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半導體異質結構一致和非一致自旋相依傳輸(2/3)

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計畫主持人：霍斯科
共同主持人：李建平

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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 (2/3)
Coherent and non-coherent spin-dependent transport in semiconductor heterostructures

計畫編號：NSC 92-2112-M-009-015
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一 摘要 (Abstract)

英文

This report summarizes the major results obtained from the second year program of the "Coherent and non-coherent spin-dependent transport in semiconductor heterostructures" project. Three subjects are discussed in the following, the spin-dependent Hall effect appeared in two-dimensional all-semiconductor quantum wells, due to spin-dependent scattering of carriers from impurities in the two-dimensional channels, spin-dependent transmission probability and tunneling time for all-semiconductor symmetric single and double barrier structures. Several publications were performed based on this year's results.

中文

此報告總括我們在「半導體異質結構中一致性與非一致性自旋相依傳輸」計劃中第二年所得之主要結果。有三個主題將在下面討論之，分別為：在二維全半導體量子井中之自旋相依霍爾效應、載子碰撞在二維通道中之雜質所導致的自旋相依散射、全半導體對稱單一位障以及對稱雙位障結構之自旋相依傳輸機率與穿隧時間。根據今年所得之結果我們也發表了些著作。

二 Spin-dependent Hall effect in two-dimensional all-semiconductor quantum wells.

The extra degree of freedom provided by the electron spin may open up a new field for semiconductor devices. The spin-transistor proposed by Datta and Das is an example of a spin-controlled device based on semiconductor two-dimensional (2-D) channels. For this reason theoretical studies of spin-dependent electron processes in two-dimensional semiconductor structures have attracted a lot of interest since a new branch of semiconductor electronics (so called spintronics) has become a focus of study.

In the absence of magnetic impurities and at low temperatures, the main source of the spin-dependent scattering processes is the spin-orbit coupling to local defects. The effect of the spin-orbit interaction on the electron transport and relaxation in 2-D semiconductor systems has been studied for a long time. We recently investigated the spin-dependent scattering processes in the bulk of non-magnetic semiconductors in the presence of the spin-orbit interaction. In semiconductor quantum wells the effect of the spin-orbit interaction on the processes of scattering becomes even more stronger that in the bulk. This is a result of the localization of electrons' wave-functions in the conduction channel. In this part of the project, we investigated a model of the spin-dependent electron scattering from impurities located in the center quantum wells of non-magnetic III-V semiconductors. We calculated contributions from the skew-scattering (SS) and side-jump (SJ) mechanisms to the spin-dependent

Hall effect (SDHE). Our calculation is based on the effective one band Hamiltonian and Rashba type model of the spin-orbit interaction. We have found large spin-dependent Hall angles (SDHA) for AlInAs/InGaAsAs/AlInAs and CdTe/InSb/CdTe symmetrical quantum wells (Figure 1 and Figure 2). For instance, in the CdTe/InSb/CdTe narrow quantum wells SDHA can reach 2.5x10^{-3} rad (Figure 3). This could be detected in the measurements of the Hall effect at low temperatures and this 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. We suggest that experimental investigations should be conducted to verify our theory predictions.

三 Electron spin filtering in all-semiconductor symmetrical tunneling structures.

For the reason of spintonics development the electronic spin polarization (filtering) in solid-state systems has attracted considerable attention. Many possible structures were investigated to reach high level electronic spin filtering and injection. Most of them consist of magnetic material elements. But in principle one can use the all- semiconductor approach utilizing multi-layered nano-systems to generate and detect the electron spin polarization. The semiconductor approach has the advantage of being compatible with conventional semiconductor technology. From this point of view the most important property of semiconductors to be utilized in all semiconductor spintronic nano-devices is the spin-orbit (SO) interaction. The control of spin in semiconductors together with modern semiconductor technology can guarantee the future of the spintronics and result a valuable commercial interest.

