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A Spin Drag Effect in Temperature Dependence of Spin-Polarized Electron Mobilities

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1. Introduction

Electronic transport properties as mobilities are determined by electron-ionized impurity (*e-ion*) scatterings at low temperatures, and electron-phonon (*e-ph*) scatterings at elevated temperatures. In high-quality, modulation-doped heterostructures of III-V semiconductors, mobilities of two-dimensional (2D) electrons increase as temperature is reduced, and approaches the highest value. Electron-electron (*e-e*) scattering has only indirect consequences in charge transport since *e-e* scattering conserves the total momentum of the system and does not affect the net flow of charges. Thus *e-e* scattering is disregarded in conventional analyses of electronic devices.

Recently spin dependent electronic transport in nanostructures of semiconductors and metals has been extensively studied to realize novel devices based on carrier *spins*. In these *spin-polarized* devices concentrations of spin-up and spin-down electrons are different, and transports of spin-up and -down electrons are separately treated. *e-e* scattering between a spin-up electron and a spin-down electron also affects spin-polarized electronic transport. If, initially, spin-up electrons are at rest and spin-down electrons flow, the spin-up electrons start moving by receiving momenta from the spin-down electrons through *e-e* scatterings. This phenomenon, sometimes called "spin Coulomb drag" or "spin drag" was pointed out by several groups [1-4] and there are some experimental attempts to detect this phenomenon.

In this presentation we study the spin drag effect in temperature dependence of mobilities for spin-up and -down electrons, and we investigate (i) conditions (temperature and spin polarization) in which the spin-drag appears distinctively, (ii) whether it is detectable in ordinary experiments, and (iii) whether it affects the functions of proposed spintronics devices. In our previous presentation [5] mobilities were calculated with *e-ion* and *e-e* scatterings alone. However, *e-ph* scattering also influences carrier transport even at low temperatures. In the present study we include *e-ph* scattering to find realistic description of the low temperature transport. Besides, we calculate mobilities with parameters available in a realistic heterostructure of GaAs so that the calculation can be compared with experimental data (when it becomes available).

2. Results: Drift transport driven by electric field

We summarize our findings below.

We applied a transport equation to spin-polarized, degenerate, 2D electrons at low temperatures and obtained transport coefficients (mobilities $\mu_{nee\pm}$ defined below) by numerically integrating collision terms. We consider the case of drift transport of spin polarized electrons driven by electric field. Spin polarization of the system is given by $P=(n_+-n_-)/(n_++n_-)$. Here $n_\pm(\mathbf{r})$ is an electron density for spin-up and -down electrons, respectively. (e.g., P = 0.5 when $n_+=1.5\times10^{11}\,\mathrm{cm}^{-2}$ and $n_-=0.5\times10^{11}\,\mathrm{cm}^{-2}$.) A spin-up electric current density (J_+) and a spin-down electric current density (J_-) are separately treated. They are given by

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

where q (= -|e| for electrons) is a charge of a particle, E is electric field, and $\mu_{nee\pm}\left(=\mu_{n\pm}\delta_{ee\pm}\right)$ is an effective mobility including the contribution from *e-e* scattering as well as *e-ion* and *e-ph* scatterings. $\mu_{n\pm}$ is the mobility due to *e-ion* and *e-ph* scatterings alone. (When $P\to0$, $\mu_{n\pm}$ turns into the conventional mobility μ_n which is commonly measured or calculated in an unpolarized electron system.) $\delta_{ee\pm}$ is a correction factor containing the contribution from *e-e* scattering. ($\delta_{ee\pm}$ approaches unity in the limit of $P\to0$.)

We numerically calculated transport coefficients by selecting parameters so that experiments could be performed in the similar conditions. We consider electrons in a 2D plane of a GaAs heterostructure with an electron sheet density $n=n_++n_-=2\times10^{11}\,\mathrm{cm}^{-2}$. We assume ionized dopants of $2\times10^{11}\,\mathrm{cm}^{-2}$ due to modulation doping separated from the 2D plane by 50 nm, and residual ionized impurities of $1\times10^{8}\,\mathrm{cm}^{-2}$ within the 2D plane. These two types of ions determine the low temperature mobility μ_n of unpolarized electrons. With the ion concentrations given above, the estimated μ_n is $2.4\times10^{6}\,\mathrm{cm}^2/\mathrm{Vs}$. This value of mobility can be experimentally realized in high-quality 2DEG of GaAs/AlGaAs heterointerfaces.

