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A Slot Aperture Enabled High Efficient and Accurate EMCD from a Single Acquisition of Momentum Resolved EELS

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EMCD (electron magnetic circular dichroism) is an electron energy loss spectroscopy (EELS) based technique to explore magnetic properties in the transmission electron microscope (TEM) [1]. However, one of the main challenges for EMCD is still the low signal-noise-ratio (SNR). In the last few years, several approaches have been proposed to improve SNR, including large angle convergent beam diffraction [2], energy filtered transmission electron microscopy [3], and scanning TEM (STEM) [4]. In these techniques, the two EEL spectra are sequentially acquired twice, which may cause substantial variation of acquisition conditions and thus leads to inaccuracy. Even for the double aperture mode [5], the chiral conditions are very hard to satisfy.

Here, we present an experimental setup by using a slot aperture in STEM to acquire the EMCD spectra from a single acquisition, which ensures the parallel acquisition of the momentum resolved EELS under the same conditions. We show that the slot aperture mode allows for much higher acquisition time to significantly improve the SNR. We demonstrate this by using the material yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) with complex crystallographic and magnetic structure, whose EMCD signal has been reported both in experiments and theory under the zone axis [112] condition [6]. In our experiment, a 17 nm thick YIG layer was grown on a $Gd_3Ga_5O_{12}$ (111) substrate and protected by a 7 nm thick Pt layer for cross section sample preparation.

EMCD measurements were conducted at 60kV using Nion HERMES with probe convergence semi-angle of 3 mrad. Figure 1(a) illustrates the slot EELS aperture, which is a gold plated nickel disk with radius of 3 mm with a narrow slot ~0.125 mm × 2 mm in the center. Figure 1(b) is the diffraction pattern for zone axis [112], where the black spots are diffraction reflections. For the general EMCD acquisition, two EEL spectra are sequentially acquired by first placing a circular aperture (red) at a position and then moving it to the other chiral position, during which inevitable variations would influence the EMCD signal. In contrast, by using the slot aperture (blue) the momentum (long edge, q_y) resolved EELS which contains data averaged along the q_x direction can be imultaneously recorded and hence the acquisition conditions are the same and the acquisition time can be very long to achieve high SNR. Moreover, the short edge constrains the q_x region which guarantees that most of the non-magnetic signal along q_x is cancelled. Meanwhile, nanometer spatial resolution is achievable. Figure 1(c) shows the HAADF (high angle annular dark field) intensity profile perpendicular to the Pt/YIG interface. The full width of half maximum is 1.8 nm for 3 mrad, even without considering the self-roughness of the interface.

Figure 2(a) shows the experimental diffraction patterns and the slot position (yellow, placed on the left side). Figure 2(b) and 2(c) shows the $q_y - E$ mappings and corresponding chiral EELS spectra extracted from red region and blue region, respectively. The EELS spectra were background subtracted by fitting a power law model in the pre-edge region and then normalized by the integration of the intensity in a window between 740 eV and 800 eV. The EMCD signal is negative, the same as that in Ref [6]. To further verify the validation, we place the slot aperture on the right side as shown in Figure 2(d-f). The corresponding EMCD signal become positive, opposite to that on the left side, which is consistent with theory.

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In summary, we demonstrate that with a slot EELS aperture we can extract high SNR and accurate EMCD signals from a single acquisition of momentum resolved EELS, which should be helpful for quantitative measurements of magnetic properties at nanometer/atomic-scale. In future, the geometry of aperture and spectrum acquisition conditions should be further optimized for quantitative analysis [7].

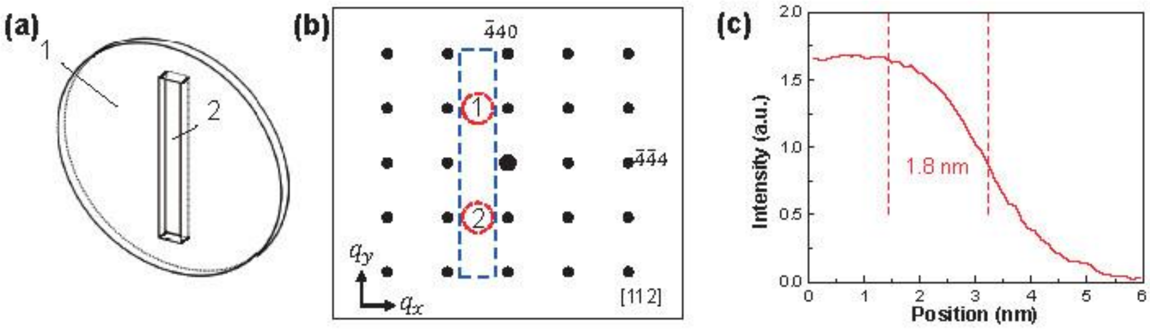

Figure 1. (a) Schematic diagram of the slot aperture. (b) Scheme of geometrical conditions of conventional circular aperture (red) and slot aperture (blue) for EMCD. (c) The HAADF intensity profile across the Pt/YIG interface.

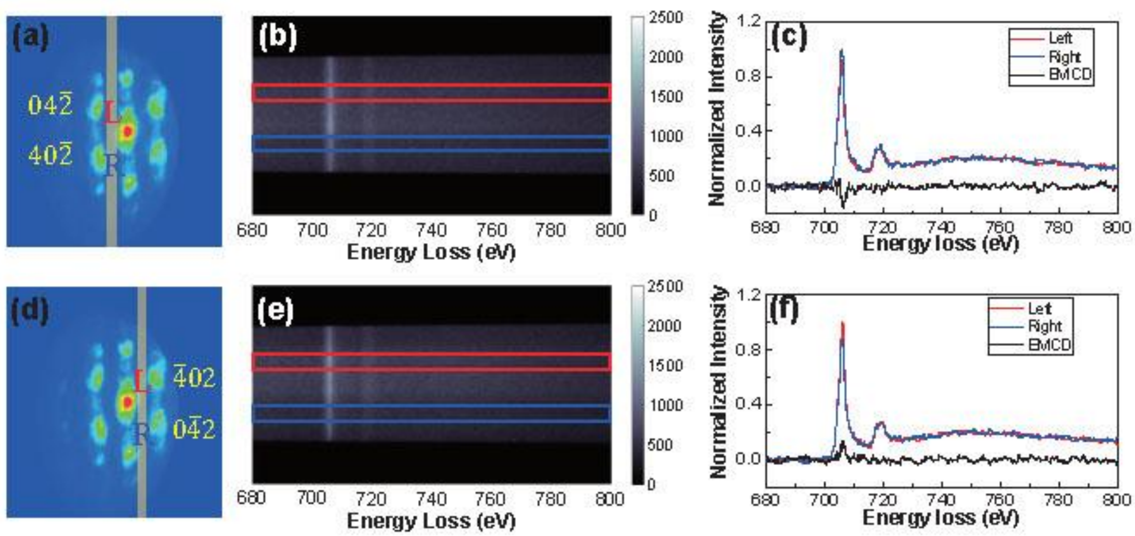

Figure 2. The experimental diffraction patterns for the slot aperture (yellow) placed in the left side (a) and the right side (d), respectively. (b, e) Experimental EELS images corresponding to (a, d) respectively. (c, f) EMCD spectra were obtained by extracting the chiral EELS spectra from the red and blue boxes respectively.

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