Extended Abstracts of the 2001 International Conference on Solid State Devices and Materials, Tokyo, 2001, pp. 128–129

E-2-4

Conditions for the Spin Rectification Phenomena Predicted for Semiconducting Triple Barrier Structures in the Presence of Rashba Spin-Orbit Coupling

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1. Introduction

There has been growing interest in the field of "spintronics" [1,2], where extra degrees of freedom provided by electron spins, in addition to those due to electron charges, are expected to play fundamentally different roles in future devices than those played by the electron charges in the conventional electronic devices. In order to explore this new field of "spintronics", it is essential to have a spin-polarized current source with which to inject spin-polarized electrons into non-magnetic semiconductors, where various properties of electronic spins, including their dynamical motions (precessions), can be studied.

In the present paper, we propose a novel device that can be used for injecting a spin-polarized current into a non-magnetic semiconductor. It is important to note that the proposed device utilizes the Rashba spin-orbit interaction, and can be fabricated using only *non-magnetic* semiconductors.

2. Structure of proposed device

An example of our proposed device using an InAlAs–InGaAs–InAlAs–InGaAs–InAlAs triple barrier structure is shown in Fig. 1, where the horizontal axis denotes the positions within the heterostructure relative to the sample surface in a direction perpendicular to the

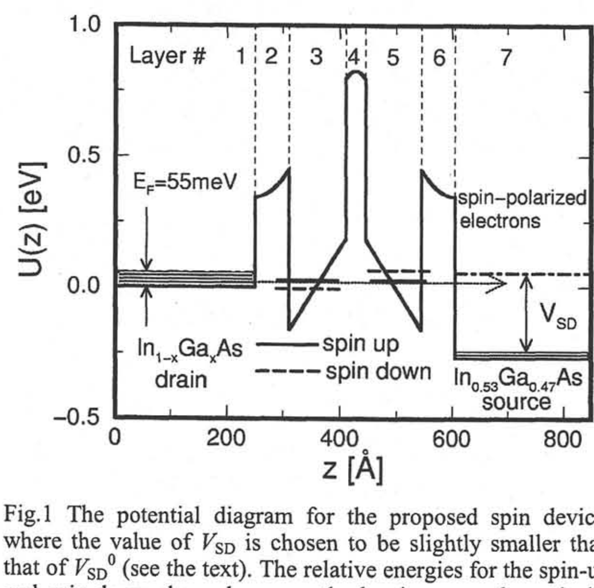

Fig.1 The potential diagram for the proposed spin device, where the value of V_{SD} is chosen to be slightly smaller than that of V_{SD}^0 (see the text). The relative energies for the spin-up and spin-down channels across the barriers are schematically shown by the horizontal solid and horizontal long-dashed lines, respectively, for a certain in-plane mode $\mathbf{k}_{\parallel}$ to illustrate the resonant condition for the transmission of the electrons. Detailed information on each layer of the structure is given in Table I.

Table I. Layer information for the proposed device in Fig.1

Layer #	Material	$D^{a)}$ [Å]	$N^{b)}$ [cm^{-3}]	Dopant
1	$In_{0.18}Ga_{0.82}As$	>500	5×10^{17}	*n*-type
2,6	$In_{0.52}Al_{0.48}As$	60	4×10^{18}	*n*-type
3,5	$In_{0.53}Ga_{0.47}As$	100	0	-
4	$In_{0.52}Al_{0.48}As$	35	1.38×10^{19}	*p*-type
7	$In_{0.53}Ga_{0.47}As$	>500	5×10^{16}	*n*-type

a)Layer thickness.
b)Impurity concentration.

constituent layers, and the vertical axis denotes the potential energies provided by the conduction band edges of the host materials. As shown in Table I, each layer in Fig. 1 is properly doped or undoped so that layers #3 and #5 in the proposed device become symmetric in relation to each other about the middle of layer #4. It is also noted that the InGaAs drain lead is properly *n*-doped (E_F=55 meV) and the InGaAs source lead is only slightly *n*-doped. Finally, a proper magnitude of electric voltage must be applied between the source and drain leads in order to maintain the symmetric structure between layers #3 and #5 as proposed. This voltage, denoted hereafter by V_{SD}^0, is found to be 0.325 eV for the device illustrated in Fig. 1.

