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# Resonant tunneling in magnetic semiconductor tunnel junctions with arbitrary magnetic alignments

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ABSTRACT

Combining an extended Julliere model with transfer matrix method, we study the spin-polarized resonant tunneling in GaMnAs/AlAs/GaAs/AlAs/GaMnAs double barrier ferromagnetic semiconductor (FS) tunnel junctions with the arbitrary angle $\theta$ between the magnetic directions of two FS's. It is shown that tunneling magnetoresistance (TMR) ratio linearly varies with $\sin^2(\theta/2)$. We also demonstrate that for the heavy and light holes, the properties of the spin-polarized resonant tunneling are obviously different. The present results are expected to be instructive for manufacturing the relevant semiconductor spintronic devices.



## 1. Introduction

Recently, ferromagnetic semiconductor (FS) such as GaMnAs with magnetic and semiconducting properties gradually becomes one of the most attractive subjects of semiconductor spintronics [1–5]. The Curie temperature of this material being as high as 150 K shows promise for possible technological relevance in recent experiments [6]. The ferromagnetism in the FS originates from the long-range ferromagnetic order between the $Mn^{+2}$ ions with spin $s=\frac{5}{2}$ medicated by uniform itinerant carrier spin [7–9]. The large tunneling magnetoresistance (TMR)(maximum 75%) [10] observed in FS GaMnAs/AlAs/GaMnAs tunnel junctions implies that even for small Mn concentrations, the spin polarization may be large [11–13]. Although there have been works on the single and double barrier tunnel junctions which are composed of FS, the effect of the orientation of the magnetizations in FS's on spin-polarized transport properties has seldom been dealt with yet. Theoretically, Bunder [14] studied the effect of relative magnetization orientations in GaMnAs/AlAs/GaMnAs tunnel junctions and obtained the dependence of TMR on $\sin^2(\theta/2)$ with $\theta$ the angle between the magnetization orientations of two FS's, however, there is a very little experimental works on it yet. The double barrier magnetic tunnel junctions composed of FS GaMnAs due to its coexistence of semiconductor properties and ferromagnetism, in which the formation of quantum well states and resonant tunneling phenomena are anticipated, have attracted much attention in recent years [15,16], however, the relative magnetization orientations of two FS's are seldom studied in GaMnAs/AlAs/GaAs/AlAs/GaMnAs tunnel junctions. Our motivation in this letter arises from two aspects, one is to reveal the related properties of coherent transport with the varied angle between the magnetic directions of two FS's, the other is to illustrate different resonant behaviors of currents between the heavy holes and light holes.

In this paper, extending the Julliere model [17] combined with transfer matrix method [18,19], we study the spin-polarized resonant tunneling in GaMnAs/AlAs/GaAs/AlAs/GaMnAs double barrier FS tunnel junctions with the varied angle between the magnetic directions of two FS's, in which not only the differences of spin splitting energies between the heavy and light holes but also the mismatches of bands and masses between the FS and SC are included. We demonstrate that the TMR ratio linearly varies with $\sin^2(\theta/2)$. It is also shown that the features of the spin-polarized resonant tunneling for the heavy and light holes are much different. The periodic behavior of TMR with the variation of quantum well GaAs width is qualitatively consistent with that in Ref. [15]. The results may be utilized as the basis for the design of semiconductor spintronic devices.

## 2. Model and theory

Consider a GaMnAs/AlAs/GaAs/AlAs/GaMnAs FS double barrier tunnel junction as shown in Fig. 1, in which $w$ and $d$ are the barrier and quantum well thicknesses, respectively. The layers are assumed in $x$–$y$ plane and to be staked along $z$ direction. A free-hole model is applied

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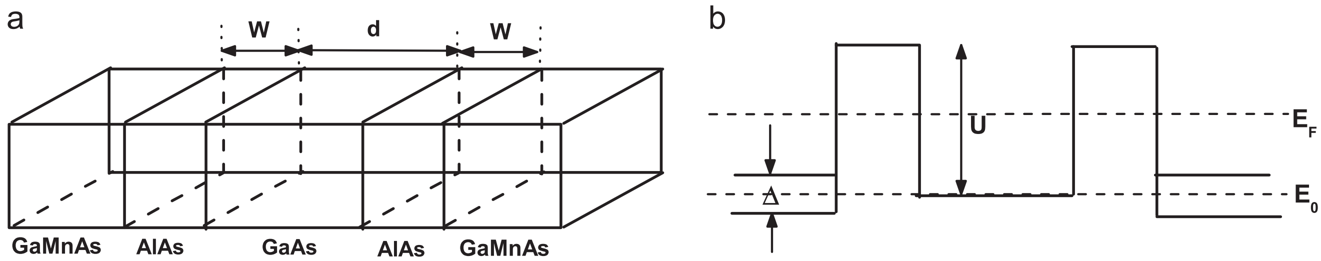


