

Comparison of the pinning energy in $\text{Fe}(\text{Se}_{1-x}\text{Te}_x)$ compound between single crystals and thin films

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Abstract. Among the families of iron-based superconductors, we investigate flux pinning mechanisms in the $\text{Fe}(\text{Se}_{1-x}\text{Te}_x)$ compound. We perform magneto-resistance and current-voltage measurements on single-crystals, as well as on several epitaxial thin films grown on different substrates (CaF_2 , LaAlO_3). The activation energy is derived as a function of magnetic field, $U(H)$. The influence of magnetic field orientation on the pinning energy activation mechanism is also studied, leading to the anisotropy analysis which reveals low anisotropy in thin films grown on CaF_2 substrate with respect to single crystals and films grown on LaAlO_3 . Concerning the dominant pinning regime, the exponents of the power law dependence $U_0(H) \propto H^{-\alpha}$ have been evaluated, confirm that weak pinning is a general characteristic of this compound. The single exponent feature, generally noticed on thin films grown on SrTiO_3 substrate and associated to a strong single vortex regime, has been observed in thin films grown on LaAlO_3 , only in the parallel configuration. At the end, this overall comparison can be useful to develop a technological material able to compete with high temperature superconductors.

1. Introduction

About seven years have gone by the discovery of superconductivity in iron-based compounds [1] and this new class of high- T_c superconductors is already looking promising for the applications. Indeed, iron-based superconductors show very high upper critical fields (H_{c2}) even close to the critical temperature (T_c), similarly to MgB_2 . Likewise MgB_2 , they are also characterized by small anisotropy factors (γ). Moreover, they do not present the technical hurdles (such as the metal-insulator transition or the d-wave symmetry of the order parameter) presented by copper oxide superconductors and show an high robustness to impurities. Up to now, the main technical limit of iron-based superconductors is the low critical temperature (the highest T_c for this class has been reported to be 56 K [2]), while the critical current density (J_c) values are comparable to those of the other high- T_c superconductors (J_c at 4.2 K and 30 T up to 10^5 A cm^{-2} have been reported [3]).

Almost all known iron-based superconductors belong to one of the following four families: a) the 1111 ReOFeAs (Re = Rare earth), b) the 122 AFe_2As_2 (A = alkaline earth), c) the 111 XFeAs (X = Li, Na), and d) the 11 $\text{Fe}(\text{Se}, \text{Ch})$ (Ch = S, Te). As it is well known [4, 5], the



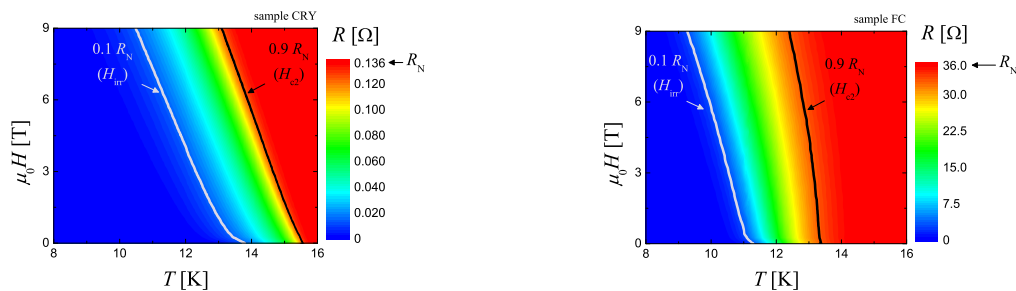


Figure 1. [color online] Field versus temperature (HT) phase diagrams for the single crystal sample [left panel] and for the thin film on CaF_2 substrate [right panel] with enlightened lines at $0.1 R_N$ (white lines) and $0.9 R_N$ (black lines).

highest T_c 's are shown by the 1111 compounds, while the 122 family presents the highest upper critical fields. Nonetheless, the interest in 11 compounds is increasing [3, 6], mainly due to their low magnetic field anisotropy, the high $H_{c2}(T)$ slope near T_c , the absence of poisonous elements and the possibility to increase the relative low T_c by growing thin films on proper substrate inducing the Volmer-Weber growth mode, which mimic the application of an external pressure (see Ref. [7] and references therein).

In this paper we study the pinning properties of the $\text{Fe}(\text{Se}_{1-x}\text{Te}_x)$ (FST) compound grown as single crystals and thin films on different substrates to show that such thin films can be promising for high-field applications.

