Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.788-789

P9-7

Feasibility of Observing a Spin Drag Effect in the Electronic Transport

Yutaka Takahashi[1], Yuuki Sato[2], Fumihiko Hirose[1] and Hitoshi Kawaguchi[1,2]

[1]Department of Electrical Engineering, Yamagata Univ.
4-3-16 Jyonan, Yonezawa, Yamagata 992-8510, Japan
Phone: +81-238-26-3296 E-mail: takahasy@yz.yamagata-u.ac.jp
[2]CREST, Japan Science and Technology Agency
4-1-8 Honmachi, Kawaguchi, Saitama 332-0012, Japan

1. Introduction

Conventional devices in high-tech electronic appliances function on transport of carrier *charges*. Electron-electron (*e-e*) scattering can be neglected in charge transport since *e-e* scattering conserves the total momentum of the system and does not affect the net flow of charges. The mobility is determined by *e*-phonon and *e*-ionized impurity scatterings.

Recently spin dependent electronic transport in nanostructures of semiconductors and metals has been extensively studied to realize novel devices based on carrier *spins*. When the flows of spin-up and -down electrons are separately treated, spin-up electrons move against spin-down electrons and vice versa. In this case the Coulomb scattering between the spin-up electron and the spin-down electron also contributes to the electronic transport. This phenomenon, sometimes called "spin Coulomb drag" or "spin drag" was pointed out by several groups [1-5] but, to the best of authors' knowledge, there is no experimental attempt to detect this phenomenon.

The targets of the present study are to numerically calculate the contribution from *e-e* scattering compared with that from *e*-ionized impurity scattering in a realistic heterostructure of GaAs, and to investigate (i) under what conditions the spin-drag appears remarkably, (ii) whether or how it is detectable, (iii) whether it affects the functions of proposed spintronics devices. We prepared the quantum transport equation, and obtained transport coefficients (mobilities and diffusion coefficients) numerically by solving the transport equation for spin-polarized, two-dimensional electrons in a GaAs heterostructure. (We applied the transport equation to low temperature, 2D degenerate electron system including *e-e* and *e*-ionized impurity scatterings in the present study.)

2. Results

We summarize our findings below.

Drift transport driven by electric field

We first consider the case of drift transport in the spin polarized electrons. We assume that electron distributions are homogeneous ($dn_\pm(\mathbf{r})/d\mathbf{r} = 0$) and the current is driven by the electric field E. ($n_\pm(\mathbf{r})$ is an electron density for spin-up and -down elctrons, respectively. The spin polarization of the system is given by $P = (n_+ - n_-)/(n_+ + n_-)$.) The electric current density is given separately for spin-up and -down electrons by

$$J_\pm = n_\pm q \mu_{nee\pm} E,$$

where q (= -|e| for electrons) is a charge of the particle, and $\mu_{nee\pm}$ is an effective mobility expressed by

$$\mu_{nee\pm} = \mu_{n\pm}\delta_{ee\pm},$$

where $\mu_{n\pm} = q\tau_{imp\pm}/m$ is a normal mobility representing *e*-impurity scattering alone, and $\delta_{ee\pm}$ is a correction factor representing the effect of *e-e* scattering. We show in Fig. 1 (lower two) the temperature dependencies of $\mu_{nee\pm}$ compared with $\mu_{n\pm}$ in 2D electrons in a GaAs heterostructure. (We have calculated for the total electron density $n = n_+ + n_- = 2\times10^{11}\,\mathrm{cm}^{-2}$, ionized impurities of $2\times10^{11}\,\mathrm{cm}^{-2}$ due to the modulation doping separated from the 2D plane by 50 nm, and the inplane impurities of $1\times10^{8}\,\mathrm{cm}^{-2}$. e.g. $n_+ = 1.5\times10^{11}\,\mathrm{cm}^{-2}$ and $n_- = 0.5\times10^{11}\,\mathrm{cm}^{-2}$ for P = 0.5.) The temperature dependence of $\mu_{nee\pm}$ becomes stronger as P increases from 0.1 to 0.5. This trend is different from $\mu_{n\pm}$ as it is independent of temperature for all P. We also show in Fig. 1 (top) the current densities of spin-up and -down electrons and their sum when the electric field E = 10 V/cm is present. Variations of $J_\pm$ are large; J_+ (J_-) decreases (increases) by more than 30%. There are extensive experimental efforts to inject or detect spin polarized current using nonmagnetic-ferromagnetic junctions, but it is still difficult to measure the spin-up and spin-down currents separately. The total current density ($J_+ + J_-$), which is easy to measure, depends on temperature only slightly.

