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Conductance modulation of a nonballistic Datta–Das spin field effect transistor

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Abstract

A Datta–Das spin field effect transistor (FET) made of a nonballistic quantum wire with a single transport channel is considered. Although there is no spin relaxation and the spin precession is not influenced by elastic scattering, successful spin FET operation can still be prevented by the conductance fluctuations. The necessary condition for the desired spin FET operation is obtained.

1. Introduction

Spin-dependent transport has been a subject of persistent interest [1, 2]. When successfully combined with semiconductor functionalities [3–5] spin-based electronics or spintronics may have considerable impact on future electronic device applications. One of the representative spintronic devices is the so-called spin field effect transistor (spin FET) proposed by Datta and Das [6]. The core idea of this device is to induce spin precession by the Rashba spin–orbit interaction [7] in a two-dimensional electron gas (2DEG) and to use spin-dependent materials, such as ferromagnets, as electron injectors and collectors so that they sense the spin precession; the conductance of the device varies sinusoidally with the spin precession angle.

While the initial proposal by Datta and Das assumes ballistic transport, it is still essential [8–13] to have a good understanding of how sensitive the spin FET is to scattering events. For example a sample may not be as ideal as desired and unintended impurities in the 2DEG may cause elastic scattering. The scattering may also be caused by tunnelling barriers [14] introduced at the 2DEG–injector (collector) interface to enhance the spin injection (detection) efficiency. Because of the difficulties in efficiently injecting spin currents from a ferromagnetic metal into a semiconductor, a working prototype of the Datta–Das spin FET has not yet been made.

Elastic scattering can induce spin relaxation when combined with spin–orbit interaction (see for instance [15]). Semiclassical Monte Carlo calculations [8–10, 16] reported that the spin relaxation can be suppressed by reducing the channel width w of the 2DEG, and that the ideal sinusoidal variation of the spin FET signal can be achieved [8]. In a recent study it has

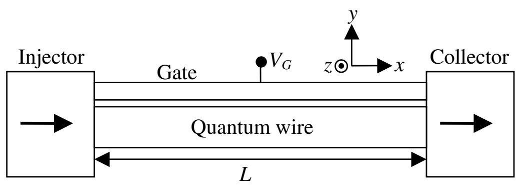

Figure 1. Schematic diagram of a Datta–Das spin field effect transistor made of a nonballistic single-channel quantum wire.

been shown that the suppression takes place even in wider channels [17]. Here we go beyond the semiclassical treatment and focus on the quantum mechanical effects which become more important as w reduces.

It was suggested [18] that a spin FET with only one transverse mode is desired to achieve large current modulation and low power consumption. Recently it was reported [19] that a single-mode spin FET exhibits interesting mesoscopic phenomena. In this paper, we consider a spin FET made of a nonballistic quantum wire ($w \to 0$) with one transport channel (figure 1). Experimentally, the formation of several micron-long quantum wires in GaAs/AlGaAs heterostructures has been reported [20]. Although elastic scattering obviously reduces the signal of the spin FET, what is important is the issue of its sinusoidal modulation by the Rashba interaction. We address this issue by employing a full quantum mechanical analysis (in the single-particle level) [21, 22] for the nonmagnetic scattering effects on such a one-dimensional (1D) spin FET. We find that even though the spin precession is not influenced by elastic scattering in the absence of magnetic field, a successful operation of a nonballistic 1D spin FET may still be prevented by the phenomenon of the conductance fluctuations unless a certain condition, (6), is satisfied.

