Visualization of Vortices Motion in FeAs Based $BaFe_{1.9}Ni_{0.1}As_2$ Single Crystal by Means of Magneto-optical Imaging

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Superconductivity has been found in newly discovered iron-based compounds. This paper studies the magnetic vortices motion in $BaFe_{1.9}Ni_{0.1}As_2$ single crystal by means of magneto-optical imaging technique. A series of magneto-optical images reflecting magnetic flux distribution at the crystal surface were taken when the crystal was zero-field cooled. The vortices behaviour, including penetration into and expelling from the single crystal with increasing and decreasing external field is discussed. The motion behaviour is similar to that observed in high-Tc superconducting materials with strong pinning, however, the flux-front is irregular due to randomly distributed defects in the crystal.

I. INTRODUCTION

The discovery of superconductivity in oxypnictides phase, LaFe(OF)As, [1, 2] has excited strong interest in understanding of physical properties of new iron-based superconducting materials, mechanism of superconductivity, and differing such FeAs-based superconducting compounds from high-T_c cuprates. Superconductivity has been found in a wide variety of compounds with Fe^{2+} square planar sheets, for example, the oxypnictides of $LaFeAsO_{1-x}F_x$ (or $LaFeAsO_{1-x}$), doped $ThCr_2Si_2$-type structure compounds of $BaFe_2As_2$,[3] LiFeAs,[4] and FeSe.[5,6,7] It is also noticed that superconductivity can be induced in $BaFe_2As_2$ by alloying Fe with the other ferromagnetic 3d elements, Co[8] or Ni,[9],[10] as that found in the oxypnictides.[11,12] Investigation on vortex properties in new Fe-based superconducting materials will provide fundamental understanding of the materials. Magneto-optical imaging (MOI) technique, as a simple and versatile method, can easily visualize local vortices motion in superconducting materials at scale of micrometer size[13]. In comparison, superconducting Quantum Interference Devices and Vibrating Sample Magnetometer normally study collective magnetic information.

While vortices motion in Co-doped $Ba(Fe_{1.8}Co_{0.2})As_2$ single crystal has been studied,[14] this paper studies the local magnetic vortices properties in Ni-doped $BaFe_{1.9}Ni_{0.1}As_2$ single crystal by means of the MOI technique with increasing and decreasing magnetic fields at zero-field cooled (ZFC). The observed vortices motion is very similar to that in high T_c cuprates with strong flux pinning strength.

II. EXPERIMENTAL DETAIL

The nominal composition $Ba(Fe_{1.9}Ni_{0.1})As_2$ single crystal samples were grown out of Fe-As flux by self-flux method as preparation of $Ba(Fe_{1.8}Co_{0.2})As_2$ single crystal.[8] The sizes of polished rectangular-shaped single crystal are $2.7 \times 1.8 \times 0.2\ mm^3$. The crystal is brittle, well-formed plates with the [001] direction perpendicular to the plane of the crystal. However, the edges of the crystal and the corners are not well-defined.

Magneto-optical images shown in the paper were captured using a MOI system[15] which was built based on the Faraday rotation of polarized light in a Bi-doped iron garnet indicator film with an in-plane magnetization. The optical cryostat was cooled by a compressor. The temperature can reach down to 10 K and field up to 27 KG. The indicator film was directly placed on the crystal with slight mechanical pressure to ensure that the field distribution at the crystal surface can be precisely imaged by indicator film.

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of electrical resistivity at *ab* plane in the absent of magnetic field, performed on a Quantum Design PPMS. The crystal shows metallic behaviour. The resistivity drops down abruptly at 18.8 K and reaches zero at 17.4 K. The transition width is 1.4 K. This value is larger than that reported for $Ba(Fe_{1.904}Ni_{0.096})As_2$ [16] of less 1 K and $Ba(Fe_{1.8}Co_{0.2})As_2$ single crystal of 0.6 K.**Error! Bookmark not defined.**

Figure 2 shows magnetization hysteresis loop of the crystal measured at 5 K with applied magnetic field along c-crystallographic direction. It can be seen that the lower critical field H_{c1} is very small, around 50 Oe. Limited by field of 5 T, the second peak is not observed at low

