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Research Article

Thermodynamic, Electromagnetic, and Lattice Properties of Antiperovskite Mn$_3$SbN

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The physical properties of polycrystalline Mn$_3$SbN were investigated using measurements of the magnetic, calorimetric, and electronic transport properties. At room temperature, the phase crystallizes in a tetragonal structure with $P4mm$ symmetry. A remarkably sharp peak in the heat capacity versus temperature curve was found near 353 K. The peak reaches 723 J mol$^{-1}$ K$^{-1}$ at its highest, which corresponds to a transition entropy of 10.2 J mol$^{-1}$ K$^{-1}$. The majority of the large entropy change appears to be due to lattice distortion from the high-temperature cubic structure to the room-temperature tetragonal structure and the accompanying Ferrimagnetic transition.

1. Introduction

Antiperovskite compounds with the formula Mn$_3$XN or Mn$_3$XC (X = Cu, Zn, Ga, Cu, In, or Sn) were discovered in the middle of the last century [1]. Recently, interest in these materials has intensively renewed owing to discoveries of new, potentially useful properties [2–4] such as the giant magnetoresistance of Mn$_3$GaC [5], negative thermal expansion (NTE) of Mn$_3$Cu(Ge)N [6] and Mn$_3$Zn(Ge)N [7], magnetostriiction of Mn$_3$CuN [8] and Mn$_3$SbN [9], and near-zero temperature coefficient of the resistivity of Mn$_3$CuN [10] and Mn$_3$NiN [11]. Specifically, Takenaka and Takagi found that Ge-doped Mn$_3$CuN compound has a large NTE (NTE parameter $=-25 \times 10^{-6}$ K$^{-1}$) [12]; using neutron diffraction, the broad NTE was determined to be associated with the local $T_4$ structure [6]. Asano et al. discovered large magnetostriiction in tetragonal Mn$_3$CuN; it expands 0.2% and shrinks 0.1% in the directions parallel and perpendicular to an external 90 kOe magnetic field, respectively [8]. In previous studies, we found a peculiar phase separation and accompanying anomaly in the electronic transport properties of Mn$_3$ZnN [13, 14], while further study indicated that the thermal expansion properties of Mn$_3$ZnN can be controlled by introducing Zn vacancies [15]. In addition, Song et al. observed a canonical spin-glass state in Mn$_3$GaN below the spin-freezing temperature of 133 K [16]. Lukashev et al. systematically studied the spin density of the spin-frustrated state of a Mn-based antiperovskite under mechanical stress [17].

The above-mentioned properties enable a variety of potential applications for this type of material. Although the prospective industrial markets are expected to be large and much effort has already been devoted to studying their structural, electromagnetic, and transport properties, further investigations on antiperovskite materials are still required. In this study, the thermodynamic, electromagnetic, and electronic transport properties of Mn$_3$SbN are investigated. In particular, we focused on the notable transition entropy that...
accompanies the magnetic and crystal structure transition above room temperature.

2. Experimental Details

A polycrystalline Mn$_3$SbN sample was prepared via the solid-state reaction of fine powders of Sb (99.99%, Rare Metallic Co.) and Mn$_2$N, which was synthesized by firing Mn powder (99.99%, Sigma Aldrich Co.) in nitrogen at 800°C for 60 h. Stoichiometric amounts of the starting materials were thoroughly mixed, and the mixture was pressed into a pellet. The pellet was sealed in an evacuated quartz tube, heated in a box furnace at 800°C for three days, and then slowly cooled to room temperature in the furnace.

The crystal structure of Mn$_3$SbN was analyzed by synchrotron X-ray diffraction (SXRD) using a large Debye-Scherrer camera at the BL15XU NIMS beam line of the SPring-8 facility in Hyogo, Japan. The SXRD data were collected for 2θ ranging from 2° to 60° at intervals of 0.003°. The incident beam was monochromatized at λ = 0.65297 Å. The evolution of the Mn$_3$SbN crystal structure with temperature was also determined via the measurement of the SXRD patterns.

The temperature dependence of magnetization was measured between 2 and 400 K with applied magnetic fields of 0.1 and 5 kOe using a Magnetic Property Measurements System (Quantum Design). The measurements were conducted on loosely gathered powder under both zero-field cooling (ZFC) and field cooling (FC) conditions. The isothermal magnetization curve was recorded at 10 K between −50 and 50 kOe. Specific heat ($C_p$) values were measured between 2 and 400 K with cooling using a Physical Properties Measurement System (Quantum Design). The sample was fixed on a stage using a small amount of grease; the heat capacity of the grease was measured first and subtracted from the total $C_p$.

