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半導體異質結構一致和非一致自旋相依傳輸(1/3)

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行政院國家科學委員會專題研究計畫期中（第一年）報告

半導體異質結構一致和非一致自旋相依傳輸 (1/3)
Coherent and non-coherent spin-dependent transport in semiconductor heterostructures

計畫編號：NSC 91-2119-M-009-003
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一 摘要 (Abstract)

英文

This report summarizes the major results obtained from the first year (8 months) program of the “Coherent and non-coherent spin-dependent transport in semiconductor heterostructures” project. Three subjects are discussed in the following including, the Anomalous Hall effect appeared in three-dimensional random arrays of small semiconductor quantum dots, spin-dependent scattering from impurities in two-dimensional channels and spin-dependent transmission probability for all-semiconductor symmetric barrier structures. Several publications were performed based on this year’s results.

中文

在此報告中，我們總結了第一年(這八個月來)有關「半導體異質結構一致和非一致自旋相依傳輸」計劃的主要結果。以下我們將討論三個有關的主題，包括發生在三維隨機排列之微小量子點中的不規則霍爾效應、來自二維通道的雜質所造成的自旋相依散射、以及擁有對稱能障結構之半導體的自旋相依穿遂機率。其中一些發表的論文都是以今年的結果當作主要的基礎。

Key words: Spintronics, Quantum dot, Quantum well, Tunneling.

二 Anomalous Hall effect in three-dimensional random arrays of small semiconductor quantum dots.

In semiconductors the most important interaction, which causes spin-dependent processes is the spin-orbit interaction. The Rashba spin-orbit coupling is an essential element of the proposed by Datta and Das the spin field effect transistor. A new branch of semiconductor electronics so called spintronics became under an extensive development recently. For this reason, the spin dependent kinetics of electrons in traditional III-V semiconductor heterostructures becomes a topic of a great interest from theoretical and practical points of view. Our study deals with a model of the spin-dependent electron scattering from nano-scale semiconductor quantum dots (antidots). Recent advances in semiconductor nano-technology allow us to consider small spherical dots (antidots) of III-V semiconductors as “artificial defects” with controllable parameters. We calculated the polarization (the Sherman function) after a single scattering and than investigate how the polarization changes after the second scattering.

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The one electron band effective Hamiltonian and the spin dependent boundary conditions for spherical quantum dots (antidots) allowed us to calculate a spin asymmetry in the electron scattering cross-section. We found a polarization produced by single and double (Figure 1) scattering of unpolirazed electron beams because by the spin-orbit interaction (Figure 2 and Figure 3). We would like to stress that, the polarization is caused by non-magnetic GaAs/InAs semiconductor structures without external magnetic fields. We should mention, that in the Anomalous Hall effect the Hall angle is proportional to the Sherman function at the Fermi energy shell. Our calculation results for three-dimensional random arrays of small semiconductor quantum dots (antidotes) suggest a small but measurable magnitude of the angle for antidotes (Figure 4). The anomalous Hall effect produced by quantum antidots is expected to be reduced by the electron impurity scattering, but should still have a significant magnitude. This effect is potentially useful in integrated electron spin-polarization devices based on all-semiconductor heterostructures.

三 Spin-dependent scattering from impurities in two-dimensional channels.

In two-dimensional quantum wells, the spin-dependence of the scattering processes is expected to be stronger than in the bulk because of the localization of electrons' wave-functions in the conduction channel and well known peculiarities in the two-dimensional electron elastic scattering cross section. It should be noted, that the problem remains complicated even for a simplest two-dimensional electron motion because in general the spin-orbit interaction should be described by a three-dimensional model.

