Formation of Skyrmion Crystal in FeGe as Probed by Small-Angle Resonant Soft X-Ray Scattering

Small-angle resonant soft X-ray scattering in resonance with the Fe *L* absorption edge has been investigated for helical magnetic order and magnetic skyrmion crystal (SkX) in B20-type cubic FeGe. Transformation of magnetic structures among helical, conical, SkX, and ferromagnetic forms is observed with the application of a magnetic field parallel to the incident soft X-ray beam. The resonant soft X-ray scattering with high angular resolution revealed transient dynamics of SkX, such as rotation of SkX and variation of the SkX lattice constant, upon the change of magnetic field.

The Dzyaloshinskii-Moriya interaction due to the breaking of inversion symmetry in the crystal lattice induces a topological spin texture in a ferromagnet, known as a magnetic skyrmion. The formation of skyrmion crystal (SkX), i.e. the triangular lattice of skyrmions (**Fig. 1a**), has been observed in bulk and thin film chiral-lattice ferromagnetic alloys lacking inversion symmetry by small-angle neutron scattering (SANS) and Lorentz force microscopy [1, 2].

In this study, to observe the formation of SkX via the synchrotron X-ray scattering technique, we developed a diffractometer for measuring small-angle resonant soft X-ray scattering at BL-16A. As shown in the schematic of the experimental geometry in **Fig. 1b**, an in-vacuum CCD camera positioned downstream of the sample is utilized to record the resonant soft X-ray scattering, and a magnetic field of up to 0.5 T is applied parallel to the incident soft X-ray by a Helmholtz coil.

With this novel technique, we obtained CCD images of small-angle resonant soft X-ray scattering for helical and SkX phases as shown in **Fig. 2a** and **b**, respectively. The twofold symmetric arc-like magnetic peaks ($Q = \pm q_h$) come from the helical magnetic ordering, and the six-fold diffraction pattern ($Q = \pm q_1, \pm q_2, \pm q_3$) characteristic of the formation of SkX appeared upon application of a magnetic field of 0.1 T. The present study reveals that the magnitude of the magnetic modulation vector in the helical phase ($|q_1|$) is slightly smaller than that in the SkX ($|q_h|$) due to the high angular resolution of resonant soft X-ray scattering, though it has been reported in a SANS study on FeGe that the magnitudes of the q vector coincide between the helical order and the SkX. In addition, a second-order magnetic scattering (2q) is also discerned in the SkX phase with two orders of magnitude weaker intensity than in the primary one (q), indicating the deviation of the actual SkX from the simple triple-q configuration.

In this study, we also surveyed the dynamics upon the transformation between the helical and the SkX magnetic structure. As shown in **Fig. 3**, we measured magnetic scattering peaks while repeating magnetic field cycles between 0 and 0.1 T. Upon the transformation from helical to SkX phase while applying a magnetic field, the rotation of SkX occurs concurrently with an expansion of the lattice constant (decreasing q value) of SkX. On the other hand, upon switching-off the magnetic field, the SkX q value abruptly increases and then turns to decrease in a few seconds, and finally the SkX vanishes abruptly, transforming to the helical phase. Namely, abrupt shrinking of SkX occurs just after switching off the magnetic field and subsequent rotation and expansion of SkX occur. These results suggest that the expansion of the lattice constant of SkX should be strongly coupled with the rotating motion of the SkX. The shrinking of the SkX may be forming micro-domains or clusters of skyrmions and then the rotation of SkX may become possible within the individual domains, resulting in the apparent rotation of the whole SkX.

In conclusion, the helical magnetic structure and the SkX in FeGe were observed by small-angle magnetic scattering with soft X-ray scattering in resonance with the Fe *L* edge. High angular resolution magnetic reflections revealed the difference in the q value between the helical order and the SkX, and also the transient motion of the SkX upon the change of magnetic field, such as the expansion of the lattice constant and concurrent rotation of the SkX. Measurements using coherent and pulsed soft X-ray will help clarify the dynamics of skyrmions and assist their application to spintronics.

