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Upper critical field and superconducting anisotropy of $BaFe_{2-x}Ru_xAs_2$ (x=0.48 and 0.75) single crystals

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Abstract

The upper critical field (H_{c2}) was determined by applying a magnetic field along the *ab* plane and *c* axis for two single crystals of $BaFe_{2-x}Ru_xAs_2$ (x=0.48 and 0.75). The anisotropy of the $H_{c2}(0)$, $\gamma(0)=H_{c2}^{ab}(0)/H_{c2}^{c}(0)$, was ~1.6 for x=0.48 and ~2.3 for x=0.75. The angle-dependent resistance measured below T_c allowed perfect scaling features based on anisotropic Ginzburg-Landau theory, leading to consistent anisotropy values. Because only one fitting parameter γ is used in the scaling for each temperature, the validity of the γ value was compared with that determined from $\gamma=H_{c2}^{ab}/H_{c2}^{c}$. The γ obtained at a temperature close to T_c was 3.0 and decreased to 2.0 at low temperatures. Comparing to the anisotropy determined for electron- or hole-doped $BaFe_2As_2$ using the same method, the present results point to consistent anisotropy in Ru-doped $BaFe_2As_2$ with other electron- or hole-doped $BaFe_2As_2$.

Keywords: Fe based superconductor, superconducting anisotropy, upper critical field

1. INTRODUCTION

The discovery of Fe-based superconductors has received tremendous attention since superconductivity was first reported in F-doped LaFeAsO [1] and K-doped $BaFe_2As_2$ [2]. Among the various series of Fe-based superconductors, a typical example is the electron- or hole- doped $AEFe_2As_2$ system (AE=Ba, Sr. Ca and Eu), which is denoted as FeAs122. Detailed studies of the doping dependence of phase diagrams have been made for TM-doped $BaFe_2As_2$ (TM=Co, Ni, Cu, Rh and Pd), which show similar behavior [2-7]. With increasing doping concentration, the antiferromagnetic order was suppressed and superconductivity was induced. On the other hand, the isovalent substitution of Fe with Ru does not provide extra carriers and the ratio of electrons and holes is constant. This type of substitution only alters the lattice constants in a similar way as the application of external pressure [7]. Several studies reported that the isovalent substitution of Fe by Ru leads to a strong increase in the As-Fe-As angle and a decrease in the As height above the Fe planes but the phase diagram is similar to that in other electron- or hole-doped FeAs122 compounds [8-10]. Angle-resolved photoemission spectroscopy (ARPES) [11, 12] found that the substitution of Fe with Ru on Fe_2As_2 practically does not alter the Fermi surface, and Density-functional calculations [13] showed that Ru substitution does not induce any charge imbalance between the bands and no additional bands related to Ru are observed at the Fermi level.

The upper critical field (H_{c2}) and anisotropy (γ) in layered superconductors are fundamental parameters that provide important insights on the pair-breaking mechanism in a magnetic field. In addition to the high critical temperature (T_c), FeAs122 superconductors possess a large H_{c2} [14-17].

The effective H_{c2} varies between the two orientations depending on the superconducting anisotropy ratio, $\gamma=H_{c2}^{ab}/H_{c2}^{c}$, where H_{c2}^{ab} and H_{c2}^{c} are the H_{c2} along the *ab* plane and *c*-axis, respectively. Despite the layered crystal structure in FeAs-based superconductors, all the FeAs-superconductors show weak anisotropy of H_{c2} compared to high temperature cuprates [18]. The anisotropy of H_{c2} is temperature dependent, which is in contrast to the case of single-band materials. Most γ values measured in FeAs122 compounds are slightly lower than those of the FeAs1111 system, such as F-doped LaFeAsO [19, 20], F-doped NdFeAsO [21] and SmFeAsO [22]. Almost isotropic H_{c2} was first realized in hole-doped $BaFe_2As_2$ [14, 23-25]. The electron-doped $BaFe_2As_2$ behaves similarly to the hole-doped system [15-17, 26]. The doping dependences of γ reported for Co-substituted $BaFe_2As_2$ are in general agreement with one another and suggest that γ is an increasing function of temperature [27, 28] This γ (T) dependence appears to be similar in all the FeAs122 materials, independently of the carrier nature [23, 24].

This paper addresses the issue of what is the upper critical field $H_{c2}(T)$ and anisotropy $\gamma(T)$ of $BaFe_{2-x}Ru_xAs_2$

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(x=0.48 and 0.75), where Ru doping does not affect the carrier density. γ was defined using temperature-dependent resistance and angle-dependent resistance measurements. The angular dependence of the resistance measurements is more reliable than the usual definition of $\gamma = H_{c2}^{ab}/H_{c2}^{c}$. The results point to consistent anisotropy in $BaFe_{2-x}Ru_xAs_2$ compared to electron- and hole-doped FeAs122 system.

