Thermodynamical consideration of spin dependent chemical potentials in bipolar conductors with identical characters between holes and electrons

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Imbalance between up spin and down spin chemical potentials are caused by spin injection and induces a spin diffusion current in spintronics devices. The application of Gibb's-Duhem equation (GDE) to single carrier conductors with spin-up and spin-down electrons yields a relation, $\Delta\mu_\alpha + \Delta\mu_\beta = 0$, where $\Delta\mu_\alpha$ and $\Delta\mu_\beta$ are the up and down spin chemical potential shifts due to the spin injection. The present study applies GDE to bipolar conductors in which both holes and electrons have approximately identical characters, i.e., a very small charge polarization Φ, which is defined as $\Phi \equiv (n_h - n_e)/(n_h + n_e)$. As a results, we have derived an equation:

$$\Delta\mu^h\,(1+\Phi) + \Delta\mu^e\,(1-\Phi) = 0 \tag{1}$$

In the above formulation, we assumed the same spin polarization between holes and electrons and $\mu_\alpha^h = -\Delta\mu_\beta^h \equiv \Delta\mu^h,\ \Delta\mu_\alpha^e = -\Delta\mu_\beta^e \equiv \Delta\mu^e$. Eq. (1) establishes a relation between the chemical potentials of holes and electrons and states that if the chemical potential of spin-up holes increases, the chemical potential of spin-up electrons will decrease accordingly.

Our previous study on entropy (S) production rate calculation in spin Hall geometry of bipolar conductors revealed that the entropy production rate $\partial S/\partial t$ is given in terms of heat current density $\boldsymbol{J}_Q$, charge current density $\boldsymbol{J}_c$, hole spin current density $\boldsymbol{J}_s^{(h)}$ and electron spin current density $\boldsymbol{J}_s^{(e)}$ as [1]

$$\frac{\partial S}{\partial t} + div\frac{J_Q}{T} = \boldsymbol{J}_Q.grad\frac{1}{T} + \frac{1}{T}\boldsymbol{J}_c.\boldsymbol{E} - \frac{1}{\hbar T}\left(\boldsymbol{J}_s^{(h)} + \boldsymbol{J}_s^{(e)}\right).grad(\Delta\mu^{(h)} + \Delta\mu^{(e)}) - \frac{1}{\hbar T}\left(\boldsymbol{J}_s^{(h)} - \boldsymbol{J}_s^{(e)}\right).grad\ (\ \Delta\mu^{(h)} - \Delta\mu^{(e)}) + \frac{1}{T}\left(\frac{n_\uparrow}{\tau_{\uparrow\downarrow}} - \frac{n_\downarrow}{\tau_{\downarrow\uparrow}}\right)(\Delta\mu^{(h)} + \Delta\mu^{(e)}) \tag{2}$$

Now, if we assume $\Phi = 0$ Eq. (1) reduces to $\Delta\mu^h + \Delta\mu^e = 0$, which was used as an assumption in our interpretation of the Hall effect in yttrium dihydride.[2] Imposing this relation in Eq. (2) gives:

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

Equation (3) implies that the usual spin current in bipolar conductor does not contribute to entropy production rather the difference between hole and electron spin currents, which is named "conjugated spin current" in the present study, contributes to the entropy production.

[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] M. Sakai et al., "Resonant Hall effect under generation of a self-sustaining mode of spin current in nonmagnetic bipolar conductors with identical characters between holes and electrons", Jpn. J. Appl. Phys. **57**, 033001 (2018).