Using the delta-doping technique, the Coulomb attractive and repulsive impurities can be precisely placed in heterostructures. It allows us to model theoretically the effect the spin-dependent scattering from the impurities located inside or outside the conductive channel. Most of the theoretical simulations of two-dimensional electron elastic scattering processes from the impurities were conducted in details in the first Born approximation. However, it is well known, when the perturbation theory is used, the dependence on spin in the elastic cross section appears only in the approximation that follows the first Born approximation. For this reason, we used in our calculations of the spin-dependent scattering cross-section the partial wave approach, which was also used in some simulations of the spin-independent elastic scattering cross-section when the first Born approximation is not applicable. In this study we calculated the spin-dependent elastic scattering cross-section for electrons scattered by impurities in two-dimensional heterostructures of III-V semiconductors (Figure 5). We used the effective one band Hamiltonian with the Ben-Daniel-Duke boundary conditions for electronic envelop-functions to calculate the spin-dependent elastic cross-section for electrons scattered from screened repulsive and attractive isolated impurities with the spin-orbit coupling. The impurities are located inside the quantum well. The one electron band effective Hamiltonian and Rashba model of the spin-orbit interaction allow us to calculate the left-right asymmetry in the electron scattering cross-section. We have found a large spin-dependent asymmetry in the elastic cross-section for electrons scattered from impurities in AlInAs/InGaAsAs/AlInAs (Figure 6) and CdTe/InSb/CdTe (Figure 7) symmetrical quantum wells.

The Sherman function amplitude for the CdTe/InSb/CdTe quantum well is predicted to be about 0.05. This could be detected with the anomalous Hall angle at zero magnetic field in the Hall effect measurements. This effect is potentially useful in integrated electron spin-polarization devices based on semiconductor heterostructures. It also can be used as a tool of determination of spin coupling parameters in III-V narrow gap semiconductor heterostructures.

四 Spin-dependent transmission probability for all-semiconductor symmetric barrier structures.

In a zinc-blend crystal with bulk inversion asymmetry (BIA, Dresselhaus type), energy bands are split for a given direction of the electron wave vector. Additional spin splitting in semiconductor quantum structures may also occur owning to the structure confinement potential invention asymmetry (SIA, Rashaba type). We recently proposed that asymmetric (SIA) non-magnetic semiconductor barrier itself could serve as a spin filter. It was demonstrated that spin-dependent electron reflection by in-equivalent interfaces resulted in the dependence of the tunneling transmission probability on the orientation of electron spin. This effect is caused by interface-induced Rashba spin-orbit coupling and can be substantial for resonant tunneling through asymmetric double-barrier or triple-barrier heterostructures. However, in the case of symmetric potential barriers, the Dresselhaus spin-orbit interaction also can lead to a dependence of tunneling on the spin orientation. We calculated the tunneling transmission probability for realistic symmetric tunnel heterostructures with a space-dependent electronic effective mass and spin-splitting parameters and obtained a large spin-filtering effect (Figure 8). The effect could be employed for creating spin filters on the base of type-II strained heterostructures like InAs/GaSb, InSb/GaSb and GaSb/GaAs (Figure 9).

Publications:

1. E. Chen, O. Voskoboynikov, and C. P. Lee, Spin-dependent electron single and double scattering from quantum dots and antidotes, *Solid State Communications* **125** (2003), pp. 381-385.
2. H. C. Huang, O. Voskoboynikov, and C. P. Lee, Spin-orbit interaction and electron elastic scattering from impurities in quantum wells, *Physical Review B*, accepted, to appear in 2003.
3. H. C. Huang, O. Voskoboynikov, and C. P. Lee, Role of spin-orbit interaction in elastic scattering of electrons in quantum wells, *Microelectronics Journal*, accepted, to appear in 2003.
4. H. C. Huang, O. Voskoboynikov, and C. P. Lee, Spin-dependent elastic scattering of electrons in quantum in quantum wells, accepted for presentation in the *Second International Conference and School on Spintronics and Quantum Information Technology (SPINTECH II),* August 4-8, 2003, Brugge (Belgium).

Figures:

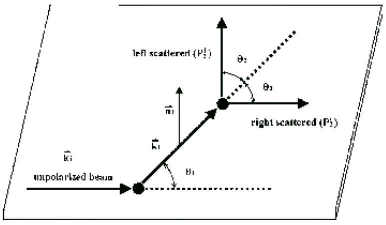


Figure 1. Schematic diagram of single and double scattering.