2. EXPERIMENTS

Single crystals of $BaFe_{2-x}Ru_xAs_2$ (x=0.48 and 0.75) were grown using a self flux method at POSTECH. The details of crystal growth and the structural characterization have been reported previously, including the Ru-doping dependent phase diagram of $BaFe_{2-x}Ru_xAs_2$ [10]. The resistance measurements were carried out at Ewha University using a variable temperature insert and a 14 T superconducting magnet. The inset of Fig. 2(b) gives the definition of angle θ used throughout this paper, where θ is the angle between the applied magnetic field H and the crystallographic *c*-axis. $\theta=0°$ corresponds to the configuration of the H//*c*-axis and $\theta=90°$ to the H//*ab* plane. A current was applied to the *ab* plane and perpendicular to the magnetic field in all cases.

3. RESULTS AND DISCUSSION

$BaFe_{1.52}Ru_{0.48}As_2$ and $BaFe_{1.25}Ru_{0.75}As_2$ show a sharp superconducting transition temperature at T_c~10.4 K and T_c~13.8 K, respectively, by a criterion of 50% of the normal-state resistance (R_n). Fig. 1 shows the temperature dependences of the resistance from 1.5 K to 40 K with different magnetic fields applied along the *ab* plane and *c*-axis. The superconducting transitions shift gradually to a lower temperature with increasing magnetic field, and the transition widths become broader for magnetic fields, both parallel to the *c*-axis and within the *ab* plane. The upper critical fields of $BaFe_{2-x}Ru_xAs_2$ crystals are determined in a criterion of 50% of $R_n(T,H)$ and are shown in Fig. 2(a). Except at around T_c, the upper critical fields $H_{c2}(T)$ exhibit a linear temperature dependence for both samples and both orientations. The linear $H_{c2}(T)$ is similar to the standard Werthamer-Helfand-Hohenberg (WHH) behavior [29]. In the weak-coupling BCS theory, a H_{c2} close to a zero temperature limit can be determined using the WHH equation, $H_{c2}(0)=0.693[-(dH_{c2}/dT)]T_c$. For x=0.48, $-(dH_{c2}^{ab}/dT)=3.01$ T/K and $-(dH_{c2}^{c}/dT)=1.92$ T/K are observed. For x=0.75, $-(dH_{c2}^{ab}/dT)=3.19$ T/K and $-(dH_{c2}^{c}/dT)=1.36$ T/K are obtained. The estimated values of $H_{c2}(0)$ were $H_{c2}^{ab}(0)=21.7$ T and $H_{c2}^{c}(0)=13.8$ T for x=0.48 and $H_{c2}^{ab}(0)=30.5$ T and $H_{c2}^{c}(0)=13.0$ T for x=0.75. The slopes of the two samples for the applied magnetic field within the *ab*-plane significantly exceeded the Pauli limit of 1.84 T/K for singlet pairing We note that a recent result reported that the WHH approximation may not be simply applied in these materials and even $H_{c2}(0)$ may be affected by the multiband property.

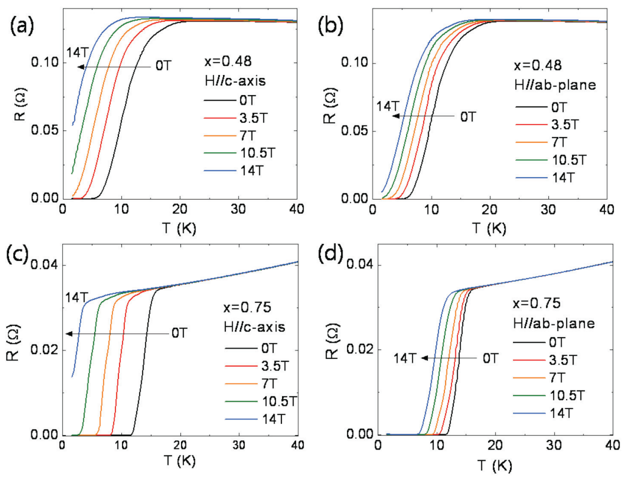

Fig. 1. Temperature dependences of the in-plane resistances for $BaFe_{1-x}Ru_xAs_2$ single crystal as fields H=0, 3.5, 7, 10.5 and 14 T with (a) x=0.48, H//c-axis, (b) x=0.48, H//ab plane, (c) x=0.75, H//c-axis and (d) x=0.75, H//ab plane, respectively.