2. Theory

A ballistic 2DEG in the xz plane can be described by the following Hamiltonian:

$$H_0^{2D} = \frac{p_x^2 + p_z^2}{2m^*} + V_c(z) + \alpha\frac{(\sigma_z p_x - \sigma_x p_z)}{\hbar}, \tag{1}$$

where the first and second terms are kinetic energy and confining potential terms, respectively, and the last term represents the Rashba interaction. Here m^* is the effective mass and α is the Rashba coefficient, whose value can be controlled [23] by the gate electrode. The Rashba term in H_0^{2D} is formally the same as the Zeeman term $-g\mu_B\vec{\sigma}\cdot\vec{B}_R$ with an effective magnetic field $\vec{B}_R = -(\alpha/g\mu_B\hbar)(p_x\hat{z} - p_z\hat{x})$ which, unlike the real field, depends on the electron momentum. $V_c(z)$ determines the width w of the 2DEG in the transverse direction z. The quantization in the transverse direction results in quantized subbands, each of which provides a transport channel. When $w \ll \hbar^2/m^*\alpha$ the intersubband mixing can be neglected [6]. Moreover the number of available channels reduces to two, including the spin degree of freedom, for sufficiently small w. In such a situation the transport via two available channels is given by a simple 1D Hamiltonian:

$$H_0 = \frac{p_x^2}{2m^*} + \alpha\sigma_z\frac{p_x}{\hbar}. \tag{2}$$

Note that due to the quantization of the transverse direction the term $\sigma_x p_z$ does not appear in H_0 and, hence, the z-component of the spin becomes a conserved quantity. Thus the two spin channels can be characterized as spin-up ($\sigma_z =\uparrow$) and spin-down ($\sigma_z =\downarrow$) channels.

In the presence of impurities the scattering effects within the two spin channels can be expressed by adding a potential term to (2),

$$H = \frac{p_x^2}{2m^*} + V(x) + \alpha\sigma_z\frac{p_x}{\hbar}, \tag{3}$$

where $V(x)$ is the nonmagnetic scattering potential causing spin-conserved scattering (for $w \ll \hbar^2/m^*\alpha$). Here we follow the standard scattering matrix approach [24]. In order to focus on scattering effects within the quantum wire of length L ($V(x)$ is nonzero only in $0 \leqslant x \leqslant L$) we assume that the injector and the detector are ideal: both of them are 100% spin polarized and the injection–detection efficiency is perfect[1]. Thus the segment with length L describes the nonballistic quantum wire while the regions $x < 0$ and $x > L$ correspond to fictitious leads which are free from any scattering (see figure 1). Though the introduction of them is rather arbitrary, scattering effects within the quantum wire are still correctly described by this approach [24].

3. Scattering effects

Consider a left-incoming scattering state $\psi = c_+\psi_+ + c_-\psi_-$, which is a superposition of the spin-up scattering state $\psi_+ = \phi_+\chi_+$ and the spin-down scattering state $\psi_- = \phi_-\chi_-$. Here $\phi_{+(-)} = \exp[\mathrm{i}k_{+(-)}x] + r_{+(-)}\exp[-\mathrm{i}k_{-(+)}x]$ for $x < 0$ and $\phi_{+(-)} = t_{+(-)}\exp[\mathrm{i}k_{+(-)}x]$ for $x > L$, where $E = \hbar^2k_{+,-}^2/2m^* \pm \alpha k_{+,-}$. The spinors are $\chi_+ = (1,0)^{\mathrm{T}}$ and $\chi_- = (0,1)^{\mathrm{T}}$ and the conservation of σ_z, $[H,\sigma_z] = 0$, is utilized. Let θ_0 and φ_0 (θ_{L} and φ_{L}) denote the polar and azimuthal angles of the spin direction at $x = 0_{\leqslant}$ ($x = L_{\geqslant}$) with respect to the z-axis. Just before the injection into the quantum wire, $x = 0_{\leqslant}$, $\tan(\theta_0/2) = |c_-/c_+|$ and $\mathrm{e}^{\mathrm{i}\varphi_0} = (c_-/c_+)|c_-/c_+|$. Right after the transmission, $x = L_{\geqslant}$,

$$\tan\frac{\theta_{\mathrm{L}}}{2} = \left|\frac{c_-t_-}{c_+t_+}\right|, \qquad \mathrm{e}^{\mathrm{i}\varphi_L} = \frac{(c_-/c_+)(t_-/t_+)}{|c_-/c_+||t_-/t_+|}\mathrm{e}^{\mathrm{i}(k_--k_+)L}. \tag{4}$$

