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Effect of residual stress on nematic domains in $BaFe_{2-x}Ni_xAs_2$ studied by angular magnetoresistance*

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We have studied the angular magnetoresistance of iron pnictides $BaFe_{2-x}Ni_xAs_2$, which shows clear 180 degree periodicity as fitted by a cosine function. In the $x = 0.065$ sample, the phase of the two-fold symmetry changes 90 degrees above the tetragonal-to-orthorhombic structural transition temperature T_s. Since the phase at low temperature is associated with the rotation of orthorhombic domains by magnetic field, we show that even vacuum grease can push the presence of orthorhombic domains at temperatures much higher than T_s. Our results suggest that residual stress may have significant effects in studying the nematic orders and its fluctuations in iron pnictides.

Keywords: superconductivity, electronic nematic fluctuations, iron pnictides

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1. Introduction

The nematic order and its fluctuations in the iron-based superconductors have attracted great interest due to its importance and intimate relationship with superconductivity.[1–6] The nematic order in these materials is established when the electronic system breaks the four-fold rotational symmetry of the underlying lattice, while the translational symmetry is unchanged. It is first shown by the transport measurement that the resistivity along the orthorhombic a and b axes of undoped and underdoped $Ba(Fe_{1-x}Co_x)_2As_2$ are distinctly different.[7] Such anisotropic resistivity under uniaxial pressure is confirmed in many other iron-based superconductors.[8–13] Further studies show that the nematic order can be revealed by many other properties, such as the spin excitations,[14,15] band structures,[8,16] magnetic susceptibility,[17] and optical properties.[18] It is shown that a transition-like behavior of the nematic phase may happen at $T^* > T_s$ without the application of uniaxial pressure and the structural transition may be a metanematic transition.[17,18] Since the establishment of nematic order is always accompanied by a structural transition at T_s that changes the lattice symmetry from C_4 to C_2 and results in the presence of twinning domains, most of the above studies involve applying a large uniaxial pressure to detwin the sample. In many cases, a characteristic temperature T^* representing the disappearance of the corresponding anisotropic properties is also found.[8,14–16]

Recently, increasing evidence has been found that the observation of a nematic-like signal above T_s may be due to the presence of pressure. The temperature dependence of the nematic susceptibility from resistivity measurements clearly demonstrates that the nematic fluctuations show a Curie–Weiss-like behavior and no additional phase transition is found.[19–21] The study on $BaFe_{2-x}Ni_xAs_2$ by neutron resonance spin echo and Larmor diffraction shows that uniaxial pressure introduces the orthorhombic lattice distortion at all temperatures,[22] which suggests that there should just be one nematic transition if the lattice and nematic phase are strongly coupled. The nuclear magnetic resonance (NMR) measurement also shows no evidence for a phase transition above T_s.[23] Moreover, it is shown by Raman scattering that a distribution of substantial residual stress remains even without any uniaxial pressure,[24] clearly demonstrating that residual stress may affect measuring nematic response above T_s.

Generally speaking, the uniaxial pressure may affect the nematic phase and its fluctuations in two ways. First, it can act as an external field to the nematic order and induce a finite order parameter above the transition temperature as described in the classic Landau theory.[21,24] In this case, it is more or less a question of resolution in determining the temperature where the anisotropic properties disappear. Second, it may introduce lattice distortion and create orthorhombic domains above T_s.[22] Any attempt to find a nematic transition higher than the structural transition has to consider the above two possible explanations.

In this article, we study the effect of residual stress on

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nematic domains above T_s by measuring the angular magnetoresistance of $BaFe_{2-x}Ni_xAs_2$. The parent compound of $BaFe_2As_2$ shows long-range antiferromagnetism with superconductivity appearing above $x \approx 0.05$.[25] The antiferromagnetic order disappears at $x \approx 0.1$, while the system becomes optimally doped in the meantime. Further doping Ni higher than ≈ 0.25 will fully destroy superconductivity. It has already been shown that the twinning orthorhombic domains below T_s can be affected by a moderate magnetic field in underdoped $Ba(Fe_{1-x}Co_x)_2As_2$.[26] Here using a similar technique, we find that the presence of nematic domains in $BaFe_{1.935}Ni_{0.065}As_2$ can be pushed to about 30 K higher than T_s by simply burying the sample within vacuum grease. Our results suggest that extreme caution should be exercised in studying the nematic signal.