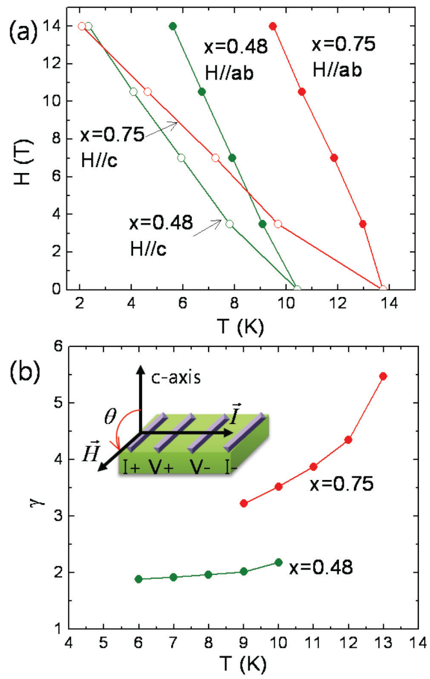

Fig. 2. Upper critical field of $BaFe_{1-x}Ru_xAs_2$ (x=0.48, 0.75) for H//c and H//ab. (b) Temperature dependence of superconducting anisotropy ratio $\gamma= H_{c2}^{ab}/H_{c2}^{c}$. The inset shows the definition of angle θ.

However, our results clearly indicate that the H_{c2} in the present system are really very high without any doubt.

According to the estimated $H_{c2}(0)$, the anisotropy at zero temperature $\gamma(0)=H_{c2}^{ab}(0)/H_{c2}^{c}(0)$ are approximately 1.6 for x=0.48 and 2.3 for x=0.75.

The order of magnitude of γ is similar to that observed in K-doped $BaFe_2As_2$ [14, 25], as well as the data taken on Co-doped $BaFe_2As_2$ [15, 16, 27]. Fig. 2(b) presents the

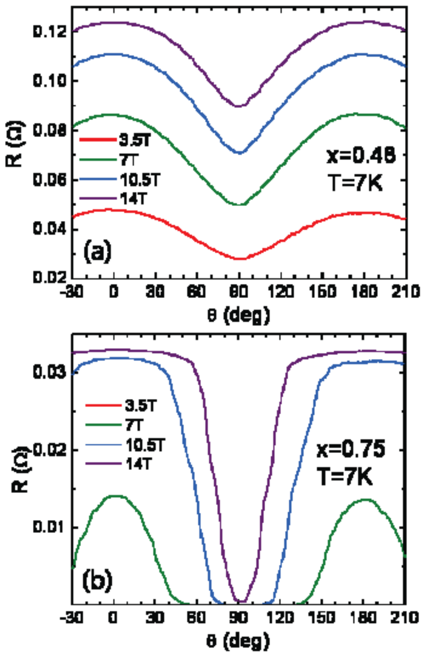

Fig. 3. Angle dependence of the resistance of $BaFe_{1-x}Ru_xAs_2$, (a) x=0.48 and (b) x=0.75 at fixed temperatures in H=3.5, 7, 10.5 and 14 T. The fixed temperature is T=7 K.

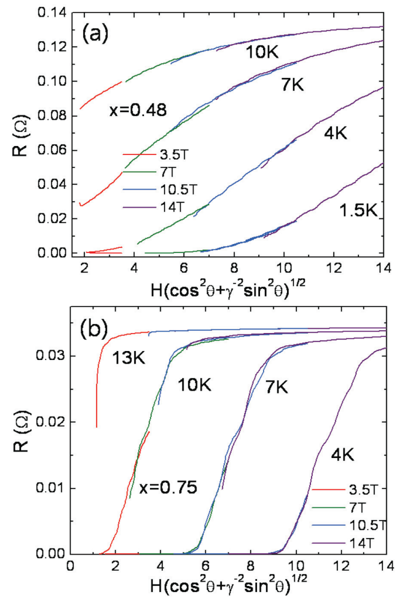

Fig. 4. Scaling of the resistance vs. $\widetilde{H} = H\sqrt{\cos^2\theta + \gamma^{-2}\sin^2\theta}$ of $BaFe_{1-x}Ru_xAs_2$ at fixed temperatures in different magnetic fields with (c) x=0.48 and (d) x=0.75. Each curve was scaled nicely by adjusting γ.