3. Results and Discussion

As shown in Figure 1, the synchrotron XRD pattern at room temperature fit well with a model pattern of the proposed structure (space group: $P4/mmm$). The structural parameters of Mn$_3$SbN were refined by the Rietveld method using the RIETAN-FP program [18]. The occupancy factors of Sb, N, Mn1, and Mn2 were refined to be 1 (fixed), 1 (fixed), 0.97(1), and 0.99(1), respectively, while the isotropic atomic displacement parameters were 0.42(1), 0.84(5), 0.86(1), and 0.78(1) Å$^2$, respectively. The lattice constants were calculated to be $a = b = 4.17994(4)$ Å and $c = 4.27718(5)$ Å. The final $R_{wp}$ and $R_{wp}$ reliability indexes were below 5.56% and 4.09%, respectively. The analysis revealed 1.91 mass% MnO in the sample as an impurity; as shown later, the magnetic, $C_p$, and $\rho$ measurements suggest that the impurity does not significantly impact the measurements of Mn$_3$SbN in this study.

Figure 2 displays the temperature dependence of magnetization of polycrystalline Mn$_3$SbN. The magnetization steeply increases upon cooling to around 353 K, which suggests the establishment of long-range magnetic order at the magnetic transition temperature ($T_c$). In addition, a small hysteresis can be observed between the heating and cooling process, implying the first-order character of the magnetic transition. The remarkable bifurcation between the ZFC and FC curves may originate from the spontaneous alignment of random magnetic Mn moments in domain boundaries. It is worth noting that the hysteresis is less significant at a higher magnetic field of 5 kOe, which supports the domain picture.

The electrical resistivity ($\rho$) was measured between 2 and 400 K with cooling and heating using a conventional four-probe technique with the same apparatus. The AC gauge current and frequency were 10 mA and 30 Hz, respectively. The electrical contacts were prepared on the surface of a bar-shaped piece of the pellet using silver paste and Pt wires.
the right inset of Figure 2, the Curie-Weiss law to the paramagnetic portion. As shown in the effective Bohr magneton ($\mu_B$), the ferromagnetic correlation is dominant in the spin system.

value of $\chi_T$ was determined to be 354 K, which suggests that ferromagnetic correlation is dominant in the spin system. The effective Bohr magneton ($\mu_{\text{eff}}$) was estimated to be 1.28 $\mu_B$/Mn from $\mu_{\text{eff}} = 2.83(C/\eta)^{0.5} \mu_B$, where $\eta$ is the number of magnetic atoms in the molecular formula ($\eta = 3$ in the present case). The value of $\mu_{\text{eff}}$ is much lower than that of other antiperovskite manganese nitrides (e.g., 2.87 $\mu_B$ for Mn$_2$ZnN [14]) and even lower than the expected moment for localized $S = 1/2$ spins, suggesting an itinerant character of the 3d electrons in Mn$_3$SbN.

From the isothermal magnetization curve (see the inset of Figure 2), it was found that the magnetization at 50 kOe is $\sim 0.35 \mu_B$/Mn, which is too small to be caused by full ferromagnetic order. The gap suggests that the spins of the Mn atoms are possibly Ferrimagnetically ordered. This Ferrimagnetic interaction is also suggested by the magnetization characteristics above 10 kOe, that is, the magnetization continuously increases with increasing magnetic field without approaching saturation. The Ferrimagnetic order of a related Mn-based antiperovskite compound was explained by a $T^{\text{gb}}$ spin structure, where two of the three Mn magnetic moments are antiferromagnetically coupled and the third exhibits FM behavior [19]. It is possible that a similar magnetic structure is established in Mn$_3$SbN below 353 K.

To further characterize the magnetic transition, the specific heat was measured from 400 to 2 K. As shown in Figure 3, the temperature dependence of $C_p$ features a sharp and narrow peak around $T_c$ ($\Delta C_p/R = 87$ and $\Delta T = 3$ K, where $R$ is the ideal gas constant). This is indicative of a first-order-like transition, as discussed in [20].

An estimation of entropy change is essential to understanding the nature of the transition of Mn$_3$SbN. The peak was roughly separated from the baseline using a polynomial function. Analysis indicates that the total transition entropy ($\Delta S$) is $\sim 1.23 R$ (10.2 J/mol K). Since the total entropy change comprises all contributions, including the lattice, electronic, and magnetic changes [20], we evaluated each contribution independently.

For the present compound, the abrupt change of the magnetization at $T_c$ may induce a large $\partial M/\partial T$; therefore, a large magnetic entropy change ($\Delta S_m$) is expected. A series of magnetization curves with small temperature steps were measured; the data allow for a rough estimation of the magnetic entropy change via the thermodynamic Maxwell relation, as follows [21]:

$$
\left( \frac{\delta S(T, H)}{\delta H} \right)_T = -\left( \frac{\partial M(T, H)}{\partial T} \right)_H.
$$

The magnetic entropy change, $\Delta S_m(T, H)$, can be calculated by

$$
\Delta S_m(T, H) = S_m(T', H) - S_m(T', 0) = \int_0^H \left( \frac{\partial M(T, H)}{\partial T} \right)_H dH.
$$

The temperature dependence of $\Delta S_m$ calculated from (2) with fields of 10, 20, 30, 40, and 50 kOe is shown in Figure 4. The $\Delta S_m$ is maximized around $T_c$, and the maximum is estimated to be $\sim 2.1 J \text{ mol}^{-1} \text{ K}^{-1}$, which implies that the lattice and electronic changes provide a fairly large contribution to the total entropy change.