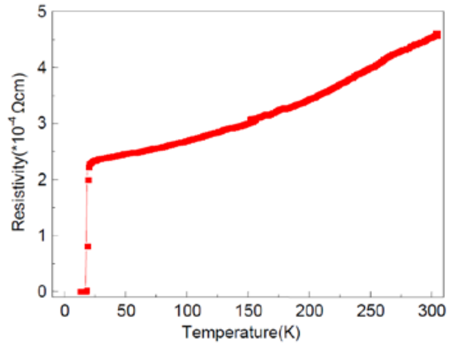

FIG. 1. Temperature dependence of resistivity.

temperature as $Ba(Fe_{1.8}Co_{0.2})As_2$.[8] It is believed that the fishtail[17] effect could be observed with higher field or at higher temperatures with the field up to 5 T as observed in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystal.[18] The detailed study of magnetization hysteresis loop is out of the scope of this paper and will be presented in another paper.

Figure 3 presents magneto-optical images taken at 10 K and different applied magnetic fields parallel to the c-direction. To clearly present images, contrast of figure 3a was enhanced only using imaging edit software. The tooth pattern domain was resulted from the field parallel to the indicator film. Some defects in indicator film can be clearly seen in figures 3d and 3e. Below 50 Oe the vortices are completely shielded from the crystal, and crystal was in Meissner state. At the field over 60 Oe, vortices started penetration into the crystal from points along the edge, as shown in figure 3a taken at 83 Oe. With increasing magnetic field, vortices penetrated into the crystal further, in addition, penetration also occurred along the crystal edges, as shown in figures 3b and 3c. At 531 Oe, the salient flux front reached the center region of the crystal shown in figure 3d, but still there was a small flux-free region. At about 584 G, vortices entered the whole crystal and flux-free region disappeared. The crystal was in mixed state. Figure 3e is the remanent state after field increases to 1800 Oe and decreases to zero. It clearly shows that the penetrated vortices are pinned in the center region of the crystal and vortices around the edges have left the crystal.

In order to clearly present progress of the flux front entering into the crystal, figure 4 shows colour-coded flux-free regions at different fields. Vortices penetration firstly

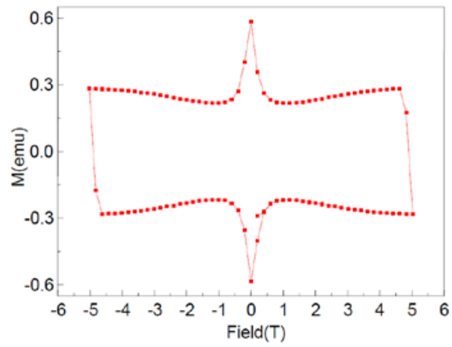

FIG. 2. Magnetization hysteresis loops measured at 5 K with the fields along c-crystallographic direction.

