Influence of the interface quality on the estimation of the spin-to-charge conversion efficiency in spin pumping experiments on $Co_2FeAl_{0.5}Si_{0.5}$/*n*-Ge

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In spintronics, which is expected to overcome the limitations of CMOS technology, achieving highly efficient spin injection/detection and conversion is extremely important. Spin pumping is believed to be a very efficient way to inject a spin current from a ferromagnetic (FM) layer to a non-magnetic (NM) layer using ferromagnetic resonance. However, generally, the influence of the quality of the FM/NM interface, which is thought to affect the spin injection efficiency and thus the estimation of the spin Hall angle θ_{SHE}, has not been intensively discussed. If the efficiency strongly depends on the interface quality, controlling the interface is indispensable to realize efficient control of a spin current with low power consumption.

In this study, we investigate the influence of the quality of the Heusler/semiconductor interface on the estimation of the spin-to-charge conversion efficiency in the semiconductor in spin pumping measurements. For the experiment, we used a sample composed of $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS) (25 nm)/ P-doped *n*-Ge (doping concentration ~10^{19} cm^{-3})/ undoped Ge(111) grown on a Si(111) substrate via molecular beam epitaxy (Fig. 1). At the interface between CFAS and *n*-Ge, phosphorus δ-doped Ge layers with ultrathin Si layers were inserted to promote the tunneling conduction for spin injection, which also enables the detection of the spin polarized current using four-terminal Hanle-effect measurements [1]. We have prepared the as-grown sample and the one annealed at 300 ℃ for 10 min under N_2 gas at ambient pressure to interdiffuse atoms at the CFAS/ *n*-Ge interface while keeping the same transport property in *n*-Ge [2]. In Ref. [2], the nonlocal spin signal decreased in the CFAS/ *n*-Ge sample after annealing with the same conditions. For these samples, we have carried out spin pumping measurements using a TE_{011} cavity of an electron-spin-resonance system with a microwave frequency of 9.1 GHz and a microwave power of 50 mW. Fig. 2 shows the magnetic-field dependencies of the electromotive force (EMF) at various temperatures. The magnitude of the EMF is quite different between the as-grown [Fig. 2(a)] and annealed samples [Fig. 2(b)]. From these results, θ_{SHE} is estimated to be 0.0015 for the as-grown sample and 0.0077 for the annealed sample at 300 K. Both values are higher than those previously reported for Ge (θ_{SHE}~0.001 [3]), indicating that the crystallinity is very important for the correct estimation of θ_{SHE}. In our presentation, we discuss the correlation between the estimated value of θ_{SHE} and the interface quality in more detail.

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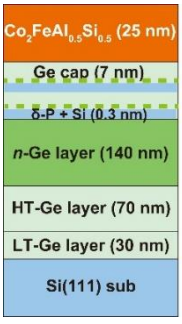

Fig. 1 Schematic sample structure of CFAS/*n*-Ge.

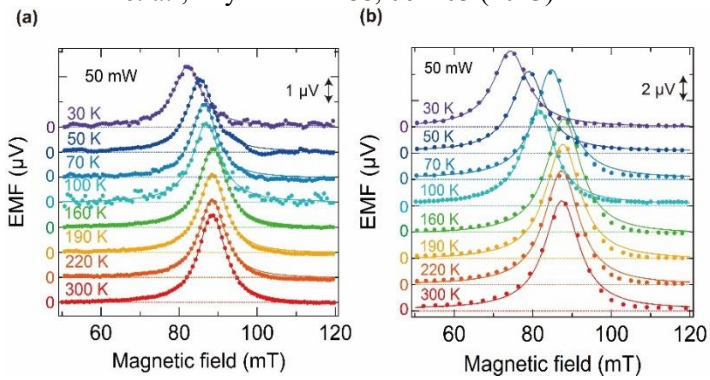

Fig. 2 (a),(b) Magnetic-field dependencies of the EMF at various temperatures measured for the as-grown sample (a) and annealed sample (b) using spin pumping. The magnetic field was applied along the [$\bar{1}$10] direction.