両極性伝導体の電荷・スピン輸送によるエントロピー生成
Entropy production for charge and spin currents in bipolar conductors

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Taniguchi has theoretically revealed the influence of spin current on the entropy production rate in presence of an electric field and temperature gradients, and shows that the spin current contributes the entropy production (Joule heating), though it is a factor of approximately 200 small compared with that due to charge current in nonmagnetic heavy metals [1]. The Joule heating due to the spin current is accounted for by the inverse spin Hall effect (ISHE), through which the spin current is transformed to the transverse charge current. The formulation developed by Taniguchi is applicable regardless of the source of spin current, i.e., an electric field, a temperature gradient, or the Hall effect. In the present study, we apply his approach to bipolar conductors in which both holes and electrons contribute to charge, spin, and heat transport. Let T, S, $\vec{E}$, $n_{\uparrow(\downarrow)}$, $\tau_{\uparrow\downarrow(\downarrow\uparrow)}$ be temperature, entropy, electric field, total up (down) spin densities, and spin relaxation times, the entropy production rate $\partial S/\partial t$ is expressed in terms of heat current density $\vec{j}_Q$, charge current density $\vec{j}_C$, hole spin current density $\vec{j}_S^{(h)}$, and electron spin current density $\vec{j}_S^{(e)}$ as

$$\frac{\partial S}{\partial t}+\mathrm{div}\,\frac{\vec{j}_Q}{T}$$
$$=\vec{j}_Q\cdot\mathrm{grad}\,\frac{1}{T}+\frac{1}{T}\vec{j}_C\cdot\vec{E}-\frac{1}{\hbar T}\left(\vec{j}_S^{(h)}+\vec{j}_S^{(e)}\right)\cdot\mathrm{grad}\left(\Delta\mu^{(h)}+\Delta\mu^{(e)}\right)-\frac{1}{\hbar T}\left(\vec{j}_S^{(h)}-\vec{j}_S^{(e)}\right)\cdot\mathrm{grad}\left(\Delta\mu^{(h)}-\Delta\mu^{(e)}\right) \quad (1)$$
$$+\frac{1}{T}\left(\frac{n_\uparrow}{\tau_{\uparrow\downarrow}}-\frac{n_\downarrow}{\tau_{\downarrow\uparrow}}\right)\left(\Delta\mu^{(h)}+\Delta\mu^{(e)}\right),$$

where $2\Delta\mu^{(h)}$ and $2\Delta\mu^{(e)}$ are the spin splittings in the chemical potentials for holes and electrons, respectively. We assumed the identical characters between holes and electrons, i.e., $n_\uparrow^{(h)}=n_\uparrow^{(e)}\left(\equiv 1/2\,n_\uparrow\right)$, $n_\downarrow^{(h)}=n_\downarrow^{(e)}\left(\equiv 1/2\,n_\downarrow\right)$, $\tau_{\uparrow\downarrow}^{(h)}=\tau_{\uparrow\downarrow}^{(e)}\left(\equiv\tau_{\uparrow\downarrow}\right)$, and $\tau_{\downarrow\uparrow}^{(h)}=\tau_{\downarrow\uparrow}^{(e)}\left(\equiv\tau_{\downarrow\uparrow}\right)$ when obtaining Eq. (1). It follows from Eq. (1) and the condition $\Delta\mu^{(h)}+\Delta\mu^{(e)}=0$ that the spin current does not contribute to the entropy production and instead the difference between the hole and electron spin currents, which is named in the present study "conjugated spin current", contributes to it. The condition $\Delta\mu^{(h)}+\Delta\mu^{(e)}=0$ is identical to the condition $\Delta E^{(h)}=\Delta E^{(e)}$, i.e., equal spin dependent effective electric field ΔE between holes and electrons [2]. In this case, the Onsager's reciprocal theorem holds between the charge and the conjugate spin currents, but it is violated between the charge and spin currents for the identical character case between holes and electrons [2].

[1] T. Taniguchi, Appl. Phys. Express **9**, 073005(2016).
[2] M. Sakai et al., Jpn. J. Appl. Phys. (in press).

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