For simplicity we assume below that injected electrons are polarized along the $+\hat{x}$-direction (figure 1) and take the ratio c_-/c_+ to be one. The ratio t_-/t_+ determines effects of the scattering on the spin precession. For the ballistic case $t_+ = t_- = 1$, thus $\theta_{\mathrm{prec}} \equiv \theta_{\mathrm{L}} - \theta_0 = 0$ and $\varphi_{\mathrm{prec}} \equiv \varphi_{\mathrm{L}} - \varphi_0 = 2m^*\alpha L/\hbar^2$. Then, as α varies, the conductance, $G \propto \cos^2(\varphi_{\mathrm{prec}}/2)$, of the ballistic spin FET exhibits a sinusoidal variation.

To address nonballistic situations (mean free path $l \leqslant L$) we first perform the gauge transformation[2]

$$\tilde{\psi} = \mathrm{e}^{\mathrm{i}(m^*\alpha x/\hbar^2)\sigma_z}\psi. \tag{5}$$

Upon transformation, the Schrödinger equations for $\tilde{\psi}_+$ and $\tilde{\psi}_-$ become identical, $\tilde{h}\tilde{\psi}_{+,-} = \tilde{E}\tilde{\psi}_{+,-}$, where $\tilde{h} = p_x^2/2m^* + V(x)$ and $\tilde{E} = E + m^*\alpha^2/2\hbar^2$. Note that the problem has now reduced to the problem of two identical copies of spinless electron propagation in potential $V(x)$. Then $\tilde{\psi}_+(\tilde{E}) = \tilde{\psi}_-(\tilde{E})$ (see [12]) and $\tilde{t}_+(\tilde{E}) = \tilde{t}_-(\tilde{E}) = \tilde{t}(\tilde{E})$. Since the transmission amplitudes before and after the gauge transformation are related by $t_+(E) = \tilde{t}(\tilde{E}) = t_-(E)$, one obtains $t_-/t_+ = 1$ regardless of $V(x)$. Equation (4) then indicates that the spin precession angles θ_{prec} and φ_{prec} have exactly the same values as in the ballistic case. Therefore the spin precession is 'inert' to the scattering.

When $|t_+^2| = |t_-^2|$, the conductance of the spin FET is proportional to $|t_{+,-}|^2\cos^2(\varphi_{\mathrm{prec}}/2)$, where both $|t_{+,-}|^2$ and φ_{prec} are evaluated at $E = E_{\mathrm{F}}$. Since φ_{prec} shows the same behaviour

[1] We also ignore Fabry–Perot-type coherent multiple scattering effects between the injector and the detector discussed by Mireless and Kirzcenow [25, 4].

[2] A similar transformation has been exploited in [12].

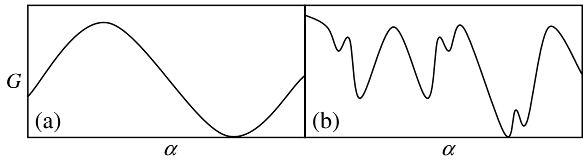

Figure 2. Schematic plots of the conductance G, varying between zero and 1 in units of e^2/h, of a 1D Datta–Das spin FET as a function of the Rashba coefficient α. (a) Ideal sinusoidal variation. (b) Sample-specific random signal due to conductance fluctuations.

as in the ballistic case, the desired sinusoidal modulation of G as a function of α can be achieved if $|t_{+,-}(E_F)|^2$ remains (almost) independent of α. In nonballistic environments, however, $|t_{+,-}(E_F)|^2$ is sensitive to α since $|t_{+,-}(E_F)| = \tilde{t}_{+,-}(\tilde{E}_F = E_F + m^*\alpha^2/2\hbar^2)$ and $\tilde{t}_{+,-}(\tilde{E})$ shows strong fluctuations as a function of $\tilde{E}$, for a fixed random potential, due to the phenomenon of the conductance fluctuations [24]. For the sinusoidal variation of G in the range $\alpha_{av} - \Delta\alpha/2 < \alpha < \alpha_{av} + \Delta\alpha/2$ one thus needs