2. Experimental details

Single crystals of $\text{Fe}_{1+y}(\text{Se}_{1-x}\text{Te}_x)$ ($y < 0.1$, $0 < x < 0.45$) were grown in self-flux by using a modified Bridgman method from high purity precursors (Fe, Se and Te granules, all with purity $\geq 4\text{N}$) melted inside a vacuum-sealed quartz tube vertically placed in a gradient furnace, and slowly cooled down (more details in Ref. [8]). Single crystals are easily cleaved in the ab -plane and characterized by X-Ray Diffraction (XRD) and Energy Dispersive X-Ray Spectroscopy (EDX) in order to check the crystal quality, composition and homogeneity. The actual composition of the crystals used in this work was found to be $\text{Fe}_{1.02}\text{Te}_{0.68}\text{Se}_{0.32}$ (nominal $x = 0.3$). Thin films were prepared in an ultra-high vacuum Plasma Laser Deposition (PLD) system from a starting target prepared by a two steps procedure from high purity materials (Fe 99.9+%, Se 99.9% and Te 99.999%), with a nominal composition $\text{FeSe}_{0.5}\text{Te}_{0.5}$, on single crystals substrates with different cell parameters and different chemical composition (more details in Ref. [9]).

Magneto-resistance and current-voltage measurements have been carried out in a Cryogen Free Magnet (CFM) system by Cryogenic Ltd. equipped with a cryogen-free variable temperature insert and a 9 T superconducting magnet. Magneto-resistance measurements have been performed by a standard 4-probe technique. Fig. 1 shows two typical field versus temperature (HT) phase diagrams realized acquiring more than 35 resistance-temperature ($R(T)$) curves, with the applied field direction parallel to the c -axis of the samples ($H \parallel c$). Current-voltage measurements have been performed in a pulsed current 4-probe technique [7] biasing the sample with rectangular current pulses 2.5 ms wide and a delay of 200 ms.

3. Results and discussion

In the following, we will present results on three different FST samples: a single crystal, which we will identify as sample CRY, and two thin films grown on a LaAlO_3 and on a CaF_2 substrate, namely sample FL and sample FC respectively.

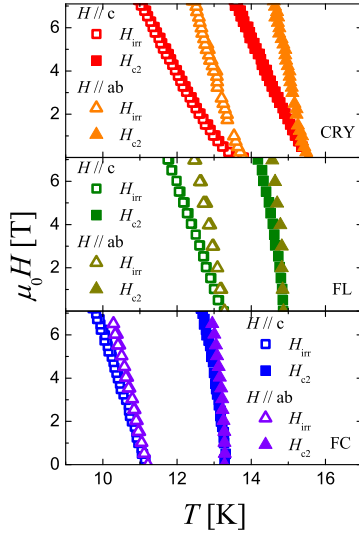


Figure 2. [color online] $H_{c2}(T)$ (full symbols) and $H_{irr}(T)$ (open symbols) curves of the three samples with the applied field parallel to sample c-axis (squares) and to sample ab-plane (triangles).

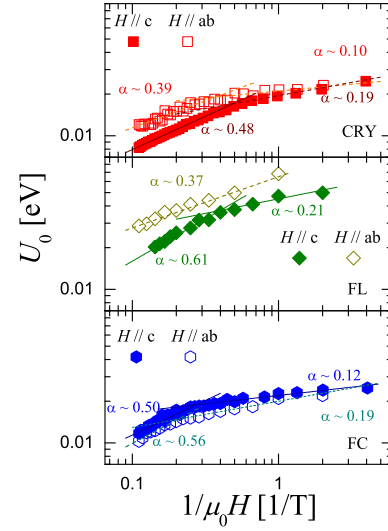


Figure 3. [color online] $U_0(H)$ curves of the three samples with the estimate of the α exponent in the power law $U_0 \propto H^{-\alpha}$.

