Spin injection efficiency from two adjoining ferromagnetic metals into a two-dimensional electron gas

Jun Wang\textsuperscript{1}, D. Y. Xing\textsuperscript{1}, and H. B. Sun\textsuperscript{2}

\textsuperscript{1}National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China
\textsuperscript{2}Department of Physics, University of Queensland, Brisbane Qld 4072, Australia

(March 22, 2022)

Abstract

In order to enhance spin injection efficiency from ferromagnetic (FM) metal into a two-dimensional electron gas (2DEG), we introduce another FM metal and two tunnel barriers (I) between them to investigate the current polarization in such ballistic FM/I/FM/I/2DEG junction. Our treatment is based on the free-electron scattering theory. It is found that due to quantum interference effect, the magnitude and sign of the current polarization exhibits periodical oscillating behavior with variation of the thickness of the middle FM metal layer or its exchange energy strength. For some suitable parameters, the spin injection efficiency may arrive over 80\% in this junction and can also be controlled by the electron density of 2DEG. Our results may shed light on the development of new spin-polarized device

71.70.Ej, 73.21.-b 73.40.Sx
In the recent years there have been much theoretical and experimental work in the spin electronics (spintronics) field\cite{1-3}, in which the degrees of freedom of both electronic spin and charge are exploited. The magnetoelectronic device based on the spin-polarized transport in the semiconductors, which was first proposed by Datta and Das\cite{4}, has numerous potential applications in the information technology (IT) industry. The injection of spin-polarized carriers from ferromagnetic (FM) semiconductor into nonmagnetic semiconductor (SM)\cite{5-6} has been achieved successfully with an efficiency $\sim 90\%$. Jonker et al.\cite{7} even observed full polarized current by using an external magnetic field. Whereas spin injection from FM metal into SM is more attractive because FM metals such as Fe have a relatively high Curie temperature, which makes them indispensable for the room temperature devices. However, the spin injection efficiency in this FM/SM junction are very low and moreover, there exist much debate on it\cite{8}.

As Schmidt et al.\cite{9} pointed out, the basic obstacle for spin-polarized injection from FM metal into SM in the diffusive system results from the conductivity mismatch between them. Although many authors\cite{10-12} have shown that this kind of conductivity mismatch could be improved by introduction of a tunnel barrier (I) between them, which can assume the tunnel conductance difference between two spin channels, the efficiency of spin injection still remain low in comparison with that from ferromagnetic-SM into SM. For instance, by interposing a tunnel barrier between FM metal and SM, Zhu et al.\cite{13} have observed experimentally 2\% efficiency of spin injection from Fe into n-GaAs at room temperature; Heersche et al.\cite{14} theoretically calculated this ballistic FM/I/2DEG(two-dimensional electron gas)\cite{15} junction and obtained $\sim 10\%$ current polarization. A Schottky barrier formed at the Fe/AlGaAs interface by Hanbicki et al.\cite{16} as a tunnel barrier can make the efficiency of spin injection $\sim 30\%$ in this junction.

In the present work, we show theoretically that the high efficiency of spin injection from FM metal into 2DEG might be achieved by introducing another FM material (FM metal or ferromagnetic SM) between them besides two tunnel barriers. In the ballistic approximation, we treat this FM/I/FM/I/2DEG junction with the free-electron scattering theory, which
has been widespread employed to deal with the interface scattering of electrons\cite{17-18}. The first FM metal of the FM/I/FM/I/2DEG junction is a source of spin injection electrons (FM1), while the middle FM metal is taken as a resonant device to tune the tunnel current (FM2). Due to the quantum interference effect, the moderate thickness of the FM2 layer or its strength of spin exchange splitting energy may induce very high degree of current polarization. FM1 can even be a normal metal in our model since FM2 is crucial to cause the spin-polarized current. Increasing exchange energy of both FM1 and FM2 as well as the strength of two tunnel barriers would lead to enhancement of current polarization. The electron density of 2DEG affects the quantum interference effect so that it can also influence the degree of current polarization.

