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Spin–Orbit Interaction and All-Semiconductor Spintronics

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The purpose of this paper is to give a brief review and trace the present-day perspectives to exploit the spin–orbit interaction in conventional nonmagnetic semiconductor nanostructures. We demonstrate theoretically that the structures can be used to design basic elements of high-speed spintronic devices. In particular we discuss spin filtering, spin-dependent confinement, and scattering in all-semiconductor nanostructures.

KEY WORDS: spin–orbit interaction; spintronics; nanoscale structures.

1. INTRODUCTION

Studies of spin-dependent confinement and transport phenomena in semiconductor nanostructures have been progressing significantly since spintronics became a focus of recent interest (see [1–7] and references therein). Basic elements of spintronic devices were assigned in the first proposition of Datta and Das [8] (see Fig. 1). Many possible structures with the basic elements were investigated and different kinds of electron spin detection methods have been developed. Most of them consist of magnetic material elements (see [1, 4, 6, 7] for references). Recently the coherent spin transport has been demonstrated in homogeneous semiconductors and heterostructures [2]. Incorporating ferromagnetic semiconductors [6, 7], one can use an all-semiconductor approach to generate, control, and detect the electron spin polarization. This approach has the advantage of being compatible with conventional semiconductor technology.

The most important property of III–V semiconductors to be utilized in all-semiconductor spintronic devices is the spin–orbit interaction (SOI) [9,10]. In III–V and II–VI semiconductors the SOI lifts the conduction state spin-degeneracy and has been used successfully to interpret experimental results in various quantum well and wire structures [10–12]. In this paper we review (in brief) the present-day perspectives to exploit the SOI in the conventional III–V nonmagnetic semiconductors to design basic, high-speed spintronic devices. To achieve this, we concentrate on spin-dependent electronic characteristics of semiconductor nanostructures.

2. SPIN-DEPENDENT TUNELING, CONFINEMENT, AND SCATTERING

The SOI in tunnel barrier structures can lead to the spin-dependent tunneling phenomenon [13]. In resonant tunnel heterostructures the spin filtering can gain a high level. Results of our recent evaluation for an asymmetric double-barrier structure are presented in Fig. 2. The polarization ratio is defined as $P(E_z, \mathbf{K}_{\|}) = (T_{\uparrow} - T_{\downarrow})/(T_{\uparrow} + T_{\downarrow})$ where $T_{\uparrow\downarrow}$ is spin-up (down) tunneling probability, E_z is the part of the electronic energy, which corresponds to the perpendicular motion to the barrier, and $\mathbf{k}_{\|}$ is in-plane wave vector. Because of the SOI symmetry to obtain a nonzero spin polarization $p = (j_{\uparrow} - j_{\downarrow})/(j_{\uparrow} + j_{\downarrow})$ in the electronic current j, we need an in-plane asymmetry in the electron occupation probability. The asymmetry can be created by an additional in-plane electric field $F_{\|}$. Figure 3 shows the calculated polarization for the asymmetric tunnel structure [13]. Results of other authors suggest that the spin filtering for all-semiconductor tunnel devices can reach almost 100% polarization for more sophisticated designs of the structures [14–17].

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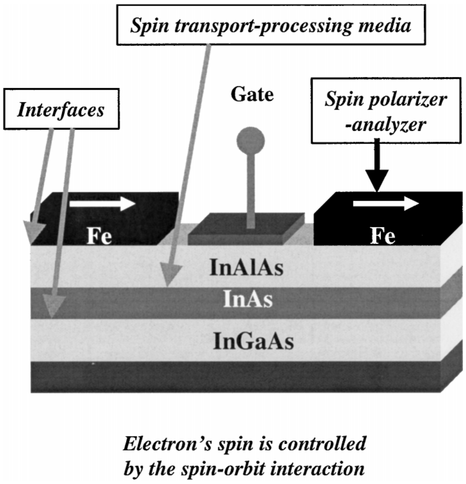

Fig. 1. Spin-FET (after Datta and Das). Basic spintronic elements.

The spin states in the quantum dots are promising candidates for realizations of qubit in the quantum computing [18]. The SOI separates states with the same orbital momentum and different spin directions [19]. The spin splitting at zero magnetic field leads to an unusual behavior of the quantum dot energy spectrum when a magnetic field is present (an analog of the general Paschen–Back effect). Figure 4 displays the calculated spectrum of InSb quantum dot as a function of the magnetic field B. The crossing of electron energy levels with different spins leads to unusual magnetic properties of quantum dots [20] and an additional degree of freedom for the electron spin state manipulation in quantum dots.

