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Abstract

The temperature and magnetic field dependences of the magnetization and critical current density of Fe_{1.04}Te_{0.6}Se_{0.4} single crystals have been investigated, and the flux pinning mechanism has been analysed. The normalized pinning force ($f_p F_p / F_{p,max}$) vs. $h(H/H_{irr})$ curves, are scaled using the Dew-Hughes theory, $f(h) \approx hp(1 - h)^q$ with $p = 1.35$ and $q = 3.06$. The angular dependence of the resistivity under different magnetic fields shows a dip-like structure, below the superconducting transition temperature. The anisotropic value of 2 was obtained using Ginzburg-Landau theory.

Keywords

single, superconducting, 4, 6se0, 04te0, crystal, fe1, flux, anisotropy, magnetic, electrical, mechanism, pinning

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The flux pinning mechanism, and electrical and magnetic anisotropy in $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ superconducting single crystal

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The temperature and magnetic field dependences of the magnetization and critical current density of $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ single crystals have been investigated, and the flux pinning mechanism has been analysed. The normalized pinning force ($f_p = F_p/F_{p,\text{max}}$) vs. $h(H/H_{\text{irr}})$ curves, are scaled using the Dew-Hughes' theory, $f(h) \approx h^p(1-h)^q$ with $p=1.35$ and $q=3.06$. The angular dependence of the resistivity under different magnetic fields shows a dip-like structure, below the superconducting transition temperature. The anisotropic value of 2 was obtained using Ginzburg-Landau theory. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4794134>]

Following the discovery of superconductivity in the REFePnO (RE =rare earth, Pn =P or As),^{1–5} doped AFe_2As_2 (A =alkaline or alkaline earth metal),^{6,7} LiFeAs ,⁸ and $((\text{Sr}_4\text{M}_2\text{O}_6)\text{Fe}_2\text{Pn}_2)$ (M =Sc, Ti, or V)^{9,10} families of iron pnictide superconductors, the observation of superconductivity in tetragonal FeSe (Ref. 11) has opened up a new window of opportunity to further understand the mechanism of superconductivity in the iron pnictides. The iron chalcogenide FeSe compounds are of great interest from the viewpoints of both the vortex properties in the mixed state and practical application. This is largely due to the relatively simple structure and similarity in the Fermi surface (E_F) of these arsenic-free compounds to the other pnictide superconductors. The E_F surfaces of FeSe and FeTe contain cylindrical hole and electron sections at the centre and the corner of the Brillouin zone, respectively.¹² It has proven difficult, however, to grow homogeneous superconductive single crystals. Therefore, attention has been paid to some extent to the Te doped systems.¹³ $\text{FeSe}_{1-x}\text{Te}_x$ compounds have the tetragonal structure, where the Fe (Se/Te) layers stack along the c -axis, and have T_c , as high as 15 K.^{13–15} The antiferromagnetic order of FeTe is gradually suppressed by increasing x in $\text{FeTe}_{1-x}\text{Se}_x$, and the maximum T_c is achieved for $x=0.5$.¹⁶

It is crucial to understand the pinning mechanism from both the practical and the fundamental point of view. There are two main interactions between vortices and pinning centres in type II superconductors: the magnetic interaction and the core interaction.¹⁷ The magnetic interaction is due to the interaction at interfaces between superconducting and non-superconducting materials parallel to the applied magnetic field. The core interaction covers pinning due to the variation in the transition temperature (δT_c) and pinning because of the variation in the charge carrier mean free path near lattice defects (δl).¹⁷ For the $\text{FeTe}_{0.5}\text{Se}_{0.5}$ single crystal, it has been found that the dominant pinning mechanism is δl pinning, which is related to small bundle vortex pinning due to randomly distributed weak pinning centres.¹⁸ Yadav *et al.*

have studied the flux pinning force, F_p , in $\text{FeTe}_{0.6}\text{Se}_{0.4}$ and found that the obtained $h_{\text{max}}=0.28$ (where h_{max} is the field corresponding to the maximum pinning force density, normalized with respect to the irreversibility field H_{irr}), which can be understood in terms of δl pinning with a mixture of surface pinning and the point core pinning due to normal pinning centres, with different ranges of the pinning interactions.¹⁹ In this work, the vortex pinning mechanisms, pinning potential, and anisotropy of $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ single crystal have been studied systematically by magnetic and transport measurements at different temperatures.

Single crystals of $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ were prepared by a self-flux method. Details of the single crystal growth are reported elsewhere.²⁰ The as-grown crystals were cleaved and cut into a rectangular shape for magnetic and transport measurements using a physical properties measurement system (PPMS, Quantum Design). The angular dependence of the resistivity was also measured with the angle, θ , ranging from 0° to 180° , where $\theta=0^\circ$ corresponds to $H//c$ and $\theta=90^\circ$ to $H//ab$, respectively.

