Element-Specific Coherent Soft X-Ray Diffraction Imaging Study of the Skyrmion-Hosting Compound $Co_8Zn_8Mn_4$

A skyrmion-hosting compound $Co_8Zn_8Mn_4$ has been examined by means of resonant soft X-ray small-angle scattering with extended reference holography. We performed element-selective study by using Co and Mn $L_{2,3}$ absorption edges. The coherence of soft X-ray beams enables reconstruction of the element-specific real-space image of local magnetization using the so-called HERALDO technique. It was shown that the magnetic moments of Co and Mn exhibit similar magnetic patterns, demonstrating elongation of the skyrmions along the principal crystallographic axes at low temperatures.

Resonant soft X-ray scattering at $L_{2,3}$ absorption edges of 3*d* electron transition metals is an element-selective probe with the possibility of distinguishing magnetic signals from different elements in multicomponent magnets. Moreover, the spatial coherence of the polarized soft X-rays provided by synchrotron radiation sources offer diverse opportunities for lens-less imaging using coherent diffraction. X-ray magnetic holography utilizes the interference between magnetic scattering from the object under investigation and the reference wave generated by charge scattering from the prepared source. In the present study, we performed holography with extended reference by auto-correlation linear differential operation (HERALDO). This technique utilizes the scattering from an extended reference object, such as a narrow slit or a sharp corner, which allows us to improve the contrast of the real-space image without compromising the resolution.

Recently, it has been reported that Co-Zn-Mn compounds with β-Mn structure exhibit nontrivial topological spin textures, such as a Bloch-type skyrmion lattice and a distorted skyrmion state [1]. Since the compounds contain two magnetic elements, competition between the magnetic interactions in non-centrosymmetric compounds results in a complex phase diagram. The typical size of a magnetic skyrmion varies in the range from a few to a few hundred nanometers, which makes them promising candidates for future spintronic applications such as skyrmion racetrack memory and logic devices. The β-Mn-type compound $Co_8Zn_8Mn_4$ exhibits a transition from the paramagnetic state to a helical or Bloch-type skyrmion lattice state at $T_c \approx 300$ K with a magnetic modulation period of 125 nm, and undergoes a spin glass transition at $T_g \approx 8$ K due to freezing of Mn spins.

The HERALDO experiments were performed in the transmission geometry [**Fig. 1(a)**] at BL-16A [2]. We fabricated a circular sample aperture with a diameter of 700 nm and a reference slit with a length of 1 µm and width of 40 nm in a gold thin plate [**Fig. 1(b)**]. The slit length and distance from the aperture were chosen according to the separation conditions, preventing the overlapping of sample autocorrelation and sample-reference cross correlation at the reconstruction. A thin plate of $Co_8Zn_8Mn_4$ with thickness of 200 nm was fabricated by the FIB thinning technique and was attached to the gold thin plate [**Fig. 1(c)**].

Circularly polarized soft X-rays with energies matching Co and Mn L_3 edges were used for the HERALDO experiment. Far-field diffraction patterns were collected with the right circular polarization and left circular polarization to produce the interference pattern and reconstruct the magnetic texture. In this case information about the magnetic texture was simply encoded in the interference term between charge scattering arising from the reference slit and magnetic scattering from the $Co_8Zn_8Mn_4$ sample. The difference between the holograms taken with the two opposite X-ray helicities provided the isolated interference term which could be inverted to the real-space image via single Fourier transform and linear differential operator [**Fig. 1(a)**].