In the free electron approximation, the Hamiltonian for the FM/I/FM/I/2DEG junction reads

\[ H = -\frac{\hbar^2}{2m} \Delta^2 + V(x) + U_1 \delta(x) + U_2 \delta(x - L) - \theta(-x) h_1 \cdot \sigma - \theta(x) \theta(L - x) h_2 \cdot \sigma, \]  

(1)

where \( m \) is the effective electron mass, \( m = m_e \) in two FM metals for \( x < L \) and \( m = m_s \) in 2DEG for \( x > L \). Here we hypothesize that FM1 and FM2 have same effective electron masses. \( h_1 \) and \( h_2 \) are respectively the internal molecular fields of the FM1 and FM2 layer and \( \sigma \) denotes the Pauli spin operator. \( \theta(x) \) is the step function. The two thin tunnel barriers are described by \( \delta \)-type potentials, which does not lose generality. We wish to point out that even our two-dimensional model were replaced by three-dimensional one with different barrier shape such as rectangle one, or Schottky barrier between FM and SM, the qualitative results in this papers would not change. \( U_1 \) at \( x = 0 \) and \( U_2 \) at \( x = L \) are related with the barrier’s width and height. The potential energy \( V(x) \) is zero for \( x < L \) and \( E_B \) for \( x > L \).

The schematic band structures of the FM/I/FM/I/2DEG junction is shown in Fig. 1. The spin quantum axis is taken along \( y \) direction and the magnetizations of two FM metals are assumed to be parallel for simplicity while the net tunnel current flows in the \( x \) direction.

In the two-band model, the energy eigenvalues of a single electron with spin \( \sigma \) (\( \uparrow \) or \( \downarrow \)) are \( E_{\uparrow}^{fm1} = (hK_{f_{\uparrow}^{m1}})^2/2m_e \) and \( E_{\downarrow}^{fm1} = (hK_{f_{\downarrow}^{m1}})^2/2m_e + \Delta_1 \) in the FM1 layer, \( E_{\uparrow}^{fm2} = \)
\((\hbar K_{fm}^2)^2/2m_e\) and \(E_{\uparrow}^{fm2} = (\hbar K_{fm}^2)^2/2m_e + \Delta_2\) in FM2 layer, and \(E_{\sigma}^{sm} = E_B + (\hbar K_{sm}^2)^2/2m_s\) in 2DEG, where \(\Delta_1 = 2h_1\) and \(\Delta_2 = 2h_2\) are the exchange energies of FM1 and FM2, respectively. \(E_B\) is the difference between the lower conduction-band edge of 2DEG and that of FM. In the two-dimensional system, the density of states in 2DEG is constant for the energy dispersion of free electrons and \(E_{\sigma}^{sm} = E_B + \pi \hbar^2 n_{2DEG}/m_s\) with \(n_{2DEG}\) being the electron density of 2DEG. In the small bias approximation, only electrons near the Fermi energy \((E_F)\) surface contribute greatly to the net tunnel current so that we can take \(E_{\uparrow}^{fm1} = E_{\uparrow}^{fm2} = E_{\sigma}^{sm} = E_F\) and \(E_{\downarrow}^{fm1} = E_{\downarrow}^{fm2} = E_{\sigma}^{sm} = E_F\). Thus, the magnitude of Fermi wave vectors in three regions can be explicitly expressed as

\[
k_{\uparrow}^{fm1(2)} = \frac{1}{\hbar} \sqrt{2m_e E_F},
\]

(2)

\[
k_{\downarrow}^{fm1(2)} = \frac{1}{\hbar} \sqrt{2m_e (E_F - \Delta_{1(2)})},
\]

(3)

and

\[
k_{\sigma}^{sm} = \sqrt{2\pi n_{2DEG}}.
\]

(4)

It is assumed that the interfaces between the tunnel barriers and FM metals or 2DEG are ideally smooth and without diffusive scattering so that the momentum along \(y\) direction keep constant when electrons are scattered by them. We define \(k_{\sigma}^y = k_{\sigma}^{fm1} \cdot \sin \phi\) in three regions and the corresponding momenta along \(x\) direction become

\[
k_{\sigma,x}^{fm1}(\phi) = k_{\sigma}^{fm1} \cdot \cos \phi
\]

(5)

for \(x < 0\),

\[
k_{\sigma,x}(\phi) = \sqrt{(k_{\sigma}^{fm1})^2 - (k_{\sigma}^y)^2}
\]

(6)

for \(0 < x < L\), and

\[
k_{\sigma,x}(\phi) = \sqrt{(k_{\sigma}^{sm})^2 - (k_{\sigma}^y)^2}
\]

(7)
for $L < x$.

