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Tunable spin transport in magnetic–electric superlattice

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Abstract

We study the spin-dependent electron transport in a special magnetic–electric superlattice periodically modulated by parallel ferromagnetic metal stripes and Schottky normal-metal stripes. The results show that, the spin-polarized current can be well controllable by modulating the magnetic strength of the ferromagnetic stripes or the voltage applied to the Schottky normal-metal stripes. It is obvious that, to the system of the magnetic superlattice, the polarized current can be enhanced by the magnetic strength of ferromagnetic stripes. Nevertheless, it is found that, for the magnetic–electric superlattice, the polarized current can also be remarkably advanced by the voltage applied to the Schottky normal-metal stripes. These results may indicate a useable approach for tunable spintronic devices.

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Keywords: Spin transport; Superlattice; Tunable magnetic–electric

Spin-dependent electron transport properties in a two-dimensional electron gas (2DEG) have attracted considerable interest with the progress in semiconductor fabrication technology in recent years [1]. Spintronic devices, such as spin memory devices [2] or spin transistors [3] hold great promise in application. Whereas, how to create a spin-polarized current is the most important problem. The feasibility of spin filtering in magnetic barriers (MB) nanostructures has been studied and discussed extensively in the last decade [4–7]. It was pointed out that the basic tunneling features are dependent on the structures of system [8]. Very recently Zhai et al. [9] showed that by placing a Schottky normal-metal (SNM) stripe parallel to the FM stripe on top of the 2DEG, the intrinsic symmetry in a single ferromagnetic (FM) stripe structure can be broken and thus spin filtering can be achieved. Further Papp et al. found that spin-polarized transport can be enhanced significantly by repeating the FM and SNM periodically on the 2DEG [10].

Since the shape of the barriers is also an important factor that influences the electron transport [11]. It means that a higher conductance and spin polarization may be achieved by an improved quantum structure. So in this Letter, a special structure is figured as a periodic magnetic–electric superlattice (MESL). Not as well as Refs. [9] or [10] with the SNM stripes parallel to the FM stripe, we considered the special structure with five SNMs stripes alternately deposited on the top of ten FM stripes in a 2DEG. On the other hand, other than Ref. [9] or [10] with the delta function-shape magnetic barriers due to the parallel magnetization FM stripes, if considered the FM stripes perpendicular magnetization [12] as shown in Fig. 1, the fringe field from wires is much more smoothly varying, so to catch on the essence of the tunable spin transport in magnetic–electric superlattice, we simplified the complicated magnetic profile to the rectangular-shaped barriers [11]. In this system, by tuning magnetic strength of the FM or the voltage applied to the SNM, the spin-dependent conductance and conductance polarization can be well controlled. In the case of magnetic superlattice, the spin-dependent transmission presents remarkable oscillation and the conductance polarization goes up with the increase

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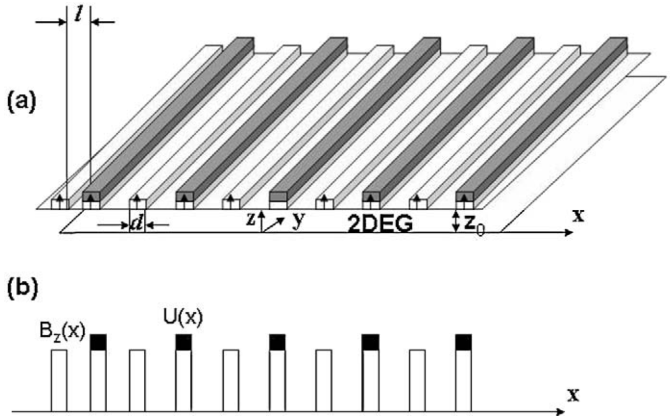

Fig. 1. (a) Schematic diagram of the model, ten parallel ferromagnetic (FM) stripes are deposited on top of (two-dimensional electron gas) 2DEG, five Schottky normal-metal (SNM) stripes are placed by an interval on FM stripes periodically. Two FM stripes and one SNM stripe are viewed as a period. The magnetization of all FM stripes is perpendicular to the x–y plane. d is the width of the FM, the same as that of SM, l is the spacing between these stripes. (b) The profile of the magnetic field $B_z(x)$ and electronic potential corresponding to (a).