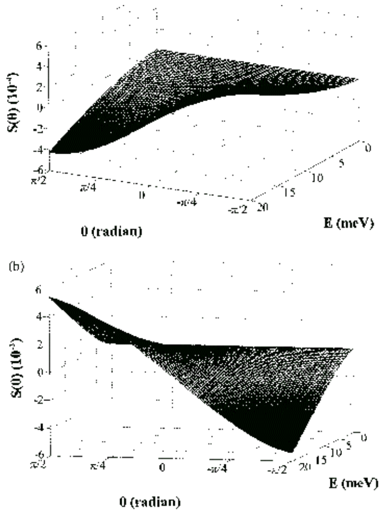


Figure 2. The Sherman function for (a) spherical InAs/GaAs quantum dots (radius- 1.3 nm) and (b) spherical GaAs/InAs antidots (radius- 6 nm). θ is the scattering angle, E is the energy of the electrons

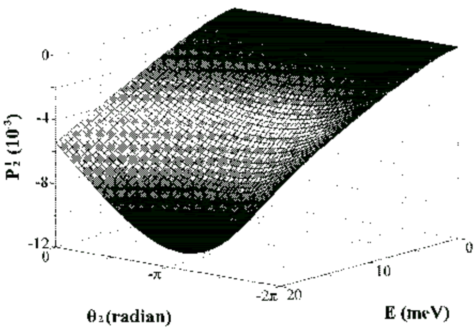


Figure 3. Energy dependence of the left-right double scattering polarization induced by scattering form spherical GaAs/InAs antidots (radius- 6 nm, $\theta_1=\pi/2$).

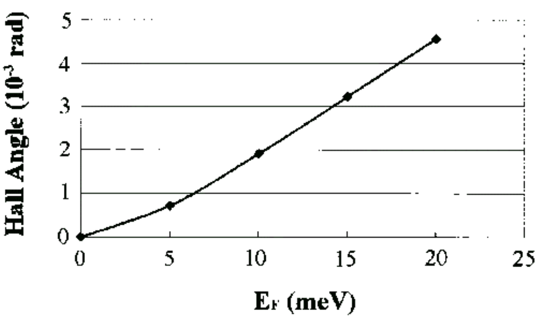
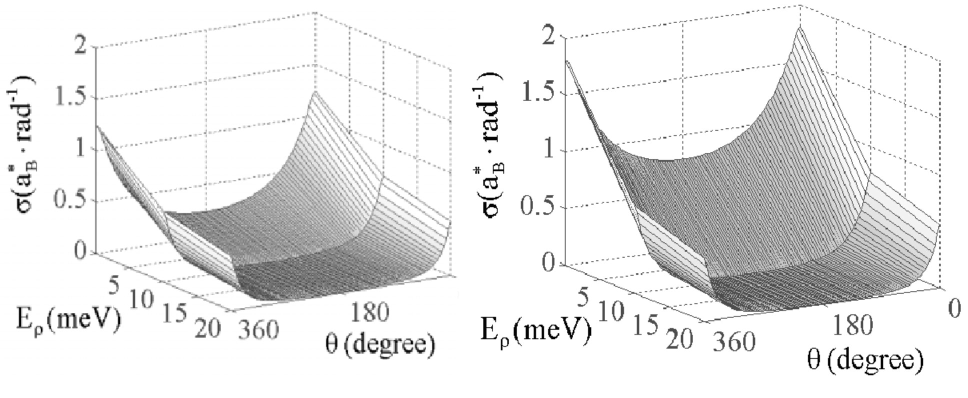
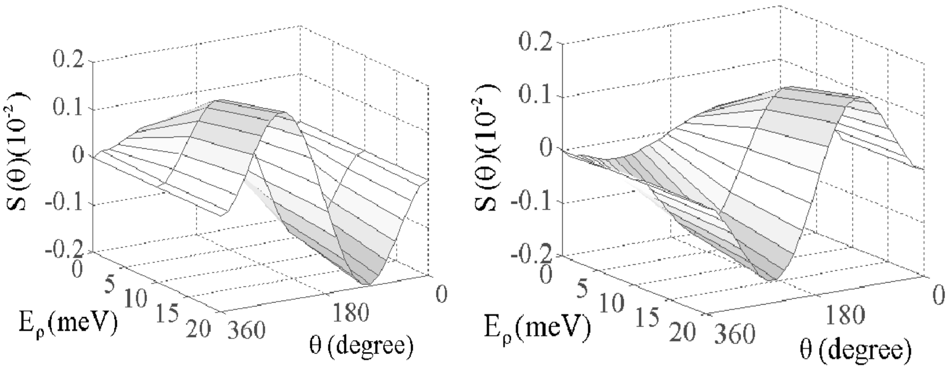


