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Published in:
Journal of Applied Physics

DOI:
10.1063/1.5144620

Publication date:
2020

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
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ABSTRACT

In this work, a systematic investigation on magnetic critical behavior is performed for the first time on an antiperovskite-type Mn$_3$GaN, which is prepared by intentionally modifying stoichiometry. According to the XRD results, the antiperovskite structure is well preserved, even though all lattice parameters shrink upon reducing Ga and N content down to 60%. The sample exhibits a ferromagneticlike feature with a Curie temperature ($T_C$) of 394 K rather than frustrated behavior in stoichiometric Mn$_3$GaN. Most importantly, the modified Arrott plots, Kouvel–Fisher plots, as well as critical isotherm method self-consistently co-confirm the critical exponents of $\beta = 0.33$, $\gamma = 1.23$, and $\delta = 4.7$, unambiguously indicating that the critical behavior follows the 3D-Ising model around $T_C$.

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I. INTRODUCTION

The modification of magnetic structure in anti-$(A_3BC)/$ perovskite-type $(ABC_3)$ materials has attracted great interest due to a variety of intriguing phenomena and potential for application, e.g., giant barocaloric effect, negative thermal expansion, as well as magnetostriction. Particularly, for antiperovskite Mn$_3$AX materials, the manipulation of magnetostucture is of great importance for fundamental research as well as its application expansion. It is well known that, in perovskite materials, the magnetic structure is mainly dominated by the distortion of $BC_3$ octahedron, which is impacted by the size of the A site atom. For instance, upon gradually replacing yttrium with a larger lanthanum atom in YTIO$_3$, the introduced GdFeO$_3$-type distortion drives the system into ferromagnetic (FM) from antiferromagnetic (AFM) order. However, antiperovskite-type materials, e.g., above mentioned Mn$_3$AX, exhibit a more complicated case: an AFM interaction, $J_1 < 0$, is present between nearest-neighbor atoms, while the next-nearest-neighbor magnetic interaction is FM ($J_2 > 0$). As a result, Mn$_3$X octahedron presents a three-dimensional geometrical frustrated behavior, leaving a path for modulating magnetostucture through tuning the competition between FM and AFM interaction. According to the study by Takenaka et al., a few percents of Fe dopants at Mn sites in Mn$_3$GaN could cause an AFM to FM phase transition, and a similar phenomenon is observed in carbon-doped samples.
Conclusively, the above-mentioned AFM–FM is modulated by breaking the frustrated state through playing competition between $J_1$ and $J_2$, therefore offering a fruitful playground to investigate the magnetostucture in such a frustrated system.

Actually, the way of magnetic coupling always significantly impacts on the magnetic critical behavior at the region of Curie temperature ($T_c$), e.g., a 3D-Heisenberg model is always prevailing in the ferromagnet with pure positive $J$ from three dimensions,\textsuperscript{12–14} while the recently attractive monolayered 2D ferromagnet with only positive $J$ in the plane only presents a 2D Ising critical feature.\textsuperscript{15} Thus, it is a fancy topic that is worth exploring, how to describe the magnetic critical behavior in such a “tuned” frustrated system with a complex competed $J$.

In the present study, we obtain a ferromagneticlike Mn$_3$GaN, which is deviated from stoichiochemistry during the preparation. The x-ray diffraction results verify the preservation of antiperovskite crystal structure, excluding the assumption that the observed ferromagneticlike behavior is caused from the Mn-rich second phase induced by spinodal decomposition. According to the modified Arrott plots, Kouvel–Fisher plots, and critical isotherm method, critical exponents of $\beta = 0.33$, $\gamma = 1.23$, and $\delta = 4.7$ are well fitted-obtained at the Curie temperature of around 394 K, obeying the critical 3D-Ising model.