Considering a single electron tunneling through the FM/I/FM/I/2DEG junction, a reflective wave would appear in the FM1 layer and a transmission wave in 2DEG. In the FM2 layer, the electron will be multireflected due to the presence of two barriers. For some suitable width ($L$) of the FM2 layer, resonant reflection or transmission may occur. This may in turn result in high degree of spin injection from FM1 into 2DEG. The wave functions in three regions are given by

$$
\psi_\sigma(\sigma m) = t_\sigma e^{(i k_{\sigma m} |x|)}
$$

for $x > L$. Here, $r_\sigma$, $a_\sigma$, $b_\sigma$, and $t_\sigma$ are spin-dependent parameters. According to the requirements of wave functions continuing and their derivatives continuing at scattering interface $x = 0$ and $x = L$, the transmission amplitude $t_\sigma$ of a single electron tunneling through this FM/I/FM/I/2DEG junction is straightforward

$$
t_\sigma = \frac{\alpha_+^+ - \alpha_-^+}{\alpha_+^- - \alpha_-^-} \frac{\alpha_+^+}{\alpha_+^-} \frac{\alpha_-^+}{\alpha_-^-} \exp(-ik_{\sigma m} |x|) - \frac{\alpha_+^-}{\alpha_-^-} \exp(i k_{\sigma m} |x|).
$$

where $\alpha_{\pm}^\pm = ik_{\sigma m}^\pm \pm i Q_1$ and $\beta_{\pm} = ik_{\sigma m}^\pm \pm i (k_{\sigma m}^\pm)' Q_2$ with $(k_{\sigma m}^\pm)' = m_e k_{\sigma m}^\pm / m_s$ and $Q_1(2) = 2m_e U_{1(2)}/\hbar^2$. When the junction is applied on a small voltage $V$ and $K_B T \ll E_F$ for low temperature, the spin-dependent charge current density can be evaluated by[14,19]

$$
J_\sigma = \frac{e^2 V k_{\sigma m}^f}{\hbar \pi} \int_0^{\phi_{\sigma C}} d\phi T_\sigma \cos \phi,
$$

where the transmission coefficient $T_\sigma = m_e k_{\sigma m}^s |t|^2 / m_s k_{\sigma m}^f$ and $\phi_{\sigma C}$ is the critical incident angle of electrons in FM1 to guarantee all momenta appearing in the integral to be real.
variables, i.e, no attenuating wave occurs in 2DEG. $\phi^C_\sigma$ is determined by Eq.(7) due to $k_{sm}^\sigma \ll k_{f1}^m, k_{f2}^m$.

From equations above, we can calculate numerically the spin-dependent current density as a function of the thickness ($L$) of the FM2 layer, in which multireflection would lead to resonant transmission of the electronic wave. Thus the transmission coefficient $T_\sigma$ will exhibit oscillating behavior as well as the current density $J_\sigma$. Their periods can be approximately expressed as $L_\sigma = \pi/k_{f2}^m$ since the critical angle $\phi^C_\sigma$ is very small from Eq. (7). Due to the presence of exchange energy of FM2 and $k_{f2}^m \neq k_{f2}^m$, the current density $J_\uparrow$ and $J_\downarrow$ have different vibrating periods so that the current polarization $p = (J_\uparrow - J_\downarrow)/(J_\uparrow + J_\downarrow)$ may arrive rather high degree at some suitable thickness $L$ as shown in Fig. 2. This characterization is the same as the tunnel magnetoresistance (TMR) effect in the FM/I/NM/I/FM junction[20] with NM denoting a normal metal, in which high TMR could be achieved because of the resonant transmission of electronic wave in the NM layer. In Fig. 2, the short and long periodical vibration of the current polarization $P$ results from the superposition of two different periods of $J_\uparrow$ and $J_\downarrow$. With the variation of $L$, plus maximum and minus maximum of $P$ would alternates to appear. From Fig. (2A), even a normal metal ($\Delta_1 = 0$) as FM1 can also lead to current polarization. This is just because the FM2 layer exists. Enlarging the exchange energy ($\Delta_1$) of FM1, the overall profile of $P$ keeps invariable whereas its amplitude increases much (the solid line e in Fig. (2B)), i.e., increasing the spin-polarized degree of FM1 will raise the spin injection efficiency from FM metal into 2DEG. When $L = 0$ and our model becomes FM/I/2DEG junction[14], the normal metal ($\Delta_1=0$) as FM1 would result in zero current polarization (Fig. 2A). While another FM metal (FM2) is interposed into such a single junction, the current polarization ($L \neq 0$) would increase greatly in comparison with that of $L = 0$ as shown in Fig. (2A-2B). As is generally admitted, the tunnel barriers can result in the growth of the current polarization, which is indeed found in our calculation by comparing three lines in Fig. (2A). The two tunnel barriers strength increase from $Z_{1(2)} = 0.5$ to $Z_{1(2)} = 1.0$ by two steps (the dimensionless $Z$ is defined as $Z_{1(2)} = Q_{1(2)}/k_{f1}^m$), both of them lead to a remarkable increase of the current polarization.
It is also shown in Fig. (2B) that the electron density of 2DEG \( n_{2DEG} \) affects the spin injection efficiency. The critical incident angle \( \phi_C^{\sigma} \) of electrons in FM1 is determined by \( n_{2DEG} \) (Eq. (7)). The larger \( n_{2DEG} \) will widen \( \phi_C^{\sigma} \) and the tunnel current density \( J_\sigma \) increases greatly, whereas the spin injection efficiency decreases. In this FM/I/FM/2DEG junction, the high degree of current polarization originates from the quantum interference effect, which usually had better be single moded in order to obtain large effects for different phase shift exist in different modes. The larger \( \phi_C^{\sigma} \) will introduce the more modes and the quantum interference effect tend to wash out so that the current polarization could decrease. This is very interesting since the \( n_{2DEG} \) can be easily controlled by an external gate voltage[21-22].