2. Experiments

The growth of single-crystal $BaFe_{1.935}Ni_{0.065}As_2$ has been reported elsewhere.[25] The structural and antiferromagnetic transition temperatures, i.e., T_s and T_N, are about 73 and 65 K, respectively.[27,28] After determining the crystal orientation by x-ray Laue method, the samples were cut into thin bars by a diamond wire saw with the long side along either the tetragonal (110) or (100) direction. In the orthorhombic state, the tetragonal (110) direction is parallel to orthorhombic a and b axes. The angular magnetoresistance was measured by the PPMS (Quantum Design) using the rotator option.

The inset of Fig. 1(b) gives the schematic diagram of the resistivity measurements by the standard four-points method. The magnetic field is effectively rotating within the a–b plane, where θ is defined as the angle between the field and current, the same as that defined in Ref. [26]. To test the effect of residual stress, two kinds of methods were used to attach the samples onto the rotator's sample puck. In the first method, the two-end points of the long side of the sample were glued onto the puck, whereas the whole sample was buried by the vacuum grease in the second method. In the following texts, the two methods will be called as two-end-points and grease methods, respectively.

3. Results and discussion

Figure 1 gives the raw data of the angular magnetoresistance of the $x = 0.065$ samples with the two-end-points method. For all the data including those of other samples, the angular dependence of the resistivity can be well fitted by the following equation:

$$R = R_0 + A\theta + R_1\cos(\theta - \theta_1) + R_2\cos(2(\theta - \theta_2)), \quad (1)$$

where the four terms correspond to a constant resistivity, a linear background, the 360-degree and 180-degree symmetrical parts of resistivity. The linear and 360-degree dependences of resistivity on the rotating angle θ are most likely due to the slight temperature gradient within the PPMS sample chamber while the sample is not strictly at the center of the rotating axis. Here we focus on the two-fold symmetry part of the resistivity.

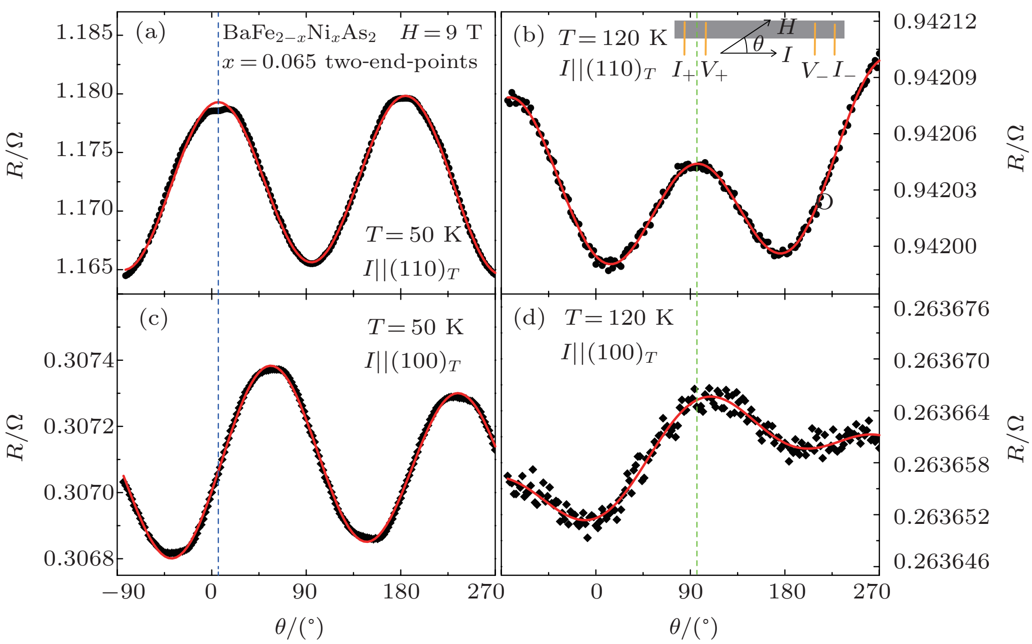

Fig. 1. (color online) Angular magnetoresistence of $BaFe_{1.935}Ni_{0.065}As_2$ with current along the (110) direction at (a) 50 K and (b) 120 K. The measurements with current along the (100) direction are shown in panels (c) and (d) at 50 K and 120 K, respectively. The inset of panel (b) shows the sketch diagram of the measurement, where θ is defined as the angle between magnetic field and current. All the measurements are taken at 9 Tesla. The solid red lines are fitted curves according to Eq. (1). The blue and green dashed lines are the positions of maximum values in panels (a) and (b), respectively.

