Microwave impedance study of superconducting (Li$_{1-x}$Fe$_x$) OHFeSe single crystal

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Abstract. Microwave (MW) surface impedance $Z_s=R_s+iX_s$ of the recently discovered high-$T_c$ iron-based superconductor (Li$_{1-x}$Fe$_x$)OHFeSe$_{0.98}$ single crystal was measured for the first time. The special X-band “hot finger” resonator allowed carrying out measurements when temperature of the sample under test can be varied from 2K to 90K and in the same time temperature of the resonator remained constant (4.2K). The unusual and important inequality $R_s<X_s$ at $T\geq T_c=42K$ was found. The possible reason of the observed feature is considered. The temperature dependence of the quasiparticle $\sigma_1$ and superfluid $\sigma_2$ conductivities and structure of energy gap are analyzed. Experiments show the temperature dependence of the field penetration depth as $T^n$ with $n=2.8$ at $T<T_c/3$. The temperature dependence of the superfluid density confirms fully gapped behavior of a superconductor with a complex gap.

1. Introduction

Recently a new iron selenide based superconductor (Li$_{1-x}$Fe$_x$)OHFeSe ($x \approx 0.2$) was found, with a high transition temperature of $T_c \approx 40$ K [1]. Its crystal structure is a quasi-two-dimensional, including (Li$_{1-x}$Fe$_x$)OH and superconducting FeSe layers. The noticeable physical feature of the material is coexistence between superconductivity and antiferromagnetism.

To date, a number of experimental studies of the properties of the electronic system in this superconductor have been carried out, aimed at establishing the structure of the energy gap [2-8], which show the complexity of the indicated task and a certain inconsistency of conclusions based on the analysis of measurement results using various experimental techniques, angle resolved photoemission spectroscopy (ARPES), scanning tunneling spectroscopy (STS), muon-spin rotation ($\mu$SR) and inelastic neutron scattering (INS).

To further characterize the superconducting gap structure, London penetration depth measurements of (Li$_{1-x}$Fe$_x$)OHFeSe single crystals were performed using a 7 MHz tunnel-diode-oscillator (TDO) based technique, from which the temperature dependence of the London penetration depth shift was obtained.
[9]. The low temperature gives clear evidence for nodeless superconductivity. The superfluid density is well fitted by a two-gap s-wave model, as well as models with anisotropic gaps.

Fe-superconductors can also have an important application value due to the ability to achieve strong critical parameters, namely, the magnetic field and electric current [10]. In addition, in recent years many approaches to implementing the Majorana zero mode (MZM) [11-13] have been proposed as an important step towards topological quantum computing [14,15]. It has recently been shown that the new superconductor (Li_{0.84}Fe_{0.16}) OHFeSe provides a perspective for the creation of qubits based on MZM [16].

It is well known, that microwave surface impedance measurement technique allows one to perform studying properties of superconductor electron system accurately using high Q-factor resonators [17-20]. However, microwave studies of the superconductor (Li_{1-x}Fe_{x})OHFeSe, as far as the authors know, have not yet been carried out. This paper presents the results of the first-time study of the temperature dependence of the X-band surface impedance of a single crystal (Li_{1-x}Fe_{x})OHFeSe in the temperature range 4.2-90K.

2. Experimental details

Single crystal of (Li_{1-x}Fe_{x})OHFeSe (with x = 0.2) was synthesized following [21]. Using the parameters \( \rho_0 = 0.1 \text{ m\Omega-cm} \) and a carrier density of \( n = 1.04 \times 10^{21} \text{ cm}^{-3} \), a mean free path of \( l = 12.4 \text{ nm} \) was estimated [21]. This is considerably larger than the Ginzburg-Landau coherence length \( \xi_{GL} = 2 \text{ nm} \) calculated from an upper critical field of \( H_{c2}(0) = 79 \text{ T} \), and therefore the material is in the clean limit.

The sample under test (SUT) was cut into a regular shape of 2x2 mm² dimension in a-b plane and of 0.16 mm thickness. It was mounted in X-band sapphire resonant cavity on a sapphire rod, which played a role of “hot finger”, when temperature of sapphire cavity wall remained constant and equaled 4.2K. The resonator was excited with \( H_{011} \) mode. It is a close analogy to [22] and was used earlier for study of superconducting FeSeTe films [23,24]. The surface impedance \( Z_s \) of the SUT was found using the standard procedure of measuring microwave response of the resonator with the superconductor sample (see, e.g. [25]) as the change in Q-factor of the resonator and the shift of the resonant frequency depending on temperature measured by means of a vector network analyzer Agilent N5230C in a temperature interval from 4.2K to 90K.

3. Experimental results and their discussion

Figure 1 shows results of microwave response of the sapphire resonator depending on temperature with the sample under test and without it.

The temperature dependence of the real and imaginary parts, \( R_s(T) \) and \( X_s(T) \), of the surface impedance \( Z_s = R_s + iX_s \) of the (Li_{0.84}Fe_{0.16})OHFeSe single crystal obtained on the basis of measured results of X-band response of the sapphire resonator is displayed in Figure 2. Note that in this experiment it is possible to find with sufficiently high accuracy only the change in surface reactance \( \Delta X_s(T) \), therefore to find the absolute value of \( X_s(T) \) we used the value of the field penetration depth at zero temperature \( \lambda(0) = 280 \text{ nm} \), obtained from μSR measurements [6]. As can be seen from Figure 2, a significant change in the \( \lambda(0) \) value does not noticeably affect the ratio of \( R_s(T) \) and \( X_s(T) \) at \( T > T_c \), i.e. in normal (N) state.
Figure 1. Q-factor and resonant frequency shift of the X-band resonator with (Li_{0.8}Fe_{0.2})OHFeSe superconductor single crystal and without the crystal depending on temperature.