Although the maximum of the current polarization \( P \) in Fig. 2 might be obtained by tuning the thickness \( L \) of FM2, it oscillates quickly with increase of \( L \) and the spin-flipping length of electrons in FM metal is rather smaller than that in SM[23]. These may cause that the maximum of \( P \) is difficult to be found in experiment. However, the FM2 layer in our model can lead to different oscillating periods of \( J_\uparrow \) and \( J_\downarrow \). Thus, fixing its thickness \( L \) and varying its exchange energy (\( \Delta_2 \)), the vibrating behavior of current polarization \( P \) should also appear. This is actually true as shown in Fig. 3. Here \( L \) is taken as 15 (Å) that is much less than the spin flipping length in FM metal. With increase of \( \Delta_2 \), \( P \) will alternate its sign and it may take its maximum over 80% at some suitable values of \( \Delta_2 \). Since the overall trend of minority spin current density \( J_\downarrow \) decreases with increase of \( \Delta_2 \), the maximum of plus current polarization \( P \) will keep upgoing. When \( \Delta_2 > E_F \), the FM2 would be a half-metal, i.e., it is a well for spin-up (majority spin) electrons and a rectangle barrier for spin-down (minority spin) electrons, then the high degree of current polarization would easily form since the transmission coefficient of spin-up electron is much larger than that of spin-down electron. This case has been discussed by Carlos Egues[24]. From Fig. 3, it is suggested that the high degree of current polarization in FM/I/FM/2DEG junction should be achieved by tuning the magnitude of exchange energy (\( \Delta_2 \)) of FM2 in experiment. For instance, we may apply an external magnetic field on FM2 and vary its strength or we would change the concentration of magnetic ions if FM2 was a ferromagnetic semiconductor.
In summary, we have investigated the spin injection efficiency from two adjoining FM metals into 2DEG with two tunnel barriers among them by employing the free-electron scattering theory. Making use of the quantum interference effect in this ballistic FM/I/FM/I/2DEG junction, the high degree of current polarization may be achieved with some suitable thickness $L$ of the FM2 layer or its exchange energy $\Delta_2$. It is also shown that the electron density of 2DEG can alter the spin injection efficiency. Our model in this paper would be an alternative to achieve high efficiency of spin injection from FM metal into 2DEG.
REFERENCES

[1] G.A. Prinz, Phys. Today 48(4), 58 (1995).

[2] M. Oestreich, Nature (London) 402, 735 (1999).

[3] S.A. Wolf, D.D. Awschalom, R.A. Buhrman, J.M. Daughton, S. von Molnár, M.L. Roukes, A.Y. Chtchelkanova, and D.M. Treger, Science 294, 1488 (2001).

[4] S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990).

[5] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, Nature (London) 402, 787 (1999); Y. Ohno, D.K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D.D. Awschalom, Nature (London) 402, 790 (1999).

[6] M. Ghali, J. Kossut, E. Janik, K. Regiński, and L, Klopotowski, Solid State Commun. 119, 371 (2001).

[7] B.T. Jonker, Y.D. Park, and B.R. Bennett, H.D. Cheong, G. Kioseoglou, and A. Petrou, Phys. Rev. B 62, 8180 (2001).

[8] P.R. Hammar, B.R. Bennet, M.J. Yang, and M. Johnson, Phys. Rev. Lett. 83, 203 (1999); 84, 5024 (2000); F.G. Monzon, H.X. Tang, and M.L. Roukes, ibid. 84, 5022 (2000); B. J. van Wees, ibid. 84, 5023 (2000).

[9] G. Schmidt, D. Ferrand, L.W. Molenkamp, A.T. Filip, and B.J. van Wees, Phys. Rev. B 62, R4790 (2000).

