Entropy production by thermodynamic currents in ambipolar conductors; the case of antiparallel spin polarization for hole and electron

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In our previous study[1], we derived a theoretical formula of the entropy production rate for ambipolar conductors: $\frac{\partial S}{\partial t} + \mathrm{div}\frac{J_Q}{T} = \boldsymbol{J}_Q \cdot \mathrm{grad}\frac{1}{T} - \frac{1}{T}\boldsymbol{J}_c \cdot \mathrm{grad}\,V - \frac{1}{\hbar T}\left(\boldsymbol{J}_s^{(h)} + \boldsymbol{J}_s^{(e)}\right) \cdot \mathrm{grad}\left(\Delta\mu^{(h)} + \Delta\mu^{(e)}\right) - \frac{1}{\hbar T}\left(\boldsymbol{J}_s^{(h)} - \boldsymbol{J}_s^{(e)}\right) \cdot \mathrm{grad}\left(\Delta\mu^{(h)} - \Delta\mu^{(e)}\right) - \frac{1}{\hbar T}\mathrm{div}\left(\boldsymbol{J}_s^{(h)}\Delta\mu^{(h)} + \boldsymbol{J}_s^{(e)}\Delta\mu^{(e)}\right)$ (1)
which showed that spin injection in ambipolar conductor results in the flow of two types of spin current, parallel spin current $\boldsymbol{J}_s^{(h)} + \boldsymbol{J}_s^{(e)}$ and antiparallel spin current $\boldsymbol{J}_s^{(h)} - \boldsymbol{J}_s^{(e)}$ and both contribute to the entropy production. Also spin injection in bipolar conductor induces imbalance between up spin and down spin chemical potentials of electrons and holes. When spin injection is achieved under constant temperature and pressure, the Gibbs-Duhem relation can be applied to bipolar conductors for getting a relationship between chemical potential of electrons $\mu^{(e)}$ and holes $\mu^{(h)}$. In terms of carrier spin polarization $P^{(h/e)} = \frac{n_\uparrow^{(h/e)} - n_\downarrow^{(h/e)}}{n_\uparrow^{(h/e)} + n_\downarrow^{(h/e)}}$ and charge polarization $\Phi = \frac{n^{(h)} - n^{(e)}}{n^{(h)} + n^{(e)}}$, the Gibbs-Duhem relation takes the following form:

$$(d\mu_\uparrow^{(h)} + d\mu_\downarrow^{(h)} + d\mu_\uparrow^{(e)} + d\mu_\downarrow^{(e)}) + \Phi(d\mu_\uparrow^{(h)} + d\mu_\downarrow^{(h)} - d\mu_\uparrow^{(e)} - d\mu_\downarrow^{(e)}) + P(-d\mu_\uparrow^{(h)} + d\mu_\downarrow^{(h)} + d\mu_\uparrow^{(e)} - d\mu_\downarrow^{(e)})$$
$$+ \Phi P(d\mu_\uparrow^{(h)} - d\mu_\downarrow^{(h)} - d\mu_\uparrow^{(e)} + d\mu_\downarrow^{(e)}) = 0. \quad (2)$$

In the above formulation we consider that $-P^{(h)} = P^{(e)} \equiv P \neq 0$; in the previous study [2] we considered $P^{(h)} = P^{(e)}$. Now we assume that $d\mu_\uparrow^{(h)} = -d\mu_\downarrow^{(h)} (\equiv -\Delta\mu^{(h)})$ and $d\mu_\uparrow^{(e)} = -d\mu_\downarrow^{(e)} (\equiv -\Delta\mu^{(e)})$. By applying these assumptions in Eq. (2) yields: $(1+\Phi)\Delta\mu^{(h)} + (1-\Phi)\Delta\mu^{(e)} = 0$. In the bipolar conductors with very small charge polarization value ($\Phi \ll 1$), the above equation reduces to $\Delta\mu^{(h)} - \Delta\mu^{(e)} = 0$. Substituting this relation in Eq. (1) gives:

$$\frac{\partial S}{\partial t} + \mathrm{div}\frac{J_Q}{T} = \boldsymbol{J}_Q \cdot \mathrm{grad}\frac{1}{T} - \frac{1}{T}\boldsymbol{J}_c \cdot \mathrm{grad}\,V - \frac{1}{\hbar T}\left(\boldsymbol{J}_s^{(h)} + \boldsymbol{J}_s^{(e)}\right) \cdot \mathrm{grad}\left(\Delta\mu^{(h)} + \Delta\mu^{(e)}\right) - \frac{1}{\hbar T}\mathrm{div}\left(\boldsymbol{J}_s^{(h)} + \boldsymbol{J}_s^{(e)}\right)\Delta\mu \,. \quad (3)$$

Eq. (3) indicates that parallel spin current contributes to entropy production and it is analogous to single carrier case while antiparallel spin current does not take part in entropy generation because it is not accompanied with the spatial increment of Gibbs free energy during the flow of antiparallel spin current hence no spin relaxation is required for continuous flow of antiparallel spin current.

[1] Aktar MST Sanjida and M. Sakai " Entropy production of bipolar conductors in spin Hall geometry" presented in 65th JSAP spring meeting on March 2018.

[2] Aktar MST Sanjida, M. Sakai, O. Nakamura, S. Hasegawa " Thermodynamical consideration of spin dependent chemical potentials in bipolar conductors with identical characters between holes and electrons" presented in 79th JSAP Autumn meeting on September 2018.