Magnetic relaxation studies on FeTe$_{0.60}$Se$_{0.40}$ superconductor

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Abstract: Among the Iron chalcogenide superconductors, FeTe$_{0.60}$Se$_{0.40}$ shows highest transition temperature of 14.5K. The Magnetic relaxation studies have been performed on the high quality FeTe$_{0.60}$Se$_{0.40}$ single crystal. The time dependence of the magnetization (M) exhibits thermally activated flux motion and the magnetization relaxation rate ‘S’ increases with the temperature. The activation energy $U(j)$ has been analyzed using the Maley’s method and correlation between the scaled activation energy $U$ and magnetization $M$ suggests the applicability of the collective pinning model and crossover from the single vortex regime to the collective bundle pinning regime in this compound.

1. Introduction

Ever since the advent of superconductivity in the Fe based compound in 2008, there have been frenetic research in the field and the transition temperature ($T_c$) reached to 56K for iron pnictide material. The FeAs layers are considered to be main structure for the superconductivity in LaO$_{1-x}$F$_x$FeAs (1111), Ba$_{1-x}$K$_x$Fe$_2$As$_2$ (122), and LiFeAs (111) compounds [1-3]. The discovery of superconductivity in the simpler but structurally similar Iron chalcogenides systems (FeSe, FeTe$_{1-x}$Se$_x$, known as ‘11’ system) gave an impetus to the activities for understanding the mechanism of the superconductivity in these pnictide superconductors [4].

The tetragonal compound FeSe shows superconductivity at 8K, which on doping with Te increases to 15K for FeTe$_{0.5}$Se$_{0.5}$. Also with the application of 7GPa pressure, the superconductivity rises to 37K for FeSe [5]. The connection between $T_c$ and the pressure is related to the enhancement of spin fluctuations and modulation of electronic properties [6] due to evolution of the inter-layer Se-Fe-Se separations in the absence of pressure [5, 6]. The absence of a coherence peak in NMR measurements on polycrystalline FeSe compound suggests the unconventional nature of superconductivity [7]. Muon spin rotation study of the penetration depth in FeSe, was consistent with either anisotropic s-wave or a two gap s-wave pairing [8].

In these iron pnictide and chalcogenide superconductors, the conducting FeAs/FeSe layers are responsible for the superconductivity, which looks very similar to the case of the HTSC cuprate materials. For cuprates superconductors, due to the high anisotropy, short coherence length, and high operation temperature, the vortex motion and fluctuations are quite strong, leading to the small pinning energy and the single vortex to vortex bundles pinning collectively by many small pinning centers. Magnetic relaxation is a valuable tool for determining vortex related parameters of a superconductor. The relaxation rate depends on the pinning parameters as well as the structure of the Abrikosov vortices and vortex lattice [9]. In the present study we have performed magnetic relaxation measurements to bring out the dynamics of vortex in the FeTe$_{0.60}$Se$_{0.40}$ compound.
2. Experimental:

The single crystals of the FeTe$_{0.90}$Se$_{0.40}$ were prepared by the chemical reaction of the high purity elements (Fe powder of 99.999% purity, Te powder of 99.99% purity, and Se powder of 99.98% purity), in stoichiometric proportion, inside the evacuated quartz tube. The thoroughly grinded mixture was slowly heated to 950°C at the rate 50°C/hrs and kept for 12 hours before cooling down to 400°C at the rate of 6°C/hrs, and then furnace cooled to the room temperature. The crystals were found to grow along the ab-plane. The detailed sample preparation method and the quality of the crystal are reported elsewhere [10]. Magnetization measurements have been performed on the high quality single crystal of FeTe$_{0.90}$Se$_{0.40}$.

The magnetization relaxation studies were performed using a SQUID (Superconducting Quantum Interference Device) magnetometer. The approximate dimension of the sample were 4 x 3 x 1 mm$^3$, with the long axis parallel to the magnetic field (H/ab). We used a scan length of 4 cm, and for each scan 32 data points were taken. This relatively short scan length minimizes the magnetic field variation during the sample movement. For the relaxation measurement, applied magnetic field was increased to 1T and then reduced to zero. The decay rate of remnant magnetization $M_{\text{rem}}$ was then recorded.

3. Results and Discussion:

The vortices in type II superconductors, moves over the characteristic pinning energy $U(j,T,B)$ upon thermal activation with an average velocity given by $v = v_0 \exp(-U(j,T,B)/k_BT)$, where ‘$v$’ is the attempt velocity of vortex movement, and $j$ is the critical current density. When a magnetic field is applied, i.e. when there gradient in the magnetic flux density in the superconductor, the Lorentz force reduces the pinning barrier and magnetic flux start penetrating in the material, and magnetization begins to decay from the critical state where $J = J_c$ and $U(j) = 0$ [9]. Using the Anderson Kim model, the time dependence of the magnetic moment is given by $M(t) = M_0(T) \left[ 1 - \frac{kT}{U} \ln \left( \frac{L}{t_0} \right) \right]$, where $M_0(T)$ is the magnetization at $t=0$, and $t_0$ is the hopping time ($10^{-12}$ s < $t_0$ < $10^{-6}$ s). Anderson Kim model assumes a linear dependence of $U$ on $J$ [9, 11].