[10] E.I. Rashba, Phys. Rev. B 62, R16 267 (2000).

[11] A. Fert and H. Jaffres, Phys. Rev. B 64, 184420 (2001).

[12] D.L. Smith and R.N. Silver, Phys. Rev. B 64, 045323 (2001); J.D. Albrecht and D.L. Smith, Phys. Rev. B 66, 113303 (2002).

[13] H.J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.P. Schönherr, and K.H. Ploog,
Phys. Rev. Lett. 87, 016601 (2001).

[14] H.B. Heersche, Th. Schäpers, J. Nitta, and H. Takayanagi, Phys. Rev. B 64, 161307 (2001).

[15] H.X. Tang, F.G. Monzon, R. Lifshitz, M.C. Cross, and M.L. Roukes, Phys. Rev. B 61, 4437 (2000).

[16] A.T. Hanbicki, B.T. Jonker, G. Itskos, G. Kioseoglou, and A. Petrou, Appl. Phys. lett. 80, 1240 (2002).

[17] Y.N. Qi, D.Y. Xing, and J.M. Dong, Phys. Rev. B 58, 2783 (1998); Th. Schäpers, J. Nitta, H.B. Heersche, and H. Takayanagi, Phys. Rev. B 64, 125314 (2001).

[18] D. Grundler, Phys. Rev. Lett. 86, 1058 (2001); C. Ciuti, J.P. McGuire, and L.J. Sham, Phys. Rev. Lett. 89, 156601 (2002).

[19] G.E. Blonder, M. Tinkham, and T.M. Klapwijk, Phys. Rev. B 25, 4515 (1982).

[20] Z.M. Zheng, Y.N. Qi, D.Y. Xing, and J.M. Dong, Phys. Rev. B 59, 14 503 (1999).

[21] J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. 78, 1335 (1997).

[22] J. P. Lu, J. B. Yau, S. P. Shukla, M. Shayegan, L. Wissinger and U. Rössler, Phys. Rev. Lett. 82, 1282 (1998).

[23] J. Kikkawa and D. Awschalom, Nature (London) 397, 139 (1999).

[24] J. Carlos Egues, Phys. Rev. Lett. 80, 4578 (1998).
FIGURES

FIG. 1. Band structures of two adjoining FM metals and 2DEG. Two tunnel barriers lie at \( x = 0 \) and \( x = L \). \( \Delta_1 \) and \( \Delta_2 \) are respectively the exchange energies of two FM. \( \uparrow \) and \( \downarrow \) represent spin-up band and spin-down band.

FIG. 2. The current polarization \( P = \frac{J_\uparrow - J_\downarrow}{J_\uparrow + J_\downarrow} \) as a function of the thickness \( L \) of the FM2 layer. The parameters are taken as \( E_F = 2.5 \) eV, \( \Delta_2/E_F = 0.3 \), and \( m_s/m_e = 0.06 \). (A) \( \Delta_1/E_F = 0 \), \( n_{2DEG} = 3.0 \times 10^{12} \text{cm}^{-2} \), solid line (a) \( Z_1 = Z_2 = 0.5 \), dot line (b) \( Z_1 = 1.0 \), \( Z_2 = 0.5 \), and dash line (c) \( Z_1 = Z_2 = 1.0 \). (B) \( \Delta_1/E_F = 0.8 \), \( Z_1 = Z_2 = 1.0 \), the solid line (e) \( n_{2DEG} = 3.0 \times 10^{12} \text{cm}^{-2} \), and dot line (f) \( n_{2DEG} = 0.5 \times 10^{12} \text{cm}^{-2} \).

FIG. 3. The current polarization \( P \) as a function of the exchange energy strength \( \Delta_2/E_F \) of FM2. \( n_{2DEG} = 3.0 \times 10^{12} \text{cm}^{-2} \) and \( L = 15 \text{Å} \). Other parameters are taken as \( \Delta_1/E_F = 0 \), \( Z_1 = Z_2 = 0.5 \) for the solid line (a), \( \Delta_1/E_F = 0 \), \( Z_1 = Z_2 = 1.0 \) for the dot line (b), and \( \Delta_1/E_F = 0.8 \), \( Z_1 = Z_2 = 1.0 \) for the dash dot line (c).
Figure 1 (Jun Wang et al.)
Figure 2 (Jun Wang et al.)

(A) \[ \Delta_1/E_F = 0 \]

(B) \[ \Delta_1/E_F = 0.8 \]
Figure 3 (Jun Wang et al.)