To investigate the electronic contribution (i.e., the Sommerfeld coefficient or $\gamma$), the $C_p/T$ versus $T^2$ plot below 10 K was analyzed by applying the approximate Debye model, as

![Figure 3: Temperature dependence of the $C_p$ of Mn$_3$SbN. The left and right insets show a linear fit to the $C_p/T$ versus $T^2$ curve and an estimation of $\Delta S$, respectively.](image3)

![Figure 4: Temperature dependence of the magnetic entropy change when the magnetic field changes from 0 to 10, 20, 30, 40, and 50 kOe, respectively.](image4)
4. Advances in Condensed Matter Physics

Lattice parameters (Å)

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Figure 5: Variation in (a) lattice parameters and (b) synchrotron XRD patterns with temperature for Mn₃SbN.

\[ C(T)/T = \gamma + 2.4\pi^4 n N_0 k_B (1/\Theta_D)^3 T^{-2} \ (T \ll \Theta_D) \]

where \( n \) denotes the number of atoms per formula unit, \( k_B \) is the Boltzmann constant, \( N_0 \) is the Avogadro constant, and \( \Theta_D \) is the Debye temperature. Fitting to the linear part of the \( C_p/T \) versus \( T^2 \) plot using the least-squares method yielded \( \gamma \) and \( \Theta_D \) values of \( \sim 7.03(1) \text{ mJ mol}^{-1} \text{ K}^{-2} \) and \( 326(2) \text{ K} \), respectively. Compared with the parameters determined for other antiperovskite nitrides, Mn₃SbN has a much lower \( \gamma \), which indicates that the electronic correlation is somewhat weakened [20]. Thus, the electronic contribution might not be a dominant contributor to the total transition entropy.

In addition to the magnetic and electronic contributions, a possible lattice change may need to be investigated to analyze the total transition entropy. The variation of the synchrotron XRD pattern with temperature was measured. As shown in Figure 5(b). It can be seen that some typical reflections disappear with temperature, for example, the two reflections (002) and (200) for the \( P4/mmm \) lattice merge to one reflection. By the Rietveld analysis of the synchrotron XRD patterns, the structural change from tetragonal to cubic was defined, and the lattice constants were determined as a function of temperature, as shown in Figure 5(a). It is obvious that lattice parameter \( c \) increases slightly with increasing temperature, whereas \( a \) gradually decreases. When the temperature crosses \( T_c \), the tetragonal structure completely transforms to an unidentified cubic structure. Hence, the lattice distortion must contribute to the total entropy change.

According to the thermodynamic relation, the magnetization \( (M) \) is equal to the first derivative of the magnetic free energy by the magnetic field, that is, \( d f / d H \) [22]. Therefore, the sharp transition indicates that the energy barrier in the free energy that separates the paramagnetic and ferromagnetic states is large. Accordingly, \( T_c \) and the energy barrier height probably correlate with the electronic density of states, which exhibits a sharp peak near the Fermi level [23]; therefore, the large entropy change is possibly related to the reconstruction of the electronic structure, which could induce the magnetic and structural transition. Since such an electronic reconstruction is often sharply reflected in a \( \rho-T \) curve, the electronic transport properties of Mn₃SbN were carefully measured (shown in Figure 6). It is evident that an abnormal drop appears at \( T_c \) in the \( \rho-T \) curve, which is indicative of an electronic structure reconstruction. In addition, as shown in the inset of Figure 6, a small hysteresis was observed between the warming and cooling curves; this is in agreement with a first-order transition.

4. Conclusions

In conclusion, the thermodynamic, electromagnetic, and transport properties of antiperovskite Mn₃SbN were studied. The phase crystallizes in a tetragonal structure with \( a = b = 4.1799(4) \text{ Å} \) and \( c = 4.27718(5) \text{ Å} \) at room temperature. The \( C_p \) measurements revealed a sharp endothermic peak in the \( C_p-T \) curve at 353 K, which corresponds to a large
entropy change (~10.2 J mol\(^{-1}\) K\(^{-1}\)). The present study clearly indicates that the entropy change is accompanied with a ferrimagnetic transition and lattice distortion as well as a possible electronic structure reconstruction.

**Conflict of Interests**

The authors declare that they have no conflict of interests.

**Acknowledgments**

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