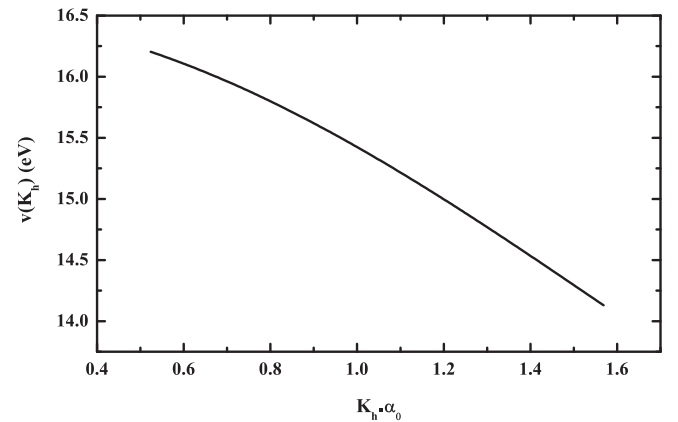


Fig. 3. $v(\mathbf{K}_h)$ as functions of $\mathbf{K}_h \cdot \alpha_0$ at 10 K where $\sigma = 0.08$, $T_c = 800$ K, and $d = 1.5$ nm.

larger the strain is, the more sensitive to the temperature the $v(\mathbf{K}_h)$ will be.

Secondly, we shall study the effect of σ on R_p and R_{AP} . The results are shown in Fig. 4 where σ varies from 0.01 to 0.16, $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $T_c = 800$ K, and $d = 1.5$ nm. Fig. 4(a) shows that both R_p and R_{AP} are nearly independent on σ at 10 K. Physically, that is because $v(\mathbf{K}_h)$ changes little when σ increases from 0.01 to 0.16, as shown in Fig. 5. This can be understood as following: From Eq. (5), we can obtain

$$v(\mathbf{K}_h) = v_0(\mathbf{K}_h) + v_0(\mathbf{K}_h) \left[2 \cos \left(\mathbf{K}_h \cdot \alpha_0 \left(1 - \frac{T}{T_c} \right) \right) - 1 \right] \sigma. \quad (9)$$

Eq. (9) shows that there is a linear relationship between $v(\mathbf{K}_h)$ and σ .

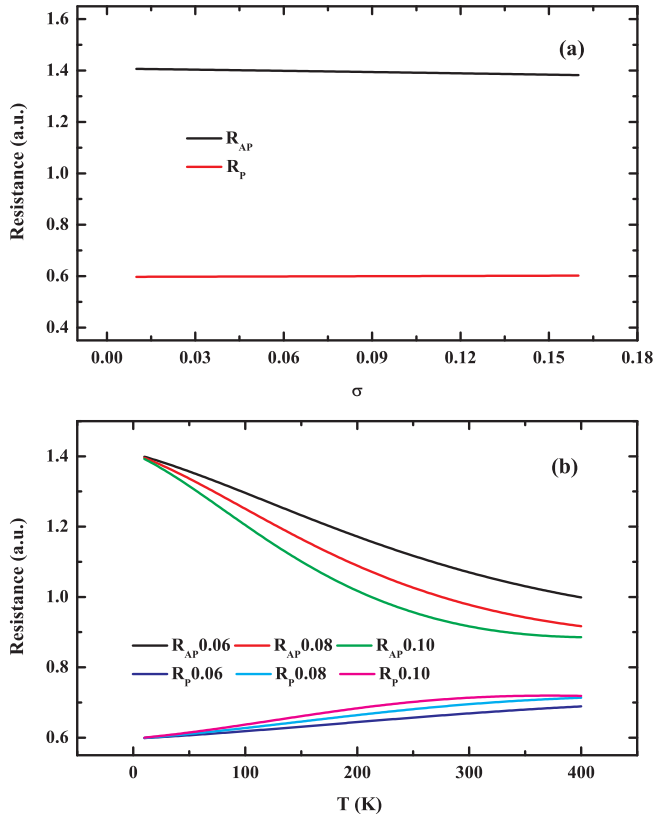


Fig. 4. (a) R_P and R_{AP} as functions of σ at 10 K, (b) R_P and R_{AP} as functions of the temperature under different $\sigma = 0.06, 0.08$, and 0.10 , where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $T_c = 800$ K, and $d = 1.5$ nm.

