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journal or publication title	Journal of Physics: Conference Series
volume	969
number	1
page range	012132-1-012132-6
year	2017-08
URL	http://hdl.handle.net/10228/00007070

doi: info:doi/10.1088/1742-6596/969/1/012132

Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: K Tsuruta *et al* 2018 *J. Phys.: Conf. Ser.* **969** 012132

IOP Conf. Series: Journal of Physics: Conf. Series **969** (2018) 012132 doi:10.1088/1742-6596/969/1/012132

Effects of dynamic stress in magnetic superlattice of a monoaxial chiral magnet $Cr_{1/3}NbS_2$

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Abstract. A monoaxial chiral magnet forms a kind of spin superlattice structure, termed chiral soliton lattice (CSL), by the application of a magnetic field H perpendicular to a helical chiral axis. It has been reported that the CSL accompanies the magnetoresistance effect as well as a discrete change in magnetization and magnetoresistance. In order to verify the effect of the structural modification on the CSL state, we measured the magnetoresistance under the dynamic stress (DS) with a frequency of the order of MHz, which was applied by a piezoelectric ceramic oscillator. The steady application of DS while decreasing H resulted in a suppression of the insertion of chiral soliton. On the other hand, the application of a pulse-like DS while H decreased assisted the insertion of chiral soliton. These results demonstrate that DS modifies the spin structure of the monoaxial chiral magnet, and we can therefore change the activation energy for the insertion of chiral soliton while H is decreased.

1. Introduction

Chirality refers to the fact that mirror images do not overlap like, as in the case of the relationship between right and left hands. In magnetic materials with spin chirality, the spin structure at zero magnetic field exhibits a helical structure with only a right- or left-handed helix owing to competition between symmetric interaction and antisymmetric Dzyaloshinskii–Moriya (DM) exchange interaction [1, 2]. A type B20 compound MnSi with a magnetic skyrmion state [3] and a monoaxial chiral magnetic material $Cr_{1/3}NbS_2$ with a chiral soliton lattice structure (CSL) under a magnetic field H [4, 5] are well known as chiral magnets that present topological solitons. In millimeter-sized single crystals of $Cr_{1/3}NbS_2$, the characteristic shapes of the magnetic curves [6-8], magnetoresistance [9], and the discrete change in magnetization [10,11] due to the CSL formation have been reported. In micro-sized single crystals, successive discontinuity in magnetoresistance was observed, and in particular, for the condition of a decreasing H at below critical magnetic field, there appeared to be a large discontinuity in terms of magnetoresistance [12]. While this phenomenon is recognized as a kind of supercooling with activation energy, details about its underlying mechanisms are not fully understood.

The magnetic properties of $Cr_{1/3}NbS_2$ are changed by structural modulations using hydrostatic pressure [13]. It is convincing that the spin texture is connected with the lattice system. We consider the resulting condition when the CSL stabilized under H influences time-dependent stresses such as periodical and temporal stresses. We expect that they function as a perturbation to disturb the change in the topological soliton or as a stimulus to overcome the activation energy. It was reported that a dynamic stress (DS) with a frequency of the order of MHz affects physical properties in a semiconductor and a cupurate superconductor [14,15].

In this study, we focus on applying DS to the monoaxial chiral magnet $Cr_{1/3}NbS_2$ as a perturbation and/or stimulus to change the physical properties via the artificial manipulation of its magnetic structure. For instance, we perform two types of measurements for the electric resistance: (1) when DS is steadily applied and (2) when DS is applied in a pulse-like manner.

2. Experimental method

A single crystal of the monoaxial chiral magnet $Cr_{1/3}NbS_2$ was prepared for the experiments. This material belongs to space group $P6_322$, and the helical chiral axis is c-axis. Single crystals were prepared using the chemical transport method [16]. The single crystal was cut into sizes 10 μm ×5 μm ×0.5 μm using the focused-ion beam technique, and it was electrically connected to the gold pattern on the silicon substrate with tungsten paste. Figure 1(a) shows the SEM image of the micro-sized sample of the $Cr_{1/3}NbS_2$. The helical chiral axis, c-axis, was parallel to the current.

