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Tunable polarization of spin polarized current by magnetic field

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ABSTRACT

The spin polarization of a high g-factor bulk semiconductor is theoretically investigated in the presence of a magnetic field parallel to a driving electric field. Calculations have been carried out using the energy-dependent relaxation time approximation in association with spin-flip scattering. As the magnitude of the magnetic field increases, the spin-polarized current alternates between the spin-up and spin-down states for the low spin-scattering system. This implies that the current polarization can be tuned by controlling the magnetic field strength, suggesting possible applications to spintronic devices. An experimental method for investigating alternative current polarization is also considered.

1. Introduction

In a spintronic device, some kinds of spin states should be created and manipulated by externally controllable factors. For non-magnetic semiconductors the typical example of this spin state would be a system with the net difference in the electronic number density between the spin-up and spin-down states, which can be achieved by the spin-injection from ferromagnetic materials. A spin-polarized current is produced by these excess number of the spins, and can be controlled by magnetic and electric field [1] through the Zeeman and Rashba effect, respectively. On the other hand, there are spintronic systems where the occupied number density of one spin states is the same as that of the opposite spin states, i.e., no excess spin density. Good examples of these systems would be the spin-interference device [2,3] and the quantum spin Hall (QSH) system [4].

Recently, the narrow gap or gapless semiconductors based on HgTe and HgCdTe have attracted much interest [5–7], since they are one of the most promising systems for spintronic device due to strong spin-obit coupling and high g-factor. The strong spin-obit coupling of HgTe/HgCdTe system makes the QSH phase [8]. In this report we have focused on the high g-factor, i.e., strong Zeeman effect of the HgTe based system. Taking into account of a spin-dependent scattering, the current polarization is achieved by creating a difference in conductivity between the two spin states. Most spintronic devices, such as spin-FETs [9], work via an electronic transport mechanism; thus the polarization of current is a key parameter rather than the number density of polarized carriers. The present study theoretically investigates the spin-current polarization of a high g-factor semiconductor according to the applied magnetic field. The electronic parameters of HgCdTe used in an experimental report are adopted for our calculation, and a qualitative comparison between the experimental and calculated results is discussed. Instead of providing an exact simulation for a real system, we propose a simple model to represent core ideas of this work. Three extreme cases will be discussed in the Section 4 in order to give clear explanations for the basic mechanism and physical meanings.

2. Relaxation time

A degenerate three-dimensional electronic system in the diffusive regime is considered, to which a magnetic field is applied in parallel with the current direction (the longitudinal configuration). Thus, there is no Hall effect and a series of Landau sub-bands are formed. It is assumed that the transport is relaxive and governed by the momentum transfer rates which are determined by the density of state of the final state in the momentum transfer process. The schematic structures of the Landau-Zeeman (LZ) sub-bands and the density of states (DOS) are shown in Fig. 1(a) and (b). Since DOS has a positive singular value at the bottom of each sub-band, the

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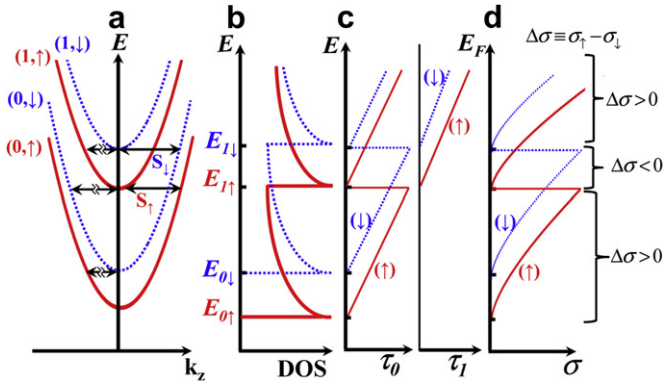

Fig. 1. (a) Dispersion relations for Landau-Zeeman sub-bands. The horizontal arrows represent interactions between the sub-bands. The broken arrows stand for the absence of interactions between different spin states, when the momentum scattering is not accompanied by a spin-flip. (b) DOS for the up- and down-spin states. (c) The energy-dependent relaxation time (τ_0 and τ_1) for two lowest Landau sub-bands. (d) The conductivity (σ) as a function of the Fermi level (E_F) at zero temperature (refer the description at the end of the Section 3). When $E_{1,\uparrow} < E_F < E_{1,\downarrow}$, the spin-down conductivity dominates over the spin-up conductivity. (c) and (d) are depicted for the negligible spin-flip system (see the text). All illustrations are schematic, and ↑ (↓) and the solid (dotted) lines indicate the spin-up (spin-down) state.

momentum transfer rate is infinite whenever elastic scattering into the bottoms of the other sub-bands becomes possible. The relaxation time is therefore proportional to the reciprocal DOS and has a value of zero at every bottom of the LZ sub-bands. This momentum relaxation gives rise to a saw-toothed structure, as illustrated in Fig. 1(c). A full theoretical investigation of this saw-toothed structure has been performed by Barker and Bridges [10]. They carried out calculations based on a relaxation matrix in consideration of self-consistency in the electron scatterings. Nicholas [11] and Eaves *et al* [12] adopted a similar saw-toothed model to explain the magnetoresistance of InSb and Ge, respectively. However, they did not examine spin-related transport. Éfros proposed a simple picture including the spin-related relaxation time to explain the experimentally observed Shubnikov-de Haas oscillation [13].