Figure 1(a) shows typical hysteresis ($M-H$) loops collected at several temperatures below T_c . The minimum in the magnetic moment located at nearly zero field represents the first magnetization peak. The field completely penetrates into the bulk of the sample after zero field cooling.¹⁸ The second magnetization peak (SMP) can be seen at 4 K, 7 K, and 8 K. The onset ($H_{\text{SMP}}^{\text{onset}}$) and peak ($H_{\text{SMP}}^{\text{peak}}$) positions of the SMP are indicated by arrows in Fig. 1(a) for $T=4$ K. Both the $H_{\text{SMP}}^{\text{onset}}$ and the $H_{\text{SMP}}^{\text{peak}}$ positions move to lower magnetic fields as the temperature increases from 4 to 10 K and completely disappear at $T=11$ K.

J_c was calculated at various temperatures from these $M-H$ loops by using the Bean model.²¹ For a rectangular shaped crystal with dimensions $c < a < b$, when $H//c$, the $J_c(H)$ is given by

$$J_c(H) = 20 * \Delta m(H) / (a(1 - a/3b)), \quad (1)$$

where Δm is the difference between the magnetizations measured during the return and the forward legs of the $M-H$ loops

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FIG. 1. (a) M-H loops of $\text{BaFe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ single crystal (b) and J_c vs. field at several temperatures.

for $H//c$ and a and b are the length and width of the sample $J_c(H)$ (Fig. 1(b)) shows a fast decrease at low fields ($H < 0.5$ T), followed by weak field dependence at high fields at $T = 4$ K. The in-field J_c is as high as 1.2×10^9 A/m² at 4 K and zero magnetic field. This value is slightly higher than the reported value (1×10^9 A/m² at $T = 1.8$ K and low field) in a $\text{FeTe}_{0.6}\text{Se}_{0.4}$ single crystal.^{19,22} It is likely that this is due to the enhanced iron concentration in $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ single crystal, which introduces more defects into the crystal structure, and consequently, higher pinning potential into the system.

In order to understand the flux pinning mechanism which controls the vortex pinning force, it is useful to look at the variation of pinning force density with the magnetic field. In the mixed state of type II superconductors, the pinning force should follow the same general relationship, if the flux pinning is dominated by a single mechanism.²³ The pinning force, defined as $F_p = \mu_0 H \times J_c$, can be calculated from the J_c values shown in Fig. 1(b). In Fig. 2, we plot the reduced pinning force f versus the reduced magnetic field h ($f = F_p / F_{p,\max}$, $h = H / H_{\text{irr}}$) at the same temperature as in Fig. 1(b). There are various methods to determine the irreversibility field, H_{irr} , from the magnetization and resistivity measurements.²⁴ Here, we use H_{irr} as the field at which $J_c(H)$ is extrapolated to 10^6 A/m². The curves show a scaling behaviour at $T < 10$ K, indicating that a single pinning mechanism dominates at this temperature range. We fit these data within the Dew-Hughes scenario

$$F_p \approx h^p (1 - h)^q. \quad (2)$$

FIG. 2. Field dependence of the reduced pinning force, with the fitting results obtained from $h^p(1 - h)^q$. Inset shows $F_p/F_{p,\max}$ as function of field.

The best fit of the curves (dashed-dotted line in Fig. 2) is obtained with an $f(h)$ dependence given by $h^{1.35}(1 - h)^{3.1}$. The obtained p and q values are slightly lower than the reported values of $p = 1.54$ and $q = 3.8$ in $\text{FeTe}_{0.6}\text{Se}_{0.4}$ single crystal,¹⁹ possibly due to excess iron concentration in this compound. The value of $p/(p + q) \approx 0.3$ agrees well with the peak positions of these compounds in the f versus h plot, and it is in good agreement with the reported value of $h_{\max} \approx 0.28$ for $\text{FeTe}_{0.6}\text{Se}_{0.4}$ single crystal.¹⁹ It should be noted that according to the Dew-Hughes theory,²³ point pinning is expected to lead to $p = 1$ and $q = 2$, with $F_{p,\max}$ occurring at $h_{\max} \approx 0.33$, whereas in a system dominated by grain boundary pinning, $h_{\max} \approx 0.2$. In the case of pinning due to variation in the superconducting order parameter, however, $h_{\max} \approx 0.7$. In our case, $h_{\max} \approx 0.3$, implying δl pinning with a mixture of point pinning and grain boundary pinning.