In the bulk of III-V and II-VI semiconductor materials the SO interaction lifts the spin-degeneracy of the conduction states in the center of the Brillouin zone. This part of the SO interaction is called the bulk inversion asymmetry (BIA) type and it is presented by the effective Dresselhaus Hamiltonian. Macroscopic effective electric fields in semiconductor nano-structures result the structural inversion asymmetry (SIA) and a linear (on the electron wave-vector **k**) term (or the Rashba type) of the SO interaction. It has been found out recently by us that the Rashba spin-orbit coupling in conventional III-V semiconductor tunnel barrier structures can lead to the spin-dependent tunneling phenomenon. The spin-polarization ratio in tunneling structures is defined as $\mathrm{P}(E_z,\mathbf{k})=\frac{T_+(E_z,\mathbf{k})-T_-(E_z,\mathbf{k})}{T_+(E_z,\mathbf{k})+T_-(E_z,\mathbf{k})}$, where $T_\pm(E_z,\mathbf{k})$ is spin-up(down) tunneling probability and E_Z is the part of the electronic energy which corresponds to the perpendicular motion to the barrier (z-axis), and $\mathbf{k}=(k_x,k_y)$ is parallel to the barrier component of the electronic wave vector. In symmetric structures with the exceptional Rashba interaction included we need to apply an external perpendicular electric field F_Z to generate the asymmetry of the tunneling probability. In the same time asymmetric structures the difference between T_+ and T_- exists with zero external electric field and there is a possibility to reverse the polarization by means of the change of the external electric field F_Z. We further investigated spin-dependent tunneling probability for realistic symmetric tunneling structures with account both the Rashba and Dresselhaus couplings. Our calculation is performed for realistic semiconductor structures on the base of the effective electronic one band Hamiltonian, energy and position dependent electron effective mass approximation, and spin-dependent Ben Daniel-Duke boundary conditions. We demonstrated that the transmission tunneling probability for a realistic symmetric single barrier structure can gain a well recognizable spin dependence for not too large in-plane wave vector of tunneling electrons. In addition one can control the magnitude of the polarization ratio by external electric field (Figure 4). The described effect can be a base for more advanced spin-filtering techniques at zero magnetic field. Our calculation results show that interplay between BIA and SIA interactions makes the spin filtering processes more rich and controllable.

四 Spin-dependent tunneling time for all-semiconductor symmetric barrier structures.

In addition we calculated spin-dependent tunneling tunneling time – a basic characteristic that determines the dynamic range of tunneling devices. There are several quantities used in description of the tunneling process with the dimensions of time. Among them we use the "stationary phase approach" to the tunneling time definition introduced by Bohm. When the spin-orbit splitting effect comes into play, the ratio of the tunneling time between electrons with different spin-polarization can gain a few orders of magnitude. We investigated the spin-dependent resonant tunneling through a symmetric double barrier structure (Figure 5). We also propose that we can manipulate the tunneling time to a great variety by changing the barrier width. The spin-splitting effect is shown to be considerably influential on the tunneling transmission characteristics. The sharp peak of the polarization efficiency and the relative ratio of the delay time provides a possible way to construct a spin filter (Figure 6). The relation between the delay time and the width is simple and can be used as a design rule to select work frequencies.

Publications:

1. H. C. Huang, O. Voskoboynikov, and C. P. Lee, Role of spin-orbit interaction in elastic scattering of electrons in quantum wells, *Microelectronics Journal*, 34 (2003), pp. 687-690.
2. H. C. Huang, O. Voskoboynikov, and C. P. Lee, Spin-dependent Hall effect in semiconductor quantum wells, *Journal of Applied Physics*, 95 (2004), pp. 1918-1922.
3. Leo Yu, H. C. Huang, and O. Voskoboynikov, Electron spin filtering in all-semiconductor tunneling structures, *Superlattices and Microstructures*, accepted, to appear in 2004.

Figures:

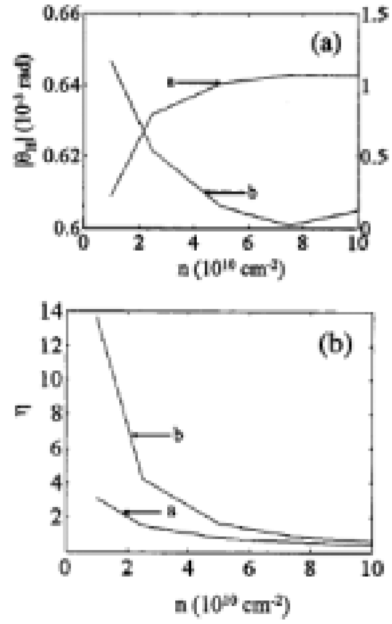

Figure 1. (a) The absolute value of the SDHA in the AlInAs/InGaAs QW and (b) the ratio between SJ and SS input into the angle as the function of the electron concentration (impurity concentration $N_{im}=10^{11}$ cm^{-2}, well width: $L=20$ nm; impurity charge: a: $Z=-1$, b: $Z=+1$).

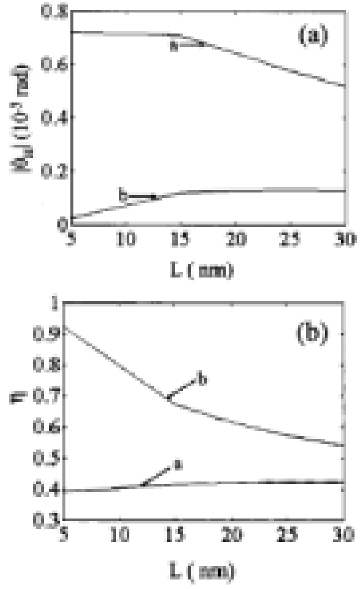

Figure 2. (a) The absolute value of the SDHA in the AlInAs/InGaAs QW and (b) the ratio between SJ and SS input into the angle as the function of the well width (n=$N_{im}=10^{11}$ cm^{-2}, impurity charge: a: $Z=-1$, b: $Z=+1$)

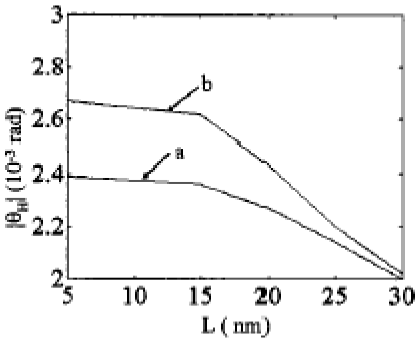

Figure 3. The absolute value of the SDHA in the InSb/CdTe QW with repulsive impurities as the function of the well width ($N_{\rm im}$=10^{11} cm^{-2}, *a*: *n*=5x10^{10} cm^{-2}, *b*: *n*=10^{11} cm^{-2}).

