Journal of Interfaces, Thin films, and Low dimensional systems 4 (2) Winter and Spring (2021) 415-420

Electrical properties of magnetic tunnel junctions affected by two types of interfacial roughness

Scientific research paper

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ARTICLE INFO

Article history:
Received 25 December 2021
Revised 6 January 2022
Accepted 9 January 2022
Available online 27 January 2022

Keywords:
Interfacial roughness
Tunnel magnetoresistance
Electrical properties
Spin polarization

ABSTRACT

The theoretical study has been done for investigating the effect of two types of rough interfacials on the electrical properties of magnetic tunneling structures. Surface roughness is found to have a strong influence on the spin polarized transport through magnetic tunneling junctions. The scattering mechanism because of rough interfaces causes reduction of the maximum achievable value for transmission probability resonance. Also, the presence of roughness interfacial causes a change in the spin polarization and the tunneling magnetoresistance ratios. The asymmetry distribution of the density of states may be reduced while the spin polarization and the tunneling magnetoresistance show an irregular behavior.

1 Introduction

Tunneling magnetoresistance (TMR) discusses the dependence of the resistance of magnetic tunnel junctions (MTJs) on the relative orientation of the magnetization directions of the ferromagnetic electrodes when their orientations changes from antiparallel AP to parallel P; TMR= G_P-G_{AP}/G_P≡R_P-R_{AP}/R_P [1,2]. Spin Filter (SF) tunneling has become a very active part of research, many efforts have been devoted to this field because of large values of TMR discovery [3,4]. During the last two decades, spintronics which indicates the manipulation of electron spin along with its charge is an interesting field of research. It is applied in a wide variety of applications such as precise detection of defective cells, data designing of single as well as parallel logic gates, computer and mobile games, storage to robotics, speed control and navigation [5-8].

The method of interfaces production has a strong effect on the magnitude and polarization of the transport through MTJs. The information about the interfaces and details of models of the interfaces are the necessary step to analyze the electrical properties of MTJs theoretically and experimentally [3-5]. Several methods have been applied to simulate the tunneling structures interfaces to describe the transport phenomena through heterojunctions, theoretically. The diagrammatic techniques within diffusive perturbation theory [9], the transfer matrix method that treats each rough interface separately [10], and the diagrammatic techniques within the Born approximation [11]. The actual MTJs contain large amounts of roughness at the interfaces between the structure layers because there are many various models that have been used to generate them. Actually, the transport through MTJs affected by the roughness type of interfaces [12] and on the other hand, due to the existence of large spin dependent

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DOI: 10.22051/jitl.2022.38934.1065

scattering, magnetic materials exhibit the high degree of SP and the TMR [13, 14] Many researches have been done to investigate the characteristics of polarized currents [15–18].

Here, the roughness scattering from the two interfaces in a double barrier MTJs has been studied. The first and third interfaces have been considered rough. The type of first interface roughness is different from the third one. They have been generated by Ballistic deposition (BD) and Random Deposition (RD) models, respectively. Indeed, in this paper the effect of two different types of used rough interfacials in MTJs structures have been investigated simultaneously on the spin dependent transport properties of MTJs.

2 Method and results

The nearly free electron approximation and the transfer matrix method have been used to calculate the electronic properties in order to study the effect of roughness type on TMR and spin polarized transport in MTJs. The MTJ considered here consists of the NM layer and two ferromagnetic semiconductor barriers. Based on the experimental works results the top and bottom interfaces have dissimilar structures in heterojunctions, and bottom/top interfacials could be much rougher or smoother than the bottom/top interfacials depending on the growth conditions [19]. Hamiltonian in the presence of applied voltage Va, is considered as

$$H_j(Z) = \frac{-\hbar^2}{2m_j^*}\frac{d^2}{dz^2} + V_j(Z) + V_j^\sigma,$$

j=1-5 (1)

where m_j^* is the effective mass in 5 regions:

$$V_j(z) = \begin{cases} 0, \quad (j=1) \\ E_F + V(r_\parallel, z) - \frac{eV_a}{4}, \quad (j=2) \\ -\frac{eV_a}{2}, \quad (j=3) \\ E_F + V(r_\parallel, z) - \frac{3eV_a}{4}, \quad (j=4) \\ -eV_a, \quad (j=5) \end{cases} \tag{2}$$