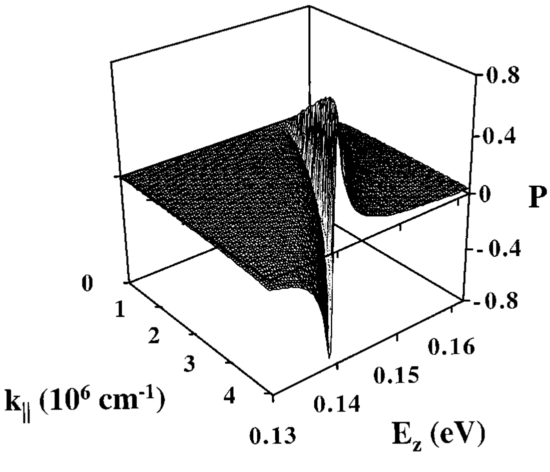

Fig. 2. Polarization ratio for InAs/GaAs/InAs/A1As/InAs barrier structure at zero bias (barrier's thickness = 3 and 1.5 nm, interbarrier distance = 6 nm).

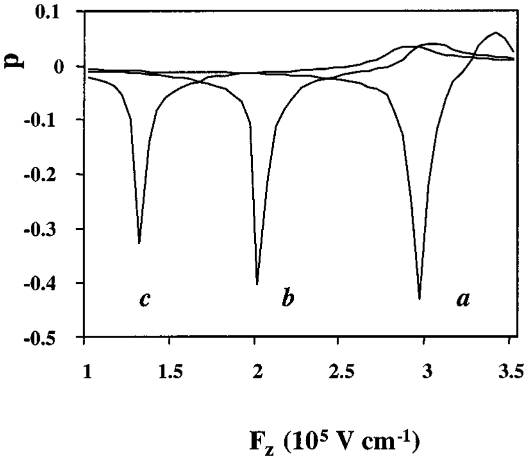

Fig. 3. Polarization of the tunnel current in the structure of Fig. 2 for $F_{\|}$: (a) 1.6×10^3; (b) 2.3×10^3; (c) 2.5×10^3 Vcm^{-1}.

In absence of magnetic impurities at low temperatures the main source of the spin-dependent scattering processes for electrons is the SOI with local defects. Recently it was proposed to detect the electron spin polarization in paramagnetic metals and semiconductors through a "spin Hall effect" [21]. We introduced a model of the spin-dependent electron scattering from an array of nanoscale all-semiconductor quantum dots (antidots)—"artificial defects." The differential cross-section ($\sigma_{\uparrow\downarrow}$) for GaAs/InAs antidots located in two-dimensional channels demonstrates a large left–right asymmetry [22] (Fig. 5). The asymmetry should lead to nonzero off-diagonal elements of the conductivity tensor for polarized electrons in semiconductor structures with random arrays of GaAs/InAs antidotes. This can provide an

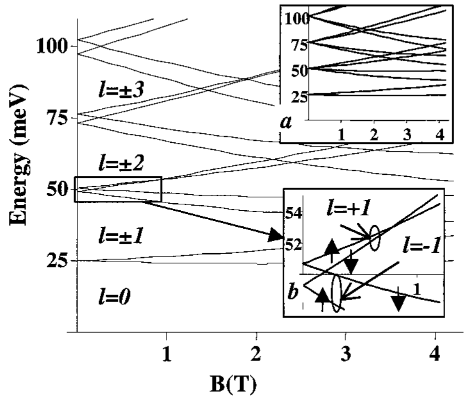

Fig. 4. Energy spectrum of a parabolic InSb quantum dot in magnetic fields [20] (l = the angular quantum number). Inserts: (a) the spectrum without the SOI; (b) only $|l| = 1$ levels with the SOL.

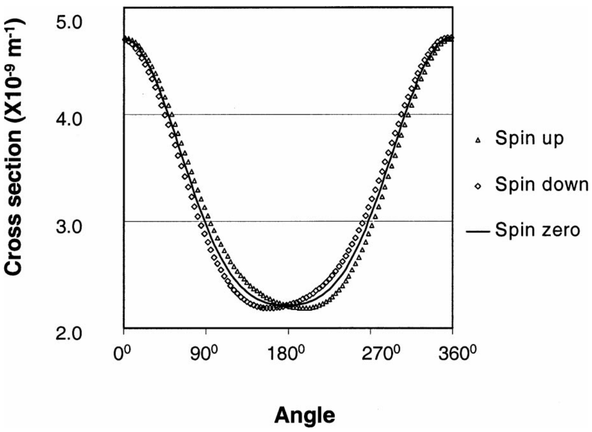

Fig. 5. Differential cross-section of GaAs/InAs two-dimensional antidot (radius = 5 nm).

opportunity to detect the spin polarization of the electron current at zero magnetic field [21].

3. CONCLUSION

Conventional semiconductor quantum structures are promising objects for spintronics. The SOI can provide us with tools to control the electron spin in all-semiconductor structures and it is worth to be exploited in semiconductor nanostructures for spintronics needs.

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