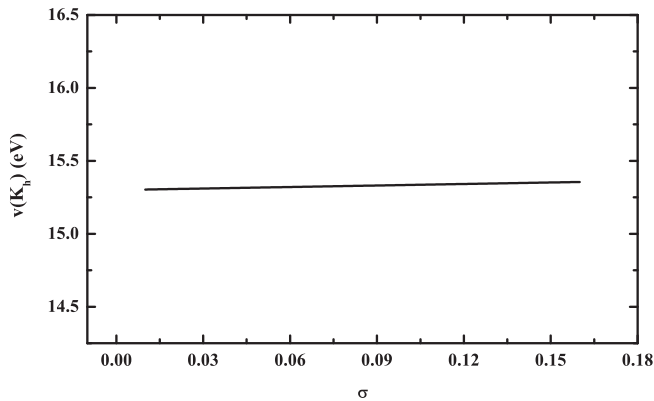


Fig. 5. $v(\mathbf{K}_h)$ as functions of σ at 10 K where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $T_c = 800$ K, and $d = 1.5$ nm.

Under the present parameters, the slope is very small, therefore, the $v(\mathbf{K}_h)$ will change little with σ . Fig. 4(b) displays the temperature dependences of R_P and R_{AP} under different σ . Evidently, the larger the σ , the more sensitive to temperature the R_P and R_{AP} . It comes from the fact that the larger the σ , the more sensitive to the temperature the $v(\mathbf{K}_h)$, as can be easily seen from Eq. (9).

Thirdly, we will discuss the effect of T_c on R_P and R_{AP} . The theoretical results are shown in Fig. 6 where T_c varies from 600 K to 1000 K, $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, and $d = 1.5$ nm. Fig. 6(a) shows the dependence of R_P and R_{AP} on T_c when temperature is at 10 K. It can be seen that both R_P and R_{AP} are nearly independent on T_c . This can be interpreted from Fig. 7 which shows that $v(\mathbf{K}_h)$ changes little when T_c increases from 600 K to 1000 K. That is because T/T_c is much smaller than 1 when $600 \text{ K} \leq T_c \leq 1000 \text{ K}$. From Eq. (5), it means that $v(\mathbf{K}_h)$ will

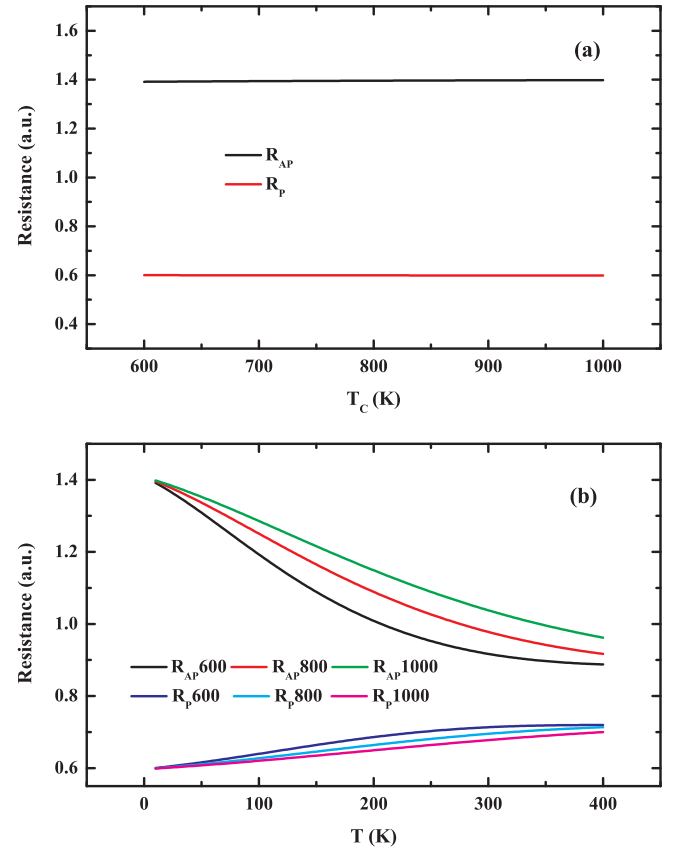


Fig. 6. (a) R_P and R_{AP} as functions of T_c at 10 K, (b) R_P and R_{AP} as functions of the temperature under different $T_c = 600$ K, 800 K, and 1000 K, where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, and $d = 1.5$ nm.

