Upper critical field, penetration depth and depinning frequency of the high-temperature superconductor LaFeAsO$_{0.9}$F$_{0.1}$ studied by microwave surface impedance.

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Temperature and magnetic field dependent measurements of the microwave surface impedance of superconducting LaFeAsO$_{0.9}$F$_{0.1}$ ($T_c \approx 26$K) reveal a very large upper critical field ($B_{c2} \approx 56$T) and a large value of the depinning frequency ($f_0 \approx 6$GHz); together with an upper limit for the effective London penetration depth, $\lambda_{eff} \leq 200$ nm, our results indicate a strong similarity between this system and the high-$T_c$ superconducting cuprates.

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The recent discovery of superconductivity in LaFeAsO$_{0.9}$F$_{0.1}$ has lead to the rapid growth in the number of superconducting layered oxypnictides with larger and larger $T_c$ ($\approx 55$K in SmO$_{0.8}$F$_{0.2}$FeAs)\textsuperscript{a} Apart from their high $T_c$, the interest in these materials stems primarily from the proximity of superconductivity to a spin-density-wave (SDW) ground state, and from the fact that multiple bands resulting from the orbitals of the conventionally pair-breaking magnetic ion Fe$^{2+}$ appear to be here directly responsible for the formation of the superconducting condensate. Both \textit{ab initio} band structure and LDA calculations\textsuperscript{3,4,5,6} show that the Fe-pnictide layers are responsible for the (super)conductivity; specifically, the 3d orbitals of the Fe$^{2+}$ ions weakly hybridized with the As$^{3-}$ 4p orbitals, form two electron and two hole pockets, while the $[RE$(OF)]$\textsuperscript{-}$ (RE = La,Pr,Ce,Sm) layers act as charge reservoirs, $\text{F}^{\text{1-}}$ causing the electron doping, the size of the RE element generating chemical pressure. The electronic structure thus consists of multiple quasi-two-dimensional Fermi surface sheets in the presence of competing ferromagnetic and antiferromagnetic fluctuations.\textsuperscript{4,6} The microscopic nature of the superconducting pairing and the symmetry of the order parameter on the other hand are still far from established, with theoretical proposals ranging from extended s-wave mediated by antiferromagnetic spin fluctuations\textsuperscript{8} to spin-triplet p-wave\textsuperscript{7}. The possibility of anomalously strong electron phonon coupling effects has also been emphasized,\textsuperscript{2} while a very small value of the electron-phonon coupling constant ($\lambda_{e-ph} < 0.21$) has been calculated.\textsuperscript{2} The expected large moment for the undoped compound ($S = 2$) is experimentally not observed, low temperature values of $\mu \approx 0.36\mu_B$\textsuperscript{10} and $\mu \approx 0.25\mu_B$\textsuperscript{11} being reported instead. In this parent compound a structural phase transition from tetragonal to orthorhombic occurs at $T_N \approx 150$K, closely related to the formation of a spin-density-wave (SDW) below $T_N \approx 135$K. Electron doping rapidly suppresses both structural and SDW transitions leading to superconductivity, possibly allowing short-range magnetic fluctuations to survive in the region of the phase diagram where superconductivity becomes the preferred ground state. Whether or not these local fluctuations are responsible for the pairing is here the fundamental question. Further evidence for possible unconventional pairing with nodal order parameter comes from specific heat\textsuperscript{12} tunneling\textsuperscript{13} magnetisation\textsuperscript{14} and NMR\textsuperscript{15} measurements.

Here we report on temperature (4.2K < $T$) and magnetic field dependence ($\mu_0 H < 16$T) of the microwave surface impedance of LaFeAsO$_{0.9}$F$_{0.1}$. The results allow us to estimate the upper critical field $B_{c2}$, the effective London penetration depth $\lambda_{eff}$ and the depinning frequency $f_0$ for this material.

Polycrystalline samples of LaFeAsO$_{0.9}$F$_{0.1}$ were prepared by a solid state reaction method and annealed in vacuum.\textsuperscript{16} Inspection with a polarized light microscope revealed dense crystallites of sizes varying between 1 and 100 $\mu$m. The resistivity of the sample under study was measured by means of a standard DC method with four-point contact geometry and current polarity inversion. The magnetic susceptibility, both zero-field (ZFC) and field cooled (FC), was measured using a SQUID magnetometer. The microwave measurements were carried out in a high-Q elliptical copper cavity at four different frequencies corresponding to four different resonant modes: the $\varepsilon_{111}$ mode at 9.1GHz, the $\varepsilon_{122}$ mode at 12.8GHz, the $\varepsilon_{211}$ mode at 15.1GHz and the $\varepsilon_{113}$ mode at 16.7GHz. The sample was mounted on a sapphire sample holder and placed in the center of the resonator. In that position, the sample lies in a microwave electric field $E_{mn}$ maximum in modes $\varepsilon_{111}$ and $\varepsilon_{113}$ and in a microwave magnetic field $H_{mn}$ maximum in modes $\varepsilon_{112}$ and $\varepsilon_{211}$. The temperature was varied between 5 and 50 K, and the applied DC magnetic field between 0 and 16 T. Directly measured quantities are the $Q$-factor and the resonant frequency $f$ of the cavity loaded with the sample. The $Q$-factor was measured by a...
modulation technique described elsewhere.\textsuperscript{17} The empty cavity absorption \((1/2Q)\) was subtracted as background from the measured data: the presented experimental curves therefore display changes occurring exclusively in the physical properties of the samples themselves. An automatic frequency control (AFC) system was used to track the source frequency always in resonance with the cavity. Thus, the frequency shift could be measured as the temperature of the sample or the static magnetic field were varied. The two measured quantities represent the complex frequency shift \(\Delta \tilde{\omega}/\omega = \Delta f/f + i\Delta (1/2Q)\).