**Fig. 1.** (a) Schematic illustration of GaMnAs/AlAs/GaAs/AlAs/GaMnAs tunnel junction with the thicknesses $w$ of AlAs and $d$ of GaAs. (b) The potential profile of the junction with $\Delta$ the splitting energy of GaMnAs and $U$ the barrier height of AlAs.

to the FS GaMnAs with $\Delta$ the difference between the tops of majority and minority valence subbands. The valence subbands comprise heavy and light holes. The hole Hamiltonian of the whole system is given by

$$H=-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial r^2}-\vec{h}(r)\cdot\vec{\sigma}\,\Theta\left[|z|-\left(\frac{d}{2}+w\right)\right]\cdots+U\Theta\left[\left(\frac{d}{2}+w\right)-|z|\right]\Theta\left[|z|-\frac{d}{2}\right],$$

with $\Theta(z)$ the Heaviside function. The first term of the right-hand is kinetic energy with effective mass $m^*$ of carriers in each layer. The second one stands for internal exchange interaction, where $\vec{h}(r)$ is the molecule field with its magnitude equal to $\Delta/2$ and $\vec{\sigma}$ is the conventional Pauli spin operator. The last one represents the effect of barrier height $U$ measured from $E_0$. At finite temperatures, the spin splitting energy $\Delta(T)$ is given by $\Delta=N_{Mn}J^{Mnh}\langle S_z\rangle$ [11], where $J^{Mnh}$ refers to the $p-d$ exchange coupling strength between itinerant holes and $Mn^{2+}$ ion impurity spins connected with $N_{Mn}$ the density of $Mn^{2+}$ impurity, and $\langle S_z\rangle$ means the thermal average of the impurity Mn ion spins.

Fig. 1 is the potential structure illustration of the junction corresponding to Fig. 1(a). The whole zone can be divided into five regions and four boundaries. The wave functions of each region can be given by

$$\Psi(z)=\begin{cases} a_1\phi_\uparrow(0)e^{ik_{1\uparrow}z}+b_1\phi_\downarrow(0)e^{ik_{1\downarrow}z}+c_1\phi_\uparrow(0)e^{-ik_{1\uparrow}z}\cdots+d_1\phi_\downarrow(0)e^{-ik_{1\downarrow}z}, & z\le -w-d/2,\\ a_2\phi_\uparrow(0)e^{ik_{2\uparrow}z}+b_2\phi_\downarrow(0)e^{ik_{2\downarrow}z}+c_2\phi_\uparrow(0)e^{-ik_{2\uparrow}z}\cdots+d_2\phi_\downarrow(0)e^{-ik_{2\downarrow}z}, & -w-d/2<z<-d/2,\\ a_3\phi_\uparrow(0)e^{ik_{3\uparrow}z}+b_3\phi_\downarrow(0)e^{ik_{3\downarrow}z}+c_3\phi_\uparrow(0)e^{-ik_{3\uparrow}z}\cdots+d_3\phi_\downarrow(0)e^{-ik_{3\downarrow}z}, & -d/2\le z\le d/2,\\ a_4\phi_\uparrow(0)e^{ik_{4\uparrow}z}+b_4\phi_\downarrow(0)e^{ik_{4\downarrow}z}+c_4\phi_\uparrow(0)e^{-ik_{4\uparrow}z}\cdots+d_4\phi_\downarrow(0)e^{-ik_{4\downarrow}z}, & d/2<z<w+d/2,\\ a_5\phi_\uparrow(\theta)e^{ik_{5\uparrow}z}+b_5\phi_\downarrow(\theta)e^{ik_{5\downarrow}z}+c_5\phi_\uparrow(\theta)e^{-ik_{5\uparrow}z}\cdots+d_5\phi_\downarrow(\theta)e^{-ik_{5\downarrow}z}, & z\ge w+d/2, \end{cases}$$

