Spin Hall effect of non-equilibrium Cu-Ir binary alloy

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Generation and detection of spin current ($\mathbf{J}_s$), which is a spin angular momentum flow, are the keys for spintronics. In order to improve the device performance and provide with 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 the building block of contemporary spintronics. 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. Apart from the usage of a simple nonmagnetic metal, element doping or alloying is also effective ways to develop spin Hall materials. Niimi *et al.* [Ref.1] investigated the SHE of Ir-doped Cu with the Ir concentration range between 1% and 12%, which exhibited the large α_{SH}. The Cu-based SH material is also advantageous from the viewpoint of practical applications because of its compatibility to the standard integrated circuit interconnection technology [Ref.2]. In spite of the attracting features of Cu-Ir, the comprehensive study on SHE for the Cu-Ir binary alloys is very limited [Ref.3]. This might be because the solubility limits are low at both Cu-rich and Ir-rich sides, which are less than 10 %, in the Cu-Ir binary phase diagram.

In this study, we carried out a comprehensive study on the SHE of Cu-Ir binary alloys by exploiting a combinatorial technique based on the thermal imaging for a composition-spread film [Ref.4]. We utilized the spin Peltier effect (SPE), which is the phenomenon of a 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 spin Hall efficiency is maximized at the composition of $Cu_{78}Ir_{22}$, which corresponds to the non-equilibrium Cu-Ir and is not thermodynamically stable in the bulk phase diagram. We also quantitatively analyzed the spin Hall efficiency for the $Cu_{78}Ir_{22}$ / Co bilayer, and its damping-like torque efficiency was obtained to be 3.9 %, suggesting that the non-equilibrium Cu-Ir alloy is a candidate of spin Hall material.

[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] K. Uchida *et al.*, *Sci. Rep.* **8**, 16067 (2018).