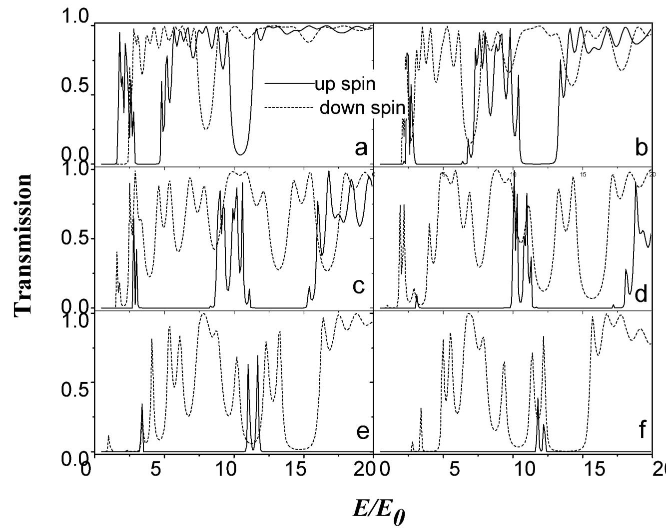

Fig. 2. The spin-down and spin-up conductance as a function of electron energy with the variation of B, (a) $B = 0.1$, (b) $B = 0.2$, (3) $B = 0.3$, (4) $B = 0.4$, (5) $B = 0.5$, (6) $B = 0.6$, the parameters used are $k_y = -1$, $U = 0$, $d = 0.5$, $l = 1.0$, $g^* = 15$, $m^*/m_0 = 0.024$.

of magnetic strength of FM. In magnetic–electric superlattice, an optimized condition for achieving a largest value of spin-dependent conductance is achieved, in addition, the polarization is enhanced with increasing either magnetic strength of the FM or the voltage applied to the SNM.

Here, we adopted two continuously alterable quantities $B_z(x)$ and $U(x)$ to express the roles of FM and SNM, respectively. As shown in Fig. 1, the $B_z(x)$ and $U(x)$ can be expressed as:

$$B_z(x) = \sum_{i=1}^{N} B\Theta\big[x - (i-1)(d+l)\big]\Theta\big[id + (i-1)l - x\big] \quad (1)$$

and,

$$U(x) = \sum_{i=1}^{N} U\Theta\big[x - (i-1)(2d+2l)\big]\Theta\big[2id + 2(i-1)l - x\big]. \quad (2)$$

Here, $\Theta(x)$ is the Heaviside step function. And the Hamilton of the system can be written as [9]:

$$H = \frac{p_x^2}{2m^*} + \frac{[p_y + eA_y(x)]^2}{2m^*} + U(x) + \frac{eg^*}{2m_0}\frac{\hbar\sigma}{2}B_z(x). \quad (3)$$

Here m_0 the mass of the free electron, m^* the effective mass, p_x and p_y the x and y components of the electron momentum, and g^* the effective Landé factor, σ is the electron spin direction (up ($\sigma = 1$) and down ($\sigma = -1$)), and $A_y(x)$ is the component of magnetic vector potential given by the Landau gauge.

For the convenience of calculation, we express all quantities in dimensionless units [13]. If the cyclotron frequency $\omega_0 = eB_0/m^*$ and the magnetic length $l_B = \sqrt{\hbar/eB_0}$ are adopted. Then, (1) the length in units $x \to l_B x$; (2) the magnetic field in $B_z(x) \to B_0 B_z(x)$; (3) the vector potential in $A_y(x) \to B_0 l_B A_y(x)$; (4) the energy in $E \to \hbar\omega_0 E$. The Schrödinger equation becomes

$$\left[\frac{d^2}{dx^2} - V(x, k_y) + 2E\right]\phi(x) = 0. \quad (4)$$

Where,

$$V(x, k_y) = \big[k_y + A_y(x)\big]^2 + 2U(x) + \frac{m^* g^*}{2m_0}\sigma B_z(x). \quad (5)$$

The same material parameters as in Refs. [9] and [10] were selected for InAs system. Here, when used $m^* = 0.024m_0$ and $g^* = 15$, and the estimate $B_0 = 0.1$ T, which is a realistic value. Then the units: $l_B = 813$ Å, and $E_0 = \hbar\omega_c = 0.48$ meV. In our calculations, the biggest B is up to 1.2, which corresponds to the realistic B about 0.12 T. So it indicates that it may be possible to prepare such a realistic periodic magnetic field [14].

By means of the continuity of the wave functions and their derivatives at the boundary, the spin-dependent transmission probability T through this system can be calculated with the transfer matrix technique [15]. In addition, one can compute the conductance G (in units of G_0 as well as that in Ref. [9] and Ref. [10]) as the electron flow averaged over half the Fermi surface [10,16]. Then to evaluate the electron spin-polarization effect in the transport process, the spin polarization of G is defined by:

$$P_G = \frac{G_+(E_F) - G_-(E_F)}{G_+(E_F) + G_-(E_F)}, \quad (6)$$

where G_+ and G_- stand for the up-spin and down-spin conductance components, respectively.

Let us first focus on the case without the SNM, which is magnetic superlattice. From Fig. 2(a), one can find that there are oscillations on both spin-up and spin-down transmission curves, and the oscillation on spin-down curve is more distinct than that on spin-up one. From Fig. 2(a) to (f), it can be seen clearly that with increasing B, the resonant peaks of up spin curve shift towards high energy region, besides, they get