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Rohit Kumar, A. Mitra, and G. D. Varma

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Rohit Kumar, A. Mitra, and G. D. Varma

AFFILIATIONS
Department of Physics, IIT Roorkee, Roorkee 247667, India

Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.
E-mail: gdvarfph@iitr.ac.in, gdvarfph@gmail.com

ABSTRACT
Superconducting thin films of two thicknesses have been fabricated on (100) oriented SrTiO$_3$ (STO) substrates using the target of composition Fe$_{1.05}$Te$_{0.50}$Se$_{0.50}$ by pulsed laser deposition technique. The structural and transport properties of the fabricated thin films have been investigated and the results indicate the enhancement in the superconducting properties with increasing thickness of the thin films. The onset of the superconducting transition temperature of the grown thin films of thicknesses $\sim 78$ nm and $\sim 177$ nm are $\sim 12.10$ and $12.62$ K at 0 T magnetic field, respectively. To estimate the upper critical fields $H_{c2}(0)$, thermally activated energy (TAE) and vortex phase diagram, the magnetoresistance measurements have been performed in the magnetic field range of 0 - 8 T. $H_{c2}(0)$ have been calculated by Ginzburg Landau (GL) theory and Werthamer-Helfand-Hohenberg model by taking the criterion of 90%, 50% and 10% of normal state resistivity and the corresponding GL coherence lengths have also been calculated. In the present work, the TAE has been estimated by conventional Arrhenius relation and modified thermally activated flux flow (TAFF) theory. The power law dependence of TAE, shows prominently the possible planer defects in the system. From the modified TAFF model, the values of fitting parameter ‘$q$’ suggests the 3 dimensional behaviour of the vortices for both the grown thin films. The vortex phase diagram study reveals the transition from the vortex liquid to vortex glass state.

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I. INTRODUCTION

Since the discovery of superconductivity in bulk Fe-based compounds, great efforts have been devoted to the preparation of thin films of different classes of iron (Fe) based superconductors (IBS) on various substrates. The thin films are useful to understand the basic intrinsic properties of IBS which are comparatively difficult to study in bulk single crystalline samples due to the small size of grown crystals of some of the IBSs, such as LnFeAs(O, F). The high quality epitaxial thin films of IBS are suitable for the production of Fe based superconducting devices such as superconducting quantum interface devices (SQUIDs), coated conductors (tapes) and Josephson junctions. The high critical current density ($J_C$) and high upper critical fields ($H_{c2}$) of these iron based superconducting thin films make them the perfect candidate for the practical applications. Furthermore, the broadening and shifting of the resistive transitions in external magnetic fields, are subject of great interest in high $T_C$ superconductors. Such behaviour of resistive transition is due to the thermal fluctuations developed via short coherence length, large anisotropy and high $T_C$. These thermal fluctuations are responsible for the thermally activated flux flow (TAFF) which leads to the tail in resistive transition induced via the motion of vortices.

In this paper, structural and superconducting properties of the Fe(Fe, Se) thin films, grown on STO with different thicknesses, have been described.

II. MATERIAL AND METHODS

Thin films with nominal composition of Fe$_{1.05}$Te$_{0.50}$Se$_{0.50}$ were fabricated on (100) oriented SrTiO$_3$ (STO) substrates using the pulsed laser deposition (PLD) technique. The used target material...
of Fe$_{1.05}$Te$_{0.5}$Se$_{0.5}$ was synthesized using solid state reaction route. The details of the pellet synthesis and the growth conditions for thin film preparation using PLD method can be seen in the previous reports.\textsuperscript{13,14} Thin films have been prepared on employing laser shots of 8000 (Thin film S1) and 16000 (Thin film S2).

III. RESULTS AND DISCUSSION

The $\theta$-2$\theta$ X-ray diffraction (XRD) patterns of thin films S1 and S2 show mainly the presence of (00l) oriented peaks, suggesting the thin film growth along the $c$-direction as shown in the Fig. 1(a, b). In the XRD patterns, the ‘$*$’ shows the peaks originating from the substates. The lattice parameters ‘c’, obtained using the (00l) peaks, are 5.9101 and 5.9020 Å for S1 and S2, respectively. With the help of (101) peak the lattice parameters ‘a’ have been found and the values are 3.8515 and 3.7301 Å for S1 and S2, respectively.

The full width at half maximum (FWHM) values have been estimated using the most intense (001) peaks and the values are 0.4318$^\circ$ and 0.4731$^\circ$ for S1 and S2, respectively. The observed values of FWHM suggest that the S1 is less crystalline as compare to S2.