3. Operating principle of proposed device

To understand how the proposed device works as a spin filter, we consider the hypothetical bound state levels formed within layers #3 (QW1) and #4 (QW2) completely ignoring both the interactions between these levels and the rest of the world and those between QW1 and QW2 themselves. In these hypothetical quantum wells, the energy dispersion relations for the confined electrons in QW1 and QW2 are, respectively, given by

$$E_{\uparrow\downarrow}^{QW1} = \frac{\hbar^2 k_{\parallel}^2}{2m^*} + E_0^{QW1} \pm |\alpha| k_{\parallel}, \quad (1)$$

and

$$E_{\uparrow\downarrow}^{QW2} = \frac{\hbar^2 k_{\parallel}^2}{2m^*} + E_0^{QW2} \mp |\alpha| k_{\parallel}, \quad (2)$$

where $\hbar$ is Planck's constant divided by 2π, m^* is the electron effective mass, $k_{\parallel}$ is the magnitude of the in-plane wave vector $\mathbf{k}_{\parallel}$ for the confined electrons, E_0^{QW1} and E_0^{QW2} are the bound state energies for QW1 and QW2, respectively, and α is the Rashba spin-orbit coupling constant [3]. In Eqs. (1) and (2), ↑ and ↓ denote the "spin-up" and "spin-down" states, respectively, where, by the terms "spin-up" and "spin-down", we denote the electronic spin states related to the upper and lower signs before the $|\alpha|k_{\parallel}$

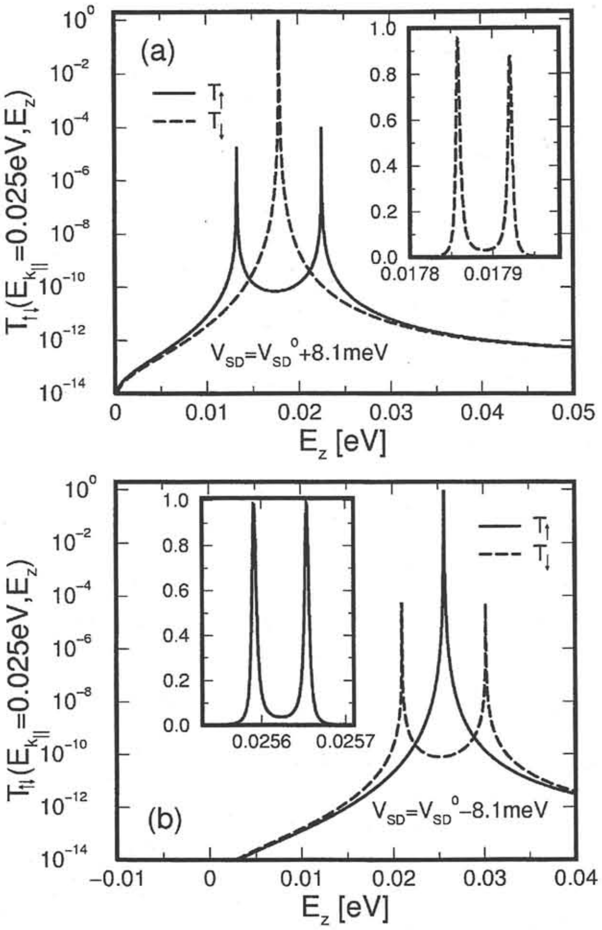

Fig. 2 The calculated values for the spin-dependent transmission coefficient [denoted by $T_{\uparrow\downarrow}(E_{\mathbf{k}\parallel}, E_z)$] across the proposed device for an in-plane mode $E_{\mathbf{k}\parallel}$=0.025 eV, as a function of z-component of the electron's kinetic energy within the drain lead (denoted by E_z). The source-drain voltage V_{SD} is chosen to be V_{SD}^0+8.1meV and V_{SD}^0–8.1meV for (a) and (b), respectively, where V_{SD}^0=325 meV (see the text) . The insets to the figures show the close-ups of the $T_\downarrow$ and $T_\uparrow$ peaks for (a) and (b), respectively, in the normal scales.

