Spin Hall effect in non-equilibrium Cu-based binary alloys

IMR, Tohoku Univ.[1], NIMS[2], CSRN, Tohoku Univ.[3], JST PRESTO[4], and CSIS, Tohoku Univ.[5],

○H. Masuda[1], R. Modak[2], T. Seki[1,2,3], K. Uchida[1,2,3], Y. Lau[1,3], Y. Sakuraba[2,4], R. Iguchi[2], and K. Takanashi[1,3,5]

E-mail: masuda1610@imr.tohoku.ac.jp

Generation and detection of spin current ($\mathbf{J}_s$), which is a spin angular momentum flow, are the key for spintronics. In order to improve the device performance and offer multi-functionalities, highly efficient conversion between charge current ($\mathbf{J}_c$) and $\mathbf{J}_s$ is indispensable. A way for the conversion from $\mathbf{J}_c$ to $\mathbf{J}_s$ is to exploit the spin Hall effect (SHE), in which the conversion efficiency is given by the spin Hall angle (α_{SH}). Thus, a nonmagnet showing large α_{SH} is required for high-efficient spintronic devices. Heavy metals such as Pt, Ta, and W are representatives of spin Hall materials at present because those simple heavy metals have potential to be incorporated into the existing spintronic device architecture. Aside from the usage of a simple nonmagnetic metal, element doping or alloying is also an effective way to develop spin Hall materials. Cu-Ir system [Ref.1-4] is an interesting spin Hall material because neither Cu nor Ir exhibits remarkable SHE. Niimi *et al.* [Ref.1] investigated the SHE of Ir-doped Cu with an Ir concentration range of 1% to 12%, which exhibited $\alpha_{SH} \sim 2.1$ %. It was also reported that the Cu doped with a very small amount of Bi (less than 0.5%) also showed even larger SHE [Ref.5]. Cu-based spin Hall materials are also advantageous from the perspective of practical applications because of its compatibility to the standard integrated circuit interconnection technology. In spite of the attracting features, the comprehensive study on SHE for the non-equilibrium Cu-based binary alloys is very limited.

In this study, we comprehensively carried out a study on the SHE of non-equilibrium Cu-Ir and Cu-Bi binary alloys by exploiting a combinatorial technique based on the thermal imaging for a composition-spread film [Ref.6]. We utilized the spin Peltier effect (SPE), which is the phenomenon of heat current generation in a linear response to $\mathbf{J}_s$ injection, as a probe of the spin-charge current conversion. The active infrared emission microscopy called the lock-in thermography allowed us to visualize the temperature modulation due to the SPE (ΔT^{SPE}), and to reveal the spatial distribution of ΔT^{SPE} in the composition-spread films. From the thermal images, we have found that the optimum Ir concentration for enhancing SHE of Cu-Ir is around 25 at.%, which corresponds to the region beyond the solubility limit and is not thermodynamically stable in the bulk phase diagram. We also evaluated α_{SH} of the $Cu_{76}Ir_{24}$ alloy using $Cu_{76}Ir_{24}$/CoFeB bilayer. We obtained $\alpha_{SH} = 6.29 \pm 0.19$ % using the harmonic Hall voltage measurements. This remarkable α_{SH} suggests that the non-equilibrium Cu-Ir alloy is a candidate of spin Hall material. In contrast to the Cu-Ir, non-equilibrium Cu-Bi binary alloys showed no remarkable SHE.

[1] Y. Niimi *et al.*, *Phys. Rev. Lett.* **106**, 126601 (2011). [2] M. Yamanouchi *et al.*, *Appl. Phys. Lett.* **102**, 212408 (2013). [3] J. Cramer *et al.*, *Nano Lett.* **18**, 1064 (2018). [4] H. Masuda *et al.*, *Phys. Rev. B* **101**, 224413 (2020). [5] Y. Niimi *et al.*, *Phys. Rev. Let.* **109**, 156602 (2012). [6] K. Uchida *et al.*, *Sci. Rep.* **8**, 16067 (2018).

