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Magnetic ground state dependent magnetostriction effects on chiral magnet $CrNb_3S_6$

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The mono-axial chiral magnet $CrNb_3S_6$ has multiple magnetic structures, such as helimagnetic, first chiral soliton lattice (CSL-1), second CSL (CSL-2), CSL-2 with irreversibility, and forced ferromagnetic phases below the magnetic ordering temperature (Tc). We performed powder x-ray diffraction analyses to investigate the effects of magnetic field and temperature on the magnetostriction. The temperature dependence of the lattice constants reveals that below Tc, the magnetostriction depends on the magnetic structure.

1 Introduction

Crystallographic chirality can be converted into a spin system by the Dzyaloshinskii-Moriya (DM) interaction deviated from the spin-orbit coupling (SOC) [1,2]. The DM interaction is allowed in a chiral space group without any rotoinversion symmetry. Further competition between the DM and exchange interactions results in the helimagnetic (HM) structure as the magnetic ground state at zero dc magnetic field (H). Magnetostriction (MS), which often appears in ferromagnets [3–5], also occurs in the magnetic materials with the DM interaction [6–10] because of a strong magnetostructural correlation.

In a prototype of the chiral magnet $CrNb_3S_6$ with a monoaxial DM vector, two types of MS have already been observed: (1) spontaneous MS due to the exchange interaction and SOC at zero H [6] and (2) paramagnetic (PM) MS due to the SOC and Zeeman energy at room temperature [7]. In $CrNb_3S_6$, the SOC originates in the hybridization between Cr and Nb [11]. These MS phenomena accompany the change in the interatomic distance between Cr and Nb. Thus, these MS effects in $CrNb_3S_6$ [6,7] are examples of SOC-induced MS [8–10]. However, MS in $CrNb_3S_6$ has not been in detail investigated over wide H and temperature T ranges.

2 Experiment

We performed powder XRD analyses at various temperatures using a synchrotron radiation XRD system with a cylindrical imaging plate at the Photon Factory at the Institute of Materials Structure Science, High Energy Accelerator Research Organization [12]. The energy of the incident x-rays was 16 keV. To produce the maximum H value of 2.2 kOe, two facing NdFeB magnets with remanence value of 13.8 and 14.5 kG were placed in the diffractometer [6]. Because the remanence of the NdFeB magnets depends on temperature, the temperature of the magnets was measured using a K-type chromel-alumel thermocouple. All XRD measurements were conducted under increasing temperature in the range 92.8–294.7 K, and the temperature of the magnets was maintained within 289.2–298.2 K.

3 Results and Discussion

Figures 1(a), 1(b), and 1(c) show the lattice constants a, c, and the unit cell volume V for $CrNb_3S_6$, respectively, at H = 0, 0.71, 1.23, and 2.16 kOe [13]. In the PM region (130 K $< T <$ 170 K), all of the lattice parameters change very little, suggesting a type of Invar effect due to competition between thermal expansion and magnetic shrinkage. In the HM region ($T <$ 130K), shrinkage along the a-axis and elongation along the c-axis occur simultaneously, so that V is almost constant. Thus, the decrease in volume on the easy plane is canceled by the increase in volume along the hard axis. In the present study, we consider two phenomena: (1) the PM Invar effect for $T > T$c and (2) MS for $T < T$c depending on the magnetic ground states.

First, we investigated the PM Invar effect by observing the effect of H on V [Fig. 1(c)]. The Invar effect at the unit-cell level at $T > T$c was also observed at H = 0.71 kOe, where the T range is almost the same as that at H = 0 Oe. The constant V characteristic of the Invar effect is not observed at H = 1.23 and 2.16 kOe. At H = 0.71 kOe, the surface is FFM and the interior is mostly HM. The HM spin alignment is assumed to stabilize the Invar effect due to competition between thermal expansion and magnetic shrinkage. Further application of H reduces the stability of HM structure, such that, for $T > T$c, thermal expansion should exceed magnetic shrinkage at H = 1.23 and 2.16 kOe.

