§29. Thermoelectric Effects in a Pseudo-one-dimensional Electron Gas with a Spin-orbit Interaction

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In semiconductor spintronics, the electron's spin degree of freedom rather than its electric charge plays the main role in transport, processing and storage of information. We consider thermoelectric effects in a pseudo-one-dimensional electron gas (P1DEG) with a spin-orbit interaction (SOI). The SOI splits the dispersion relation of the P1DEG into subbands with an energy gap.

The SOI is proportional to $(\vec{E} \times \vec{p}) \cdot \vec{S}$, where $\vec{E}$ is the electric field, $\vec{p}$ the momentum and $\vec{S}$ the spin of the electron. As typical SOIs in III-V semiconductor heterostructures, the Rashba SOI (RSOI) and the Dresselhaus SOI (DSOI) are often discussed [1)].

In the thermoelectric effect, an electrochemical potential gradient or a temperature gradient applied to the P1DEG induces an electric current and a heat current. We found by means of theoretical calculation that the transport coefficients of the P1DEG with the RSOI oscillates as the electrochemical potential is changed.

In the present paper, we apply not only the electrochemical potential gradient (i.e., voltage bias) but also a temperature gradient along the x direction (Fig.1). A P1DEG system connects particle baths with a temperature and an electrochemical potential (T_ℓ, μ_ℓ) on the left and $(T_{\rm r}, \mu_{\rm r})$ on the right. The system Hamiltonian is given by

$$\hat{\mathcal{H}} = \frac{\hat{p}_x^2 + \hat{p}_y^2}{2m^*} + \alpha_{\rm RSO} \left(\hat{p}_x \hat{\sigma}_y - \hat{p}_y \hat{\sigma}_x\right), \qquad (1)$$

where m^* is the effective mass of an electron and $\alpha_{\rm RSO}$ the strength of the Rashba interaction. We impose the periodic boundary conditions in the y direction as in the previous work [2)]. To compute the linear response, we put $T_\ell = T - \Delta T/2$, $T_{\rm r} = T + \Delta T/2$, $\mu_\ell = \mu - \Delta\mu/2$ and $\mu_{\rm r} = \mu + \Delta\mu/2$ with $\Delta T \ll T$ and $\Delta\mu \ll \mu$.

The Hamiltonian (1) can be diagonalized and the eigenvalues are obtained. We choose the y direction as the quantization axis of the electron spin. We calculated the electric current $I_{\rm e}$ and the heat current $I_{\rm Q}$ in the x direction carried by electrons. The total electric current and the total heat current are given by

$$I_{\rm e}^{\rm total} = \tilde{\sigma}\left(-\Delta\mu/e\right) - \tilde{\epsilon}\Delta T, \qquad (2)$$

$$I_{\rm Q}^{\rm total} = \tilde{\pi}\left(-\Delta\mu/e\right) - \tilde{\lambda}\Delta T, \qquad (3)$$

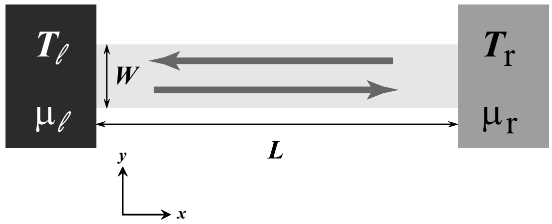

Fig. 1: A quantum wire under electrochemical potential and temperature gradients. The temperature and the electrochemical potential of the left particle bath are T_ℓ and μ_ℓ, respectively. Those of the right particle bath are $T_{\rm r}$ and $\mu_{\rm r}$.

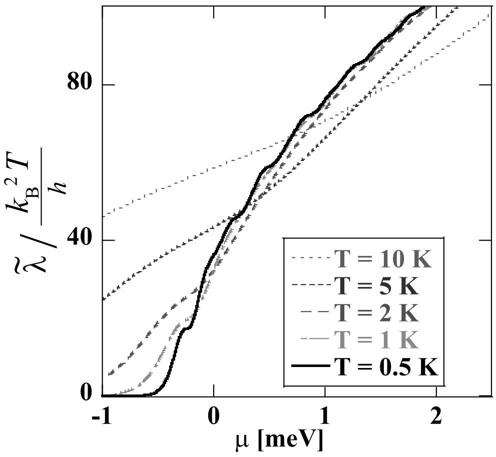

Fig. 2: The transport coefficient $\tilde{\lambda}$ against the electrochemical potential μ.

where $\tilde{\sigma}, \tilde{\pi}$ and $\tilde{\lambda}$ are the transport parameters. We confirm that the Onsager relation $\tilde{\pi} = T\tilde{\epsilon}$ is fulfilled. One of he transport coefficients $\tilde{\lambda}$ is shown in Fig. 2, where we used the same values for an InGaAs/InAlAs heterojunction as in the previous work [2)]: $\alpha_{\rm RSO}\hbar = 3 \times 10^{-11}$ eV·m and $m^* = 0.041\ m_{\rm e}$. We also set $W = 1\mu$m.

Figure 2 shows the electrochemical potential dependence of $\tilde{\lambda}$ at T =10, 5, 2, 1, and 0.5 K. As the temperature T decreases, $\tilde{\lambda}$ has narrower plateaus than $\tilde{\sigma}$ does.

We have predicted that transport coefficients $\tilde{\sigma}, \tilde{\epsilon}, \tilde{\pi}$ and $\tilde{\lambda}$ have quantum oscillations in the SOI system. These quantum oscillations appear around subband edges. If there are no SOIs ($\alpha_{\rm RSO} = 0$) in the present hamiltonian (1), all bands are degenerated to the one band $\epsilon = \hbar^2 k^2/2m^*$. Therefore, the quantum oscillation disappears in the case of $\alpha_{\rm RSO} = 0$.

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1) N. Hatano, R. Shirasaki and H. Nakamura, *Phys. Rev. A* 75, 032107 (2007).

2) N. Hatano, R. Shirasaki and H. Nakamura, *Solid State Commun.* 141, 79 (2007).