The field emission scanning electron microscopy (FESEM) images of the cross-sectional part of the thin films have been shown in the Fig. 1(c and d). From these images, the observed values of film thicknesses are $\sim$78 nm and $\sim$177 nm for S1 and S2, respectively.

The main panels of Fig. 2(a, b) show the temperature dependent resistivity measurements from 300 – 2 K at 0 T magnetic field. The inset of each figure shows the magnetoresistance data in the magnetic fields 0, 0.2, 0.5, 1, 1.5, 2, 3, 4, 6 and 8 T. The onsets of superconducting transition temperature ($T_{\text{onset}}$) at 0 T field have been found at 12.10 and 12.62 K for S1 and S2, respectively. The higher $T_{\text{onset}}$ value of S2 is possibly due to the higher c/a ratio as observed in the previous report.\textsuperscript{15} The insets of the Fig. 2(a) and (b) show the broadening and shifting of the magnetoresistance data with the application of magnetic field. Using the magnetoresistance data, the upper critical field ($H_{\text{C2}(0)}$), thermal activation energy (TAE) and vortex phase diagram have been estimated.

In the present work, the $H_{\text{C2}(0)}$ values have estimated using Ginzburg-Landau (GL) theory and the Werthamer Helfand Hohenberg (WHH) model for the criteria of 90%, 50% and 10% of normal state resistivity ($\rho_n$). From the GL theory, the $H_{\text{C2}(0)}$ values have been estimated by using the equation (1).\textsuperscript{16}

$$H_{\text{C2}(T)} = H_{\text{C2}(0)} \left(1 - \frac{r^2}{1 + r^2}\right)$$

Where $t = T/T_{90}$ is the reduced temperature.

From the calculations, the $H_{\text{C2}(0)}$ have been found 207.9, 47.6 and 14.4 T for S1 and S2, respectively. The $H_{\text{C2}(0)}$ values have also been estimated using the WHH model (Equation (2)).

$$H_{\text{C2}(0)} = -0.693T_C \frac{dH_{\text{C2}}}{dT} \bigg|_{T=T_C}$$

From the WHH model, the estimated values of $H_{\text{C2}(0)}$ are 128.25, 46.15 and 18.03 T for S1 and 175.26, 45.28 and 22.01 T for S2 for 90%, 50% and 10% of $\rho_n$, respectively. Both the models show the highest values of $H_{\text{C2}(0)}$ for S2. These $H_{\text{C2}(0)}$ values are comparable to the previously reported ones of Fe(Te, Se).\textsuperscript{17,18}

Using the $H_{\text{C2}(0)}$ values, the coherence lengths ($\xi_0$) of both thin films have also been calculated using the relation: $H_{\text{C2}(0)} = \phi_0/(2\pi\xi_0^2)$, where $\phi_0 = 2.067 \times 10^{-15}$ Tesla–m$^2$, is the flux.
quantum. The values of $\xi(0)$, estimated with the values of $H_c2(0)$ of GL theory, are 1.03, 2.47 and 4.3 nm for S1 and 1.26, 2.63 and 4.78 nm for S2. The values of $\xi(0)$, obtained with the $H_c2(0)$ values of WHH model, are 1.60, 2.67 and 4.2 nm for S1 and 1.37, 2.69 and 3.86 nm for S2.

Using the magnetoresistance data, the activation energies ($U_0$) of the grown thin films have been calculated using the conventional and the modified TAFF models. In the conventional TAFF method, $U_0$ values have been estimated using the Arrhenius relation$^{19}$ (Eq. (3)).

$$\rho = \rho_0 \exp\left(\frac{U_0}{T}\right)$$

where, $\rho_0$ is the normal state resistivity.

From the Fig. 2(c) and (d), the plots between $\ln(\rho/\rho_{18})$ versus $1/T$ (K$^{-1}$) have been drawn to find out $U_0$ values. The linear regression of the curves has been extrapolated for all the magnetic fields which meet at the same point close to the $T_c$. The obtained values of $U_0$ have been shown in the Fig. 3(a, b) for S1 and S2 thin films.

Furthermore, it has been observed that the Arrhenius plots of $\ln(\rho/\rho_{18})$ versus $1/T$ are not completely linear in the entire temperature range rather show non-linear behaviour in the lower temperature range with round curvature. Zhang et al.$^{20}$ suggested that in the nonlinear region, the modified equation should be used for the analysis of $U_0$ using Eq. (4).

$$-\frac{\partial \ln \rho}{\partial T}^{-1} = \left[U_0(1 - t)^q - T\right][1 + qt/(1 - t)]$$

where, $q$ is the free parameters and $t=T/T_c$.