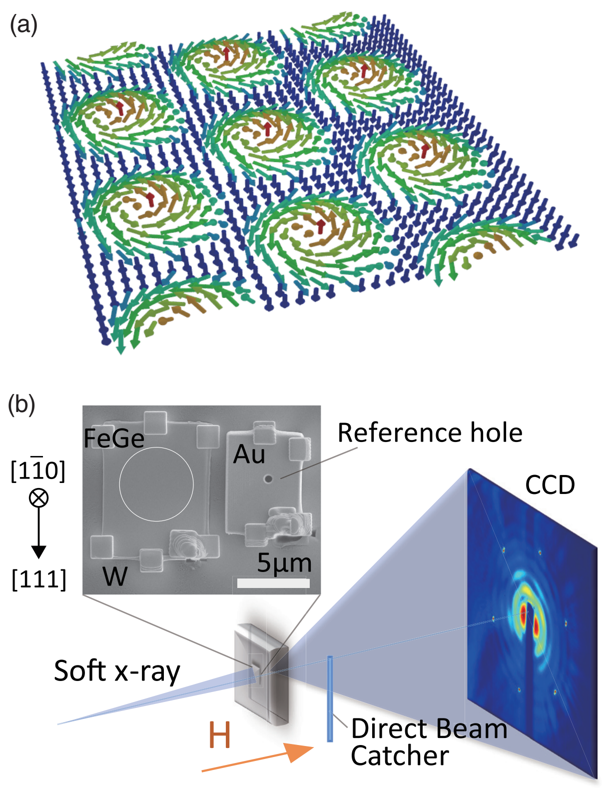

Figure 1: Schematic illustrations of **(a)** magnetic structure of skyrmion crystal and **(b)** small-angle resonant soft X-ray scattering and picture of sample.

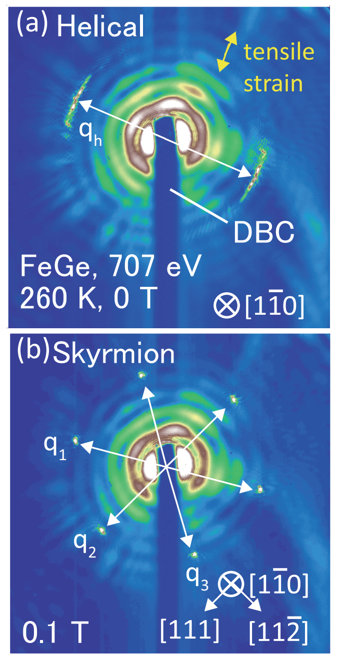

Figure 2: Observed CCD images of small-angle resonant soft X-ray scattering for **(a)** helical and **(b)** SkX.

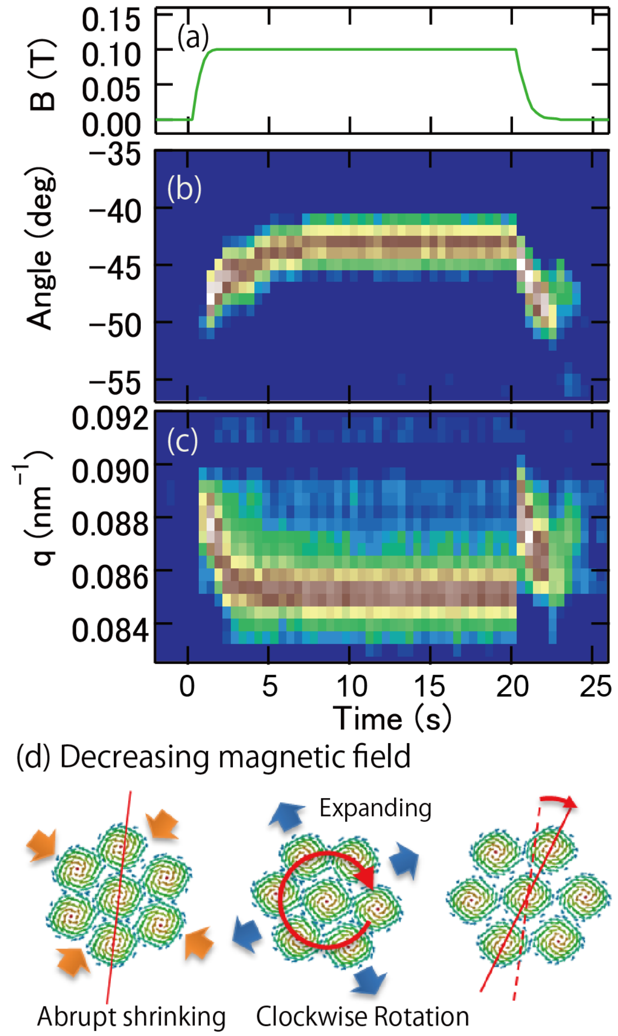

Figure 3: Temporal change of applied magnetic field **(a)**, azimuthal angle ϕ **(b)**, and magnitude of q vector ($q = |q|$) **(c)** of magnetic scattering from helical and SkX magnetic structures. **(d)** Schematic pictures of transient variation in magnetic structure from the SkX to helical magnetic structure with decreasing magnetic field.

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