Upper critical field and thermally activated flux flow in LaFeAsO\textsubscript{1-x}F\textsubscript{x}

Mahboobeh Shahbazi  
*University of Wollongong, msm979@uow.edu.au*

Xiaolin Wang  
*University of Wollongong, xiaolin@uow.edu.au*

C Shekhar  
*Banaras Hindu University India*

O N. Srivastava  
*Banaras Hindu University India*

Z W. Lin  
*Univ Technol Sydney*

*See next page for additional authors*

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M. Shahbazi,$^1$ X. L. Wang,$^{1,a}$ C. Shekhar,$^2$ O. N. Srivastava,$^2$ Z. W. Lin,$^3$ J. G. Zhu,$^3$ and S. X. Dou$^1$ 

$^1$Institute for Superconducting and Electronic Materials, University of Wollongong, Innovation Campus, Northfields Avenue, Fairy Meadow NSW 2519, Australia. 
$^2$Department of Physics, Centre of Advanced Studies for Physics of Materials, Banaras Hindu University, Varanasi-221005, India. 
$^3$Faculty of Engineering and Information Technology, University of Technology, Sydney, City Campus, P.O. Box 123, Broadway, NSW 2007, Australia. 

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The magneto-resistance, critical current density, $J_c$, upper critical field, $H_{c2}$, and flux pinning properties of LaFeAsO$_{1-x}F_x$ superconductors were investigated systematically by magnetic and magneto-transport measurements in the fields up to 13 T over a temperature range of 5–35 K. It was found that the $H_{c2}$ increased with increasing fluorine concentration up to $x \leq 0.15$, while with higher fluorine doping, $H_{c2}$ decreased. A peak effect in the $J_c$ as a function of field was observed at $T < 15$ K for both the 5% and 15% fluorine doped samples. The broadening of the superconducting transition in magnetic field can be well understood by the thermally activated flux flow model. The pinning potential, $U_p$, scales as $U_p/k_B \propto B^{-n}$ with $n = 0.13$ for $B < 1$ T and $n = -0.68$ for $B > 1$ T for LaFeAsO$_{0.85}F_{0.15}$. 

These can be seen that the as-prepared sample is nearly single phase with tetragonal structure having the P4/mmm symmetry and the lattice parameters $a = 4.023$ Å and $c = 8.709$ Å. The $J_c$ values were calculated from the M-H loops at different temperatures by using the extended Bean model: 

$$J_c = \frac{2^*\Delta M/[(1 - l/3w)], \ where \ l \ and \ w \ are \ the \ sample \ dimensions \ perpendicular \ to \ the \ applied \ field, \ and \ \Delta M \ is \ the \ height \ of \ the \ magnetization \ loop. \ The \ J_c \ versus \ magnetic \ field \ at \ different \ temperatures \ are \ shown \ in \ Fig. \ 2. \ At \ 5 \ K \ for \ the \ x = 0.15 \ sample, \ the \ J_c \ is \ approximately \ 10^3 \ A/cm^2 \ at \ zero \ field \ and \ then \ decreases \ to \ 320 \ A/cm^2 \ at \ 1.2 \ T. \ The \ J_c \ increases \ slightly \ with \ increasing \ magnetic \ field \ and \ reaches \ a \ peak \ value \ of \ 330 \ A/cm^2 \ at \ about \ 2.2 \ T \ (Fig. \ 2), \ then \ decreases \ with \ field. \ The \ same \ peak \ effect \ can \ be \ seen \ at \ 10 \ and \ 15 \ K, \ but \ in \ lower \ magnetic \ fields. \ A \ similar \ peak \ effect \ has \ also \ been \ detected \ for \ LaFeAsO_{0.95}F_{0.05}. \ The \ observation \ of \ the \ peak \ effect \ in \ our \ La_{1111} \ compounds \ is \ in \ agreement \ with \ what \ has \ been \ reported \ in \ SmFeAsO_{1-x}F_x$ (Ref. 2) and NdFeAsO$_{1-x}F_x$ (Ref. 10) compounds.