Diffusive transport driven by density gradient

We next consider the case that the current is driven by the density gradient of spin-up and -down electrons, *i.e.*, $dn_\pm(\mathbf{r})/d\mathbf{r} \neq 0$. When *e-e* scattering is included, diffusion currents for spin-up and -down electrons are given by

$$\mathbf{J}_\pm = -qD_{ee\pm}\frac{\partial n_\pm}{\partial \mathbf{r}} - qD'_{ee\pm}\frac{\partial n_\mp}{\partial \mathbf{r}},$$

where $D_{ee\pm}$ and $D'_{ee\pm}$ are diffusion coefficients. It should be noticed that the current of spin-up electrons is driven not only by $\partial n_+/\partial r$, but also by $\partial n_-/\partial r$. When *e-e* scattering is ignored, the spin-up (spin-down) current is driven by $\partial n_+/\partial r$ ($\partial n_-/\partial r$) alone. ($J_\pm = -qD_\pm \partial n_\pm/\partial r$) In actual experimental situations the spatial gradient of electron densities is easily created. One way to achieve this is to generate carriers in the heterostructures or quantum wells of compound semiconductors by tightly focused, circularly polarized light. For example, consider the case that spin-up

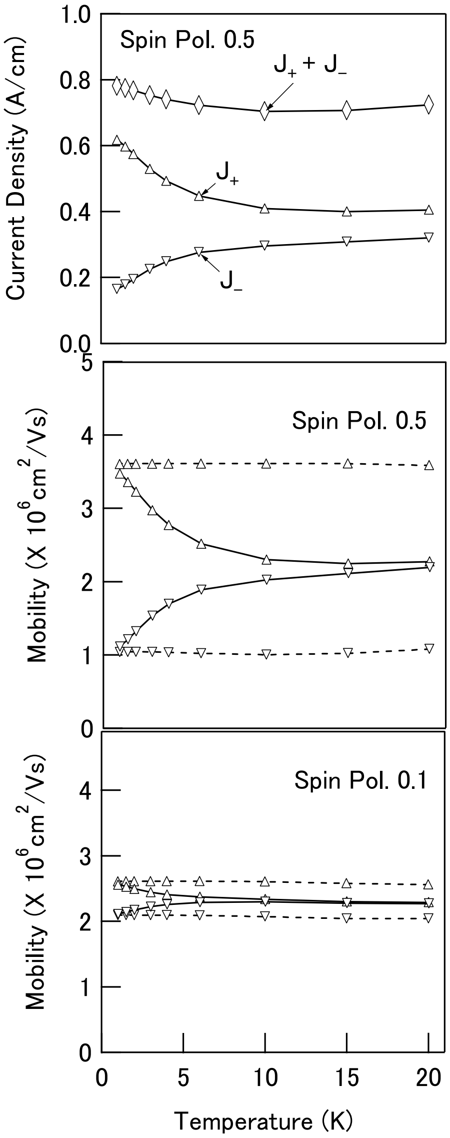

Fig. 1 *Lower two*: Electron mobilities $\mu_{nee\pm}$ (solid lines) and $\mu_{n\pm}$ (dashed lines) for the electron density 2 x 10^{11} cm^{-2}. $\Delta(\nabla)$ for spin-up (spin-down) electrons. *Top*: Electric current densities of spin-up and –down electrons and their sum when the electric field 10 V/cm is applied.

