# Extended harmonic Hall measurement of spin-orbit torque efficiencies in antiferromagnet/ferromagnet heterostructures

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Manipulating the magnetization direction in antiferromagnet (AFM)/ ferromagnet (FM) heterostructures using a spin-orbit torque (SOT) has attracted much attention as a promising ingredient for next-generation spintronics devices [1]. Successful implementation depends on understanding of the mechanism for SOT generation. While a theoretical work points out that non-collinear AFM ordering gives rise to the Berry curvature resulting in an intrinsic spin Hall effect [2], there have been few experimental studies on evaluation of SOT in AFM/FM systems and the generation mechanism has not been clarified well. Recently, an extended harmonic measurement technique has been developed, which allows reliable SOT determination without artifacts due to thermal effects [3]. In this work, we evaluate SOT in heterostructures with AFM PtMn and FM CoFeB using the extended harmonic measurement technique to obtain clues for the mechanism of SOT in AFM/FM systems.

The used heterostructures are comprised of a Pt (or Ru)/PtMn/CoFeB multilayers with an in-plane axis and various PtMn and CoFeB thicknesses. The films are processed into 10 μm wide × 50 μm long Hall bar structures. In-plane AC current is applied and 1st and 2nd harmonic Hall voltages are measured while rotating an external in-plane magnetic field $H_{ext}$ [2].

Figure 1(a) shows azimuthal angle $\varphi$ dependence of 2nd harmonic Hall resistance ($R_{2\omega}$) for various $H_{ext}$ with the fitting curves. Field-like (FL) torque, a component of SOT, is directly obtained from the fitting. Slonczewski-like (SL) torque, the other component of SOT, is obtained from the slope of the linear fit to the dependence of SL torque-induced resistance ($R_{SL}$) on the inverse of the sum of $H_{ext}$ and effective anisotropy field $H_K^{eff}$ shown in Fig. 1(b). Note that the $y$-intercept is due to the anomalous Nernst and spin Seebeck effects. Fitting leads to the SL torque efficiency $|\xi_{SL}| = 0.13$ and the FL torque efficiency $|\xi_{FL}| = 0.061$. These values are comparable to or larger than that previously reported in a Pt/CoFeB system measured with the same method [4], suggesting a contribution of AFM ordering to the SOT in PtMn system.

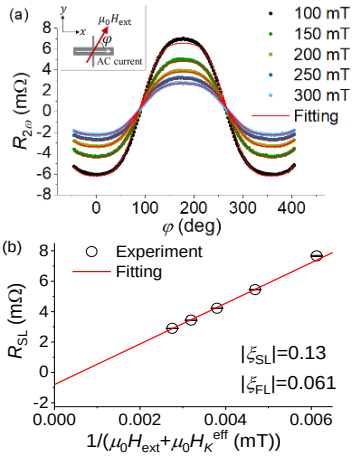


**Figure 1**: (a) Azimuthal angle $\varphi$ dependence of $R_{2\omega}$ and fitting results in various magnetic fields values. (b) Experimental and fitting results of $R_{SL}$. Here, $\mu_0$ denotes the permeability in free space.

A portion of this work was supported by the ImPACT Program of CSTI, JST-OPERA, and JSPS KAKENHI Grant Number 17H06093.

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