Vortex phase diagram of pristine and irradiated Co-doped BaFe$_2$As$_2$

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Abstract. Vortex phase diagram is studied up to $H = 170$ kOe in a pristine and Xe (800 MeV, $B_{ph}= 20$ kOe) irradiated Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ single crystals. In both samples, temperature dependence of resistivity ($\rho$) and current ($I$)-voltage ($V$) characteristics are carefully measured with a voltage resolution better than 1 nV. In the pristine sample, clear indication of vortex glass transition is obtained. Critical exponents in the pristine sample show little magnetic field dependence unlike the case for SmFeAsO$_{0.85}$ crystal. Rather, it is similar to the case of YBa$_2$Cu$_3$O$_y$ single crystals. In the irradiated sample, both vortex glass and Bose glass scalings give reasonable overlaps of $I$-$V$ curves.

1. Introduction

After the discovery of superconductivity in LaFeAs(O,F) with a superconducting transition temperature $T_c \sim 26$ K [1], efforts are focused on the elucidation of mechanism of superconductivity in the new family of superconductors. On the other hand, since most of iron-based superconductors have attractive superconducting parameters for applications including very high upper critical field and large enough critical current density [2], understanding of superconducting properties including vortex pinning is also required. In cuprate superconductors, large thermal fluctuations causes fast relaxation of shielding current [3]. At the same time, under the influence of such strong thermal fluctuations, whether superconducting phase can exist or not under magnetic field has been questioned. One novel notion of vortex system called “vortex glass” has been suggested theoretically [4,5] and soon after that experimentally demonstrated [6,7]. The vortex glass phase is claimed to be a true superconducting phase in the sense that linear resistivity vanishes in the limit of $J \rightarrow 0$. This is in contrast to the conventional notion of vortex motion via thermally activated creep, which predicts a small but finite value of resistivity in the low current limit. Whether similar state exist in the newly found iron-based superconductors is a matter of importance both from fundamental and application point of view. In the present study, we carefully measured temperature dependence of resistivity ($\rho$) and current ($I$)-voltage ($V$) characteristics up to 170 kOe in a well-characterize single crystal of Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ with a small anisotropy [2,8]. We also measure Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ single crystals irradiated by high energy Xe ions to evaluate the effect of artificial defects on the vortex state.
2. Experiments

Crystals used in the present studies are grown by the flux method as described in Ref. [8]. Some of the crystals are irradiated by 800 MeV Xe to introduce defects in the system. Changes in the superconducting properties including \( T_c \) and critical current (\( J_c \)) are described in Ref. [9]. Transport measurements up to \( H = 170 \) kOe are performed at the High Field Laboratory in Tohoku University using Nanovolt Preamplifier (Keithley 1802 with 2001). To reduce heating at contacts due to a finite value of contact resistance, we coat the contacts by Sn solder or sputter gold. The contact resistance thus obtained is much less than 100 m\( \Omega \). When temperature dependence of resistivity is measured, the sweep rate of the temperature is set to 0.03 K/min. so that there will not be large thermal gradient between the sample and the thermometer.

3. Results and discussion

Figures 1 (a) shows temperature dependence of resistivity for \( H//c \) in a pristine sample. Magnetic field shifts the superconducting transition in almost parallel fashion. It makes a good contrast to the behavior in a more anisotropic SmFeAsO\(_{0.85}\) single crystal, where the transition broadens significantly at high fields [10]. The absolute value of resistivity at \( T_c \) is less than 100 \( \mu \Omega \)cm, indicating that the crystal is of high-quality. We can define the upper critical field, \( H_{c2} \), by the mid point of the resistive transition. Temperature dependence of \( H_{c2} \) for \( H//c \) is plotted in Fig. 3(a). The slope of \( H_{c2} \) at mid-field range (\( H \sim 100 \) kOe) is about -24 kOe/K consistent with our previous study [8]. At the foot of resistive transition, resistivity vanishes gradually especially under magnetic field. Close to the vortex glass transition, \( T_g \), resistivity is expected to change as \( \rho \sim |T-T_g|^{\frac{1}{2}} \), where \( \nu \) and \( z \) are static and dynamic exponents and \( d \) is the dimension of the vortex system. We can safely assume \( d=3 \) in most of iron-based superconductors. In Fig. 1(b), the inverse of temperature derivative of logarithm of resistivity, \( (d\ln\rho/d\ln T)^{-1} \), is plotted as a function of temperature from 1 kOe to 170 kOe. We evaluate \( s=\nu(z-1) \) and \( T_g \) for each field from the slope of line and the intercept with respect to the \( T \) axis, respectively. Thus determined \( T_g \) and field dependence of \( s \) is plotted in Figs. 3(a) and 3(b), respectively.

Figure 2(a) shows logarithmic plot \( I-V \) characteristics for the pristine sample at \( H=40 \) kOe. It is evident that as the temperature is lowered, linear \( I-V \) characteristics turn into nonlinear concave down curves. At even lower temperature, \( I-V \) becomes power-law at \( T_g \) as predicted theoretically. Since this slope is \( (z+1)/2 \), we can evaluate the dynamical exponent \( z=3.6 \) at this field.

Another prediction of the vortex glass theory is that \( I-V \) curves when they are properly scaled, there will be universal curves one above and one below \( T_g \). By trimming \( T_g, \nu, \) and \( z \), we can overlay all the \( I-V \) curves into two scaled \( I-V \) curves as shown in Fig. 2(b). Positive curvature for each curve at higher current region is the result of heating.