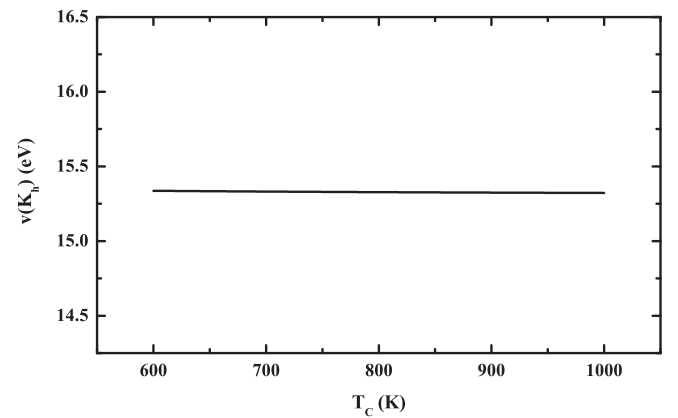


Fig. 7. $v(\mathbf{K}_h)$ as functions of T_c at 10 K where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, and $d = 1.5$ nm.

change little. Fig. 6(b) displays the temperature dependence of R_P and R_{AP} for different T_c : The larger the T_c , the less sensitive to temperature the R_P and R_{AP} . The result can be easily understood from Eq. (5): The larger the T_c , the less sensitive to the temperature the $v(\mathbf{K}_h)$.

Finally, we will compare our theory with experiments. As stated above, the most fundamental feature discovered by the experiments is that the decrease of TMR with rising temperature is mostly carried by a change in the R_{AP} , and the R_P changes so little that it seems roughly constant, if compared to the R_{AP} . In order to reproduce this feature, we draw up Fig. 8 to show the temperature dependences of the R_P , R_{AP} and TMR where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, $T_c = 800$ K, and $d = 1.5$ nm. Under those parameters, the R_{AP} just lies in the dropping region of the

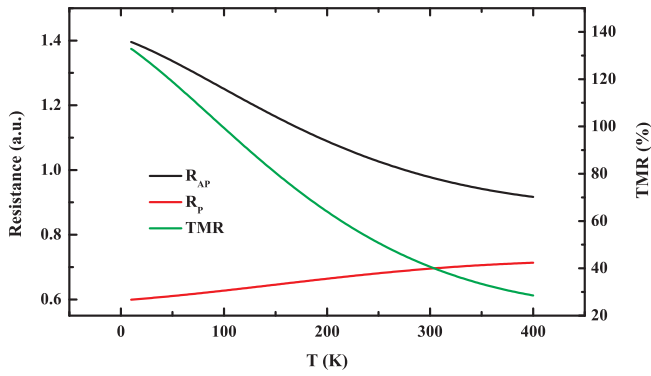


Fig. 8. R_P , R_{AP} , and TMR as functions of temperature where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, $T_c = 800$ K, and $d = 1.5$ nm.

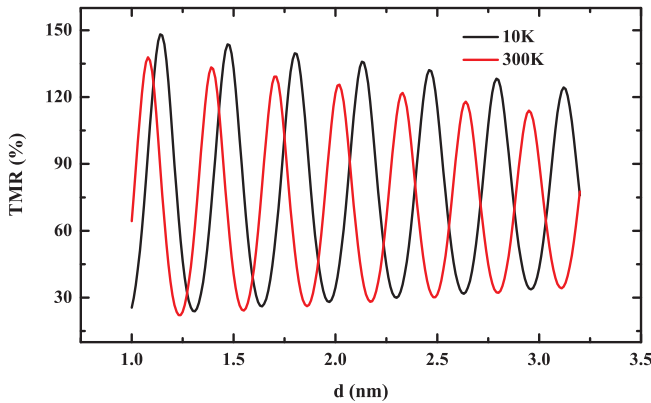


Fig. 9. TMR as functions of barrier thickness d at 10 K and 300 K where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, and $T_c = 800$ K.