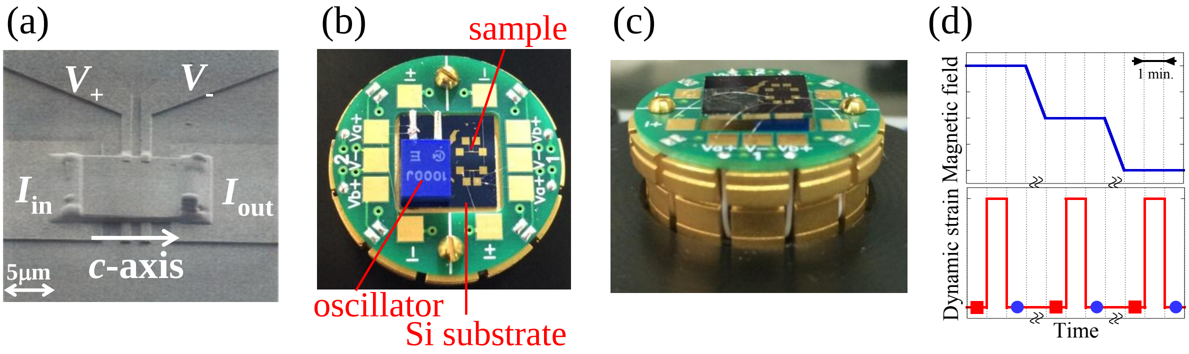

Figure 1. (color online) (a) SEM image of the micro-sized single crystal $Cr_{1/3}NbS_2$. (b)(c) Picture of the sample setting for experiments (1) and (2), respectively. (d) Relationship between timing of the applied DS and that of the changing magnetic field. Red squares and blue circles indicate the timing of measuring resistance.

A piezoelectric ceramic oscillator manufactured by Murata Manufacturing Co., Ltd. was used as the source of the DS. The resonance frequency of the oscillator was about 1 MHz. Because the resonance frequency changes with temperature, the frequency of the applied voltage to the oscillator was tuned at each measurement temperature. For the first experiment (1), the oscillator was placed beside the sample, as shown in Fig. 1(b), and for the second experiment (2), the oscillator was placed under the substrate, as shown in Fig. 1(c). In both experiments, the DS was propagated to the sample via the substrate. In (1), the H dependence of the electric resistance R was measured for both the increasing and decreasing H under a constant application of DS. In (2), R was measured at each H for the decreasing H immediately after applying the pulse DS for 1 min., as shown in Fig. 1(d). In both experiments, a current of 1 mA was applied to measure R.

3. Experimental results and discussion

3.1. Steady application of dynamic stress

The magnetic transition temperature T_c of the sample was approximately 124 K, and the critical field H_c for the forced ferromagnetic state was about 2.5 kOe at a temperature (T) of 100 K. Figure 2(a) shows the H dependence of R for some magnitudes of the DS at 100 K. Here, "off" indicates the measurement without DS, and the voltage value (V) is the amplitude of the voltage applied to the oscillator. V is treated as an equivalent to the magnitude of the DS. For zero DS, R decreases as H increases, while a finite hysteresis and large jump were observed as H decreased. These behaviors of R as a function of H are consistent with results reported by Togawa et al. [12]. H which large jump appeared tends to decrease with increasing V. Focusing on the area of hysteresis (S), it exhibits prominent increase for V to more than 4 V_{pp}.