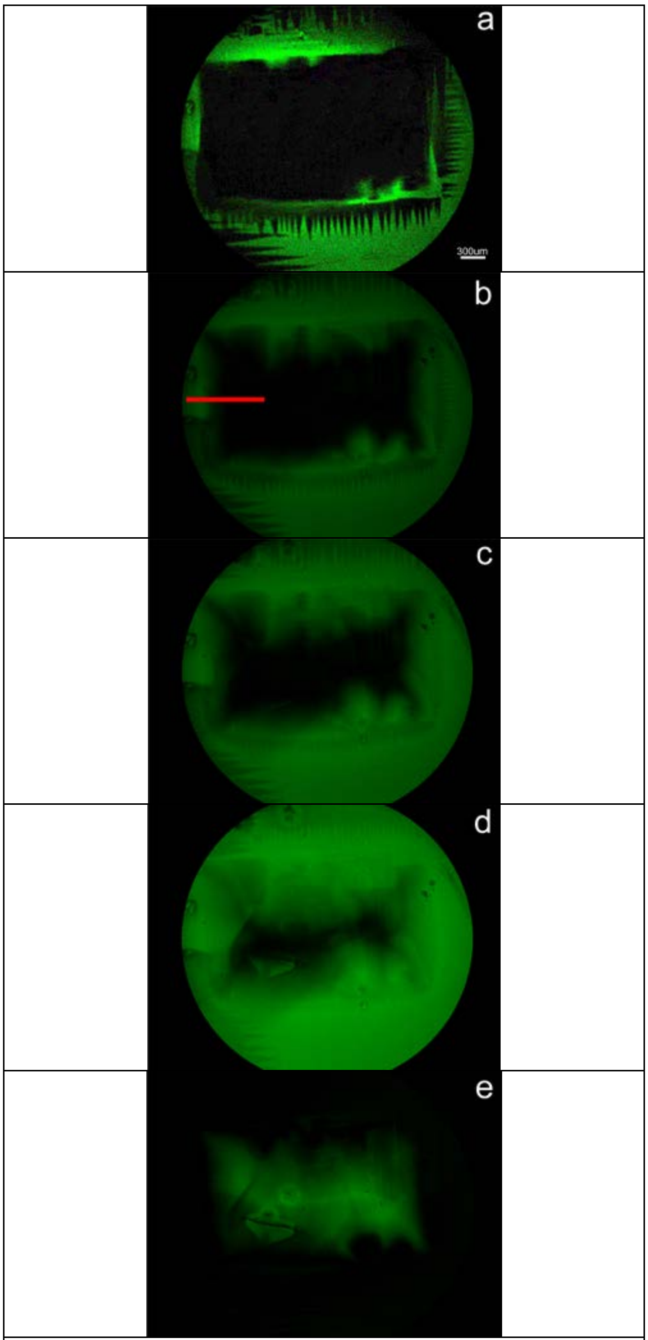

Figure 3. Magneto-optical images taken at 10K and applied magnetic fields of 83 G (a), 265 G (b), 354 G (c), 531 (d) and remanent state (e).

occurs at the defect points along the edges. With increasing field, vortices penetrate also along the edge, forming irregular shape of flux fronts. As a result of increasing field, flux-free region continuously shrinks. This observation means that the crystal has strong vortex pining force to damp the vortices motion. It can also be seen that vortices penetrate into the crystal from the defect points along the edges, but these points are not the starting points of the channels along which the vortices can easily enter the crystal. These defects might be caused by crystal structure

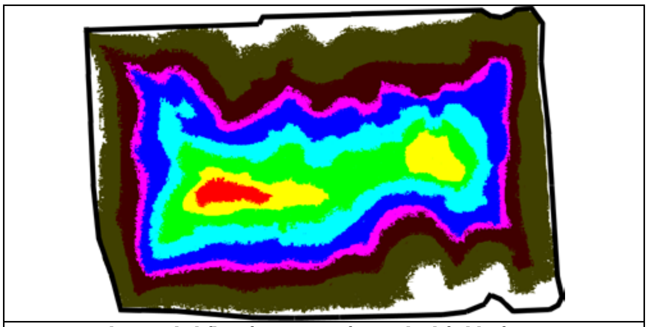

FIG. 4. Colour coded flux-free region for applied field of 109Oe, 135Oe, 265Oe, 299Oe, 354Oe, 430Oe, 502Oe, and 531Oe. The black line is outline of the crystal.

defects which are randomly distributed in the crystal, and therefore, the shapes of the flux front are irregular.

The critical current can be estimated using Bean critical state model,[19]

$$\frac{d}{dt}B_z(x) = \mu_0 J_c . \qquad (1)$$

According to the field distribution along the white line shown in figure 3b, the J_c is estimated to be 5.5 × 10^5 A/cm^2. This value is similar with the value reported in unirradiated $Ba(Fe_{0.93}Ni_{0.07})_2As_2$ crystal at 10 K.[20]

IV. CONCLUSION

A single crystal $Ba(Fe_{1.9}Ni_{0.1})As_2$ was grown from Fe-As flux with transition temperature of 18.8 K and transition width of 1.4 K. Vortices motion in the crystal was studied by means of magneto-optical imaging technique with increasing and decreasing applied magnetic field parallel to the c-direction at ZFC. In general, vortices penetrate into the crystal with increasing field from defects and edges. The vortices pinning effect is also clearly presented after decreasing the field to zero. Such behaviour is very similar to the vortices motion observed in cuprates with strong pinning. However, the irregular shape of the flux-front is observed due to structure defect randomly distributed in the crystal. The J_c estimated from the flux distribution is about 5.5 × 10^5 A/cm^2.

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