CHINESE JOURNAL OF PHYSICS VOL. 38, NO. 6 DECEMBER 2000

Spin-Dependent Resonant Tunneling Based Spin Valves and Spin-Current Sources

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(Received June 30, 2000)

We describe a principle for designing double-barrier magnetic tunneling structures that could produce a spin current with controllable spin direction or have an optimal spin valve effect. The principle is based on the finding that, by tuning the energy positions of the spin-dependent resonant tunneling of a double-barrier junction, a fully spin-polarized current and optimal magnetoresistance could be achieved. This is illustrated by numerical calculations within a 3-dimensional effective single-electron model of the spin-dependent currents in several tunneling structures.

PACS. 73.40.Gk – Tunneling.
PACS. 73.40.Sx – Metal-semiconductor-metal structures.
PACS. 73.50.Jt – Galvanomagnetic and other magnetotransport effects.

I. Introduction

Spin-dependent transport through a tunneling junction currently attracts much attention due to its possible applications in magnetic and magnetoelectronic devices [1-3]. For example, a trilayer junction with high magnetoresistance (MR) is a current switch controlled by flipping the spin of one magnetic electrode. This spin valve effect can be utilized in magnetic sensors and magnetic random access memory [4]. A tunneling structure that produces a spin-polarized tunneling current is a spin current source and is useful in, e.g. spin-resolved electron tunneling microscopy. These exciting prospects have in recent years stimulated considerable efforts in searching for tunneling structures with high MR (see, e.g. [1-4] and references therein).

Resonant tunneling (RT) is known to give rise to fascinating phenomena such as negative differential resistance that have been utilized in, e.g. various double-barrier RT devices. In a double-barrier structure, electrons with energy at the energy level of a quasibound well state can have unit transmission probability while the transmission probability of electrons with other energies is several order of magnitude smaller. Thus, if the energy level of the quasibound states in the double-barrier structure is spin-dependent, the tunneling current would have a substantial dependence on the spin direction of the tunneling electrons. In this paper, we propose to exploit this spin-dependent RT to design magnetic tunnel junctions that could have a large MR or a pure spin-polarized current with controllable spin direction.

Physically, there are two origins that can cause the spin-dependent RT in a double-barrier junction. One is the spin-orbit coupling. The coupling between the transverse (in-plane) motion of an electron and its spin can lead to RT at the energy that depend on the spin direction [5]. However,

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this spin-spliting is generally small (meV) [5]. The other is due to the use of a ferromagnet (FM) as the well layer between the two barriers in the tunnel structure. In this case, electrons with different spin states would experience different potentials in the well region, leading to RT at different energies. This spin-spliting is proportional to the exchange field of the FM and is generally large (eV, see below). The energy positions of the well states are mainly determined by the barrier heights and the well width. Thus, for a double-barrier junction (NM/I/FM/I/NM) with a thin well layer where NM, I denote, respectively, a nonmagnetic metal and an insulator, the electrons with spin parallel to the magnetization of the FM would experience RT at several energy levels below the Fermi level (E_F) while the electrons with opposite spin might have no RT. If the magnetization of the FM is flipped, the opposite would be true. Clearly, this concept can be utilized to design a spin current source with spin direction controlled by rotating the magnetization of the FM. If, further, one uses a ferromagnet as the electrodes to form a FM/I/FM/I/FM junction, a nearly optimal MR effect can be achieved when the magnetization of the well ferromagnet is flipped from that parallel to the magnetization of the electrodes to the antiparallel one. Below we present our free-electron model calculations to demonstrate these remarkable spin-dependent RT effects.

Consider a double-barrier junction grown in the z direction. The junction consists of five different regions (layers). The electron effective mass and band potential within each layer are assumed to be constant, but can differ in different regions. The transverse motion of the electrons is also taken into account by solving a three-dimensional one-electron Schrödinger equation which for the longitudinal wavefunctions in the jth region is

$$\left[-\frac{\hbar^2}{2m_j^*}\left(\frac{d^2}{dz^2} - k_t^2\right) + V_j - h_j\sigma_j - eF_j z - E\right]\psi(z) = 0 \tag{1}$$

where the constants V_j, h_j and F_j are the band edge, exchange field and electric field in the jth region respectively. k_t is the transverse wave vector, and the Pauli matrix σ is taken along the magnetization direction h_j in the jth region. By matching boundary conditions $\psi(z)$ and $[\psi'(z)/m^*]$ at each interface using a 4-by-4 transfer matrix method [6], we obtain the overall transfer matrix of the junction. The transmission probability T is given by the transfer matrix elements and the tunneling current can be obtained by an integration of T [6].

