Physica E 41 (2009) 1193–1196

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Possible magnetoresistance effect in abrupt ferromagnetic semiconductor n–n heterojunction

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ARTICLE INFO

Article history:
Received 4 September 2008
Accepted 27 January 2009
Available online 4 February 2009

PACS:
72.25.Hg
73.40.−c
85.75.−d

Keywords:
Ferromagnetic semiconductor
Heterojunction
Magnetoresistance

ABSTRACT

Magnetic semiconductors have generated continuing interest because of their potential for use in spintronic devices. In this article, we propose and theoretically analyze the magnetoresistance effect in an abrupt n–n ferromagnetic-semiconductor/ferromagnetic-semiconductor heterojunction. The current–voltage properties of the structure on magnetic moments parallel or antiparallel are analyzed by the double schottky barriers model. The model shows that the current saturates in both directions and the configuration can achieve a large magnetoresistance.

1. Introduction

The subject of ferromagnetic semiconductors (FSs) has attracted continuously theoretical and experiment works because of their potential for use in spintronic devices, and leading to significant technological advances [1–3]. Using FSs is one of the key issues for incorporating electron spin into well-developed semiconductors, and overcoming the so-called conducting mismatch between ferromagnetic metals and nonmagnetic semiconductors [4]. At present, most researches are focused on two types of ferromagnetic semiconductors. One is called diluted magnetic semiconductors (DSM), in which magnetic ions are doped into conventional semiconductors to achieve ferromagnetism [5–7]. The other is concentrated ferromagnetic semiconductors, in which the magnetic ions are an intrinsic part of the lattice, such as europium chalcogenides [8,9]. Adopting FSs, many hybrid devices have been theoretically proposed and experimentally realized. Especially, a magnetic bipolar transistor building on magnetic semiconductor/normal semiconductor p–n junctions has been predicted that the current amplification of the transistor can be tuned by spin [10,11]. All of the researches make the scientists believe that electronic devices in the near future will employ the electron spin degree of freedom [12].

Predicting and analyzing various spintronic device architectures adopting FSs for possible technological application is a fundamental issue for spin-polarized transport in semiconductors. So, in this article we propose and theoretically analyze a possible magnetoresistance effect in a novel abrupt n–n FS1/FS2 heterojunction.

2. Operating principle and calculation model

For a normal n–n semiconductor heterojunction, shown in Fig. 1, with interface states $>10^{13}\,\mathrm{cm}^{-2}$, its I–V properties can be analyzed within a double schottky barrier model [13,14], and the current saturates in both directions [15]. The total current density J_T is given by

$$J_T = \frac{2J_{s1}J_{s2}sh\left(\frac{qV}{2k_BT}\right)}{J_{s1}\exp\left(\frac{qV}{2k_BT}\right)+J_{s2}\exp\left(-\frac{qV}{2k_BT}\right)} \quad (1)$$

where J_{s1}, J_{s2} are the reverse saturation current densities for barriers I and II, and are given by

$$J_{s1} = A^*T^2\exp\left(-\frac{q\phi_1}{k_BT}\right) \quad (2)$$

$$J_{s2} = A^*T^2\exp\left(-\frac{q\phi_2}{k_BT}\right) \quad (3)$$

where A^* denotes the Richardson constant ($A^* = 120\,\mathrm{A/cm^2\,K^2}$), q the electronic charge, k_B the Boltzman constant, J_1, J_2, ϕ_1, ϕ_2 and V

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doi:10.1016/j.physe.2009.01.013

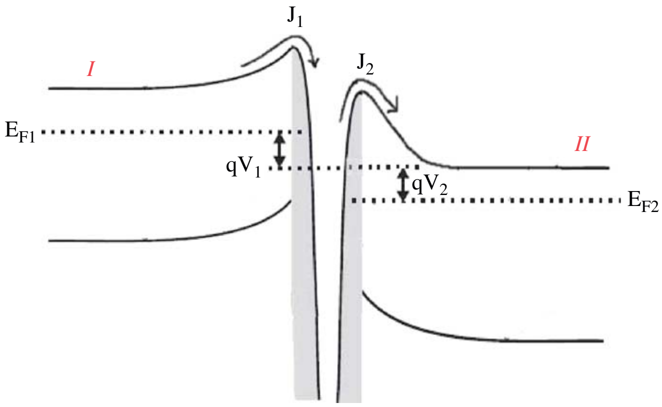

Fig. 1. Double schottky barrier model for the n–n semiconductor heterojunction.

the currents density, schottky barrier heights and voltages for heterojunction.

On changing the normal semiconductor to FS and fabricating FS1/FS2 heterojunction, the *I–V* transport properties can be analyzed by double schottky barrier model with considering the impact of ferromagnetic component. In the use of ferromagnetic semiconductor, a number of simplifying assumptions were made. Most important, we treat carrier states as nondegenerate and its splitting produces spin-polarized electronics. The carrier band splitting can be of the Zeeman and exchange type. The former arises from an application of a magnetic field, while the latter comes from the exchange coupling in ferromagnetic semiconductors. Due to this we mainly discuss the magnetoresistance effect, which produced by the two ferromagnetic semiconductor layers parallel or antiparallel, so we only consider the exchange energy, and define it as Δex.