Next, the MS below Tc, depending on various magnetic ground states, was investigated by observing the T dependence of the unit cell parameters below Tc at various H values. According to the trend of the lattice constant on the ferromagnetic plane parallel to the magnetic anisotropy vector [$a(T)$ in Fig. 1(a)], the MS at $T <$ 103 K can be divided into two categories; the first occurs at 0 Oe (HM) and 0.71 kOe (CSL-1), and the second occurs at 1.23 kOe (CSL-2) and 2.16 kOe [CSL-2 with irreversibility, CSL-2(NL)]. The value of a at $T <$ 103K is almost the same at H = 0 and 0.71 kOe. At T = 103 K, a discretely changes at H = 0.71 kOe, and for 107 K $< T < T$c, the T dependence of a at H = 0.71 kOe is similar to that at H = 2.16 kOe. At $T <$ 110K and H = 2.16 kOe, the T dependence of a is opposite to that at H = 0.71 kOe. An increase in a due to MS at $T < T$c was observed at 1.23 kOe; it stabilizes the CSL-2 state at $T <$ 120K and FFM state in narrow T region of 120 K $< T < T$c. The large increase in a during warming occurs in the CSL-2 phase. Figure 1(b) shows the T dependence of the lattice constant along the hard axis, $c(T)$; the increase at $T < T$c and H = 0 Oe changes to a discrete increase at 103 K and H = 0.71 kOe. Considering the behavior at 93 K, the HM and CSL phases should be placed in the same category, as suggested in the analysis of a, whereas CSL-2 and CSL-2(NL) should be categorized separately. Other features have already been observed in the results for a. The unit-cell volume V is almost constant at $T < T$c and

H = 0 Oe and just below 103 K at H = 0.71 and 2.16 kOe. However, at H = 1.23 kOe, the volume exhibits thermal expansion. Because the change in c is much larger than that in a, the T dependence of V below Tc is qualitatively the same as that of c. In addition to a, c, and V, the ratio of c and a, c/a, provides information on the uniaxial distortion of the hexagonal unit cell in the two MS phenomena mentioned above [13].

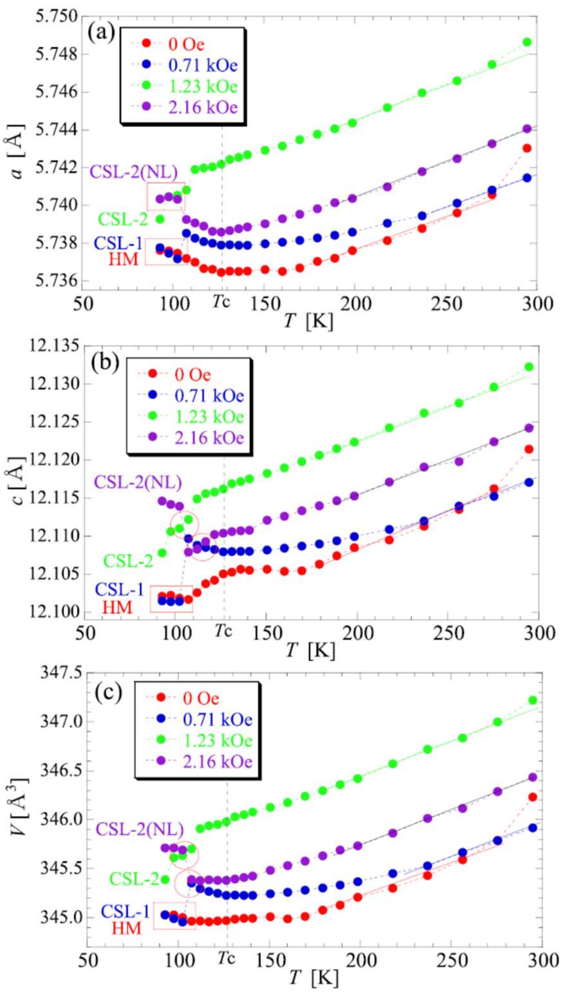

Fig. 1: Lattice parameters a (a), c (b), and V (c) at H = 0, 0.71, 1.23, and 2.16 kOe [13]. The position of Tc is represented with a broken line. The qualitative behavior above 200 K, characterized with a straight line, in all of a, c, and V is independent of H. The T region categorized as a group is presented with red rectangle or circle.

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