Figures 1(a) and 1(b) show the angular magnetoresistance along the (110) direction with the two-end-points method at 50 K and 120 K, respectively. At low temperatures below T_s, it has already been shown that the two-fold symmetry of the resistivity comes from partially detwinning of the sample due to very strong magnetoelastic coupling in iron-based superconductors.[26] The reason lies in the fact that the resistivity along the orthorhombic a axis ρ_a is smaller than that along the orthorhombic b axis ρ_b,[7] while the magnetic susceptibility $\chi_b > \chi_a$.[17] Therefore, the rotating of the magnetic field will result in the change of orthorhombic domain ratio that leads to the angular dependence of the resistivity, which gives θ_2 about 0 neglecting the error in determining the absolute value of θ, as shown in Fig. 1(a). With temperature increasing above T_s, θ_2 shifts 90 degrees as shown in Fig. 1(b).

Figures 1(c) and 1(d) show the angular magnetoresistance along the (100) direction with the two-end-points method. At 50 K, the phase is about 45° different from that along the (110) direction, while there is no difference between two directions at 120 K. As pointed out in Ref. [26], the difference of θ_2 suggests that the two-fold symmetry is associated with the angle between the field and lattice axes at low temperatures. Apparently, figures 1(b) and 1(d) suggest that the two-fold symmetry at high temperatures is associated with the angle between the field and the current.

Figures 2(a) and 2(b) plot the temperature dependence of θ_2 and R_2/R_0 for the two-end-points method. As discussed above, the difference of θ_2 between the (110) and (100) directions disappears at about 85 K, which is slightly higher than T_s. We note that the value of R_2/R_0 is almost two orders of difference between T_s and 90 K, so the presence of $\theta_2 = 0$ above T_s may be due to the tail of the transition generally observed in a second-order transition if one assumes that the residual stress plays a negligible effect in the two-end-points method. There is a minimum of R_2 at about 90 K, suggesting that there are two components of two-fold symmetry with different phases. At low temperatures, the amplitude of the one with $\theta_2 = 0$ is much larger than that with $\theta_2 = -90°$. While both amplitudes decrease with increasing temperature, the one with $\theta_2 = 0$ decreases much faster than that with $\theta = -90°$, giving a minimum of R_2 as a result of cancellation between these two components.