Differences between the diffraction patterns taken with the two opposite X-ray polarizations at photon energies $E = 779$ eV and $E = 640.5$ eV are shown in **Figs. 1(d)** and **1(e)**, respectively. The highest harmonics of the interference pattern can be found at $q_{max} = 0.2$ nm^{-1} which corresponds to the real-space resolution of 32 nm. **Figures 1(f)** and **1(g)** show the sample reference cross correlations taken from reconstructions of holograms for Co and Mn, respectively. Elongated skyrmions can be observed at the holograms taken both at $E = 779$ eV and $E = 640.5$ eV. The magnetic structures exhibited by magnetic elements Mn and Co are similar to each other within the resolution limit. The signal-to-noise ratio is worse in the case of the measurement at the Mn L_3 edge due to the higher absorption of soft X-rays at $E = 640.5$ eV and smaller concentration of Mn atoms compared to Co. The different magnitude of the magnetic moment between Co and Mn is another reason for this. Therefore, the real-space image reconstructed for Mn atoms is slightly blurred [**Fig. 1(g)**].

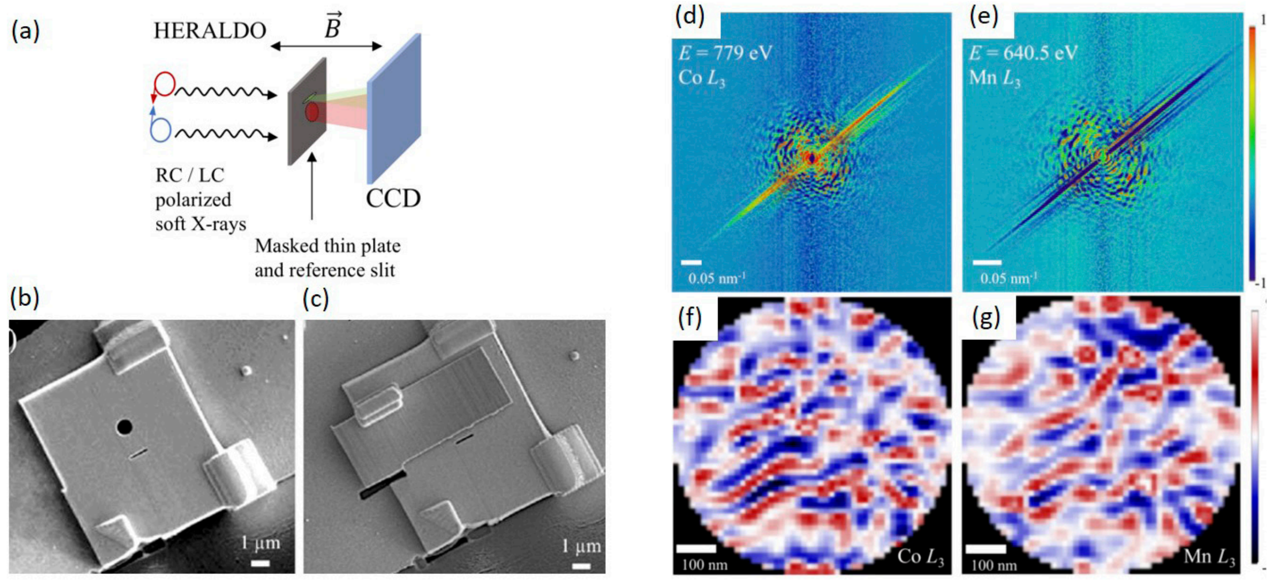

Figure 1: Coherent soft X-ray diffraction imaging setup **(a)** and SEM images [**(b)** and **(c)**] of the thin plate sample fabricated by FIB for the HERALDO experiment. Coherent diffraction patterns [**(d)** and **(e)**] and reconstructed magnetic images [**(f)** and **(g)**] observed at Co and Mn absorption edges, respectively. Reprinted figures with permission from [2] Copyright (2019) by the American Physical Society.

In conclusion, we have demonstrated lens-less soft X-ray imaging of magnetic texture at cryogenic temperatures and applied magnetic fields. HERALDO imaging was used with circularly polarized soft X-rays. Soft X-ray imaging methods allow us to simultaneously obtain element-selective real-space information and will be useful for further investigations of nontrivial magnetic textures.

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