Let us consider a spin valve based on the FM/I/FM/I/FM structure. Assume the FM is a 3d transition metal. Stearns has analysized tunneling spin-polarization of Fe, Co and Ni, and found that spin-dependent tunneling is dominated by the itinerant d-like electrons having a nearly free-electron band [7]. We thus assume that the FM has an exchange field of 1.9 eV, an effective mass of 1 m_e, and E_F of 2.1 eV, similar to that of Fe [7]. We further assume that the insulator (I) has a barrier height of 3 eV (0.9 eV above E_F) and an effective mass of 0.4 m_e [3]. For simplicity, the width of both the barriers and well is set to 10 Å. Nonetheless, it is possible to make such thin barrier and well layers [8]. In Fig. 1 we plot the calculated T at zero bias and zero transverse wave-vector for the parallel magnetization alignment (parallel case) and also for the magnetization of the well layer being antiparallel to that of the two electrodes (antiparallel case). Fig. 1 shows that in the parallel case, the first RT level for the spin up and down electrons is located at -1.55 eV and 2.23 eV, respectively and there are three resonant levels below E_F. In comparison, in the antiparallel case, the first spin up and down resonant levels are located at 2.23 and 2.55 eV, respectively, both being above E_F. This explains the interesting behavior of the

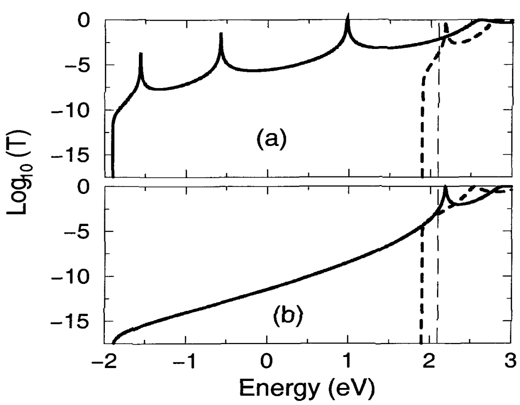

FIG. 1. Zero bias transmission coefficient (T) vs. electron energy (zero transverse energy) for a double-barrier tunneling junction: (a) the parallel and (b) antiparallel cases (see text). Solid line is for T"" and dashed line is for T##. The Fermi energy is 2.1 eV (vertical line).

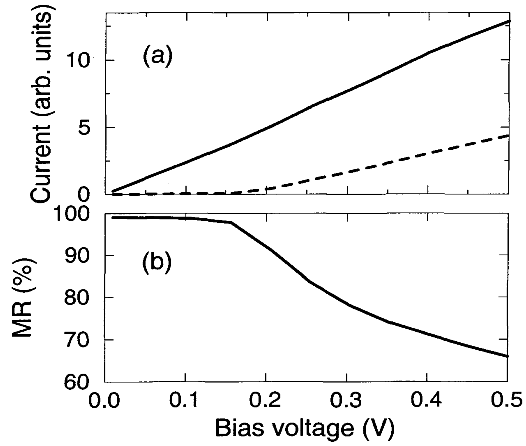

FIG. 2. Tunneling current (a) and magnetoresistance (MR) (b) vs. bias voltage. In (a), solid line is for the parallel case and dashed line, for the antiparallel case (see text).

calculated tunneling current and MR ratio vs. bias voltage plotted in Fig. 2. Because there are three RT levels below E_F in the parallel case, the tunneling current goes up monotonically as the bias voltage increases (Fig. 2a). In contrast, in the antiparallel case, the tunneling current is extremely small at bias voltages below 0.15 V (Fig. 2b). The current then goes up abruptly at 0.15 V due to the appearance of the first RT level below E_F, thereby contributing to the current integration. Clearly, the MR of the junction, defined as the relative conductance change due to the magnetization flip of the well FM, will be large when the bias voltage is below 0.15 V. Indeed Fig. 2b shows that the MR is near the optimal value (100%) at these small bias voltages. Above 0.15 V, the MR decreases with increasing bias voltage, but is still larger than the MR reported for the single barrier tri-layer structures [3, 9].

A strategy for designing an optimal spin valve using double-barrier structures thus follows. Because the transmission probability T of the tunneling electrons is extremely small unless their energies are near a RT level, the dominant contribution to the current comes from those electrons having an energy close to a RT level. Thus, the tunneling structure should be made such that the numbers of resonant levels below E_F in the two spin alignments have a maximum difference. In particular, if only one alignment has RT levels below E_F, the MR would be optimal and a perfect spin valve can be achieved for small bias voltages, as shown above. For a carefully made double-barrier structure with a thin well and flat interfaces such that in the antiparallel case there is no RT level below E_F, the optimal condition would be satisfied since at least one RT level (spin up state) in the parallel case appears below E_F.