oscillation. And because the amplitude of R_{AP} is much larger than that of R_P , the R_P changes so little that it seems roughly constant. It can be seen from Fig. 8 that the theoretical results agree qualitatively well with the experiments [3,17–25]. Here, it should be pointed out that, the experimental results are only within part range of the parameters in the present model. If the whole range is taken into consideration, R_P and R_{AP} may decrease, or increase, or even oscillate with increasing temperature, which one happens depends on the detailed range of $v(\mathbf{K}_h)$, as can be easily seen from Fig. 1. This suggests that, if the MgO barrier is replaced by another kind of material, the R_P , R_{AP} and TMR may decrease, or increase, or even oscillate with temperature, that is to say, the situation can be quite different from the case of MgO-based MTJs discussed here.

On the other hand, we also calculate the influence of temperature on the TMR oscillations with barrier thickness. The result are shown in Fig. 9 where $\mathbf{K}_h \cdot \alpha_0 = \pi/3$, $\sigma = 0.08$, and $T_c = 800$ K. Fig. 9 indicates that both the amplitude and period decrease weakly with rising of temperature. This can be understood as follows. When temperature varies from 10 K to 300 K, $v(\mathbf{K}_h)$ will vary correspondingly from 15.3 eV to 16 eV. As pointed out in Ref. [15], the amplitude and period of TMR will both decrease as $v(\mathbf{K}_h)$ increases. It means that the weak decrease of the amplitude and period roots from the small variation of $v(\mathbf{K}_h)$, from 15.3 eV to 16 eV. This theoretical result is in agreement with the experiments [4,13].

4. Conclusion

So far, we have developed a tunneling theory to study the temperature effects in the MTJs with periodic grating barrier. The theory is an extension of our previous work where the barrier is treated as a diffraction grating with intralayer periodicity. Physically, the extension

is done mainly through the so-called Patterson function approach. Within the framework of this extension, one can easily take into account the influence of the lattice distortion of the barrier on the tunneling process of the electrons. We find that the distortion can account for the effects of temperature on the MTJs with periodic grating barrier.

Theoretically, the distortion of lattice of the barrier can be described by the defect concentration and the strain, they can both modify highly the scattering potential of the barrier. Although the defect concentration is nearly independent on the temperature, the strain depends strongly upon the temperature of the system. As a result, with the thermal activation of the scattering potential of the barrier, the tunneling process of the electrons will be highly changed by the temperature of the system, that is just the origination of the effects of temperature on the MTJs with periodic grating barrier. With this mechanism, the R_P , R_{AP} and TMR can all oscillate with the variation of temperature. For a certain concrete range of temperature, the three can occur as increasing, decreasing, or oscillating with rising of temperature. As such, the theory can explain the experiments on the MgO-based MTJs: First, it reproduces the most fundamental feature of the temperature effects: The decrease of TMR with rising temperature is mostly carried by a change in the R_{AP} , and the R_P changes so little that it seems roughly constant, if compared to the R_{AP} . Secondly, it shows that both the amplitude and period of oscillation of the TMR with regard to the barrier thickness decrease weakly with rising temperature. And thirdly, it demonstrates that, for the annealed MTJ, the R_{AP} is significantly more sensitive to the strain than the R_P , and for non-annealed MTJ, both the R_P and R_{AP} are not sensitive to the strain.

Recently, Hu and co-workers [30] find an interesting result of the MgO-based MTJs with Co_2MnSi electrodes. One can easily see from the Fig. 4 of Ref. [30] that the R_P oscillates with the temperature, but the R_{AP} dose not. Here, it is worth noting that the situation of Co_2MnSi electrodes is much distinct from the case considered in this paper, because Co_2MnSi is half-metallic while the present electrodes are conventional. In order to discuss this intriguing property, one needs further to take into account the half-metallic characteristics of the electrodes. We believe that it can be interpreted within the framework of our model. The work is in progress and will be published elsewhere.

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