that, $V(r_\parallel, z) = \phi_0[\theta(z - f(r_\parallel))]$, where θ(z) is the unit step function and $f(r_\parallel)$ is interface thickness of the rough interfaces [19]. The wave function presents as

$$\psi_j = \sum_q (a_{j\sigma}^\gamma(\boldsymbol{q}) e^{(ik_j z)} + b_{j\sigma}^\gamma(\boldsymbol{q}) e^{-(ik_j z)}) e^{(i\boldsymbol{q}.\boldsymbol{r}_\parallel)}, \tag{3}$$

in each region. q=(q_x, q_y) is the transverse wave vector, k_j is the wave numbers in each jth region, and $r_\parallel = (x, y)$ is the in-plane coordinate vector. $a_{j\sigma}^\gamma(q)$ and $b_{j\sigma}^\gamma(q)$ correspond to forward and backward propagation states, respectively. The direct and scattered components of the transmission probability have been denoted by $\gamma = 0$ and ±. Based on the transfer matrix:

$$\begin{bmatrix} a_{5\sigma}^{(+)} \\ a_{5\sigma}^{(0)} \\ a_{5\sigma}^{(-)} \\ 0 \\ 0 \\ 0 \end{bmatrix} = M \begin{bmatrix} 0 \\ a_{1\sigma}^{(0)} \\ 0 \\ b_{1\sigma}^{(+)} \\ b_{1\sigma}^{(0)} \\ b_{1\sigma}^{(-)} \end{bmatrix}, \tag{4}$$

where $a_{1\sigma}^{(\pm)} = 0$ denotes that in layer 1 there is only the direct incident component [19].

$b_{s\sigma}^{(\gamma)} = 0$ since there is no reflection in the last region. The transmission through the MTJs can be considered by the continuity conditions of the wave function ψ and the probability current density of the electron (1/m*)(dψ/dz) as follows

$$T_\sigma^{(\gamma)}(E_z, V_a) = \frac{k_5^{(\gamma)}}{k_1^{(\gamma)}}\frac{m_1^*}{m_5^*}\left|\frac{a_{5\sigma}^{(\gamma)}}{a_{1\sigma}^{(\gamma)}}\right|^2, \tag{5}$$

Total transmission is achieved by $T_{tot} = \sum_\gamma T^{(\gamma)}$. [19]. Moreover, the current density can be written as [20]

$$j(V_a)=\frac{em^*K_BT}{4\pi^2\hbar^3}\int_0^\infty T(E_z,V_a)\ln\frac{1+\exp(\frac{(E_F-E_z)}{K_BT})}{1+\exp(\frac{(E_F-E_z-eV_a)}{K_BT})}dE_z, \quad (6)$$

where $T(E_z,V_a)$ is the transmission probability. As presented before, the spin polarization is obtained from the current densities, $sp=\frac{j_\uparrow-j_\downarrow}{j_\uparrow+j_\downarrow}$. $J_{\uparrow(\downarrow)}$ and $J_{P(AP)}$ are the portion currents of spin up (down) and parallel (anti-parallel) configurations, respectively [21,22]. The values of used parameters are as the following. The thicknesses of barriers and quantum wells are 0.5 and 0.75 nm, respectively. $m_1=m_0$ and $m_2=1.5m_0$ for the electron effective mass in NM and FMS materials, respectively which m_0 is the electron mass in free space. Also, E_F is the electron Fermi energy which has been taken as 1.25eV. The parameters for EuS barrier layers are I =0.1eV and S=7/2 [23], and T_c is 16.5K [24,25]. In the calculation, the applied voltage is $V_a = 50mV$.

For each spin, there are two fundamental parallel conduction channels in SF structures. The net current density is the average of the spin-up and spin-down current densities $j_{net}=(j_{up}+j_{down})/2$. Indeed the Spin-up and spin-down electrons fell the different heights of the barriers and therefore, the spin channel with the lesser barrier height has a greater transmission coefficient. This indicates that the current entering the collector electrode is spin polarized. The first and third rough interfaces have been produced by two standard models of deposition, BD and RD respectively. Random deposition (RD) is the simplest model of surface generation which during this model each particle is randomly released over a position (site) of a surface and added to the top of the selected column. The produced interface/surface is uncorrelated because the growth of columns is independent of each other. The common deposition model is the Ballistic deposition (BD). In this model, a particle is dropped over a randomly chosen position (site) above the surface located at a distance that is larger than the maximum height of the interface, therefore the surface heights depend on the neighboring columns heights and hence the generated interface/ surface is correlated [26,27]. As a difference of the present work with previous ones, it is interested to investigate the effect of two types of interfacials roughness on the electrical properties of MTJs, simultaneously.

