

Electronic Spin Filter via Spin Superlattice

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Recently there was a proposal for a spin filter by using the spin superlattice structure. In a certain energy range, the proposed structure exhibits a high spin filtering efficiency close to 100%. Unfortunately such energy range turns out to be narrow. In this paper, we report a method to widen the energy range by using an analogy to optical anti-reflection coating. In optics, it is well known that a stack of alternating layers of two dielectric materials can function as a highly transmissive or reflective filter for wide range of wavelength. Since electrons also have wave character as light, it would be possible to make an electronic analog of an optical filter. We demonstrate that alternating layers of two materials with different g-factors can function as a spin filter that allows electrons to be transmitted only when their spins point towards a certain particular direction. This spin-superlattice-based spin filter operates in wide energy ranges, curing the problem in the previous proposal.

Keywords : spin filter, spin superlattice

1. Introduction

There are growing interests in using the spin degree of freedom for electronic devices. It has been suggested that the utilization of the spin degree of freedom may facilitate the realization of non-volatile, higher speed, and lower powered devices compared to conventional charge-only devices [1]. One of major concerns in this spin-based technology or spintronics is to find a way to generate highly spin-polarized current within semiconductors. There were many attempts to make the spin-polarized current. Attempts to inject a highly spin-polarized current from conventional metallic ferromagnets into semiconductors suffer from the conductance mismatch problem [2] and ways to overcome the problem are under investigation [3]. There are also attempt to generate spin-polarized currents by optical methods. Recently a still alternative approach [4, 5] has been proposed based on the wave nature of electrons. In the proposal in Ref. 5, an asymmetrical-shaped profile of the magnetic fringe field is generated by ferromagnetic strips deposited on the 2D electron gas system. Since such magnetic field profile serves as a spin-dependent potential energy profile, the resonant transport through such potential structure can

lead to the spin filtering. However since this proposal utilizes fringe field of the ferromagnets, it can be applied only to the thin film. On the other hand, the proposal in Ref. 4 based on spin superlattice is applicable to bulk as well. However a shortcoming of this proposal is that the energy window of the high spin-polarization is narrow.

In this paper, we revisit the spin superlattice structure and demonstrate that the energy window for high spin filtering efficiency can be considerably widened by using the analogy to the anti-reflection film coating in optics. Our analysis indicates that this method is superior to those in Refs. [4, 5].

2. Spin Superlattice

In optics, the dielectric coating is a widely used tool for high reflection or transmission of light in optical instrument. Alternating coating of two materials with the different reflective indices leads to this result [6]. Likewise, stack of alternating semiconductors may serve as an “anti-reflection coating” for electrons. In order to achieve the spin filter functionality, however, the stack should serve as an “anti-reflection coating for one particular spin direction only. One way to achieve this spin-selectivity is to apply a uniform external magnetic field. Due to the Zeeman coupling, the field then generates the spin-dependent potential energy profile. This is the main idea of the

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Fig. 1. A superlattice which consists of ZnSe and ZnMnSe.

spin filtering proposal [4] based on the spin superlattice structure.

As demonstrated in Ref. 4, however, the energy window for efficient spin filtering is narrow. In order to cure this problem, we use the analogy to optical anti-reflection coating again. In optics, it is well known that the wavelength window for efficient anti-reflection can be significantly widened by tuning the thickness of each material layer to one-fourth of the average wavelength over the window. It is then reasonable to expect that by a similar tuning of the semiconductor layer thicknesses, the energy window for the spin filtering may be widened. We demonstrate below that this is indeed the case.

Suppose two kinds of semiconductors with different effective g-factor are deposited in the alternating order (for example, ZnSe, ZnMnSe as in Fig. 1). The regularly arranged device as this is called superlattice.