where

$$\phi_\uparrow(\theta)=\begin{pmatrix}\cos\theta\\ \sin\theta\end{pmatrix}\quad\text{and}\quad\phi_\downarrow(\theta)=\begin{pmatrix}\sin\theta\\ -\cos\theta\end{pmatrix}$$

are the spin components of wave function, $k_{n\uparrow(\downarrow)}=\sqrt{2m^*(E\mp\Delta/2-U)/\hbar^2-k_\parallel^2}$ is $z$ component of wave-vector with $n=1\sim5$ for five regions. For $n=2,3,4$, $\Delta=0$ and for $n=1,3,5$, $U=0$. The wave functions are matched at the interfaces through the continuity of the wave functions and their derivatives, and we get a set of matrix equations for the coefficients.

$$M_{2n-1}(a_n,b_n,c_n,d_n)^T=M_{2n}(a_{n+1},b_{n+1},c_{n+1},d_{n+1})^T, \tag{1}$$

with $(a_n, b_n, c_n, d_n)^T$ the transposed matrix and

$$M_{2n-1}=\begin{pmatrix} \cos\frac{\theta}{2}e^{ik_{n\uparrow}z_n} & -\sin\frac{\theta}{2}e^{ik_{n\downarrow}z_n}\cdots & \cdots\cos\frac{\theta}{2}e^{-ik_{n\uparrow}z_n} & -\sin\frac{\theta}{2}e^{-ik_{n\downarrow}z_n}\\ \sin\frac{\theta}{2}e^{ik_{n\uparrow}z_n} & \cos\frac{\theta}{2}e^{ik_{n\downarrow}z_n}\cdots & \cdots\sin\frac{\theta}{2}e^{-ik_{n\uparrow}z_n} & \cos\frac{\theta}{2}e^{-ik_{n\downarrow}z_n}\\ ik_{n\uparrow}\cos\frac{\theta}{2}e^{ik_{n\uparrow}z_n} & -ik_{n\downarrow}\sin\frac{\theta}{2}e^{ik_{n\downarrow}z_n}\cdots & \cdots-ik_{n\uparrow}\cos\frac{\theta}{2}e^{-ik_{n\uparrow}z_n} & ik_{n\downarrow}\sin\frac{\theta}{2}e^{-ik_{n\downarrow}z_n}\\ ik_{n\uparrow}\sin\frac{\theta}{2}e^{ik_{n\uparrow}z_n} & ik_{n\downarrow}\cos\frac{\theta}{2}e^{ik_{n\downarrow}z_n}\cdots & \cdots-ik_{n\uparrow}\sin\frac{\theta}{2}e^{-ik_{n\uparrow}z_n} & -ik_{n\downarrow}\cos\frac{\theta}{2}e^{-ik_{n\downarrow}z_n} \end{pmatrix}. \tag{2}$$

The matrix equations that connects the coefficients can be deduced as

$$(a_5,b_5,c_5,d_5)^T=M_{total}(a_1,b_1,c_1,d_1)^T, \tag{3}$$

where $a_5$, $b_5$ are the final transmission coefficients and

$$M_{total}=M_8^{-1}M_7M_6^{-1}M_5M_4^{-1}M_3M_2^{-1}M_1.$$

In the light of incident majority holes ($a_1=1, b_1=0$) and no reflection in the last region ($c_5=0, d_5=0$) for instance, we can obtain the other four coefficients of reflections in the first region $c_1$, $d_1$ and transmissions in the right region $a_5$, $b_5$ by solving above equations. With the aid of the coefficients obtained above, we can calculate the conductivities for arbitrary magnetization configurations using Landauer Büticker formalism. The total current is given by $I_{total}=\sum_\sigma(I_{h\sigma}+I_{l\sigma})$. Here, $h$ and $l$ represent the incident heavy and light holes with spin $\sigma=\uparrow(\downarrow)$ corresponding to majority (minority) state which is parallel (antiparallel) to the local magnetization in the left FS. For incident heavy holes with spin $\sigma$, the tunneling current $I_{h\sigma}$ can be written as [20]

$$I_{h\sigma}=\frac{Ae}{2\pi\hbar}\int_0^{+\infty}\mathrm{d}E[f(E-eV)-f(E)]T_\sigma(E,\theta), \tag{4}$$