II. EXPERIMENTAL

The preparation of the explored sample has been discussed in our previous work.\textsuperscript{16} Conventional x-ray diffraction (XRD) measurements were performed using a Rigaku D/max 2500 diffractometer with Cu Ka radiation ($\lambda = 1.5418$ Å) at room temperature, operated at 50 kV and 45 mA. Isothermal $M(H)$ data were recorded with a commercial SQUID magnetometer (MPMS Quantum Design) after zero field cooling from 400 K. After each completed data set, the field was oscillated to zero and then the sample was heated up to 400 K before the next cycle start. For the temperature dependent magnetization measurements, the temperature was carefully increased at a rate of 0.5 K/min.

III. RESULTS AND DISCUSSION

Figure 1 displays the XRD diagrams of our Mn$_3$Ga$_{0.6}$N$_{0.4}$, together with a Mn$_3$GaN for a reference. As shown in Fig. 1(a), both Mn$_3$GaN and Mn$_3$Ga$_{0.6}$N$_{0.4}$ present several diffraction peaks of (110), (111), (200), (220), (311), and (222), indicating their polycrystalline nature of the cubic antiperovskite structure. Additionally, two tiny peaks of MnO, which are not negligible, appear in both samples, indicating that a small amount of MnO is formatted probably during the sinter process. Actually, MnO is paramagnetic (PM), and when compared with the main antiperovskite phase its tiny mount can be ignored to influence our analysis. Interestingly, all peaks of Mn$_3$Ga$_{0.6}$N$_{0.4}$ shift to higher angle side, which suggests the reduction of lattice parameters, and such result is fully expected in the nonstoichiometric sample due to the vacancy caused lattice distortion. For instance, the diffraction angle of (220) planes increases from 33.94° to 34.45°, which means that the lattice parameter of (220) planes accordingly declines from 3.90 to 3.85 Å calculated by the Bragg equation. Meanwhile, the two peaks of MnO stay constantly in Mn$_3$Ga$_{0.6}$N$_{0.4}$, which perfectly excludes the possibility of measurement error induced peak shifting.

For the ferromagnetic–paramagnetic (FM–PM) phase transition, the critical behavior at around $T_c$ is described by a series of interrelated critical exponents according to the Landau theory.\textsuperscript{16} Near the vicinity of the phase transition point, the divergence of correlation length is defined as $\xi = \zeta_0 |(T - T_c)/T_c|^{\beta}$, causing universal scaling laws for the spontaneous magnetization $M_s$, the inverse initial magnetic susceptibility $\chi_0^{-1}$, $\beta$, $\gamma$, and $\delta$ are employed to characterize a set of magnetic behaviors including the $M_s$ below $T_c$, the $\chi_0^{-1}$ above $T_c$, as well as the $M(H)$ at $T_c$, respectively. Accordingly, at the temperature range around $T_c$, mathematical definitions of above-mentioned three exponents for magnetization are described as

$$M_s(T) = M_0(-e)^{\beta}, \quad e < 0, \quad T < T_c,$$  

$$\chi_0^{-1}(T) = \left(\frac{h_0}{m_0}\right)e^{\gamma}, \quad e > 0, \quad T > T_c,$$  

$$M = DH^{1/8}, \quad e = 0, \quad T = T_c,$$

where $e = (T - T_c)/T_c$ is the reduced temperature and $M_0$, $h_0/m_0$, and $D$ are critical amplitudes.\textsuperscript{18} In addition, by using the scaling hypothesis, the magnetic equation of state is described as

$$M(H, e) = e^\delta f_{\pm}(H/e^{\delta})^\gamma,$$

where $f_+$ and $f_-$ are regular analytic functions for $T > T_c$ and $T < T_c$, respectively.