When that the magnetic field \vec{H} is applied along the z-direction, the eigenenergy of an electron is given by the sum of kinetic, Zeeman and Landau energy,

$$E_{n,k_z,s} = \frac{\hbar^2 k_z^2}{2m^*} + g_{eff} s \mu_B H + \hbar \omega \left(n + \frac{1}{2} \right). \quad (1)$$

For simplicity of illustration, let us focus on the electron motion along the z-direction and ignore the Landau level, which is related to the motion perpendicular to the z-direction. For this longitudinal motion, the eigenenergy reduces to

$$E_{k_z,s} = \frac{\hbar^2 k_z^2}{2m^*} + g_{eff} s \mu_B H = \frac{\hbar^2 k_z^2}{2m^*} + sV, \quad V = g_{eff} s \mu_B H. \quad (2)$$

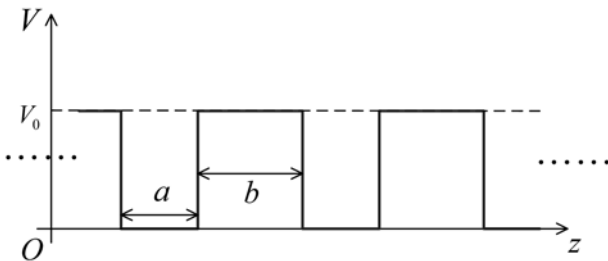


Fig. 2. Profile of the conduction band bottom as a function of z for the spin up electron with $g_{eff} > 0$ ($V_0 = 5$ meV). $V = 0$ for ZnSe and $V = V_0$ for ZnMnSe.

Suppose that the effective g-factor of one semiconductor is much larger than the other. Then energy separation due to the spin in the semiconductor with low g_{eff} can be ignored compared to the other semiconductor having with g_{eff} . Effective g-factor within each layer can be treated as constant and the profile of the conduction band bottom as a function of z becomes as Fig. 2 (the figure is for spin up, and for spin down case, it is obtained simply by replacing V_0 with $-V_0$).

3. Calculation of the Transmissivity

To calculate the transmissivity we have to calculate the wavefunction of an electron. The potential is constant in each material, the wavefunction of an electron can be written as linear combination of two exponential forms e^{ikz} and e^{-ikz} , where $\hbar k = \sqrt{2m^*E_0}$ (in region where $V = V_0$, $\hbar k$ is replaced by $\hbar \rho = \sqrt{2m^*(E_0 - V_0)}$). The indices of amplitudes in each component are depicted in Fig. 3. The subscript r or l of the amplitudes A and B denotes the wave traveling right (+z direction) or left (-z direction), and the superscript n denotes the unit number, where each unit consists of two layers of semiconductors lying successively (Fig. 3).

From the boundary conditions, one can obtain the following recursion relations.

$$\begin{pmatrix} A_r^n \\ A_l^n \end{pmatrix} = \frac{1}{2} \begin{pmatrix} e^{-ik(z_n+a)} & e^{-ik(z_n+a)} \\ e^{ik(z_n+a)} & e^{ik(z_n+a)} \end{pmatrix} \begin{pmatrix} e^{i\rho(z_n+a)} & e^{-i\rho(z_n+a)} \\ -\alpha e^{i\rho(z_n+a)} & \alpha e^{-i\rho(z_n+a)} \end{pmatrix} \begin{pmatrix} B_r^n \\ B_l^n \end{pmatrix}$$

$$\begin{pmatrix} B_r^n \\ B_l^n \end{pmatrix} = \frac{1}{2\alpha} \begin{pmatrix} \alpha e^{-i\rho z_n} & -e^{-i\rho z_n} \\ \alpha e^{i\rho z_n} & e^{-i\rho z_n} \end{pmatrix} \begin{pmatrix} e^{ikz_n} & e^{-ikz_n} \\ -e^{ikz_n} & e^{-ikz_n} \end{pmatrix} \begin{pmatrix} A_r^{n-1} \\ A_l^{n-1} \end{pmatrix} \quad (3)$$

, where $\alpha = \rho/k$. For calculating the transmissivity, we need only the ratio of the first and the last coefficient. Successive applications of above relations result in

$$\begin{pmatrix} A_r^N \\ A_l^N \end{pmatrix} = M \begin{pmatrix} A_r^0 \\ A_l^0 \end{pmatrix}, \quad (4)$$

