Time-resolved x-ray detected ferromagnetic resonance measurements in a CoFe/NiO/Fe/NiFe multilayer structure

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Antiferromagnetic NiO films have been studied as highly effective media for spin currents, mostly by the inverse spin Hall effect (ISHE).[1)] The study is still incomplete because ISHE has only been used to probe the dc spin current, while the ac spin current has not been measured. Therefore, we propose using the x-ray detected ferromagnetic resonance (XFMR) technique by which ac spin currents can be detected via the spin transfer torque exerted upon a ferromagnet.[2)] To this end, we measured XFMR in a CoFe/NiO/Fe/NiFe multilayer and element-specifically probed the spin dynamics of the ferromagnetic layers.

An epitaxial multilayer structure was grown by molecular beam epitaxy as MgO(001) subtrate/MgO (5)/$Co_{50}Fe_{50}$ (5)/NiO (4)/Fe (1)/$Ni_{80}Fe_{20}$ (25)/MgO (3) (thicknesses in nm). After the growth, we performed field-cooling (FC) from 270°C to room temperature at 10 kOe in an Ar atmosphere. We carried out XFMR measurements on beamline 4.0.2 at the Advanced Light Source. A static magnetic field H was parallel to the FC direction. 4-GHz microwaves were supplied through a waveguide with a variable delay relative to the x-ray pulses, and generated an in-plane rf magnetic field orthogonal to the FC direction.

Figure 1(a) shows the XFMR delay scans for the Co and Ni L_3 edges, i.e., the CoFe and NiFe magnetizations parallel to the x-rays at a grazing angle of 40° to the sample surface. The amplitudes and phases were extracted by fitting sine curves to the data at different H, as shown in Fig. 1(b) and 1(c). The FMR magnetic field, where the amplitude reaches its maximum, was around 60 Oe for both the CoFe and NiFe layers, and the layer precessions were always in-phase at each H. These unexpected results indicate that the CoFe and NiFe layers are strongly exchange coupled and rotate entirely together. An ac spin current could not be observed in this sample due to the exchange coupling. We suspect two possible origins of the coupling: either the NiO layer contains (1) oxygen deficiencies and metallic Ni components mediating the coupling, or (2) pinholes through which the ferromagnetic layers directly couple to each other.

1) H. Wang, *et al*., Phys. Rev. Lett. **113**, 097202 (2014); 2) J. Li, *et al*., Phys. Rev. Lett. **117**, 076602 (2016).

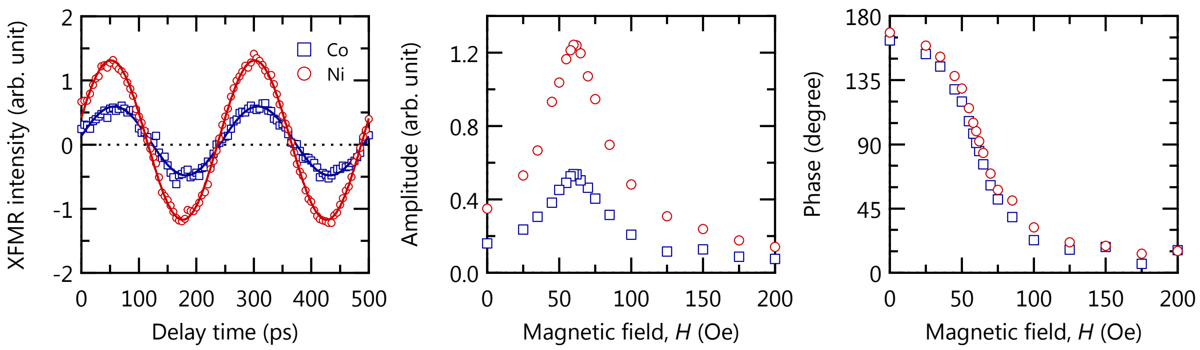

Fig. 1. (a) XFMR delay scans at H = 60 Oe, (b) fitted amplitudes, and (c) fitted phases for Co (blue squares) and Ni (red circles) L_3 edges. The sine curves in (a) are fits to the experimental data.