terms, respectively, in Eqs. (1) and (2). The spin rectification behavior of the device is attained when there is a slight difference in the relative potential energies between QW1 and QW2 in such a way that the difference between the values of the resultant E_0^{QW1} and E_0^{QW2} leads to a resonance condition between the electronic states for a given in-plane mode $\mathbf{k}_\parallel$ that are formed within QW1 and QW2, respectively (i.e. $E_\uparrow^{QW1} = E_\uparrow^{QW2}$ or $E_\downarrow^{QW1} = E_\downarrow^{QW2}$ for spin-up and spin-down electrons, respectively).

4. Results of calculation

The actual performance of the proposed device as a spin-filter is evaluated by calculating the spin-dependent transmission coefficient $T_{\uparrow\downarrow}(E_{\mathbf{k}\parallel}, E_z)$ (↑ for "spin-up" and ↓ for "spin-down") across the device for a selected in-plane mode $\mathbf{k}_\parallel$, where the values of $E_{\mathbf{k}\parallel}=\hbar^2 k_\parallel^2/2m^*$ and $E_z=\hbar^2 k_z^2/2m^*$ are defined within the drain lead [4,5].

We show, in Fig. 2(a)(b), the calculated values for $T_{\uparrow\downarrow}(E_{\mathbf{k}\parallel}, E_z)$ as a function of E_z for an in-plane mode $E_{\mathbf{k}\parallel}$=0.025 eV, where the voltages applied between the source and drain leads are $V_{SD}=V_{SD}^0\pm8.1$meV [+ sign for Fig. 2(a) and – sign for Fig.2(b)]. We find that the peak values of $T_\downarrow$ ($T_\uparrow$) are about four orders of magnitude larger than those of $T_\uparrow$ ($T_\downarrow$) for $V_{SD}=V_{SD}^0$+8.1meV ($V_{SD}=V_{SD}^0$–8.1meV), thus realizing excellent spin-filtering performance. The actual values of the spin-dependent tunneling currents across the proposed device that are measurable experimentally are obtained by summing the transmission coefficients over all available in-plane modes $\mathbf{k}_\parallel$ and integrating the results by E_z:

$$I_{\uparrow\downarrow} = \frac{|e|}{h}\int_0^{E_F} \sum\nolimits_{\mathbf{k}_\parallel} T_{\uparrow\downarrow}(E_{\mathbf{k}_\parallel}, E_z)\, dE_z\,. \tag{3}$$

We have obtained $I_\downarrow$=12.2 A/cm^2 (1.18×10^{-2} A/cm^2) and $I_\uparrow$=1.36×10^{-2} A/cm^2 (12.6 A/cm^2) for $V_{SD}=V_{SD}^0$+8.1meV ($V_{SD}=V_{SD}^0$–8.1meV). This indicates that the proposed device has an excellent property as a spin filter, realizing almost 100% spin polarization [defined by $|I_\uparrow - I_\downarrow|/(I_\uparrow + I_\downarrow)$] for the injected electrons.

4. Conclusions

We have proposed a novel device that utilizes the Rashba spin-orbit interaction in semiconducting triple barrier structures which can be used as a spin rectifier. We have calculated the spin-dependent tunneling currents $I_\uparrow$ (spin up) and $I_\downarrow$ (spin down) through the device and found that the spin polarization of the transmitted current is almost 100%. We also showed that the polarization of the transmitted current is switched between the spin-up and spin-down states by controlling the source-drain bias voltage.

Acknowledgments

The authors thank Professor S. Datta at Purdue University for useful discussions. This research work is supported by the NEDO International Joint Research Grant Program.

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