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LETTERS TO THE EDITOR

Millimeter-wave study of London penetration depth temperature dependence in Ba(Fe$_{0.926}$Co$_{0.074}$)$_2$As$_2$ single crystal

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In-plane surface Ka-band microwave impedance of optimally doped single crystals of the Fe-based superconductor Ba(Fe$_{0.926}$Co$_{0.074}$)$_2$As$_2$ ($T_c = 22.8$ K) was measured. Sensitive sapphire disk quasi-optical resonator with high-$T_c$ cuprate conducting endplates was developed specially for Fe-pnictide superconductors. It allowed finding temperature variation of London penetration depth in a form of power law, namely $D_k(T) \propto T^n$ with $n = 2.8$ from low temperatures up to at least 0.6 $T_c$ consistent with radio-frequency measurements. This exponent points towards nodeless state with pair-breaking scattering, which can support one of the extended $s$-pairing symmetries. The dependence $k(T)$ at low temperatures is well described by one superconducting small-gap ($D \% 0.75$ in $kT_c$ units, where $k$ is Boltzmann coefficient) exponential dependence. © 2011 American Institute of Physics [doi: 10.1063/1.3660321]
measurements of small-sized superconductors with high Q-factor, namely, $Q > 10^5$ in temperature interval from 4 to 30 K. We also developed a novel technique for processing the frequency response of the resonators with partial removal of mode degeneracy and perturbed resonance Lorenz line, which allowed us precise determination of the resonance frequency and the Q-factor and thus accurate finding $Z_s$.

The results of resonant frequency $f(T)$ measurement of the resonator with and without the studied crystal are shown in Fig. 1. To obtain $X_s(T)$ from measured $f(T)$ we use the well-known expressions (see, e.g., Refs. 22, 24, and 25). One can obtain expression for surface temperature variation of the surface reactance $\Delta X_s(T)$ through the temperature changing the resonator frequency $\Delta \omega(T)$,

$$A_s\Delta X_s(T) = -2\Delta \omega(T)/\omega(T), \quad (1)$$

where $\omega = 2\pi f$, $A_s$ is the inclusion coefficient of the sample under test. It depends on geometry and dimensions of the sample and field structure (mode) in the resonator. In a given work $A_s$ was evaluated by simulation of the resonator using Microwave Studio CST. We obtain $A_s = 2.83 \cdot 10^{-3}$ mOhm$^{-1}$ at interaction of HE$_{11}$-mode with a sample of $2.50 \times 3.50 \times 0.10$ mm dimensions.

Evidently, in a case of WGM slotted resonator (see inset in Fig. 1), analogously to other resonator techniques, the most appropriate approach can be one, at which variation $X_s(T)$ is determined as

$$\Delta X_s(T_{ref}) = X_s(T_{ref}) - X_s(T_{ref}), \quad (2)$$

where $T_{ref}$ is a certain reference temperature. Because $X_s(T) = \omega(T)\mu_0\lambda(T)$ at $T \ll T_c$, we can write

$$\Delta X_s(T_{ref}) = \omega(T)\mu_0\Delta \lambda(T_{ref}), \quad (3)$$

where $\Delta \lambda(T_{ref}) = \lambda(T)-\lambda(T_{ref})$. From (1) and (3) $\Delta \lambda(T_{ref})$ can be expressed as

$$\Delta \lambda(T_{ref}) = -2\Delta \omega(T_{ref})/A_s\omega^2(T)\mu_0, \quad (4)$$

where $\Delta \omega(T_{ref}) = \omega(T) - \omega(T_{ref})$.

The experimental temperature law $\Delta \lambda(T_{ref})$ allows one to extrapolate it to $T \to 0$ and, knowing $\lambda(0)$ from other measurements, to determine $\lambda(T)$.

It is worthy to note that in $\Delta \omega(T_{ref})$ the variations $\Delta \omega_{\mu}(T_{ref})$ and $\Delta \omega_{\epsilon}(T_{ref})$ conditioned by temperature dependences both of sapphire permittivity $\epsilon$ and the disk dimensions are deducted by means of subtracting the

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**FIG. 1.** The resonant frequency shift of the resonator with (curve 1) and without (curve 2) single crystal Ba$_{1-x}$Co$_{x}$Al$_2$ sample depending on temperature. Inset shows the slotted sapphire disk resonator with a single crystal Ba$_{1-x}$Co$_{x}$Al$_2$ in a slot. The superconducting films (1) are sputtered on the sapphire sapphire substrates (2), a sapphire disk (3) with a single crystal Ba$_{1-x}$Co$_{x}$Al$_2$ (4) in a radial slot is sandwiched between superconducting YBa$_2$Cu$_3$O$_{7-\delta}$ endplates (1).
corresponding curves of $f(T) = \cos(2\pi)$ in Fig. 1. The value of $X_c(T)$ was determined from the measured dependence $\Delta(T)$, calibrated using the value $\lambda(0) = 208\text{ nm}$ from the previous measurement.  

The temperature variation of London penetration depth, $\Delta(T)$, determined from microwave data is presented in Fig. 2. The observed dependence of $\Delta(T)$ follows a power law, $\Delta(T) \sim T^n$ with $n = 2.8$ from low temperatures up to at least $0.6T_c$. The obtained dependence is similar to frequency range measurements, although $n$ is rather distinguished from them. When the given work results were processed, a work was arrived indicating $n \approx 2.66$. The difference $\Delta(T) = \Delta(T) - \lambda(0)$ and the superfluid density, $n_s(T) = [\lambda(0)/\lambda(T)]^2$, are commonly used to analyze penetration depth data and compare the calculations making certain assumptions regarding the superconducting gap structure.  

The temperature dependence $[\lambda(0)/\lambda(T)]^2$ is shown in Fig. 2 (see inset), where one can see the calculated curves for a power law $\Delta(T) \sim T^{n-2.8}$ and for exponential law $\Delta(T) \sim \exp(-\Delta(0)/kT)$ with $\Delta(0) = 0.75\text{ nm}$ in $kT_\text{c}$ units, where $k$ is Boltzmann coefficient. At low temperatures $\Delta(0) \approx \Delta(T)$ up to $T \approx T_c/3$. One can see that at least at low temperatures both functional laws are very close. The fact means that the temperature dependences of both London penetration depth and the superfluid density indicate evident absence of nodes of superconducting gap function and allow concluding about one of the expended $s$-wave symmetries of the studied pnictide.  

In summary, we carried out microwave surface impedance measurements of the optimally doped single crystal BaFe$_{1-x}$Co$_x$As$_2$ ($x = 0.074$) with critical temperature $T_c = 22.8\text{ K}$ and found the power-law exponent $n = 2.8$ in temperature dependence of the London penetration depth. The obtained dependence is similar to radio-frequency measurements indicating no noticeable frequency dependence of the response. This exponent points towards nodeless state with pairbreaking scattering, which can support one of the extended $s$-pairing symmetries. The temperature dependence $[\lambda(0)/\lambda(T)]^2$ calculated for a power law $\Delta(T) \sim T^{0.8}$ and exponential law for one superconducting small-gap ($\Delta kT_c = 0.75$) superconductor are very close. If another gap exists, it has a small weight coefficient.

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