In this study the spin-dependent saw-toothed structure is adopted for the energy-dependent relaxation time, which generalizes the Barker's theory [10] to include a spin-related picture. Our study is not extended to profound spin effects such as the vertex correction [14]. As shown in Fig. 1(c), this saw-toothed structure is characterized as follows. For a given spin resolved LZ sub-band the relaxation time has a value of zero at every bottom of the sub-band and linearly increases as the energy increases up to the bottom of the next sub-band. The magnitude of the abrupt change in the relaxation time at the sub-band bottom is same for all LZ sub-bands in our model. The relaxation time is dependent on the spin-flip rate. When the probability of a spin-flip is low, the inter-sub-band transitions between different spin states are absent (see the horizontal broken arrows in Fig. 1(a)). As depicted in Fig. 1(c), the energy at which the relaxation time has a zero-value is different for each spin state in this case. For the system with high spin-flip rate, there would be a strong scattering at the every sub-band bottom regardless of the spin state. Then, the relaxation time is zero whenever the energy is at the bottom of any spin sub-band (refer the middle inset in Fig. 3(a)).

3. Model and calculation

Two kinds of spin polarization are considered in this work. The first is the current polarization, P_I, which represents the spin polarization of the electrically conducting current, and the other is the density polarization, P_N, representing the difference in electronic number density between two spin states. Both of these polarizations are defined by

$$P_I \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \quad \text{and} \quad P_N \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}, \tag{1}$$

where σ is the conductivity, and N is the electronic number density in the conduction band. The spin state of a physical quantity is designated by a subscript arrow in which ↑ (↓) stands for the spin-up (spin-down) state. Because σ is proportional to the number density times mobility near the Fermi level, P_I depends on the number of spin states and transport mechanism near the Fermi level, while P_N is determined by overall summation of the spins in the conduction band. A good example to elucidate the difference between P_I and P_N is ferromagnetic metals such as cobalt. When cobalt is magnetized, the total occupied density of spin-up states in the conduction band is larger than that of spin-down states, and the magnetization direction is determined by the spin-up electrons. Thus, P_N has a positive value in this case. However, the electrical current is dominated by the spin-down electrons and P_I is negative, because the spin-down electrons occupy more states at the Fermi level than the spin-up electrons do. Therefore, the magnetization direction in this system is opposite to the spin-direction of the majority spin current. In this work, we will focus on the transport mechanism rather than the electronic density near the Fermi level in order to determine P_I of a semiconductor.

From relaxation time approximation in the linear response regime to an electric field, E_{field}, the deviation of the electronic distribution function from equilibrium state, δf, is given by $\delta f/\tau \cong eE_{\text{field}} \times v \times \partial f_0/\partial E$, where e is the electronic unit charge, f_0 the electronic distribution function in an equilibrium state, E the electron's energy, τ the relaxation time, and v the velocity of the electron. Taking account of the spin state and Landau-Zeeman sub-band induced by magnetic field, B, current density, J, can be written as $J_{n,\uparrow\downarrow} = -e\int v_{n,\uparrow\downarrow}\delta f \mathrm{DOS}_{n,\uparrow\downarrow}\mathrm{d}E$. n = 0,1,2,… refers to the nth Landau level, and $(n, \uparrow\downarrow)$ stands for Landau-Zeeman sub-band with the spin up/down state. DOS is given by $(eB/h)(2/hv)$ where h is the Plank constant, eB/h the Landau level degeneracy and $2/hv$ the one dimensional density of state. By definition of conductivity, $\sigma_{\uparrow\downarrow} \equiv \sum_n J_{n,\uparrow\downarrow}/E_{\text{field}}$, and from the method formulated by Argyres [15], the conductivity including spin states in the longitudinal configuration can be written as

$$\sigma_{\uparrow\downarrow} = \frac{2e^3}{h^2}B\sum_{n,\uparrow\downarrow}\int \mathrm{d}E\left(-\frac{\partial f_0}{\partial E}\right)\tau_{n,\uparrow\downarrow}v_{n,\uparrow\downarrow}, \tag{2}$$

where one can refer the previous section regarding the definition of $\tau_{n,\uparrow\downarrow}$.

HgCdTe is used as a model system for a low spin-scattering and high g-factor semiconductor. The details of HgCdTe in our model are same as those used in the experimental study by Lee et al. [16]. The momentum relaxation time estimated from the experimentally measured mobility is about 1 ps at 2 K, whereas the spin relaxation time measured by Murzyn *et al.* [17] is 356 ps at 150 K. Since the spin relaxation time is large in comparison with the momentum relaxation time, the spin-flip mechanism can be ignored during the momentum transfer process in our system. The composition of $Hg_{1-x}Cd_xTe$ is $x = 0.23$, the corresponding band gap, E_g, is 0.11 eV, and the total carrier density is $1.27 \times 10^{15} cm^{-3}$. The g-factor, g^*, and effective mass, m^*, are obtained from E_g [18], which are −102 and 0.00826 times the free electron mass, respectively. The total carrier density $(N_\uparrow + N_\downarrow)$ is assumed to be independent of the magnetic field, from which the Fermi level, E_F, is determined. The Fermi level