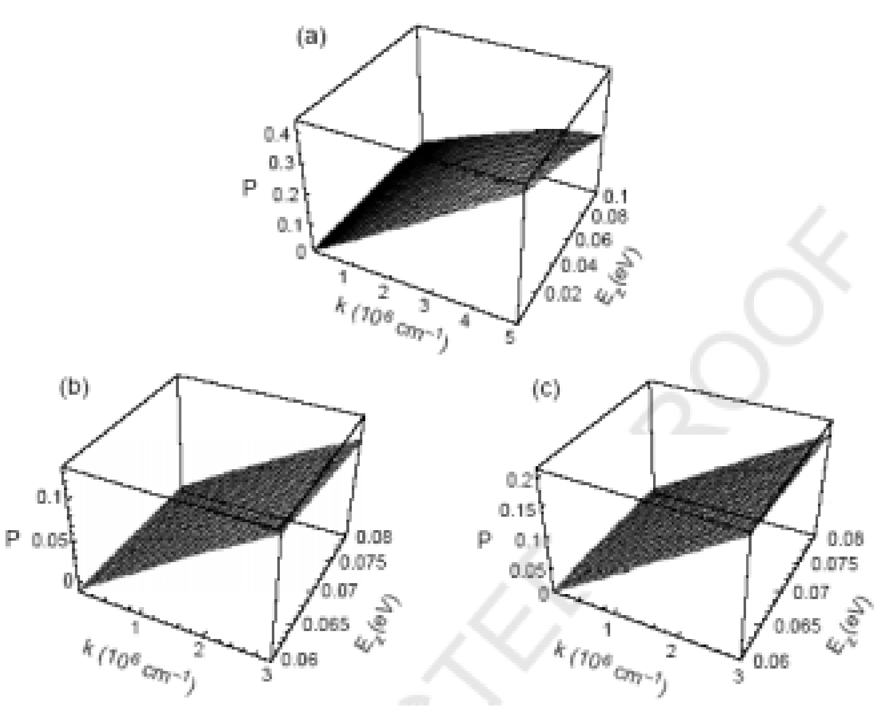

Figure 4. (a) The polarization ratio for $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ symmetric single-barrier structure without an external electric field; (b) the polarization ratio for the same structure with the external electric field $F_z = +5 \times 10^4$ V cm^{-1}; (c) the polarization ratio for the same structure with the external electric field $F_z = -5 \times 10^4$ V cm^{-1}.

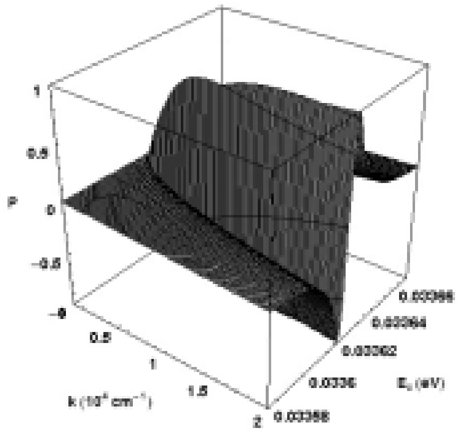

Figure 5. Polarization *P* calculated for 2 x $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ double barrier structure. Barrier width - 60nm, distance between barriers- 120 nm

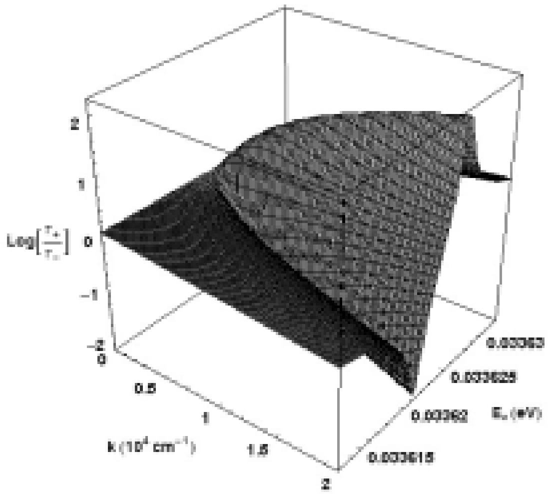

Figure 6. Ratio between the delay time for different polarizations of the electron spin. The structure is the same as in Fig. 5.