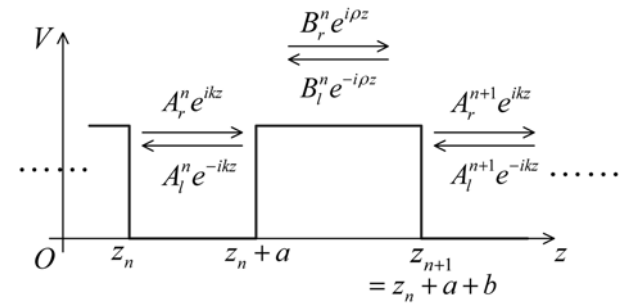


Fig. 3. Wave function form in each interval and illustration of the indices.

where

$$M = \begin{pmatrix} e^{-ik(Na+(N-1)b)} & -e^{-ik(Na+(N-1)b)} \\ e^{ik(Na+(N-1)b} & e^{ik(Na+(N-1)b)} \end{pmatrix} \left[\begin{pmatrix} \cos \rho a & -\frac{i}{\alpha} \sin \rho a \\ -i\alpha \sin \rho a & \cos \rho a \end{pmatrix} \begin{pmatrix} \cos kb & -i \sin kb \\ -i \sin kb & \cos kb \end{pmatrix} \right]^{N-1} \times \begin{pmatrix} \cos kb & -i \sin kb \\ -i \sin kb & \cos kb \end{pmatrix} \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

If the electrons are incident from left, we can assign the coefficients $A_l^0=1$, $A_r^0=r$, $A_r^N=t$, $A_l^N=0$. If we denote M as $M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$, the reflection rate R is $R=|r|^2 = \left| \frac{C}{D} \right|^2$. From the flux conservation, $T+R=1$, and therefore the transmissivity can be obtained as $T=1-R=1-\left| \frac{C}{D} \right|^2$.

4. Results and Discussion

First, take particular value for E_0 . And determine the length of layers to be exactly 1/4 of the spin up electron's wavelength of energy E_0 . In Fig. 4, we plot transmissivity as function of incident electron energy E. In the figure, the potential V_0 is chosen to be 1/2 of the reference electron energy E_0 , and the number of layers is set to 20 (or 10 units). We also plot polarization $P=T_{\uparrow}-T_{\downarrow}$ as a function of E in Fig. 4.

Near the reference energy E_0 , the transmissivity is nearly 0 for spin up state, and nearly 1 for spin down state.

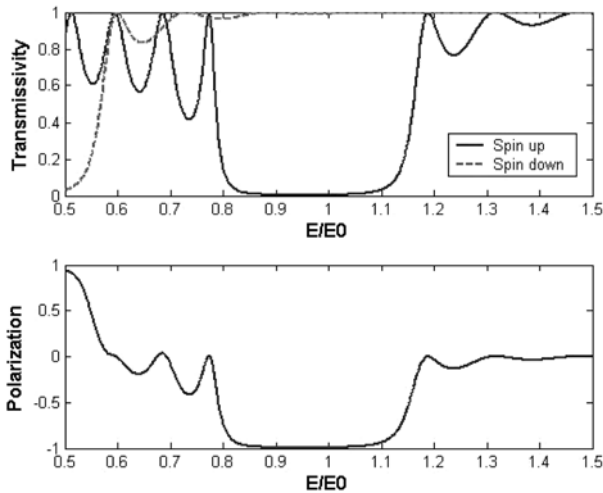


Fig. 4. Transmissivity and polarization as a function of electron energy E divided by reference energy E_0 .

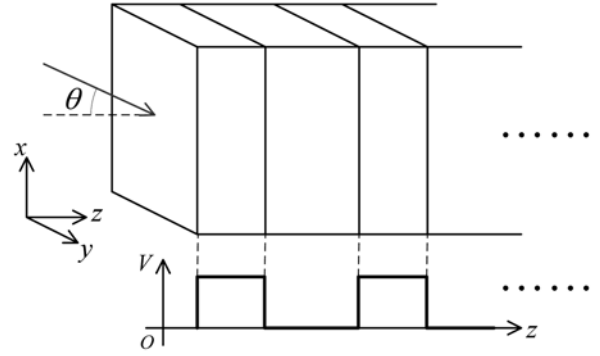


Fig. 5. Schematic plot of electron beam incident with finite angle θ .