Figure. 1 shows the spin filter transmission probability through MTJs with mentioned rough interfaces. The resonant tunneling in these curves occur when the incident electron energy coincides with the energy of the lowest quasi-bound energy level in the quantum well. For a MTJs with perfect interfaces, the transmission probability reaches unity at the resonance.

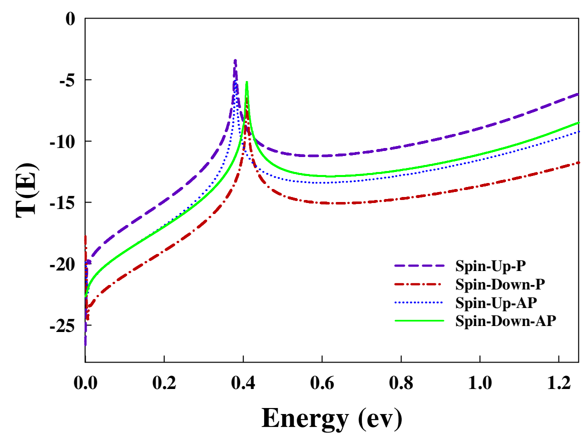

Figure 1. The logarithm of Spin filter transmission probabilities as a function of incident electron energy for two different spin orientations and parallel and antiparallel alignments. .

The scattering mechanism because of rough interfaces causes a reduction of the maximum achievable value of transmission probability resonance. The calculations have been carried out at T=0K.

The transmission coefficient for the spin-up orientation of electrons in the parallel alignment is higher than the spin-down electrons and also higher than the two-spin orientations at anti-parallel alignment. Also there is a small difference in the current density in both magnetic configurations. Based on the results of Fig. 1, for the electrons with spin- up orientation the transmission probability in the parallel alignment has the bigger values than the spin-down electrons. Moreover, it is bigger than the two-spin orientations at anti-parallel alignment. There is a small difference in the current density in both magnetic configurations.

In order to investigate the effect of temperature variations on the transport through rough MTJs, the transmission probability has been calculated for spin–up orientation and parallel alignment.

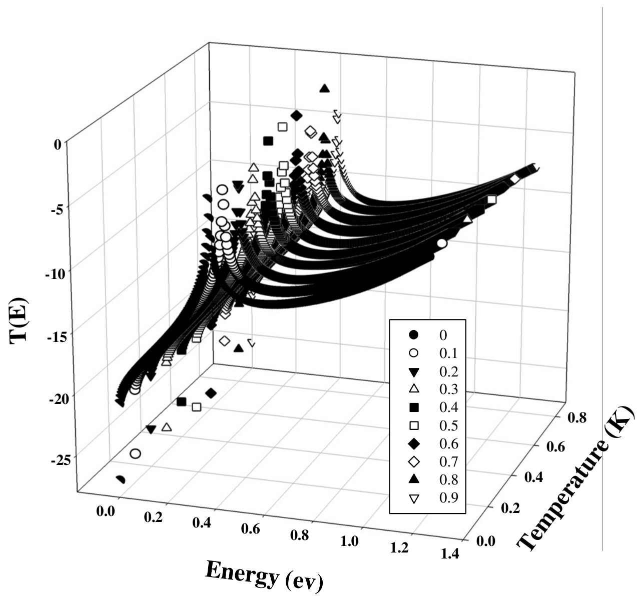

Figure 2. The logarithm of transmission probability has been calculated for spin–up orientation and parallel alignment for different values of temperature.

The results present the temperature dependence of the spin polarization for MTJs with rough interfaces. At temperatures T >T_c, there is no spin splitting. This splitting ascribed to the exchange splitting of the EuS conduction band. Therefore, the transmission coefficients for two spin orientations coincide [12].

Figures 3 and 4, show the spin polarization and the TMR as a function of the NM (quantum well) layer thickness at T = 0 K while the bias voltage Va = 50 mV is applied to the junction.