![Figure 1](image1.png)

**Figure 1.** (a) Temperature dependence of resistivity for \( H//c \) in a pristine Ba(Fe\(_{0.925}\)Co\(_{0.075}\))\(_2\)As\(_2\) at \( H=0, 1, 5, 10, 20, 40, 70, 100, 115, 130, 150, \) and 170 kOe. (b) \( (d\ln\rho/d\ln T)^{-1} \) as a function of temperature in the same field range as (a). The smallest part is fitted by a straight line to evaluate critical exponents and \( T_g \).
In Figure 3(a), the vortex glass transition temperature $T_g$'s in a pristine sample determined from $\rho$-$T$ and I-V measurements are plotted with the $H_{c2}$ line. Even at the highest field of 170 kOe, the vortex fluid region with a finite resistivity is only 2 K wide below the superconducting transition. The crystal is in the true superconducting state with vanishing linear resistivity below $T_g$.

Finally, magnetic field dependence of critical exponents is plotted in Fig. 3(b), Since there are some ambiguity in the determination of each critical exponent $\nu$ and $z$, we only plot the magnetic field dependence of $s=\nu(z-1)$ determined from $\rho$-$T$ and I-V measurements. It is obvious that the magnetic field dependence of $s$ is very weak. It makes a good contrast to the result in another iron-based superconductor single crystal SmFeAsO$_{0.85}$ [10]. As long as we are measuring critical exponents of a transition of the same universality class, critical exponents should be universal. In YBCO films and single crystals, magnetic field dependence of $s$ is reported to be weak as in our case [6]. However, in the case of YBCO, there is always a possibility to cause a competition between the vortex glass induced by point defects and Bose glass [11] induced by twin boundaries. Depending on the magnetic field range, one of these transitions can win and critical exponents, in principle, can crossover from one set to another. In optimally-doped BaFe$_2$As$_2$ and other iron-based superconductors except for the under-doped region, twin-boundaries related to the formation of orthorhombic phase is absent. So, it is unlikely that critical exponents show strong field dependence.

**Figure 2.** (a) I-V characteristics of a pristine Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ at $H = 40$ kOe from $T=19.8$ K and 22.5 K. (b) Scaled plot of I-V curves of a pristine Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ at $H = 20$ kOe with $T_g=21.9$ K, $n=2.8$ and $z=3.4$.

In Figure 3(a), the vortex glass transition temperatures $T_g$'s in a pristine sample determined from $\rho$-$T$ and I-V measurements are plotted with the $H_{c2}$ line. Even at the highest field of 170 kOe, the vortex fluid region with a finite resistivity is only 2 K wide below the superconducting transition. The crystal is in the true superconducting state with vanishing linear resistivity below $T_g$.

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**Figure 3.** (a) The upper critical field $H_{c2}$ and vortex glass transition field $H_g$ in a pristine Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$. $H_g$ is determined from $\rho$-$T$ (closed circles) and I-V (crosses) measurements. (b) Magnetic field dependence of the critical exponent for a pristine and 800 MeV Xe irradiated Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$. 

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We also made similar sets of $\rho$-T and I-V measurements on an Xe irradiated (800 MeV, $B_\Phi$=20kOe) Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$. The obtained phase diagram (not shown) is very similar to that for the pristine sample shown in Fig. 3(a) with a slight shrinkage of the vortex fluid region. In this irradiated sample, both vortex glass and Bose glass scalings work equally well, partly because the temperature range for the measurements is narrow. In Fig. 3(b), we also plot magnetic field dependence of critical exponent $s$ for the irradiated sample. Compared with the pristine sample, the value of $s$ is slightly suppressed. However, in YBCO single crystals with columnar defects created by heavy-ion irradiation, $s=\nu(z-1)$ is reported to be close to 1 [12]. The intermediate value of $s$ in the 800 MeV Xe irradiated sample may find its explanation in the structure of defects. According to the recent transmission electron microscope observation, defects created by 800MeV Xe are not columnar defects as in the case of 200 MeV Au irradiated Ba(Fe$_{0.9}$Co$_{0.1}$)$_2$As$_2$ [13]. Rather, they are cascade defects. Such cascade defects have certain degree of correlation along the incident beam and can work as intermediate pinning between point and columnar defects. Actually, angular dependence of resistivity in 800 MeV Xe irradiated sample shows a weak dip when the field is applied along the incident beam direction of c-axis.

4. Summary
We have investigated vortex phase diagram of pristine and Xe (800 MeV, $B_\Phi$=20 kOe) irradiated Ba(Fe$_{0.925}$Co$_{0.075}$)$_2$As$_2$ single crystals up to $H=170$ kOe. In both samples, temperature dependence of resistivity ($\rho$) and current(I)-voltage(V) characteristics are carefully measured by using a Nanovolt Preamplifier. In the pristine sample, clear indication of vortex glass transition is obtained. Critical exponents in the pristine sample show little magnetic field dependence unlike the case for SmFeAsO$_{0.85}$ crystal. Rather, it is similar to the case of YBa$_2$Cu$_3$O$_7$ single crystals. In the 800 MeV Xe irradiated sample, both vortex glass and Bose glass scalings give reasonable overlap of I-V curves and the critical exponent is slightly suppressed compared with that in the pristine sample.

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