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Charge conductance and spin-polarized current across a metal/cubic semiconductor with Dresselhaus spin-orbit coupling junction

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ABSTRACT

We theoretically study the charge conductance across a metal/cubic semiconductor with Dresselhaus spin-orbit coupling junction. The conductance at a zero-applied voltage is calculated by using a free electron and scattering methods. The carrier density of semiconductor and the strength of Dresselhaus system are investigated on the overall conductance. We found that the conductance appears a kink feature which occurs when the Fermi level reaches the coincidence of Dresselhaus spin-orbit coupling band interaction. The Dresselhaus coupling strength increases, the conductance decreases until the strength reaches a critical value. Beyond this value, the conductance gradually increases with the coupling strength. The conductance can be enhanced when both types of interface spin scattering (spin-flip and non-spin-flip) are risen under certain condition. The spin polarization of current in the Dresselhaus system at a zero-applied voltage is also studied. We found that its magnitude is large by increasing the carrier density and it weakly depend on the interfacial scattering. However, at the low carrier density, the sign of spin polarization switches when both types of interface spin scattering are taken into account.

1. Introduction

The advantage of large spin degrees of freedom, including the magnitude and direction, provides a large possibility for the design of spintronic devices [1–8]. The starting point of spintronics is the appearance of spin aligned with a certain direction, the electron flow can give rise to spin-polarized

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current. One of the important devices is a ballistic spin field effect transistor (SFET) that was proposed by Datta and Dass. It consists of two Ferromagnetics (FM) separated by a semiconductor (SC) [9], based on the spin precession controlled by an external gate voltage via a spin-orbit coupling. A source and drain are FM acting as the injector and detector of electron spin.

Recently, the large spin polarization can be found in a non-magnetic semiconductor due to the spin-orbit interaction. It is known that in a SC, lacking inversion symmetry gives rise to the Rashba effect [10–12], resulting in an imbalance spin-dependence of charge conductance and spin-polarized current. In addition to the Rashba effect in a SC, the Dresselhaus spin-orbit coupling caused by the bulk inversion asymmetry exists widely in III–V compound semiconductor with Zinc-blende crystal structure [13]. The significant progresses have been made in both theoretical and experimental investigations of spin-dependent tunneling through the heterostructures consisting of the Dresselhaus spin-orbit coupling [8,14–22]. An important parameter to determine the efficiency of spin-dependent across such heterostructure is the interface properties (i.e., spin-flip and non-spin-flip scattering potentials) [23–26]. They can cause significant modification of spin current and spin accumulation near the interface [27]. Furthermore, the combining effects of both types of spin-flip and non-spin-flip scattering can enhance the charge conductance [28,29] and the magnetoresistance [30,31]. These studies aim to utilize spin-dependent current to develop such devices in the future. When the optimal design of the next generation devices based on the Dresselhaus system, one needs to understand and characterize properties of semiconductor materials in tunneling junctions. In addition, the improvement methods to find the alternative spin polarization of Dresselhaus spin-orbit coupling using a junction conductance measurement are the challenge research.

In this work, the charge conductance and the spin polarization of current across a metal/cubic semiconductor with Dresselhaus spin-orbit coupling in a ballistic limit are investigated. The electron density of Dresselhaus system is varied to consider the overall conductance. We found that the conductance at a zero-applied voltage exhibits a characteristic kink and gets a maximal value of the spin polarization of current when the Fermi level hits the intersection of the Dresselhaus splitting band. The interface spin scattering is taken into account by using the normal and spin-flip potential barriers. We show how both types of scattering barriers affect on the conductance and spin polarization of current. We first describe this paper as following, the quantum tunneling model and assumptions are introduced in Section 2. The results and discussions are in Section 3, and the last one is conclusions.

2. Model and assumptions

A metal/cubic semiconductor with Dresselhaus spin-orbit interaction is modeled by an infinite two-dimensional (2D) system which lies on xz plane. The region at $x < 0$ is occupied by metal while the Dresselhaus system is in $x > 0$. These two regions are separated by a flat interface at $x = 0$ where interfacial scattering (we are only interested in the elastic scattering) is represented by a Dirac-delta function potential [32]. The Hamiltonian in the one-band effective mass approximation with exchange interaction in a metal and the Dresselhaus spin-orbit coupling system has the following form

$$\vec{H} = \left\{ \hat{p} \frac{1}{2m(x)} \hat{p} + V(x,z) \right\} \hat{I} + \vec{H}_D(x). \tag{1}$$

The Schrödinger equation is expressed in a 2×2 matrix acting on the spinor states. I is 2×2 identity matrix and the momentum operator $\hat{p} = -i\hbar(\hat{x}\frac{\partial}{\partial x} + \hat{z}\frac{\partial}{\partial z})$. The effective mass $m(x)$ is position dependent; i.e., $[m(x)]^{-1} = m^{-1}\Theta(-x) + (m^*)^{-1}\Theta(x)$, where m and m^* are the effective electron mass in a metal and the Dresselhaus system, respectively. $\Theta(x)$ is the Heaviside step function. $V(x,z)$ is also a position dependent function, modeled by the expression

$$V(x,z) = H\delta(x) - E_F(\Theta(-x)), \tag{2}$$

where H represents the scattering potential at the interface. The diagonal elements of H, $H^{\uparrow\uparrow}$ and $H^{\downarrow\downarrow}$ correspond to the non-spin-flip scattering potential of the junction while the off-diaganal elements, $H^{\uparrow\downarrow} = H^{\downarrow\uparrow}$ describe the spin-flip scattering. $E_F = (\hbar^2 q_F^2)/(2m)$ is the Fermi energy of metal. The Dresselhaus Hamiltonian term $\underset{D}{H}(x)$ is written as