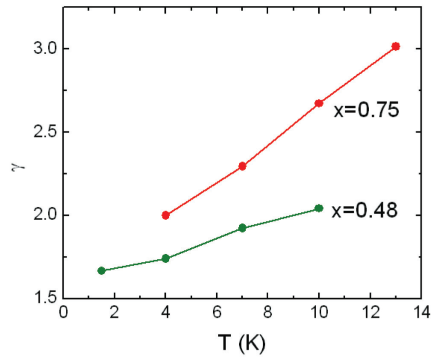

Fig. 5. Temperature dependence of γ(T) which is defined by angle-dependent resistance.

temperature dependence of the anisotropy ratio, γ(T). Considering the uncertainties in determining the upper critical field in different formulae and by different criteria, the anisotropy ratio may be subject to modification. In particular, in the case of broad superconducting transitions, contributions from superconducting fluctuations and current percolation have a potential influence. In addition, the zero-temperature value $H_{c2}(0)$ is determined using the experimental data near T_c. Because of the limited magnetic field up to 14 T, the possible γ(T) obtained is restricted in the range of 4 K using a single criterion. This concern can be eliminated by measurements of the angle-dependent resistance R(θ,H).

Fig. 3(a) and (b) present the angular dependence of resistance R(θ,H) at 7 K in H=3.5, 7, 10.5, and 14 T for the $BaFe_{1.52}Ru_{0.48}As_2$ and $BaFe_{1.25}Ru_{0.75}As_2$, respectively. At each magnetic field, the resistance decreases at around θ =90°. According to the single band anisotropic Ginzburg-Landau (GL) theory, the resistance in the mixed state depends on the effective field $H/H_{c2}^{GL}(\theta)$, where $H_{c2}^{GL}(\theta) = H_{c2}^{ab}/\sqrt{\cos^2\theta + \gamma^{-2}\sin^2\theta}$. In this case, the resistance measured at different magnetic fields but at a fixed temperature should be scalable with the variable, $H/H_{c2}^{GL}(\theta)$. Therefore, using the scaling variable, $\widetilde{H} = H\sqrt{\cos^2\theta + \gamma^{-2}\sin^2\theta}$, the resistance at a certain temperature should collapse onto a single curve when an appropriate γ value is chosen [30]

The R(θ ,H) at different magnetic fields as a function of the scaling variable H are scaled nicely by adjusting γ, as shown in Fig. 4(a) and (b), respectively. The values of γ are thus obtained for temperatures 1.5, 4, 7, 10 K. Because only one fitting parameter γ is used in the scaling for each temperature, the value of γ is more reliable than that determined from the ratio of H_{c2}^{ab} and H_{c2}^{c}, as used above.

Fig. 5 presents the temperature dependence of γ(T) using the criterion of R(θ,H). γ(T) shows a linear dependence, and valuable information of γ(T) can be obtained over a wide range of temperatures around 9 K with the same 14 T superconducting magnet. γ(T) of x=0.48 is 2.0 for 10 K and that of x=0.75 is 3.0 for 13 K, which are lower than γ =5-8 in the AFe_xSe_2 and FeAs1111 system [21, 22] but consistent with γ =2-3 in the electron- and hole- doped FeAs122 [14, 15, 28] and FeAs111 system [31]. γ decreases with decreasing temperature. This type of temperature dependence of γ (T) is not expected for a single band anisotropic superconductor but might be due to the effect of multi-band superconductivity.

In addition, the good scaling features based on the anisotropic GL theory suggest a field-independent γ in the temperature and field range measured. The small γ can be understood qualitatively based on band-calculations [32] and ARPES experiments [33, 34], where it was confirmed that the Fermi-surface sheets are not two-dimensional cylinder like but rather exhibit a complicated three-dimensional feature with significant dispersion along the c-axis. Further studies of the angle-dependent resistance measurements at higher magnetic fields should be performed to clarify the field-independent γ. The $H_{c2}(T)$ and γ(T) of $BaFe_{1-x}Ru_xAs_2$ system for different doping levels will need to be examined in a future study.

In conclusion, we studied the upper critical field (H_{c2}) and superconducting anisotropy (γ) of $BaFe_{2-x}Ru_xAs_2$ (x=0.48 and 0.75) single crystals in magnetic fields up to 14 T. The $H_{c2}(0)$ values estimated by the WHH equation were $H_{c2}^{ab}(0)$=21.7 T and $H_{c2}^{c}(0)$=13.8 T for x=0.48 and $H_{c2}^{ab}(0)$=30.5 T and $H_{c2}^{c}(0)$=13.0 T for x=0.75, where $\gamma(0)=H_{c2}^{ab}(0)/H_{c2}^{c}(0)$ is approximately 1.6 for x=0.48 and 2.3 for x=0.75. The resistive determination of H_{c2} is strongly criterion dependent. γ(T) was also determined by examining the angle-dependent resistance, which follows a scaling based on anisotropic GL theory. These results strongly suggest that the angular dependence of the resistance R(θ,H) is more reliable than a resistive determination. γ(T) showed a linear temperature dependence. γ(T) for x=0.48 increased from 1.7 for 1.5 K to 2.0 for 10 K, whereas γ(T) for x=0.75 increased from 2.0 for 4 K to 3.0 for 13 K.

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