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Nonlinear Effect of Spin Pumping in Microfabricated Devices with Permalloy/Pt

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[Introduction]

The simultaneous utilization of charge and electron spins; spintronics, has attracted much interest because of its potential application to replace the existing semiconductor devices. In order to realize high performance in spintronic devices, it is necessary to establish an effective way for spin injection. Recently, some experiments shows that the spin injection by spin pumping[1], where a precessing magnetization in a ferromagnetic material emits pure spin current into an adjacent material, is effective to overcome the impedance mismatch problem[2]. Although the spin current detected via the inverse spin Hall effect is known to be almost proportional to the excitation power in a linear region of the magnetization precession[3], only a few experiment have been performed in a nonlinear region. In this study, spin pumping was examined with applying a large excitation power to understand the efficiency of spin pumping in the nonlinear region of the magnetization precession.

[Experiments]

Figure 1 shows a schematic illustration of the device structure. The device consists of a Permalloy (Py)(10 nm)/Pt(10 nm) bilayer element with a lateral dimension of 2×50 μm, and a pair of Au electrodes, where both of them are placed on an Au coplanar waveguide (CPW). The devices were fabricated on a thermally oxidized Si substrate by using ion beam sputtering, electron beam lithography and Ar-ion etching. The rf magnetic field (h_{rf}) was applied to the bilayer element by injecting rf power (P) into the CPW. Figure 2 shows the dc voltage measured along the bilayer element with changing the rf power, which corresponds to the inverse spin Hall voltage in Pt. The inset shows the integrated voltage (I) as a function of P. Although I increased almost proportional to P for $P \leq 10$ mW, for $P \geq 10$ mW, a deviation of I from the linear relationship was observed. The nonlinear behavior was also observed in the FMR spectra. We will discuss the origin of the nonlinear behavior by comparing the experiment and the numerical calculation.

[1] Y. Tserkovnyak *et al.*, Phys. Rev. Lett. **43**, 117601 (2002).

[2] E. I. Rashba *et al.*, Phys. Rev. B **62**, R16267 (2000).

[3] K. Ando *et al.*, J. Appl. Phys. **109**, 103913 (2011).

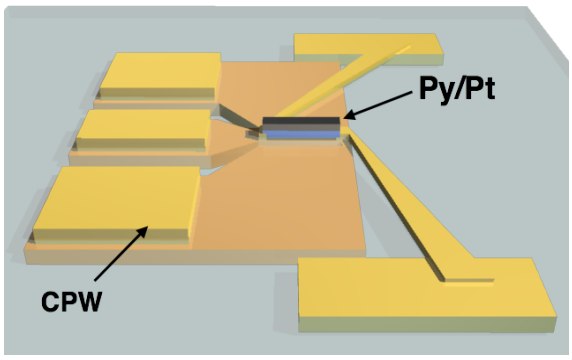

Fig. 1. Schematic illustration of the device structure. The Py/Pt bilayer element was fabricated on the signal line of the coplanar waveguide (CPW).

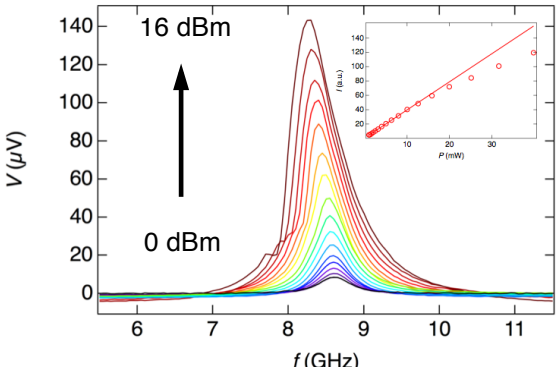

Fig. 2. Rf power dependence of the electromotive force. The inset shows the integrated voltage (I) as a function of the rf power (P).