![FIG. 1: (Color online) temperature dependence of the resistivity; top left hand side inset: resistivity plotted versus \(T^2\), showing a deviation above \(T \approx 200\text{K}\); bottom right hand side inset: the superconducting transition.](image1)

![FIG. 2: (Color online) temperature dependence of the susceptibility measured in zero field (ZFC) and in applied magnetic field (FC, 200e).](image2)

The temperature dependence of resistivity and susceptibility are shown in Fig. 1 and Fig. 2 respectively. Remarkably, the normal state resistivity has a quadratic temperature dependence up to about 200K. The midpoint of the resistive transition yields \(T_c=23.7\text{K}\) with a width \(\Delta T \approx 4\text{K} \) (90\% - 10\% criterion), while the onset of diamagnetism from the susceptibility curve (ZFC) becomes discernible below \(T \approx 22\text{K}\). Both data sets reveal a sample with some degree of inhomogeneity, with a fluorine content slightly different from the nominal value of 0.1. The field-cooled (FC) susceptibility shows significant flux penetration for fields as low as 20 Oe. The two panels of Fig. 3 show the measured complex frequency shift for various values of the applied DC magnetic field in the microwave mode \(e\text{TE}_{112}\). For a thick sample there is a proportionality between the complex frequency shift and the surface impedance: \(Z_s \propto -i\Delta \tilde{\omega}/\omega\). The factor of proportionality can be determined from the normal state resistivity \(\rho_n(T = 30\text{K}) = (0.20 \pm 0.05)\text{m\Omega cm}\). From the surface impedance one can determine the complex penetration depth \(\lambda = \lambda_1 - i\lambda_2\) through\textsuperscript{18}

\[Z_s = i\mu_0 \omega \lambda .\] (1)

The resulting temperature dependencies of \(\lambda_1\) and \(\lambda_2\) in zero applied magnetic field are shown in Fig. 4. In

![FIG. 3: (Color online) temperature dependence of the complex frequency shift in various applied magnetic fields: imaginary part in the top panel and real part in the bottom panel.](image3)

![FIG. 4: (Color online) temperature dependence of the complex penetration depth (left axis) and the complex impedance (right axis) in zero applied magnetic field.](image4)

the normal state one has \(\lambda_1 = \lambda_2 = \delta_n/2\), where \(\delta_n\) is the normal metal skin depth. In the opposite limit


\[ \sigma_{\text{eff}} = \frac{1}{\sigma_{\text{eff}}} = \frac{1 - \frac{b}{1 - i(\omega_0/\omega)}}{(1 - b)(\sigma_1 - i\sigma_2) + b\sigma_n} + \frac{1}{\sigma_n} \frac{b}{1 - i(\omega_0/\omega)}. \]
closer than previous results to the line of the electron-doped cuprates on the Uemura plot. Note that our measurement does not rely on any assumption regarding the distribution and arrangement of the vortex lattice within the sample in order to extract $\lambda_{\text{eff}}$. The obtained values of upper critical field, $B_{c2}$=56T, and slope near $T_c$, $d^2B_{c2}/dT^2 = -2.5T/K$, are in substantial agreement with other resistivity measurements: for compounds with nominally the same doping, Zhu et al obtain the same value of $B_{c2}$ and a similar slope ($d^2B_{c2}/dT^2 = -2.3T/K$) using formula for their fit while Hunte et al obtain $B_{c2}$ in the range 62-65T and a similar slope by applying the conventional one-band Werthamer-Helfand-Hohenberg theory. Their result is closer to that reported by Fuchs et al on As-deficient LaFeAsO$_{0.9}$F$_{0.1}$ samples, whose value of $d^2B_{c2}/dT^2$ near $T_c$ is considerably larger. The measurement of the depinning frequency yields $f_0 \approx 6$GHz: a number well into the microwave range. Typically, copper based high-$T_c$ superconductors have depinning frequencies slightly higher than 10GHz while the depinning frequencies in classical bulk superconductors are below 100MHz. This result therefore also points to a substantial communality of features between these novel materials and the cuprates.

In summary, microwave surface impedance measurements on the novel superconductor LaFeAsO$_{0.9}$F$_{0.1}$ provide estimates of the upper critical field ($B_{c2}$=56T) and the penetration depth ($\lambda_{\text{eff}} \leq 200nm$); the latter appears to be substantially smaller than the values estimated from measurements carried out by other techniques. Together with the large value of the depinning frequency ($f_0 \approx 6$GHz), these results yield a phenomenological picture of this system that closely resembles that of the high-$T_c$ cuprate superconductors.

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