The time decay of the magnetization (-M) measured at different temperatures, in 1T magnetic field along the ab-plane is plotted in log-log scale in Figure 1. The logarithmic decay of the non-equilibrium magnetization (-M) is as expected from the thermally activated motion of the flux creep. The temperature dependence of the normalized relaxation rate $S = |d \ln M/d t|$ obtained from this data, is shown in the figure 2. The relaxation rate increases linearly with the increase in temperature but shows a tendency of slower relaxation at higher temperatures. The extrapolation of the relaxation rate $S$ gives a finite value of $S$ at $T=0K$ which may be due to either quantum tunneling of vortices or the multi gap nature of the compound like for the MgB$_2$ [12]. We have calculated the characteristic pinning energy using the expression $T/(S(T,B)) = U_c(T,B)/k_B + \mu(T,B)CT$, where $C=\text{ln}(2v_0B/(dH/dt))$ is a weakly temperature dependent parameter [13]. By extrapolating the curve T/S vs. T down to zero temperature, we got the value of the activation energy $U_c(0)/k_B = 9K$ at 1Tesla field. This value is small compared to that for the SmFeAsO$_{0.6}$F$_{0.4}$ (40K), PrFeAsO$_{0.6}$F$_{0.4}$ (75K), Ba(Fe$_{0.9}$Co$_{0.1}$)$_2$As$_2$ single crystal (75K), YBCO film (100-400K), and MgB$_2$ (3000K) [13-16]. The parameter $C$ can be determined from the curve $t^-d \ln M/d \ln t$ ‘vs S/T and we find $C = 0.306$. The slope of the T/S vs T gives the value of $\mu C = 0.201$ at low temperatures in 1T field. This gives the $\mu = 0.67$. This value is much less than the Anderson-Kim’s criterion of $\mu = 1$ for the thermally activated flux creep motion.

Another important feature that characterizes the vortex dynamics is the dependence of activation energy $U$ on the critical current $J$ and hence on magnetization ‘M’. Models based on the vortex glass and
collective pinning-collective flux creep theories have derived an inverse power law expression for $U(J)$ that can be generally written as $U(J) = U(0) (J_c/J)^\mu$, where $U_c$ is the characteristic pinning energy and the exponent $\mu$ determine the nature of the pinning barrier. In order to meet the boundary condition $U(J) = 0$ at $J = J_c$, this expression can be modified as $U(J) = U_c [(J/J_c)^\mu - 1]$. The exponent $\mu = -1$ in the above equation describes the Anderson Kim barrier linear in $J/J_c$, whereas the positive value of $\mu$ leads to a non-linear U-J dependence and describe the collective creep barrier. The collective pinning-collective flux creep model considers the current dependence of the flux bundle size, and the different regimes of the bundle size lead to different power law behavior [9,11,17]

**Figure 1.** The log-log plot of magnetization ‘$M$ (emu/mole)’ versus time ‘$t$ (second)’ at various temperature measured in the $H=1T$ along the ab-plane of the crystal.

**Figure 2.** The temperature dependence of the normalized relaxation rate $S = |d\ln M/d\ln t|$ measured at 1T field ($H/ab$). The inset shows the $T/S$ vs $T$ curve, intercept of which gives the value of $U_c(0) = 9K$.

**Figure 3.** Magnetization dependence of the scaled flux creep activation energy $U(K) = T[A - |d M / d \ln t|]$, calculated using Maley’s techniques with parameter $A=14$.

**Figure 4.** The plot of activation energy versus $M$ on a double logarithmic scale. The solid lines are drawn to show the slopes of the curve.
We used Maley’s method to analyze the activation energy $U(j)$. This model proposes that the magnetic relaxation data at different temperatures can be scaled by the general relation $U/k_B = -T \ln (dM/dt) - A$, where ‘$A$’ is the constant that depends on the average hopping velocity only [18]. The figure 3 shows the magnetization dependence of the of the flux creep activation energy, where all the curves at different temperatures seems to fall on a single universal curve for $A = 14$. However the double log-log plot of $U(j)$ versus $M$ shows two different slopes, leading to the two different power law regime depending on the value of $j$ (figure 4). The slopes of the low temperature and high temperature region are found to be $0.78$ ($\mu=7/9$) and $0.37$ ($\mu=1/3$) respectively. The low temperature value of the slope $0.78$ ($\mu=7/9$), match well with the $\mu=7/9$, which corresponds to the flux creep caused by the large vortex bundles. In the collective flux creep model for the three dimensional superconductors, where the size of bundle is more than the penetration depth of the system, the activation energy has, $U(j) \sim j^{-7/9}$ dependence, where $J$ is the critical current density [14,17]. It is noted here that the FeTe$_{0.60}$Se$_{0.40}$ crystal shows the fish tail effect in the magnetic isotherm curve [10]. This fischtail behavior can be understood as due to cross over in the vortex dynamics with increasing magnetic field, when the system undergo from single vortex regime to the collective bundle pinning regime or the occurrence of the first order phase transition from an ordered elastically pinned low vortex phase to a high field disordered phase.

4. Conclusion:

We have measured the magnetic relaxation on the FeTe$_{0.60}$Se$_{0.40}$ crystal. The logarithmic decay of the non-equilibrium magnetization is as expected from the thermally activated motion of the flux creep. The activation energy is found to follow $U(j) \sim j^{-7/9}$ dependence on the activation energy suggesting the size of the magnetic flux bundle to be greater than the penetration depth. This behavior along with the fish tail effect observed in the magnetic isotherms shows the crossover form the single vortex regime to the collective bundle pinning regime.

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