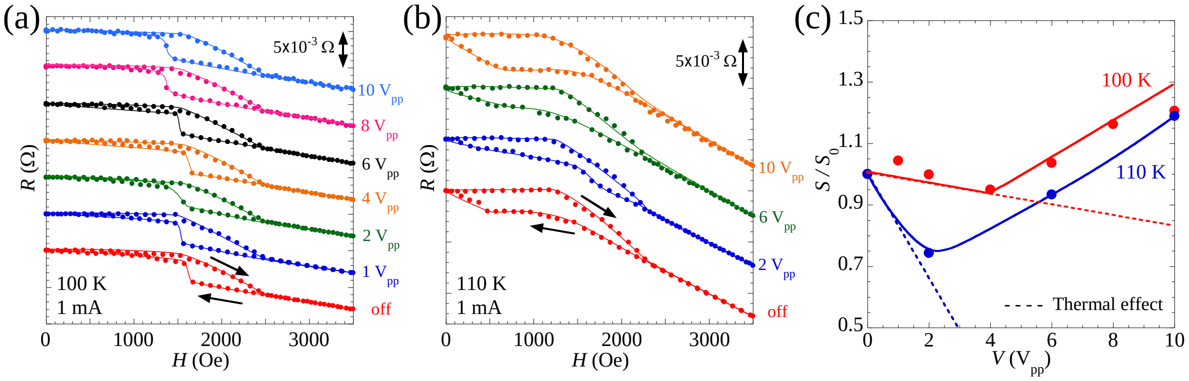

Figure 2. (color online) Magnetic-field H dependence of electric resistance R of $Cr_{1/3}NbS_2$ under a DS condition at T = 100 K (a) and 110 K (b). (c) DS dependences of the hysteresis area S normalized with the hysteresis area without DS (S_0). The magnitude of DS is evaluated with the applied voltage V to the oscillator. Broken lines are visual guides for the thermal effects caused by oscillations.

Figure 2(b) shows the H dependence of R for each magnitude of the DS at 110 K. By increasing T from 100 K to 110 K, the shape changed and the overall hysteresis increased. When the magnitude of the DS was increased, S decreased at a voltage less than 2 V_{pp} whereas S tended to increase at more than 2 V_{pp}. This behavior is qualitatively consistent with what was observed at 100 K.

Figure 2(c) shows the V dependence of S/S_0. Indeed, when the V was applied to the oscillator, the sample was slightly heated by oscillating. It was reported that the S became smaller with increasing temperature to less than T_c in the T range, where the qualitative behavior of the R-H curve did not change [12]. In the region where the V applied to the oscillator was small, the hysteresis area became smaller with increasing V. This phenomenon is surely due to the heat generation caused by the oscillations, and its thermal effect is shown by visual guides in Fig. 2(c). However, when V increases further, S turns to increases, and this phenomenon cannot be explained by increasing the T of the sample. This is considered to be the effect of stationary DS. Indeed, the ratio of the increase in S/S_0 as a function of V is consistent with the data at 100 K and 110 K. According to the theoretical study, the elastic torsion can modify the DM vector [17]. In particular, when decreasing H from the forced ferromagnetic state, the insertion of topological solitons may be restricted because the DM vector is spatially disturbed. If the above scenario is true, it is reasonable that the increase of S results from the application of stationary DS.

3.2. Pulse-like application of dynamic stress

We investigated the effect of a pulse-like DS at T = 100 K in the process of decreasing H, from 3500 Oe, as shown in Fig. 3. As seen in the red plots of Fig. 3(a), the DS was not applied until H = 1645 Oe. For reference, the green plots and broken line are the results obtained varying H roughly in the situation without DS. Figure 3(b) shows an enlarged view for H = 1640 ± 10 Oe. The pulse-like application of DS was carried out below 1645 Oe. The red plots show R before applying the pulse-like DS, and the blue plots show the value after applying the pulse-like DS for each field. The latter measurement was conducted successively after the former measurement, and both measurements were carried out at the same H. The time interval of the pulse-like DS was less than 1 min., and so the heating can be neglected. From 1645 to 1636 Oe, as shown by black arrows in Fig. 3(b), R did not change before or after applying the pulse-like DS. However, at H = 1635 Oe, as shown by the red arrow, the pulse-like application of DS changed the R remarkably. This behavior is due to the magnetic transition from the forced ferromagnetic state to the CSL state. There, many topological solitons should be inserted collectively. In fact, after waiting for several tens of minutes and an increased temperature just before applying the pulse-like DS, there was no change in the electrical resistance. Thus, we confirmed that the above phenomenon does not originate in both the relaxation effect and heating one. A series of results implies that by applying pulse-like DS, we have succeeded in manipulating the activation energy for the transformation from the forced ferromagnetic state to the CSL state.