In order to clarify the nature of the PM–FM transition, we measured the isothermal magnetic field dependent magnetization $M(H)$ curves of Mn$_3$Ga$_{0.6}$N$_{0.4}$ at selected temperatures from 376 to 400 K and applied magnetic fields up to 50 kOe. The gapped temperature $\Delta T$ is set as 1 K. For all $M(H)$ measurements, the sample was cooled down from 400 K under a zero field after stabilizing at
400 K for 10 min. Then, the initial magnetization was recorded upon gradually increasing the magnetic field till 50 kOe. To explore the critical exponents of the transition, modified Arrott Plots of $(H/M)$ dependent $M$ herein is performed by the Arrott–Noakes equation,\textsuperscript{19}

$$(H/M)^{1/\gamma} = ae + bM^{1/\beta},$$

where $e = (T - T_C)/T_C$ is the reduced temperature, which is the same as in Eq. (2), and $a$ and $b$ are constants. According to the Landau mean-field description, Eq. (5) degenerates to a standard Arrott Plot, in which the critical exponents $\gamma$ and $\beta$ are 1 and 0.5, respectively.\textsuperscript{20} As a result, an ideal mean-field model described system constitutes a set of parallel straight lines, and the isotherm at the Curie temperature pass the origin.\textsuperscript{20} As shown in Fig. 2(b), the Mn$_3$Ga$_{0.6}$N$_{0.6}$ just presents a set of quasistraight lines, and their positive slope indicates a second-order nature of PM–FM transition according to the Banerjee criterion.\textsuperscript{21} However, a slightly up-convex of mean-field Arrott-curves suggests that the system cannot be treated as an ideal mean-field model. To further explore its critical essence, two other three-dimensional (3D) models are presented to make a comparison: 3D Heisenberg model with $\gamma = 1.436$ and $\beta = 0.378$, and 3D-Ising model with $\gamma = 1.230$ and $\beta = 0.330$.\textsuperscript{22} As shown in Fig. 2(c), the modified Arrott-plotted curves with Heisenberg critical values are obviously down-concave, indicating that the Heisenberg model is not satisfied to describe the phenomenon. However, the 3D-Ising model provides an outstanding linear fitting, definitely confirming the signature of 3D-Ising type transition. Moreover, it is worth noting that the Curie temperature of 394 K is meanwhile determined, in which the modified straight curve directly passes the origin.

To further distinguishingly confirm the critical model from the Mean-field model and the 3D-Ising model, a rigorous interactive way is used:\textsuperscript{23} According to Eqs. (1) and (2), the results of spontaneous magnetization $M_s(T)$ and $\chi_0^{-1}(T)$ could be fitted by the linear extrapolation from the high-field region to the intercepts with the axis $M_s^{1/\beta}$ and $(H/M)^{1/\gamma}$, respectively; therefore, a set of fitting values of $\beta$ and $\gamma$ are obtained. As shown in Fig. 3(a), two solid curves nicely fit the temperature dependent $M_s(T)$ and $\chi_0^{-1}(T)$ results both, accordingly two critical exponents, $\beta = 0.330$ with $T_C = 394.2$ K and $\gamma = 1.241$ with $T_C = 394.2$ K, are obtained. Such values again pronounce the dominance of the 3D-Ising model. To further cross-check the critical exponents deduced from our current-obtained temperature dependent magnetization results, an alternative method named Kouvel–Fisher plots is used, and its mathematical description is\textsuperscript{24}

$$\frac{M_s(T)}{dM_s/dT} = \frac{T - T_C}{\beta},$$

and

$$\frac{\chi_0^{-1}(T)}{d\chi_0^{-1}(T)/dT} = \frac{T - T_C}{\gamma}.$$  

Therefore, according to Eqs. (6) and (7), $M_s(T)/[dM_s(T)/dT]$ and $\chi_0^{-1}(T)/[d\chi_0^{-1}(T)/dT]$ are, respectively, as linear functions of
temperature with slopes $1/\beta$ and $1/\gamma$. The fitting results are given in Fig. 3(b), claiming the fitting values for $\beta = 0.340$ with $T_C = 394.2$ K, and $\gamma = 1.244$ with $T_C = 394.0$ K, respectively. As expected, the Kouvel–Fisher fitted values are highly consistent with former calculated critical components and $T_C$ from modified Arrott–Noakes plots, which cross-confirms the description of the 3D-Ising model.