Figure 4. The absolute value of the Anomalous Hall angle for a random array of GaAs/InAs antidots (radius- 6 nm)



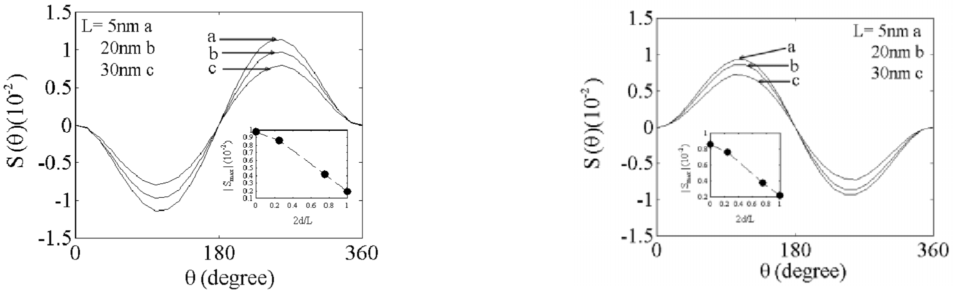
(a) (b)

Figure 5. The elastic scattering cross section for impurities located in the center of AlInAs/InGaAs/AlInAs quantum well (width - 20 nm): (a) repulsive impurity, (b) attractive impurity. $E_\circ$ is the in-plane electronic energy.



(a) (b)

Figure 6. The Sherman function for impurities located in the center of AlInAs/InGaAs/AlInAs quantum well (width - 20 nm): (a) repulsive impurity, (b) attractive impurity.



(a) (b)

Figure 7. The Sherman function for impurities located in the center of CdTe/InSb/CdTe quantum wells with different widths at E_0=0.02 eV: (a) repulsive impurity, (b) attractive impurity.

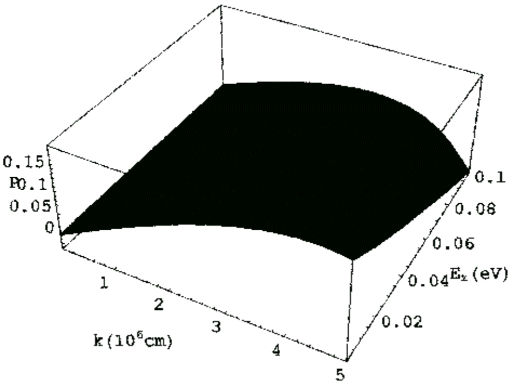


Figure 8. Coefficient of the polarization efficiency **P** as a function of the in-plane to the barrier wave vector **k** and transition energy of electrons for the symmetric InAs/InGaAs/InAs barrier.

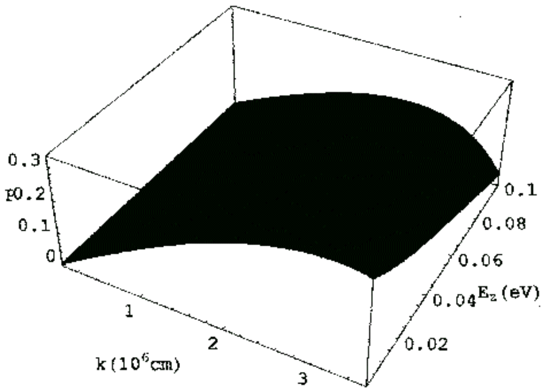


Figure 9. Coefficient of the polarization efficiency **P** as a function of the

in-plane to the barrier wave vector **k** and transition energy of electrons for the symmetric InSb/GaSb/InSb barrier.