For the calculation of $U_0$ from the modified TAFF model, the graphs between $-\ln(\rho/\rho_{18})/dT^{-1}$ versus $T$ (K) have been plotted in Fig. 3(a, b).$^{20}$ The dotted lines of regression curve in Fig. 3(a, b) show the goodness of the fit. The obtained values of $U_0$ are shown in the Fig. 3(c).

The variations of $U_0$ values, calculated from the Arrhenius relation and modified TAFF model, with magnetic fields are shown in Fig. 3(c). Both the models suggest the crossover from the single vortex pinning to collective vortex pinning regime. The $U_0$ values estimated from Arrhenius relation are found close for both the thin films in the low magnetic fields ($\mu_0H \leq 2$ T) while in higher magnetic fields ($\mu_0H \geq 3$T) the $U_0$ values are high for S2 than S1. Similar results of $U_0$ have been obtained via modified TAFF model for $\mu_0H \leq 2$ T and $\mu_0H \geq 3$T (see Fig. 3c). On comparing both the models, the $U_0$ values obtained via modified TAFF model are found high. Furthermore, the modified TAFF model provides better and more accurate results than that of the Arrhenius relation.$^{21,22}$

Also, the $U_0$ values have been fitted with the power law relation: $U_0(H) \sim H^a$, where, $a$ shows the planer and point defect dominating regions when it is 0.5 and 1, respectively.$^{23}$ Both the models suggest that the planer defects are dominating for both the thin films when $\mu_0H \leq 2$ T. While for $\mu_0H \geq 3$T, S2 shows presence of planer defects while S1 shows the presence of point defects from both the models.

From the modified TAFF model, the $q$ values have also been estimated. The variations of $q$ with magnetic fields have been shown in Fig. 3(d). For high $T_c$ superconductors, the value of $q=1.5$ corresponds to three dimensional (3D) behavior, whereas $q=2$ corresponds to the two dimensional (2D) behavior. Our results show $q$ values $\leq 1.5$, which strongly suggest the 3D behaviour of the vortices. Such 3D behaviour of vortices have also been reported for LiFeAs superconductors.

To estimate the vortex glass (VG) transition states, the graphs between $(\ln(\rho/\rho_{18})/dT)^{-1}$ vs $T$ for the applied magnetic fields have
been plotted as shown in Fig. 4(a, b).\textsuperscript{11,12} According to the VG transition theory, near to the VG transition region, the resistivity decays as \( \rho \propto (T - T_g) \), where \( T_g \) is the VG temperature. Critical temperature (\( T^* \)), \( T_g \) and corresponding magnetic fields (\( \mu_0 H^* \) and \( \mu_0 H_g \)) have been established from \((\text{dln}(\rho/\rho_{18})/\text{dT})^{-1} \) vs T plots. Using the relation \((\text{dln}(\rho/\rho_{18})/\text{dT})^{-1} \propto (T - T_g) \) in the resistive tail region, the \( T_g \) values have been estimated.\textsuperscript{11} \( T^* \) is the boundary above which the \((\text{dln}(\rho/\rho_{18})/\text{dT})^{-1} \) vs T plots deviate from linearity.
It is also associated with the transition region from the unpinned-pinned vortex liquid (VL) in the vortex melting regime where the resistivity tends to zero. Below the VG transition line (Tg), the true superconducting state emerges and the strong pinning behaviour is effective below Tg. The vortex phase diagrams have been found for thin films S1 and S2 using the values of Tg, T* and T90 (T90 is 90% of ρ0) as shown in Fig. 4(c, d) and found similar to 122-type K0.78Fe1.70Se2 single crystals.21 The VG to VL transitions are similar to the results of Hänisch et al.23 On comparing the VL regions of thin films S1 to that of S2, we see that the VL region of S2 is found at high temperature which suggests better superconducting properties of S2. Also, the transition from the unpinning to pinned VL is found high for S2 thin films. It is clear from Fig. 4(c, d), that the VG transition for thin film S2 is at higher temperatures, which in turn suggests that S2 has stable VG phase at higher temperature.

IV. CONCLUSIONS

The ρ-T measurements of grown films S1 and S2 show Tc,onset of 12.10 and 12.62 K, respectively. Hc2(0) values have been found highest for S2 from both GL theory and WHH model. U0 values suggest the presence of planar and point defects from both the models. The q values suggest the 3D behaviour. The vortex phase diagrams have been found similar to 122-type single crystals.

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