$$\Delta\left(\frac{m^*\alpha^2}{2\hbar^2}\right) = \frac{m^*\alpha_{av}\Delta\alpha}{\hbar^2} \ll E_c, \tag{6}$$

where $E_c \approx (\hbar v_F/L)(l/L)$ is the Thouless correlation energy [26] over which $\tilde{t}_{+,-}(\tilde{E})$ is correlated [24] and v_F is the Fermi velocity[3]. Equation (6) is the condition for the successful sinusoidal variation of the spin FET signal. For the case $\Delta\alpha = \pi\hbar^2/m^*L$, the value for $\Delta\varphi_{prec} = 2\pi$ in the ballistic case, and (6) reduces to $L \ll l(\hbar v_F/\pi\alpha_{av})$, which can be fulfilled simultaneously with the nonballisticity condition $l \leqslant L$ since $\alpha_{av}/\hbar$ is usually smaller than v_F.[4] Figures 2(a) and (b) show schematic plots of G as a function of α in two situations; (a) when (6) is satisfied, showing the desired sinusoidal variation, and (b) when it is severely violated. Figure 2(b) indicates the sample-specific random signal arising as a result of strong fluctuations in $\tilde{t}_{+,-}(\tilde{E}_F = E_F + m^*\alpha^2/2\hbar^2)$, which depends significantly on α. Lastly, two remarks are in order. First, for a given $\Delta\alpha$, smaller α_{av} is preferred by (6) for the minimal 'damage' by the conductance fluctuations. Second, the amplitude of the G modulation is subject to sample-to-sample fluctuations even when (6) is satisfied, since $|t_{+,-}|^2$ depends on details of the nonballistic samples.

4. Inhomogeneous Rashba coefficient

Lastly we consider briefly the case where the Rashba coefficient α is not homogeneous. An example is the case where the gate in figure 1 covers only a part of the quantum wire, so that α becomes an x-dependent function $\alpha(x)$. To address the effects of its x dependence we consider the following Hamiltonian:

$$H^{\text{inh}} = \frac{p_x^2}{2m^*} + V(x) + \frac{\sigma_z}{2\hbar}[\alpha(x)p_x + p_x\alpha(x)]. \tag{7}$$

Note that the Rashba term in (3) is replaced by its symmetric combination, so that the Hamiltonian remains Hermitian. The gauge transformation will be a generalization of equation (5),

$$\tilde{\Psi} = \mathrm{e}^{\mathrm{i}(m^*/\hbar^2)\sigma_z \int^x \mathrm{d}x'\alpha(x')}\Psi, \tag{8}$$

[3] To be precise, v_F is the Fermi velocity in the gauge-transformed system. However, when v_F is sufficiently larger than $\alpha/\hbar$, which is usually valid, the Fermi velocity in the original system is again comparable to v_F and we may not distinguish the two.

[4] For example, $\alpha_{av}/\hbar v_F \approx 0.1$ for $In_{1-x}Al_xAs/In_{1-x}Ga_x$.

where Ψ is the scattering state in inhomogeneous system. Under this transformation the Schrödinger equations for $\tilde{\Psi}_+$ and $\tilde{\Psi}_-$ become identical, $\tilde{h}^{\mathrm{inh}}\tilde{\Psi}_{+,-} = \tilde{E}\tilde{\Psi}_{+,-}$, where $\tilde{h}^{\mathrm{inh}} = p_x^2/2m^* + V^{\mathrm{inh}}(x)$. Here the effective potential $V^{\mathrm{inh}}(x)$,

$$V^{\mathrm{inh}}(x) = V(x) - \frac{m^*\alpha^2(x)}{2\hbar^2}, \tag{9}$$

is 'renormalized' by $\alpha(x)$. Thus the inhomogeneous α can induce backscattering and reduce the mean free path l just as an inhomogeneous $V(x)$ does. Note that for a given slope $\mathrm{d}\alpha/\mathrm{d}x$ this backscattering effect becomes stronger as the average α value gets larger since $\alpha(x)$ affects $V^{\mathrm{inh}}(x)$ quadratically. Once this reduction of l by the inhomogeneous $\alpha(x)$ is taken into account, the rest of the analysis is the same as for the homogeneous α case and the results will be similar.