Due to this we adopt different FS materials, they have unequal coercivities, and their magnetic moments can switch separated by an external magnetic field and form the parallel or antiparallel state. When the two FS layers are parallel, the two schottky barrier heights are low for spin up electrons and high for spin down electrons. So, a relatively large spin up current flows, while little spin down current flows. When the two FS layers are antiparallel, both spin up and down electrons have a barrier profile consisting of one low barrier height and one high barrier height. Hence, both low spin up and down current flow. The operating way is similar with the two-current model [16]. So, the resistance of the abrupt ferromagnetic semiconductor n–n heterojunction is small when the two magnetic moments are parallel, and large when antiparallel. This is completely based on the different schottky barrier heights for spin up and down electrons.

We now consider a simple theory that describes the magnetoresistance of this FS n–n heterojunction, which is shown in Fig. 2. The current densities, when the two layers are parallel (J_p) or antiparallel (J_{ap}), are given by the sums of the two current for each spin channel

$$J_p = J_{\uparrow\uparrow} + J_{\downarrow\downarrow} \quad (4)$$

$$J_{ap} = J_{\uparrow\downarrow} + J_{\downarrow\uparrow} \quad (5)$$

Considering the normal double schottky model describing above and adding the ferromagnetic component, the current densities $J_{\uparrow\uparrow}, J_{\downarrow\downarrow}, J_{\uparrow\downarrow}$ and $J_{\downarrow\uparrow}$ can be expressed as

$$J_{\uparrow\uparrow} = \frac{2J_{s1(\uparrow)}J_{s2(\uparrow)} sh\left(\frac{qV}{2k_BT}\right)}{J_{s1(\uparrow)}\exp\left(\frac{qV}{2k_BT}\right) + J_{s2(\uparrow)}\exp\left(-\frac{qV}{2k_BT}\right)} \quad (6)$$

$$J_{\downarrow\downarrow} = \frac{2J_{s1(\downarrow)}J_{s2(\downarrow)} sh\left(\frac{qV}{2k_BT}\right)}{J_{s1(\downarrow)}\exp\left(\frac{qV}{2k_BT}\right) + J_{s2(\downarrow)}\exp\left(-\frac{qV}{2k_BT}\right)} \quad (7)$$

$$J_{\uparrow\downarrow} = \frac{2J_{s1(\uparrow)}J_{s2(\downarrow)} sh\left(\frac{qV}{2k_BT}\right)}{J_{s1(\uparrow)}\exp\left(\frac{qV}{2k_BT}\right) + J_{s2(\downarrow)}\exp\left(-\frac{qV}{2k_BT}\right)} \quad (8)$$

$$J_{\downarrow\uparrow} = \frac{2J_{s1(\downarrow)}J_{s2(\uparrow)} sh\left(\frac{qV}{2k_BT}\right)}{J_{s1(\downarrow)}\exp\left(\frac{qV}{2k_BT}\right) + J_{s2(\uparrow)}\exp\left(-\frac{qV}{2k_BT}\right)} \quad (9)$$

where $J_{s1(\uparrow)}, J_{s1(\downarrow)}, J_{s2(\uparrow)}$ and $J_{s2(\downarrow)}$ are defined as

$$J_{s1(\uparrow)} = A^*T^2\exp\left(-\frac{q\phi_{1\uparrow}}{k_BT}\right) \quad (10)$$

$$J_{s1(\downarrow)} = A^*T^2\exp\left[-\frac{q(\phi_{1\uparrow} + \Delta ex1)}{k_BT}\right] \quad (11)$$

$$J_{s2(\uparrow)} = A^*T^2\exp\left(-\frac{q\phi_{2\uparrow}}{k_BT}\right) \quad (12)$$

$$J_{s2(\downarrow)} = A^*T^2\exp\left[-\frac{q(\phi_{2\uparrow} + \Delta ex2)}{k_BT}\right] \quad (13)$$

where $\phi_{1\uparrow}$, $\phi_{2\uparrow}$, $\Delta ex1$, $\Delta ex2$ are the schottky barrier heights and exchange energy for FS1 and FS2.

So, the magnetoresistance (MR) for the junction is given as

$$MR = \frac{J_p - J_{ap}}{J_{ap}} \times 100\% = \frac{(J_{s2(\downarrow)} - J_{s2(\uparrow)})(J_{s1(\downarrow)} - J_{s1(\uparrow)})}{\left[J_{s1(\uparrow)}\exp\left(\frac{qV}{2k_BT}\right) + J_{s2(\downarrow)}\exp\left(-\frac{qV}{2k_BT}\right)\right]\left[J_{s1(\downarrow)}\exp\left(\frac{qV}{2k_BT}\right) + J_{s2(\uparrow)}\exp\left(-\frac{qV}{2k_BT}\right)\right]} \times 100\% \quad (14)$$

3. Numerical results

According to Eqs. (4)–(13), we have calculated the current densities of the junction when the two FS layers are parallel or antiparallel. The barrier height $q\phi_{1\uparrow}$ and exchange energy $\Delta ex1$ are assumed to be larger than $q\phi_{2\uparrow}$ and $\Delta ex2$, and set as $q\phi_{1\uparrow} = 0.6$ eV, $\Delta ex1 = 0.3$ eV, $q\phi_{2\uparrow} = 0.4$ eV, $\Delta ex2 = 0.25$ eV.

In Fig. 3, the *J–V* curves are shown as a function of the bias voltage, when the magnetic moments are parallel or antiparallel. It is shown clearly that the current densities saturate in both direction with different values whenever the magnetic moments are parallel or antiparallel. This is corresponding with the normal abrupt n–n heterojunction. However, when the forward voltage is applied, the current density J_p is several times large than J_{ap} before current saturated. The MR curve shown as a function of the bias voltage is also displayed in Fig. 4. It is obviously that a large MR