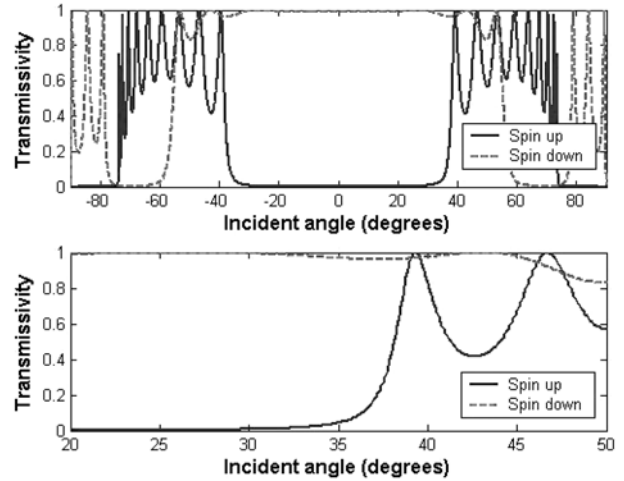


Fig. 6. Transmissivity as a function of incident angle.

Therefore it can operate as an efficient spin filter. Note also that the spin filtering remains efficient over an energy window of width $\sim 0.4 E_0$. Thus the spin filtering by the spin superlattice is tolerant against the energy variation.

Next we examined the angle dependence of the incidence ray. Suppose electrons move in 3D and the layers are extended in x-y plane.

The effect of the incident angle is to reduce the wave number as $\cos\theta$ in 1D case, and the transmissivity can be easily calculated by 1D case. The result is shown in Fig. 6 (energy of the incident electrons are set to be reference energy E_0).

Note that the transmissivity of spin up is nearly 0 (and the transmissivity of spin down is nearly 1) for a wide range of angles (about ± 40 degrees). Thus this mechanism of spin filtering is tolerant against the angle variation as well.

If we use different thickness of the layers, i.e. other than the one quarter of the wavelength of the electrons, the polarization goes lower and the energy-range of the

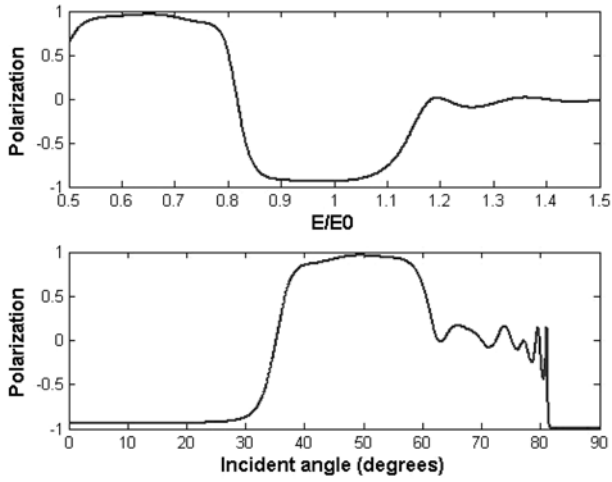


Fig. 7. Incident energy and angle dependence of the polarization with different layer length ($a = 3\lambda_1/8$, $b = \lambda_2/8$, where λ_1 , λ_2 are the wavelengths of electrons with energy E_0 in each layer). In lower figure, energy of the incident electrons is E_0 .

highly polarized region gets narrower. At the same time, the center position of the highly polarized region is

shifted, which makes the tolerant angle narrower (Fig. 7).

In summary, we demonstrated that the stack of alternating layers of two materials with different g-factors, or spin superlattice, can be used for efficient spin filtering. In contrast to the earlier proposals of the spin filtering [4, 5] using the g-factor engineering, which are efficient only in a narrow energy range, our mechanism of the spin filtering is tolerant against the energy variation and also against the incident angle variation.

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