The temperature dependence of resistance for samples with different fluorine concentrations at zero magnetic field is shown in the inset of Fig. 3. The resistance starts to drop at the temperature of 27.5, 26, and 27.5 K and then vanishes below 25.5, 24, and 25.5 K for the 5%, 15%, and 20% fluorine doped samples, respectively. The resistance for the $x = 0.05$ and 0.2 fluorine doped samples decreases linearly with decreasing temperature down to $T_c$, whereas, the resistance for the $x = 0.15$ sample decreases down to 70 K and then increases again, reaching a maximum at the onset of $T_c$. A similar resistance peak anomaly has been detected in other superconductors and it is usually related to sample

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$^a$Author to whom correspondence should be addressed. Electronic mail: xiaolin@uow.edu.au.
inhomogeneities and enhanced electron scattering in the vicinity of $T_c$. The residual resistance ratio ($R_{RRR} = R_{300 \text{ K}} / R_{28 \text{ K}}$) is 7.98, 2.67, and 8.72 for the 5%, 15%, and 20% fluorine doped samples, respectively, which indicates that the scattering for the 5% and 20% fluorine doped samples is higher than for the 15% fluorine doped sample. The $D_T = T_c(90\%) / T_c(10\%)$ for zero magnetic field is only 2.4, 1.8, and 2.6 K for the 5%, 15%, and 20% fluorine doped samples, respectively, which is much smaller than the value of 4.5 K for LaFeAsO$_{0.89}$F$_{0.11}$ reported earlier, indicative of relative good chemical homogeneity of our samples.

As the $J_c$ drops to zero at a temperature of about 20 K in $H > 2$ T, the 90% and 10% of normal state resistance can be regarded as the upper critical field in the ab-plane and along c direction, $H_{c2}^{ab}$ and $H_{c2}^c$, respectively. The temperature dependence of upper critical field in ab plane and along c direction is shown in Fig. 4. The estimated slope $dH_{c2}^{ab}/dT$ for $H_{c2}^{ab}$ is $-4.1, -6.8$, and $-3.5$ TK$^{-1}$ for 5%, 15%, and 20% fluorine doped samples, respectively. The $dH_{c2}^{ab}/dT$ for $H_{c2}^{ab}$ is $-1.8, -2.1$, and $-1.5$ TK$^{-1}$ for the 5%, 15%, and 20% fluorine doped samples, respectively. The $B_{c2}^{ab}(0) = \frac{1}{(a^2 + 1)^{1/2}}$ for the 5%, 15%, and 20% fluorine doped samples, respectively. These values are much greater than the highest value of 60 T which was reported earlier.

It has been reported that the Pauli-limiting (PL) effect is responsible for the $H_{c2}$ values in high fields in As-deficient LaFeAs$_{1-x}$O$_x$F$_y$ superconductors. The $B_{c2}(0)$ of the PL effect is lower than what is estimated using the WHH formula and can be calculated using $B_{c2}(0) = B_{c2}^{whh}/\sqrt{1 + \alpha^2}$, where $\alpha$ is the Maki parameter. The $\alpha$ values are sample dependent and can vary between 0.25 and 3 for the La-1111 and Nd-1111 compounds. $\alpha$ is 1.31 for As-deficient LaFeAs$_{1-x}$O$_x$F$_y$, which is 0.25 for La-1111 samples. Therefore, the $B_{c2}(0)$ values should be almost the same as those obtained from the WHH estimation. It should be noted that we are unable to estimate $\alpha$ values precisely for our samples because of the lack of $H_{c2}$ data in high magnetic fields. The Ginzburg–Landau coherence length at zero temperature ($\xi_{GL} = \phi_0/2\pi \rho / H_{c2}$) is 15, 10, and 5 T for the 5%, 15%, and 20% fluorine doped samples, respectively.
The broadening of the superconducting transition in the magnetic field is caused by the thermally activated flux flow in NdFeAsO$_{1-x}$F$_x$ superconductor. Furthermore, the estimated anisotropy $\gamma (=H_{c2}^{ab}/H_{c2}^{ab})$ in the temperature range of $17 < T < 28$ K is 2.3, 3.2, and 2.4 for the 5%, 15%, and 20% fluorine doped samples, respectively. These values are smaller than the reported values for LaFeAsO$_{0.85}$F$_{0.15}$ polycrystalline superconductors. As the $U_o$ decreases weakly with field, it is expected that single-vortex pinning may co-exist with collective creep in low field ($<1$ T), and then the collective creep dominates for $B > 1$ T for all our La-1111 samples with various F concentrations.