electrons are optically generated in Gaussian density distribution with FWHM of 10 μm and peak density of n_+ = 2.0 x 10^{11} cm^{-2} in the presence of unpolarized 2D electrons of $n_\pm$ = 0.5 x 10^{11} cm^{-2}. Then, we have, in the circular region 5 μm from the center, the distribution with $n = n_+ + n_- = 2\times10^{11}\,\mathrm{cm}^{-2}$, P = 0.5, and $\partial n_+ / \partial r = 1.5\times10^{14}\,\mathrm{cm}^{-3}$ ($\partial n_- / \partial r = 0$). We have calculated the temperature dependencies of current densities in the conditions assumed above. We show the results in Fig. 2. The current densities show strong temperature dependence, much larger than the variation in the field driven transport. It should be noticed that the total current density ($J_+ + J_-$) also shows large variation when the temperature is raised from 1 K to 20 K. (We also plot the current density

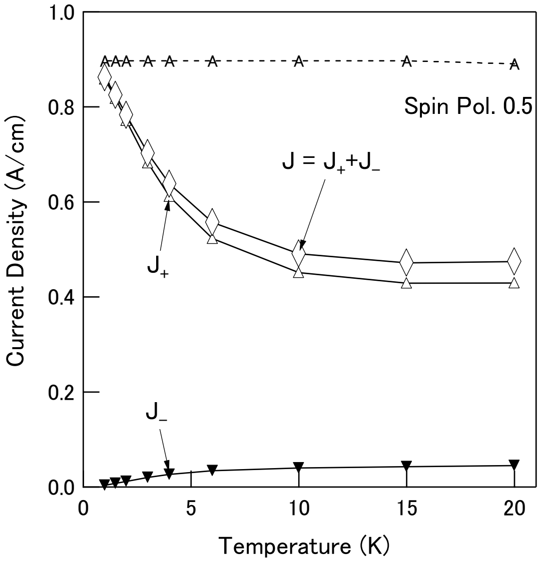

Fig. 2 Electric current densities (solid lines) of spin-up and –down electrons and their sum driven by the electron density gradient $\partial n_+ / \partial r = 1.5\times10^{14}\,\mathrm{cm}^{-3}$. Also shown (dashed line) is a current density when *e-e* scattering is ignored.

of spin-up electrons when *e-e* scatttering is not included. (a dashed line) Its temperature dependence is very small. The current density of spin-down electrons vanishes in this case as $\partial n_- / \partial r = 0$.)

3. Conclusions

We have calculated the transport coefficients (mobilities and diffusion coefficients) of spin-polarized 2D electrons in order to investigate the effect of *e-e* scattering on the electron transport. In the electric field driven drift transport, the current densities J_+ and J_- show characteristic temperature dependence as the spin polarization increases. But the total current ($J_+ + J_-$), which is easy to measure, shows small temperature variation even when P = 0.5. In the diffusion current driven by the density gradients, the total current also shows large variation with temperatures.

We expect this variation can be optically detected by measuring the density profile of electrons in the temporally and spatially resolved PL or pump-probe technique.

Acknowledgements

Y.T. was supported by the Grant-in-Aid for Scientific Research (16560002) from the Japan Society for the Promotion of Science.

References

[1] I. D'Amico and G. Vignale, Phys. Rev. B **62** (2000) 4853.
[2] K. Flensberg, T. S. Jensen, and N. A. Mortensen, Phys. Rev. B **64** (2001) 245308.
[3] Y. Takahashi, K. Shizume, and N. Masuhara, Physica E **10** (2001) 22.
[4] I. D'Amico and G. Vignale, Phys. Rev. B **62** (2000) 4853.
[5] I. D'Amico and G. Vignale, Phys. Rev. B **68** (2003) 045307.