The temperature dependence of the resistivity for $H//c$, is shown in Fig. 3(a), where the onset of T_c gradually shifts to lower temperatures with increasing magnetic field. It is worth noting that the shape of $\rho_{ab}(T)$ with $H//c$ is comparable to those for (Ba, K) Fe_2As_2 and (Ba, Rb) Fe_2As_2 single crystals,^{25,26} and it is different from the shapes for $\text{SmFeAsO}_{0.8}\text{F}_{0.2}$ and $\text{NdFeAsF}_{0.82}\text{F}_{0.18}$ single crystals,^{27,28} where resistive tails were clearly observed for $H//c$. According to the thermally activated flux flow model, the resistivity can be described by the following Arrhenius equation:

$$\ln R(T, H) = \ln R_0 - U_0/T. \quad (3)$$

Therefore, the activation energy, $U_0(H)$, is the slope of the lower part of the curve in the Arrhenius plot. In order to study the flux motion in $\text{Fe}_{1.06}\text{Te}_{0.6}\text{Se}_{0.4}$ single crystal, we plot the resistivity as a function of $1/T$ at different magnetic fields up to 13 T. Figure 3(b) shows the Arrhenius plot of the resistivity for $H//c$. The linear dependence of $\ln \rho$ vs. $1/T$ in the lower part of the curves indicates that this part can be described by the thermally activated flux flow model.²⁹ Similar measurements were performed for $H//ab$ and also for several angles, from 0° up to 90° for $H = 6$ T, and $U_0(H)$ was calculated from the corresponding data.

The magnetic field dependence of the pinning potential for $H//c$ and $H//ab$ is shown in Fig. 4(a). The best fit to the experimental data yields a value of the pinning potential of 404 K for $H//ab$ at $H = 0.1$ T. The activation energy drops very slowly with increasing applied magnetic field for $H < 5$ T, scaled as $H^{-0.1}$, and then decreases slowly as $H^{-0.61}$

FIG. 3. (a) Temperature dependence of resistivity under different magnetic fields for $H//c$. (b) Arrhenius plots of the resistivity for the same magnetic fields.

FIG. 4. (a) Magnetic field dependence of U_0 for $H//ab$ and $H//c$. (b) Angular dependence of U_0 for $H=6$ T.

for $H > 5$ T. This indicates that the pinning potential is almost field independent for $H < 5$ T. The angular dependence of the pinning potential for $H=6$ T is shown in Fig. 4(b). The pinning potential values increase when the sample is rotated from $H//c$ to $H//ab$.

The angular dependence of the resistivity for the $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ at 14 K is shown in the inset of Fig. 5. All the curves have a symmetric cup-like shape, and the minimum value is at $\theta = 90^\circ$. According to the anisotropic Ginzburg-Landau model, the effective upper critical field, $H_{c2}^{\text{GL}}(\theta)$, can be characterized as¹⁷

$$H_{c2}^{\text{GL}}(\theta) = H_{c2,ab}/(\sin^2\theta + \Gamma^2\cos^2\theta)^{1/2}, \quad (4)$$

where Γ is the anisotropy of the sample. As the resistivity in the mixed state depends on the effective field,³⁰ the angular dependence of the resistivity can be scaled as $\rho = \rho_0 f(H)/H_{c2}^{\text{GL}}$, where ρ_0 is the temperature independent part of the resistivity. Then, the resistivity measured under different magnetic fields should collapse into one curve at a certain temperature if the anisotropy parameter is properly scaled. Good scaling behaviour can be obtained for $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ with $\Gamma=2.5$ at $T=14$ K, as shown in the main panel of Fig. 5. This value is higher than the obtained value of $\Gamma=2$ for $\text{Fe}_{1.11}\text{Te}_{0.6}\text{Se}_{0.4}$ single crystal.³¹ It should also be mentioned that the anisotropy values were obtained using different methods, GL theory in our work, and the ratio of the upper critical field along the ab -plane and to that along the c -axis.

In summary, we have studied the pinning mechanism, pinning potential, and anisotropy of $\text{Fe}_{1.04}\text{Te}_{0.6}\text{Se}_{0.4}$ single

FIG. 5. Scaling of the resistance as a function of $H/(\sin^2\theta + \Gamma^2\cos^2\theta)^{1/2}$, based on GL theory at $T=14$ K. Inset shows the angular dependence of the resistivity at 14 K under different magnetic fields.

crystal. The obtained values of p and q based on the Dew-Hughes model indicate the existence of δl pinning, with a mixture of surface and point core pinning in this compound. In addition, the pinning potential value was obtained using the thermally activated flux flow model. The anisotropy value was obtained using GL theory.

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