In Fig. 1 the HT phase diagrams of sample CRY and FC, with $H \parallel c$, are shown. In both phase diagrams the irreversibility line ($H_{irr}(T)$) and the $H_{c2}(T)$ curve are reported. The $H_{irr}(T)$ line is determined by the 10% criterion of the normal state resistance (R_N) in the $R(T)$ curve, while the $H_{c2}(T)$ line is defined by 90% of R_N . In Fig. 2 we show $H_{irr}(T)$ and $H_{c2}(T)$ data of all three samples both in the case of applied field parallel to sample c-axis and to ab-plane ($H \parallel ab$). It results that the $H_{c2}(T)$ slope values evaluated near T_c are equal to 3 for sample CRY, to 14 for sample FL and to 6 for sample FC, in good agreement with the literature [5]. Moreover, it is evident the larger field anisotropy of sample CRY with respect to sample FL, while sample FC shows a substantial isotropy. Indeed, the anisotropy factors $\gamma = H_{c2}^{\parallel}/H_{c2}^{\perp}$ evaluated at $0.98 T_c(0)$ are 1.9 for sample CRY, 1.7 for sample FL and 1.3 for sample FC. We found the same anisotropic behavior in the activation energy for vortex motion as a function of the applied field $U_0(H)$ displayed in Fig. 3. Here, U_0 has been evaluated via the relation $U(H, T) = U_0(H) g(t)$ [10], with $g(t) = (1 - t)(1 - t^4)^{1/2}$ and $t = T/T_c$, where $U(H, T)$ values have been deduced from the Arrhenius plots of the $R(T)$ at different applied magnetic fields. The $U_0(H)$ curve for sample FL shows a crossover from a weak field dependence to a power law dependence in the case $H \parallel c$, which can be associated to the crossover from a single vortex pinning regime [11] to a collective-pinning one [12], according to the literature [13]. On the contrary, in the case $H \parallel ab$ no crossover is present thus pointing out the higher anisotropic behavior of the pinning properties in the films grown on LaAlO_3 substrates. For sample CRY, the $U_0(H)$ curves for $H \parallel c$ and $H \parallel ab$ exhibit anisotropy, although in both cases a field dependence crossover is observed. Instead, for sample FC no evident anisotropy can be observed in the $U_0(H)$ curves, in the full field range. This feature is confirmed by the pinning force $f_p = F_P/F_{P,max}$ curve as a function of the reduced field $h = H/H_{irr}$ shown in Fig. 4. Here, the H_{irr} values have been evaluated as the extrapolated zero value in the Kramer plots, where $J_c^{1/2} H^{1/4}$ is plotted as a function of H [14], with the critical current density J_c defined by the standard $1 \mu\text{V}/\text{cm}$ criterion. In Fig. 4 the $f_p(h)$ curves are shown at three different temperatures (8.0, 8.6, 9.3 K) in the case $H \parallel c$ and also at 9.3 K for the case $H \parallel ab$. All three curves can be fitted by a single

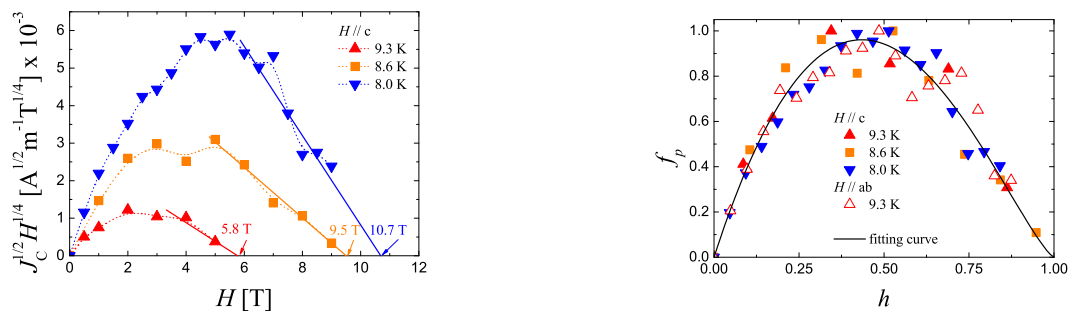


Figure 4. [color online] Left panel: Kramer plots for sample FC in the case $H//c$ at 8.0, 8.6 and 9.3 K, with the indication of the extrapolated zero value of H_{irr} . Right panel: $f_p(h)$ curves for sample FC at the same three temperature in the case $H//c$ (full symbols) and at 9.3 K in the case $H//ab$ (open triangles) with the fitting curve $h(1-h)^{1.3}$ (black solid line).

function $C h^p (1-h)^q$ with $p = 1$ and $q = 1.3$. According to the Dew-Hughes model [15], this behavior can be ascribed to the presence of δT_c volume pins, regardless of the temperature.

4. Conclusions

We have carried out a comparison of the pinning properties of the 11 iron-based compound $\text{Fe}(\text{Se}_{1-x}\text{Te}_x)$ realized in the form of single crystal and thin films on different substrates. We have shown that the thin films deposited on CaF_2 substrate are characterized by an high isotropy, whereas films deposited on LaAlO_3 and single crystals have a similar anisotropy. Moreover, the pinning sites in the CaF_2 samples have been basically identified having 3D δT_c nature. Considering that for high field applications high $H_{c2}(T)$ slope near T_c , good in-field isotropy and strong pinning are required, we conclude that $\text{Fe}(\text{Se}_{1-x}\text{Te}_x)$ films grown on proper substrates are good candidates for further developments in coated conductors.

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