In summary, LaFeAsO$_{1-x}$F$_x$, with various F concentrations shows a superior $J_c$ field dependence at low temperatures. A peak effect in the $J_c$ versus field was observed in the $x = 0.05$ and 0.15 samples. High value of $dH_{c2}^{ab}/dT = 6.8$ T K$^{-1}$ was obtained for the $x = 0.15$ sample with the $H_{c2}^{ab}(0) = 122$ T. The thermally activated flux flow is responsible for vortex behaviors in the tails of the RT curves.

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$H_{c2}^{ab}$)}^{1/2}$, where $\phi_0 = 2.07 \times 10^{-7}$ Oe $\cdot$ cm$^2$) is 2.06, 1.64, and 2.18 nm for the 5%, 15%, and 20% fluorine doped samples, respectively. These values are smaller than the reported values for LaFeAsO$_{0.89}$F$_{0.11}$ compound. Furthermore, the estimated anisotropy $\gamma (=H_{c2}^{ab}/H_{c2}^{ab})$ in the temperature range of $17 < T < 28$ K is 2.3, 3.2, and 2.4 for the 5%, 15%, and 20% fluorine doped samples, respectively.

The broadening of the superconducting transition in the magnetic field is caused by the thermally activated flux flow in NdFeAsO$_{1-x}$F$_x$ superconductor. Thus we use the same model to discuss the broadening of resistance in our samples. According to the thermally activated flux flow model, the resistance is $R(T, B) = R_0 \exp [-U_0/k_BT]$, where $R_0$ is the flux-flow activation energy, which can be obtained from the slope of the linear part of an Arrhenius plot, $R_0$ is a parameter, and $k_B$ is Boltzmann’s constant. In Fig. 5, we plot the data as $\ln R$ versus $T^{-1}$. The thermally activated behavior of the resistance is immediately apparent. The best fit to the experimental data yields values of the activation energy, $U_0/k_B$ of $1130$ and $910$ K in the low field of $0.1$ T for the 5% and 15% fluorine doped samples, respectively. These values are lower than $U_0$ value for a polycrystalline NdFeAsO$_{0.82}$F$_{0.18}$ sample ($U_0/k_B = 2000$ K for a magnetic field of $0.1$ T).}

Figure 5(b) shows the magnetic field dependence (up to $13$ T) of $U_0$ for all samples. We can see that the values of $U_0$ for LaFeAsO$_{0.89}$F$_{0.15}$ drop very weakly with field for $B < 1$ T, scale as $B^{-0.13}$, and then decrease as $B^{-0.68}$ for $B > 1$ T. The activation energy of the 5% and 20% fluorine doped samples shows a similar trend with field. The field dependence of $U_0$ in our samples is the same as what we have found for NdFeAsO$_{1-x}$F$_x$ sample, indicating that the vortices should have the same nature in both La-1111 and the Nd-1111 polycrystalline superconductors. As the $U_0$ decreases weakly with field, it is expected that single-vortex pinning may co-exist with collective creep in low field ($<1$ T), and then the collective creep dominates for $B > 1$ T for all our La-1111 samples with various F concentrations.

In summary, LaFeAsO$_{1-x}$F$_x$, with various F concentrations shows a superior $J_c$ field dependence at low temperatures. A peak effect in the $J_c$ versus field was observed in the $x = 0.05$ and 0.15 samples. High value of $dH_{c2}^{ab}/dT = 6.8$ T K$^{-1}$ was obtained for the $x = 0.15$ sample with the $H_{c2}^{ab}(0) = 122$ T. The thermally activated flux flow is responsible for vortex behaviors in the tails of the RT curves.

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FIG. 5. (Color online) (a) Arrhenius plot of the electrical resistance of LaFeAsO$_{0.89}$F$_{0.11}$. $U_0$ is given by the slope from a linear fitting. (b) Magnetic field dependence of $U_0$ for LaFeAsO$_{1-x}$F$_x$ ($x = 0.05, 0.15, 0.20$).