Anisotropy of spin-dependent electron transport in nonmagnetic resonant tunneling structures

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***Abstract*—The spin-orbit coupling in noncentrosymmetrical semiconductor nanostructures gives rise to Rashba and Dresselhaus effects through which electron momentum and spin are coupled. Following some recent theoretical studies which indicate that in resonant tunneling structures where one of the effects is dominant a significant level of spin polarization might be obtained, we extend the previous model to account for both of these effects. Furthermore, we investigate their possible use in overcoming some limitations imposed by the presence of only one spin-dependent mechanism. The dependence of transmission probabilities on lateral momentum direction (i. e. anisotropy) is recovered in the proposed model, thus offering means to improve the design of existing nonmagnetic spin filters.**

***Index Terms*—spin, tunneling (Rashba effect, Dresselhaus effect, resonant tunneling, spin-filter)**

I. Introduction

THE nonvanishing spin-dependent terms in the Hamiltonian for electrons in a given semiconductor heterostructure appear whenever there is no inversion symmetry in the system. The effects of inversion asymmetry (IA) in heterostructures are conveniently divided into those arising from the properties of the semiconductor material itself - bulk inversion asymmetry (BIA), and to those arising from the IA of the structure - structure inversion asymmetry (SIA), which may be induced either by growing an asymmetric structure or by the use of external electric field.

The present-day interest in these effects is refueled by the nascent field of spintronics [1] the essential prerequisite for which is to have a device capable of producing spin-polarized current. The spin-injection into semiconductors from ferromagnetic materials [2], [3] and magnetic semiconductors [4], [5] has already been demonstrated experimentally and investigated theoretically [6]-[8]. However, there seem to be many ambiguities when transferring from a conceptual solution to real devices [9], [10]. A principal benefit of all-semiconductor spin-filters is that they are expected to be easily incorporated into the existing semiconductor technology.

During the past couple of years, there has been a number of papers [11]-[16] relevant to our work. Here we consider the one-sided collector case applied to a InAs-GaAs-AlAs system where the advantage of carefully tailored anisotropy is clearly visible.

II. Summary

The main features of spin dependent transport in resonant tunneling structures are illustrated for the case of a triple-barrier resonant tunneling diode (TB-RTD) shown in Fig. 1.

We consider the conduction-band electrons described by the two-component envelope function

$$\psi(z) = \eta_+(z)\chi_+ + \eta_-(z)\chi_-, \tag{1}$$

where χ_+ and χ_- are two orthogonal spinors and $\eta_+(z)$ and $\eta_-(z)$ are complex functions describing the spatial distribution of probability amplitudes along z||[001]. The envelope functions $\psi(z)$ are obtained by solving the envelope function Schrödinger equation

$$H\psi(z) = E\psi(z), \tag{2}$$

with the spin-dependent effective Hamiltonian H, which includes the Rashba contribution due to SIA (denoted by H_R), [17]-[21], and Dresselhaus contribution due to BIA (denoted by H_D), [11], [22]. Let $\mathbf{k}_{||}$ be the in-plane wave vector, $k_x=k_{||}\cos\varphi$ its component along [100] and $k_y=k_{||}\sin\varphi$ the component along [010] direction. We assume that electrons in regions 1 and 9 (the emitter and collector, respectively, see Fig. 1.) are in thermodynamical equilibrium with Fermi levels $E_{F,e}=E_{F,c}$, as long as the applied voltage V_{CE} is equal to zero, and that with $V_{CE}>0$ the equilibrium is approximately retained but with $E_{F,e}-E_{F,c}=V_{CE}$, leading to a net current density J. Far away from the junction, the electrons spin is coupled only with the crystal field of the bulk material, i.e. only the BIA term exists. The spin states are then described by the spinors

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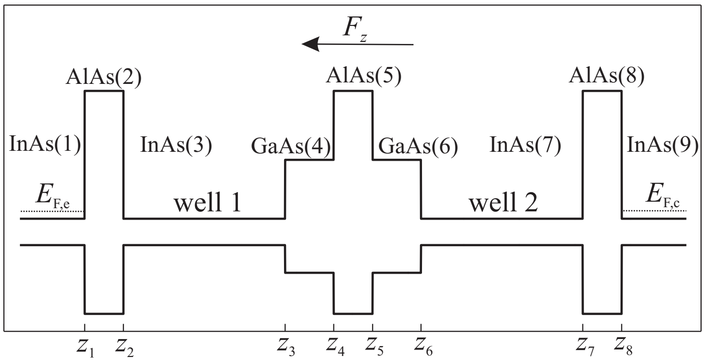

Fig. 1. The conduction and valence band edge profile of TB-RTD based on InAs-AlAs-InAs-GaAs-AlAs-GaAs-InAs-AlAs-InAs. In calculations $E_{F,e}$=0.1eV (N_D~10^{18}cm^{-3}) and T≈0K was used. Layers are assumed to be grown along z||[001] with z_1=0, z_2=24Å, z_3=124Å, z_4=154Å, z_5=178Å, z_6=218Å, z_7=318Å, z_8=332Å. F_z represents the external electric field.

$$\chi_\sigma(\varphi) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -\sigma\exp(-i\varphi) \end{bmatrix},\ \sigma = \pm\,. \tag{3}$$

The electrons with $\chi_\sigma(\varphi)$ are said to be forming the "σ" spin-subband of the given region (1 or 9). Since H_R and H_D do not commute, the spin of an electron incident to the junction from either side is going to be changed in the process of tunneling. Hence, if the electron approaches the junction from e.g. the emitter's "σ" spin-subband, we may associate to it both the probability of tunneling into the collector's "+" and "–" spin-subband, $T_{\sigma+}$ and $T_{\sigma-}$, respectively.

Dividing up the overall current density J into contributions from electrons with a given φ and spin-state "σ" in the collector region, $j_\sigma(\varphi)$, we may write the expression for the average spin polarization of J along the spin-analyzing axis described by the spin operator $\sigma_\omega=\sigma_x\cos\omega+\sigma_y\sin\omega$ as

$$P(\omega) = -\frac{1}{J}\int_{\varphi_c-\Delta\varphi/2}^{\varphi_c+\Delta\varphi/2}\left[j_+(\varphi)-j_-(\varphi)\right]\cos(\varphi+\omega)\,d\varphi\,. \tag{4}$$

Simple symmetry considerations reveal that $P(\omega)$=0 if $\Delta\varphi$ (the collector opening angle) in Eq. (4) is equal to 2π. Therefore, in order to obtain nonzero $P(\omega)$ it is necessary to have $\Delta\varphi$<2π.

In this paper we discuss the influence of various quantities from Eq. (4) on the magnitude of $P(\omega)$ and, particularly, the manner in which the presence of both H_R and H_D affects the dependence of transmission probability resonances on φ. A numerical simulation is carried out to demonstrate the salient features of the structure from Fig. 1.

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