Based on the results, TMR and spin polarization oscillate by increasing the thickness of the NM layer. For the MTJs with perfect (no rough) interfaces, TMR and spin polarization have the well-defined peaks. The origin of this oscillatory behavior is related to the quantum-well states of the NM layer and the spin-polarized resonant tunneling. An electron entering on a MTJ has a maximum quantum mechanical tunneling probability and its energy agrees to a resonant state in the NM layer. The height of peaks reduces as the thickness of NM layer increases [25, 27, 28].

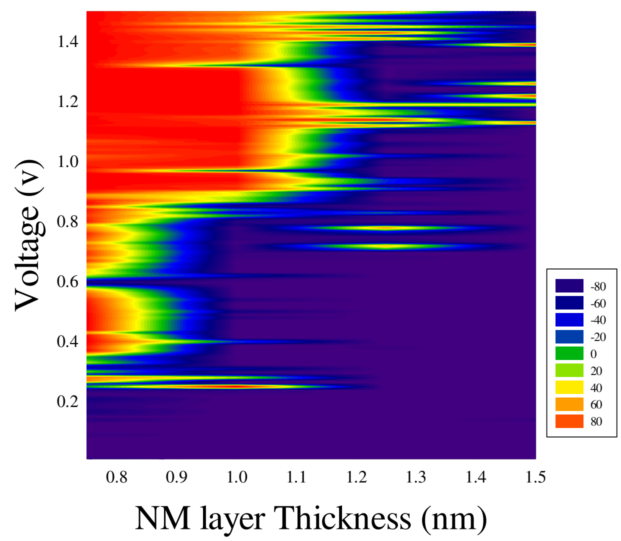

Figure 3. Spin polarization as a function of the thickness of NM well layer and applied voltage, at T = 0 K.

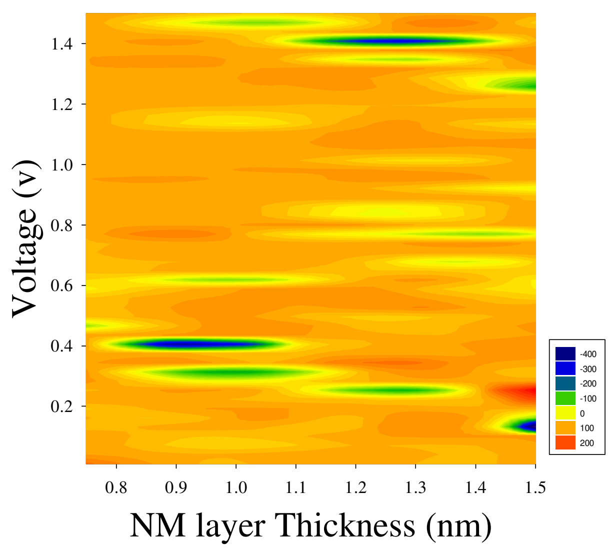

Figure 4. TMR as a function of the thickness of NM well layer and applied voltage, at T = 0 K.

Based on Figs. 3 and 4, the spin polarization and the TMR change periodically as the variation of NM layer thickness. The period and value of these parameters vary as a function of the applied voltage and the NM layer thickness. The presence of roughness interfacial may cause spin-flip scattering through the transport. This could be the origin of change in the spin polarization and the TMR quotients. Because, some of the majority electrons change their spin orientation and they tunnel into the corresponding minority states.

Therefore, the asymmetry distribution of the density of states may be reduced. Moreover, the location and the amount of resonant energies vary by increasing the NM layer thickness.

The electron scattering phenomena can create the valleys and peaks resonance energies. This indicates that for MTJs by rough interfaces, the spin polarization and the TMR show an irregular behavior. The results are in a good agreement with experiments, electron transport via imperfections and roughness goes to a reversal in the sign of the SP and the TMR ratios while typical nonlinear tunneling currents have been observed in the current-voltage charactristics [3]. These behaviors of the spin polarization and the TMR reveal the influence of interfaces roughness type [27, 28]. Also, changing the rough interfaces in MTJ has no effective effect on the obtained results.

4 Conclusions

In the present study, the effect of two different types of rough interfacials in a magnetic tunneling structure has been investigated. The first and third interfacials have been generated with two different standard models of deposition. The transport properties of the MTJs have been calculated, the results show that the scattering mechanism because of rough interfaces tends to reduce the maximum achievable value of the transmission probability resonance. Also, the spin polarization and the tunneling magnetoresistance ratios are strongly affected by the roughness, while the asymmetry distribution of the density of states is reduced as they present the irregular behaviors.

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