5. Conclusion

In summary, we have studied a 1D Datta–Das spin FET made of a nonballistic quantum wire and identified the necessary condition, (6), for the sinusoidal modulation of the spin FET signal in nonballistic environments. We suggest that the impurity scattering effects, which can be very harmful for the spin FET operation, can be avoided by tuning the parameters of a spin FET to satisfy the inequality (6) we presented.

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References

[1] Wolf S A, Awschalom D D, Buhrman R A, Daughton J M, Von Molnar S, Roukes M L, Chtchelkanova A Y and Treger D M 2001 *Science* **294** 1488
[2] Prinz G A 1995 *Phys. Today* **48** 58
Prinz G A 1998 *Science* **282** 1660
[3] Tang H X, Monzon F G, Lifshitz R, Cross M C and Roukes M L 2000 *Phys. Rev.* B **61** 4437
[4] Mireles F and Kirzcenow G 2001 *Phys. Rev.* B **64** 024426
Mireles F and Kirzcenow G 2002 *Phys. Rev.* B **66** 214415
[5] Matsuyama T, Hu C M, Grundler D, Meier G and Merkt U 2002 *Phys. Rev.* B **65** 155322
[6] Datta S and Das B 1990 *Appl. Phys. Lett.* **56** 665
[7] Bychkov Yu A and Rashba E I 1984 *J. Phys. C: Solid State Phys.* **17** 6039
Bychkov Yu A and Rashba E I 1984 *JETP Lett.* **39** 78
[8] Bournel A, Dollfus P, Bruno P and Hesto P 1998 *Eur. Phys. J. AP* **4** 1
[9] Kiselev A A and Kim K W 2000 *Phys. Rev.* B **61** 13115
[10] Mal'shukov A G and Chao K A 2000 *Phys. Rev.* B **61** 2413
[11] Pareek T P and Bruno P 2002 *Phys. Rev.* B **65** 241305
[12] Schliemann J, Egues J C and Loss D 2003 *Phys. Rev. Lett.* **90** 146801
[13] Cahay M and Bandyopadhyay S 2004 *Phys. Rev.* B **69** 045303
[14] Rashba E I 2000 *Phys. Rev.* B **62** 16267
[15] Zutic I, Fabian J and Das Sarma S 2004 *Rev. Mod. Phys.* **76** 323
[16] Kiselev A A and Kim K W 2000 *Phys. Status Solidi* b **221** 491
[17] Holleitner A W, Sih V, Myers R C, Gossard A C and Awschalom D D 2006 *Preprint* cond-mat/0602155
[18] Shafir E, Shen M and Saikin S 2004 *Phys. Rev.* B **70** 241302
Pramanik S, Bandyopadhyay S and Cahay M 2005 *IEEE Trans. Nanotechnol.* **4** 2
[19] Lee H W, Caliskan S and Park H 2005 *Phys. Rev.* B **72** 153305

[20] Liang C T, Simmons M Y, Smith C G, Ritchie D A and Pepper M 1999 *Appl. Phys. Lett.* **75** 2975
[21] Hausler W 2004 *Phys. Rev.* B **70** 115313
[22] Nikolic B K and Souma S 2005 *Phys. Rev.* B **71** 195328
[23] Nitta J, Akazaki T, Takayanagi H and Enoki T 1997 *Phys. Rev. Lett.* **78** 1335
Nitta J, Meijer F E and Takayanagi H 1999 *Appl. Phys. Lett.* **75** 695
[24] Datta S 1995 *Electronic Transport in Mesoscopic Systems* (Cambridge: Cambridge University)
Dittrich T 1998 *Quantum Transport and Dissipation* (New York: Wiley)
[25] Mireless F and Kirzcenow G 2002 *Europhys. Lett.* **59** 107
[26] Lee P A and Stone A D 1985 *Phys. Rev. Lett.* **55** 1622
Larkin A I and Khmel'nitskii D E 1986 *Sov. Phys.—JETP* **64** 1075