Figure 2. X-band microwave surface impedance of (Li_{0.8}Fe_{0.2})OHFeSe superconductor single crystal depending on temperature.
For a normal metal and, as a rule, for superconductor in normal state the real $R_s$ and imaginary $X_s$ parts of the surface impedance are equal, as is obvious from elementary electrodynamic considerations [17-19]. However, the studied $(Li_{1-x}Fe_x)OHFeSe$ (with $x \approx 0.2$) sample displayed the noticeable difference $R_s < X_s$ at $T > T_c$ (see Figure 2). Such an effect is not unique, because it was observed earlier in other superconductors (see e.g. [26,27]) and was explained by presence or occurrence of the antiferromagnetic (AFM) state [26] and AFM fluctuations [27]. Assuming a dynamic permeability of the form $\mu(T) = \mu_0(1 + i\mu'')$ and measuring the surface impedance $Z_s$ one can evaluate $\mu''$ at $T > T_c$ (see e.g. [26]). In our case this value is $\sim 0.4$. However $\mu''$ is unknown for S-state, therefore hereinafter for the analysis of the complex conductivity of the sample under test the traditional procedure of processing the experimental data of $Z_s(T)$ in S-state was realized, i.e. assuming $\mu''=0$.

In this assumption the penetration depth $\lambda(T)$, the quasiparticle conductivity $\sigma_1(T)$ and the superfluid component conductivity $\sigma_2(T)$ depending on temperature are presented in Figure 3, Figure 4 and Figure 5 accordingly. If we assume the dependence $\Delta\lambda(T) \sim (T/T_c)^{n}$ at $T << T_c$ [28], then on the basis of the fitting experimental data (see Figure 3) we can find the value $n = 2.8$, which agrees well with the value obtained using TDO based technique [9]. Consequently, microwave measurements confirm the conclusion of the work [9] that in this superconductor there are no nodes of the gap function (i.e. the fully gapped behavior of the SUT takes place).

Figure 3. Temperature dependence of the field penetration depth $\lambda$ in $(Li_{0.8}Fe_{0.2})OHFeSe$ superconductor single crystal at $T << T_c$. Inset shows the field penetration depth $\lambda$ over wider temperature interval.
We note that the dependence $\sigma_1(T)$ at $T < T_c$ is similar to the temperature dependence in the optimally doped Fe-pnictides BaFeCoAs [25] and Fe-chalcogenides FeSeTe [23,24], an increase of $\sigma_1(T)$ is
observed as $T$ decreases immediately below $T_c$ to $T \approx 7T_c/8$, at which the slope of the dependence $\sigma_i(T)$ changes. The effect can be due to a sharp decrease in the scattering rate of quasiparticles with decreasing temperature and, apparently, is a common characteristic feature of Fe-containing superconductors.

The temperature dependence of the density of the normalized superfluid component of the electron system $\rho_s(T) = n_s(T)/n_s(0) = [(\lambda(0)/\lambda(T))^2$ clearly differs from the dependence on the BCS dependence (Figure 6). A change in the sign of the curvature $\rho_s(T)$ at a certain temperature indicates that the superconductor under investigation has a complex gap structure.

On the other hand, fitting results in the temperature range $T < T_c/2$ using the function

$$
\Delta(\lambda) = \frac{\lambda(0)\sqrt{nA(0)/2k_B T}}{exp \left[-\frac{\Delta(0)}{k_BT}\right]}
$$

for single gap and using the function [9]

$$
\rho_s(T) = x\rho_{s1}(\Delta_1, T) + (1-x)\rho_{s2}(\Delta_2, T)
$$

for two gaps (see e.g. [9]) show better agreement with the experimental data in the case of two gaps approximation with $\Delta_1(0) = 0.38$ and $\Delta_2(0) = 1.17$ in $kT_c$ units at $x = 0.03$ (Figure 6).

It should be noted here that the quantitative data on the structure of the energy gap in this paper and in [9] clearly do not coincide. If we additionally take into account that low-temperature scanning tunneling microscopy suggests that $(Li_{1-x}Fe_x)OHFeSe$ is a simple $s$-wave superconductor with a strong coupling mechanism [4, 5], we understand that further research is needed.
Obviously, a more complete analysis of the obtained dependence $\rho_s(T)$ in the entire temperature range of the S-state of the sample is required, taking into account the different possible scenarios of the gap function.

4. Conclusion

For the first time microwave surface impedance of the recently discovered high-$T_c$ iron-based superconductor ($\text{Li}_{0.84}\text{Fe}_{0.16})\text{OHHFe}_{0.98}\text{Se}$ single crystal was measured. The special X-band “hot finger” resonator allowed carrying out measurements when temperature of the sample under test can be varied from 2K to 90K and temperature of the resonator remained constant (4.2K). The unusual and important inequality $R_c<X$ at $T>T_c=42K$ was found. The possible reason of the observed feature is manifestation of magnetic property of the superconductor sample in normal state. The quasiparticle $\sigma_1$ and superfluid $\sigma_2$ conductivities depending on temperature were obtained. Structure of energy gap was evaluated. Experiments show the temperature dependence of the field penetration depth as $T^3$ with $n=2.8$ at $T<T_c/3$. The dependence of the superfluid density on temperature confirms fully gapped behavior of a superconductor with a complex gap.

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