Comparison of the pinning energy in \(\text{Fe(Se}_{1-x}\text{Te}_x)\)
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 \(\text{Fe(Se}_{1-x}\text{Te}_x)\) 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 \((\gamma)\). 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 = \text{Rare earth})
, b) the 122 \(AFe_2As_2\) (\(A = \text{alkaline earth})
, c) the 111 \(XFeAs\) (\(X = \text{Li, Na})
, and d) the 11 Fe(Se, Ch) (\(Ch = S, Te)\). As it is well known [4, 5], the
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.

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.
of the applied field $U$ found the same anisotropic behavior in the activation energy for vortex motion as a function evaluated at $0$ $\gamma$ while sample FC shows a substantial isotropy. Indeed, the anisotropy factors

Moreover, it is evident the larger field anisotropy of sample CRY with respect to sample FL, $H_{c2}$ to 14 for sample FL and to 6 for sample FC, in good agreement with the literature [5].

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 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 $\gamma = H_{c2}/H_{c2}^1$ 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 $\mu$V/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 $\delta T_c$ volume pins, regardless of the temperature.

4. Conclusions
We have carried out a comparison of the pinning properties of the 11 iron-based compound Fe(Se$_{1-x}$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 $\delta T_c$ 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 Fe(Se$_{1-x}$Te$_x$) films grown on proper substrates are good candidates for further developments in coated conductors.

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