Consider now the spin polarization of tunneling current of a seven layer structure [NM/I_S/I_C/FM/I_C/I_S/NM]. The spin-polarization (P) is defined as

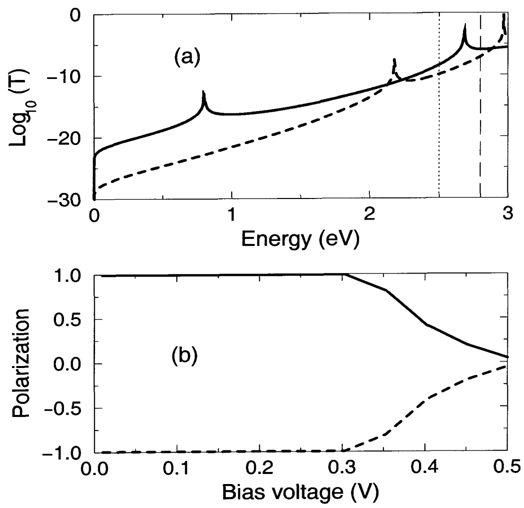

FIG. 3. (a) Zero bias transmission coefficient (T) vs. electron energy (zero transverse energy) for a seven layer tunneling junction (see text). Solid line is for $T_{""}$ and dashed line is for $T_{\#\#}$. The Fermi energy (2.8 eV) and the side barrier (I_S) height (2.5 eV) are indicated by the vertical lines, respectively. (b) Tunneling current spin-polarization vs. bias voltage. Solid line is for the parallel case and dashed line, for the antiparallel case.

$$P = \frac{J_{"} \text{ ¡ } J_{\#}}{J_{"} + J_{\#}} \tag{2}$$

where $J_{"}$ and $J_{\#}$ are the tunneling currents for the spin up and down states, respectively. The same parameters of the FM as above except E_F of 2.8 eV are assumed. The band edge of 0 eV and effective mass of 1 m_e for the NM are used. The central barriers (I_C) have a barrier height of 4.5 eV and an effective mass of 0.4 m_e, while those of the side insulator (I_S) are 2.5 eV and 0.4 m_e, respectively. The width of all the barriers and the well is set to 10Å. The RT states are determined mainly by the central barrier height. The role of the side barriers (I_S) will become apparent shortly.

In Fig. 3a we plot the transmission coefficient of this structure. Note that there are three RT peaks below E_F but only one of them (spin up state) is above the side barrier height. This latter resonant peak is much fatter than the other two RT peaks. Thus one can expect that the tunneling current will be dominated by this spin up RT peak and have a 100% spin-polarization. If the magnetization of the central FM is flipped with the magnetization of the two electrode layers fixed via, e.g., the exchange biasing [3], the spin state of those RT states will be reversed. Thus fully polarized current with the opposite spin can be obtained. In other words, one can select the spin direction by flipping the magnetization of the central FM. This is demonstrated by the numerical results displayed in Fig. 3b which shows that the current polarization at small bias voltages (below 0.3 V) is 100% and -100%, respectively, before and after flipping. When the bias voltage is larger than 0.3 V, the other RT peak (spin down state) is pulled down below E_F, thereby destroying the optimal spin-polarization. The effect of the side barriers is to diminish the strength of the minor

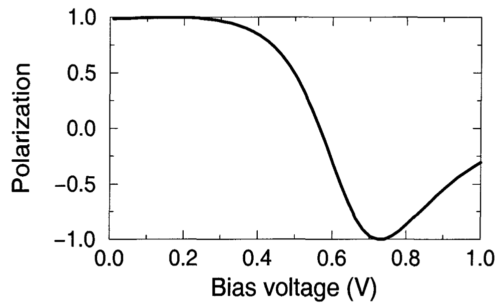

FIG. 4. Tunneling current polarization for a seven layer junction with semiconductor electrodes (see text). The Fermi energy is 0.01 eV.

RT peaks (below the side barrier height) so that the main RT peak (above the side barrier height but below E_F) would dominate the tunneling current. Without the side barrier, the minor RT peaks can have a contribution comparable to that of the main RT peak, thus reducing the spin polarization.

Finally, one can design another type of spin current sources with the spin direction controlled by bias voltage, based on the S/I/FM/I/S structures where S denotes a semiconductor. To illustrate this, we use the same parameters as in the preceding example except that the band edge and effective mass of the semiconductor electrodes are set to 2.6 eV and 0.1 respectively. We plot the polarization vs. bias voltage in Fig. 4 for a small E_f of 0.01 eV. The polarization is initially +100% when the spin up resonant state is below E_F. As the bias voltage increases, this state gradually falls below the band edge of the electrode. On the other hand, the spin down RT state comes down below E_F at 0.72 eV, leading to -100% spin-polarization. Thus one can control the tunneling current polarization by adjusting the bias voltage instead of applying a magnetic field.

This work is supported by the National Science Council of ROC (NSC 88-2112-M002-0043, NSC 89-2112-M002-0025).

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