To reveal third critical component $\delta$ which appears in Eq. (3), the isothermal magnetization $M(H)$ result at the critical temperature of 394 K together with a double-logarithmic plot is shown in Fig. 4. According to Eq. (3), $\delta$ is calculated as 4.727 by the slope of a linear double-logarithmic plot shown in the inset of Fig. 4. Alternatively, the Windom scaling law works,

$$\delta = 1 + \frac{\gamma}{\beta},$$

where $\beta$ and $\gamma$ are obtained from modified Arrott plots or Kouvel–Fisher fitting. Accordingly, $\delta$ is calculated as 4.727, which is exactly the same as the value deduced from Eq. (3).

It is worth noting that the obtained critical exponents and $T_C$ are verified reliably by a scaling analysis. According to Eq. (4), the scaling equation displays that $M(H, \epsilon) \propto H^{\beta/\gamma}$ should lead to two different branches: $T > T_C$ and $T < T_C$. The isothermal magnetization curves around $T_C = 394$ K are plotted in Fig. 5 with an aid of critical exponents $\beta = 0.33$, $\gamma = 1.23$. As a result, all plots evolve into two independent sets of curves as expected: $T > T_C$ and $T < T_C$, indicating that the reliability of the obtained critical exponents. For a comparison, the obtained critical exponents of Mn$_3$Ga$_{0.6}$N$_{0.4}$ as well as that from different theoretical values are listed in Table I.

FIG. 3. (a) Temperature dependence of the spontaneous magnetization $M_S$ (left) and the inverse initial susceptibility $\chi_0^{-1}$ (right) with solid fitting curves for Mn$_3$Ga$_{0.6}$N$_{0.4}$. The curves represent fits of Eqs. (1) and (2) to the data with the exponents $\beta = 0.33$ and $\gamma = 1.24$. (b) Kouvel–Fisher plots of $M_S(dM_S/dT)^{-1}$ (left) and $\chi_0^{-1}(\partial \chi_0^{-1}/\partial T)^{-1}$ (right) with solid fitting curves.

FIG. 4. Isotherm $M(H)$ plot collected at $T_C = 394$ K for Mn$_3$Ga$_{0.6}$N$_{0.4}$. Inset: The same data shown in double-logarithmic plot with a solid fitting curve.

FIG. 5. Scaling plots of the $M(H)$ data of Mn$_3$Ga$_{0.6}$N$_{0.4}$ for temperatures ranging from 376 K to 400 K using the values $\beta = 0.33$, $\gamma = 1.23$, and $T_C = 394$ K. Inset: scaling plot in a double-logarithmic scale.
IV. CONCLUSION

In summary, we report systematical investigations on critical behavior of ferromagneticlike antiperovskite-type Mn$_3$Ga$_{0.6}$N$_{0.6}$, which is produced away from the stoichiometry. Around its $T_C$ of around 394 K, according to the modified Arrott plots, Kouvel–Fisher plots, and critical isotherm method, three critical exponents, $\beta$, $\gamma$, and $\delta$, are deduced to be 0.33, 1.23, and 4.7, respectively, which are highly in agreement with the 3D-Ising model. Moreover, the calculated values follow the scaling equation, again confirming the intrinsic 3D-Ising essence of ferromagneticlike Mn$_3$Ga$_{0.6}$N$_{0.6}$.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Grant Nos. 51372056, 51672057, and 51722205), International Science & Technology Cooperation Program of China (Grant No. 2012DFR50020), the Fundamental Research Funds for the Central Universities (Grant No. HIT.BRETIV.201801), and the Natural Science Foundation of Heilongjiang Province (Grant No. E2018032).

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TABLE I. Comparison of critical exponents of Mn$_3$Ga$_{0.6}$N$_{0.6}$ with different theoretical models.

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<tr>
<th>Composition</th>
<th>Technique</th>
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<th>$\Gamma$</th>
<th>$\delta$</th>
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<tr>
<td>Mn$_3$GaN</td>
<td>Modified Arrott plots</td>
<td>0.330 ± 0.006</td>
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<td>This work</td>
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