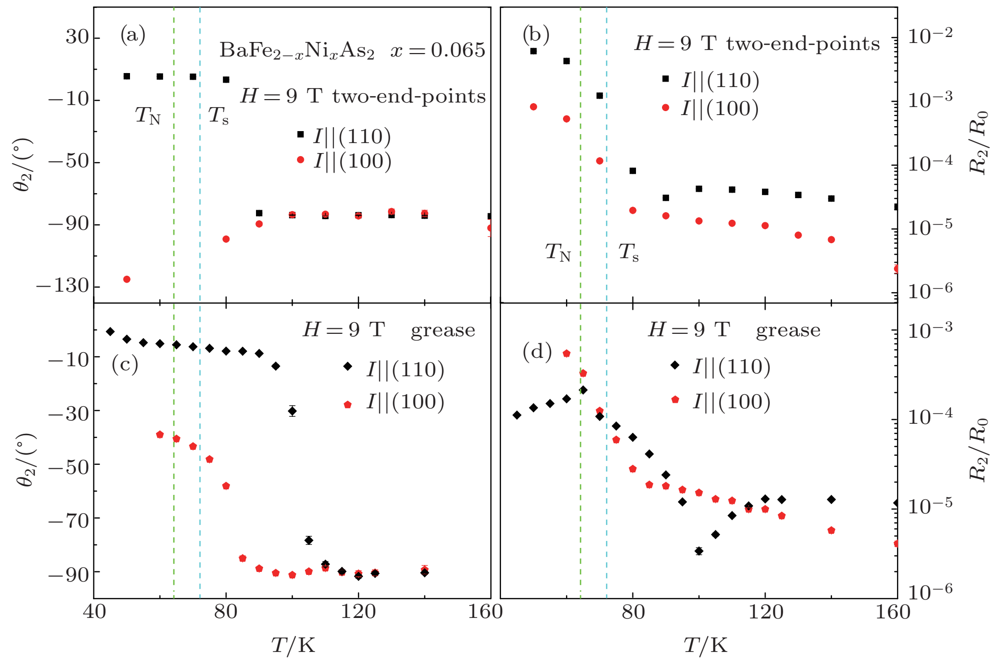

Fig. 2. (color online) Temperature dependence of θ_2 and R_2/R_0 as defined in the main text for the $x = 0.065$ samples. (a) and (b) are obtained by the two-end-points method, while (c) and (d) are obtained by the grease method. All the measurements are taken at 9 Tesla. The green and cyan dashed lines represent antiferromagnetic transition and structural transition temperatures, respectively. The black squares and red circles represent current following along the tetragonal (110) and (100) directions, respectively.

Since the component with $\theta_2 = -90$ only depends on the angle between the magnetic field and current, it can be understood within a general picture that the magnetic field changes the motion of the conducting electrons as in a normal metal. The minimum and maximum of the magnetoresistance thus happen when the current is parallel and vertical to the magnetic field, respectively, as shown in Figs. 1(b) and 1(d).

Figures 2(c) and 2(d) show the temperature dependence of θ_2 and R_2/R_0 for the $x = 0.065$ samples with the grease method, respectively. Surprisingly, θ_2 along the (110) direction drops to $-90°$ at about 110 K, much higher than that in the two-end-points method, while that along the (100) direction shows little change. Consistently, the minimum of R_2/R_0 is also increased to about 100 K.

As discussed above, the change of θ_2 from 0 to -90 degrees is associated with the disappearance of orthorhombic domains. Since the orthorhombic structure is always coupled to the nematic order in iron pnictides, a natural conclusion from the above results is that the nematic domains can survive at temperatures much higher than T_s even without the presence of uniaxial pressure. While the vacuum grease seems to be isotropic, it is possible that significant residual stress may build up gradually during its solidification with decreasing temperature. On the other hand, the middle part where the resistivity measurement is taken in the two-end-points method seems to have much less residual stress.

We have also measured the angular magnetoresistance of the parent compound $BaFe_2As_2$ as shown in Fig. 3. R_2/R_0 shows clear transition behavior at T_s/T_N without any minimum, like that in the $x = 0.065$ sample. Correspondingly, θ_2 just changes about 3 degrees across the transition. This may be because it is harder to move the orthorhombic domains in the parent compound, the two-fold symmetry is thus dominated by the regular magnetoresistance with $\theta_2 = -90°$. Therefore, detecting the presence of nematic domains above T_s by angular magnetoresistance is not always suitable.

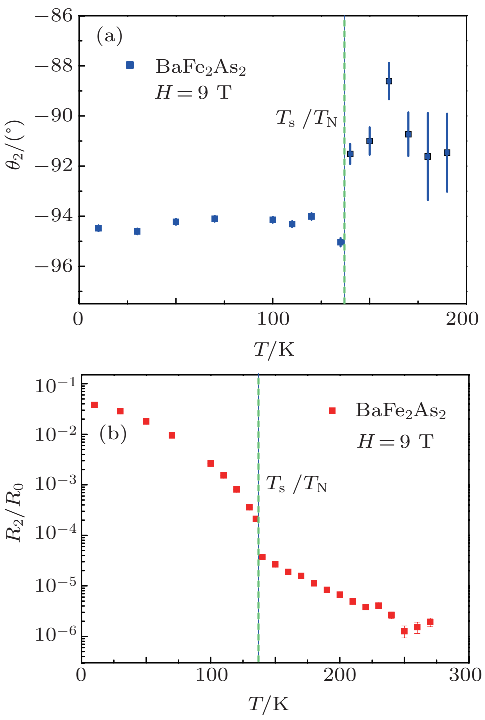

Fig. 3. (color online) Temperature dependence of (a) θ_2 and (b) R_2/R_0 for $BaFe_2As_2$ by the two-end-points method. The magnetic field is 9 Tesla. The dashed green line indicates the antiferromagnetic and structural transition temperatures.

4. Conclusion

In summary, we have carried out angular magnetoresistance in $BaFe_{2-x}Ni_xAs_2$ system. The presence of nematic domains above T_s can be detected by the phase change of the two-fold symmetry. Our results suggest that even vacuum grease may lead to residual nematic domains at high temperatures. Therefore, extreme caution should be exercised in studying nematic signals whenever the sample needs to be glued or even greased on to a sample holder.

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