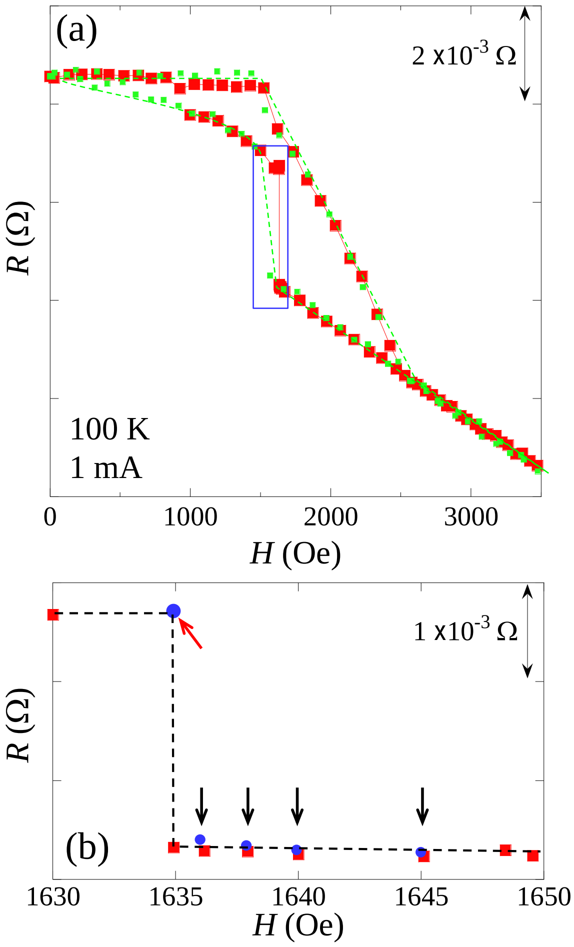

Figure 3. (color online) (a) Magnetoresistance $R(H)$ of $Cr_{1/3}NbS_2$ at T = 100 K in experiments involving the pulse-like application of DS. The pulse-like application was carried out below 1645 Oe. Based on preliminary experiments, the reference data shown by green plots and the broken line indicate a R-H curve without DS. (b) R-H curve in the process of decreasing H for H = 1640 ± 10 Oe, corresponding to the enlarged figure of the blue square in (a). Plots of red squares and blue circles indicate before and after the application of DS for each magnetic field, respectively. Some arrows show the field values for which the pulse-like application of DS was performed.

Dynamic stress, DS, modulates the crystal lattice. In $Cr_{1/3}NbS_2$, DM vectors could be modulated by DS. In the present experimental setting, the structural modulation has no specular directivity. Thus, we assume that there are two effects: One is heating effect that is equivalent to making a state instable thermodynamically, and it is inevitable effect in the case of stationary DS. Another is the effect of structural modulation, in which the phase transformation is restricted or motivated positively. In the present study, the stationary DS corresponds to the former, and it restricts the insertion of the topological solitons in the process of decreasing H. On the other hand, the pulse-like DS does to the latter, and it reduces any activation energy of the transition from the forced ferromagnetic state to the CSL state, resulting in finishing a kind of magnetic supercooling. We suppose that this activation energy of the transition from the forced ferromagnetic state to the CSL state is enhanced in thin film with clean surface. Indeed, the big jump in magnetoresistance has not been observed in the millimeter sized crystal. For any specimen for the DS experiment of $Cr_{1/3}NbS_2$, the thin film with clean surface is promising.

4. Conclusion

Magnetoresistance measurements were performed on a micro-sized single crystal of the monoaxial chiral magnet $Cr_{1/3}NbS_2$ in order to verify the dynamic stress (DS) effect. Based on the results, in the case of experiment (1), where the DS was steadily applied, the transition from the forced ferromagnetic state to the CSL state was suppressed during the process of decreasing magnetic field. We consider that the lattice would be modulated by the application of DS, resulting in the distortion of the DM vectors. We also succeeded in changing the state from the forced ferromagnetic state to the CSL state in experiment (2) when the DS was applied in pulses. There, we succeeded in the artificial transition from the forced ferromagnetic state to the CSL state by using dynamic stimulus. Thus, the spin-phase orders in $Cr_{1/3}NbS_2$ generated by the DM vectors are modulated by dynamic structural modulation.

Acknowledgments

This work was supported by a Grants-in-Aid for Scientific Research, Grant No. (S) 25220803 and Grant-in-Aid for Exploratory Research, Grant No. 15K13958 from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan. This work was also supported by the Center for Chiral Science at Hiroshima University (the MEXT program for promoting the enhancement of research universities, Japan) and the JSPS Core-to-Core Program, A. Advanced Research Networks.

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