We show in Fig. 1 the temperature dependence of mobilities at P = 0.1 and 0.5. Solid lines are for $\mu_{nee\pm}$ (*e-ion*,

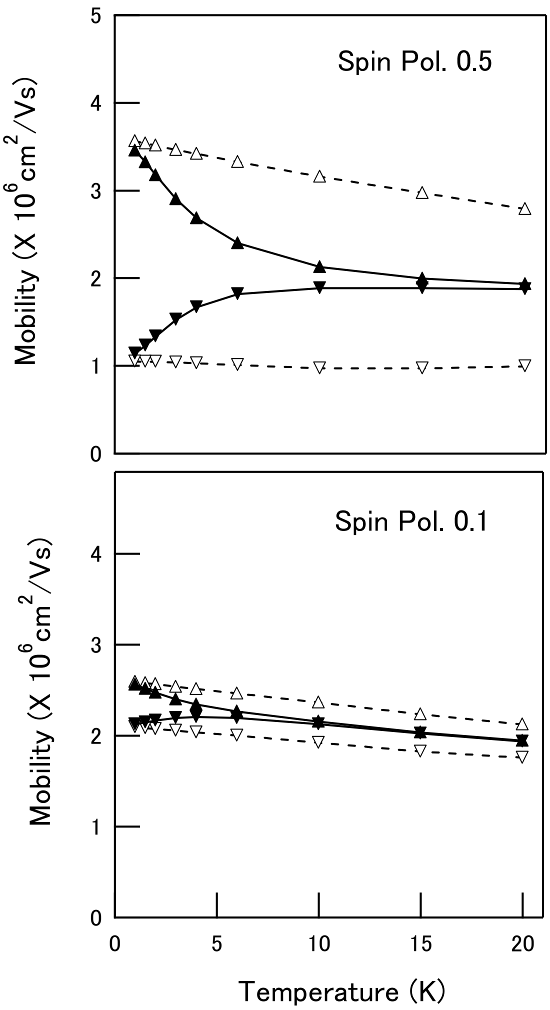

Fig. 1 Electron mobilities $\mu_{\mathrm{nee}\pm}$ (solid lines) and $\mu_{\mathrm{n}\pm}$ (dashed lines) for the electron density 2 x 10^{11} cm^{-2}. ▲ and Δ for spin-up electrons, and ▼ and ∇ for spin-down electrons.

e-ph and *e-e* are included), and dashed lines for $\mu_{n\pm}$ (*e-ion* and *e-ph*). *e-ph* scattering causes slight (and almost linear) decrease of the mobility as the temperature is raised, which is seen in the plots of $\mu_{n\pm}$. As *e-e* scattering is included, $\mu_{nee\pm}$ show distinctive temperature dependence. We notice in the down-spin (minority-spin) mobilities that μ_{nee-} is larger than μ_{n-} at all temperatures although the additional scattering process (*e-e*) is included in the former. This is caused by Spin-Drag. A drift velocity of an up-spin (majority-spin) electron is faster than a down-spin (minority-spin) electron. In the *e-e* scattering a minority-spin electron which is moving at slower velocity receives momentum from a majority-spin electron which is moving faster, and the minority-spin electron is *accelerated*.

We show in Fig. 2 the current densities of spin-up and -down electrons and their sum when the electric field E = 10 V/cm is applied. The spin-up current (J_+) *decreases* by 40% from 1 K to 20 K, while the spin-down current (J_-) *increases* by almost two-fold. Thus the spin-drag effect would be detected in the resistivity measurement if J_+ and J_- could be measured separately. (Spin-dependent current detection is still difficult, to our regret.) We also show the

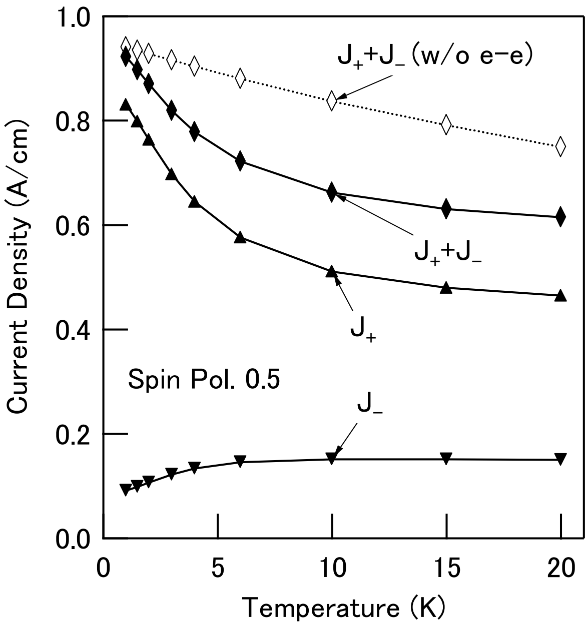

Fig. 2 Electric current densities of spin-up (▲) and -down (▼) electrons and their sum (♦) driven by the in-plane electric field 10 V/cm. Also shown (dotted line) is a current density when *e-e* scattering is ignored.

total current densities (J_+ +J_-), which is easy to measure, *with* (solid line) and *without* (dotted line) the contribution from *e-e* scattering. The latter shows gradual, linear decrease with temperature, while in the former the total current decreases *sublinearly* from 1 K to 20 K. Thus, even in this case, it is very likely that the effect of *e-e* scattering can be detected in experiments.

3. Conclusions

We have found that (i) the spin-drag effect appears at low temperatures (T < 20 K) in high quality 2DEG (μ_n ~ 10^6 cm^2/Vs). The effect is large in highly spin-polarized electrons. (ii) The total current densities (J_+ +J_-) including the effect of *e-e* scattering shows characteristic sublinear temperature dependence, different from the linear temperature dependence of the total current without *e-e* scattering. We expect this sublinear temperature dependence of total current is a detectable signature of *e-e* scattering.

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