Microwave Study of $FeSe_{0.3}Te_{0.7}$ Thin Film by TE_{011}-Mode Sapphire Dielectric Resonator

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***Abstract*—High quality epitaxial thin films of $FeSe_{1-x}Te_x$ ($x = 0$–1) have been successfully fabricated. Their superconducting transition temperatures are around 8–13 K. Microwave properties of a film ($x = 0.7$) was studied by a sapphire dielectric cavity at 9.315 GHz. The cavity, which has a quality factor of 45000 in room temperature with TE_{011}-mode, is specially designed for the measurement of small samples with the sapphire cylinder having a small hole in the center. Thin film samples with dimension of 1–2 mm can be put in the middle of the hole, supported by a very thin sapphire rod. The cavity is sealed in a vacuum chamber soaked in the liquid ^4He and the temperature of the thin sapphire rod (hence the sample) can be controlled from 1.6 K to 60 K with a stability about ±1 mK. Temperature dependence of transmission response and Q-factors were measured by a network analyser (Agilent N5230C). The results showed a clear signature of multi-gap superconductivity. No evidences of existence of node in the energy gap were found as the normalized change in the surface reactance and the corresponding normalized change in the in-plane penetration depth have flat dependence at low temperatures.**

***Index Terms*—Cavity resonator, microwave measurement, multi-gap, node.**

I. INTRODUCTION

JUST as CuO-plane is the basic building block of high-T_c cuprate superconductors, the FeAs-layer is the basic structure of the newly discovered FeAs-based superconducting pnictides [1]. However, unlike the rigid CuO-plane in cuprates, partial substitution of Fe by Co or Ni, or As by P within the FeAs-layer can effectively induce superconductivity [2]–[4]. In this sense, the discovery of superconductivity in binary $FeSe_x$ ($T_c \sim 8$ K) is of great interests, since it only contains the superconducting FeSe-layer which has identical structure as FeAs-layer, and the Se deficiency may be the reason of the superconductivity [5].

For this new family of high-T_c superconductors, the pairing symmetry of its superconducting gap is a key to understand the mechanism of superconductivity. Extensive experimental and theoretical works have been done to address this important issue for FeAs-based superconductors. Although there is still no consensus, more and more evidences point to multi-gap nodeless superconductivity, possibly an unconventional $s^{\pm}$ paring mediated by antiferromagnetic fluctuations [6]. For the prototype $FeSe_x$ superconductor, however, there were very few experiments to study the superconducting gap structure. This is due to its relatively lower T_c and lack of sizable high-quality single crystals [7], [8]. However, muon-spin-rotation (μSR) study and thermal conductivity measurement has been taken and its result indicates that $FeSe_x$ superconductor is a multi-gap nodeless superconductor [9], [10].

Low-temperature microwave measurement is a powerful tool which is different from thermal conductivity measurement to study the superconducting gap structure. K. Hashimoto *et al.* have taken microwave measurement on $PrFeAsO_{1-y}$ and got a full gap with nodeless result which is contradicted to the multi-gap structure get from other method such as specific heat measurement and μSR experiments [11].

II. EXPERIMENT

High quality epitaxial thin films of $FeSe_x$, FeTe and $FeSe_{1-x}Te_x$ have been successfully fabricated [12], [13]. Their superconducting transition temperatures are around 11–13 K. One intriguing fact has been found that superconductivity appears when the first-order magnetic and structural phase transition softens, and when the Fe-Te-Fe bond angles become larger. Much of the physical properties need to be studied.

In this paper, $FeSe_{1-x}Te_x$ ($x = 0.7$) film was measured by a sapphire dielectric cavity resonator at 9.375 GHz. It is a close analogy to [14]. The film deposited on the $LaAlO_3$ substrate by a pulsed laser deposition method [12], [13] has $T_{c\ onset} = 14.8$ K and a transition broad $\Delta T = 4$ K. The cavity resonator, which has a quality factor of 45000 in room temperature, is specially designed for the microwave measurement of small samples at TE_{011}-mode, with the sapphire cylinder having a small hole along the center line. The sample with thickness of 100 nm and other dimensions less than 1.5 mm is put in the center of the hole but isolated from the cylinder, supported by a very thin sapphire rod. The cavity is sealed in a vacuum chamber soaked in the liquid ^{4}He and the temperature of the sapphire rod (hence the sample) can be controlled from 1.6 K to 60 K with a stability about ±1 mK while keeping the cavity remains in 4.2 K. The temperature dependence of resonance frequency

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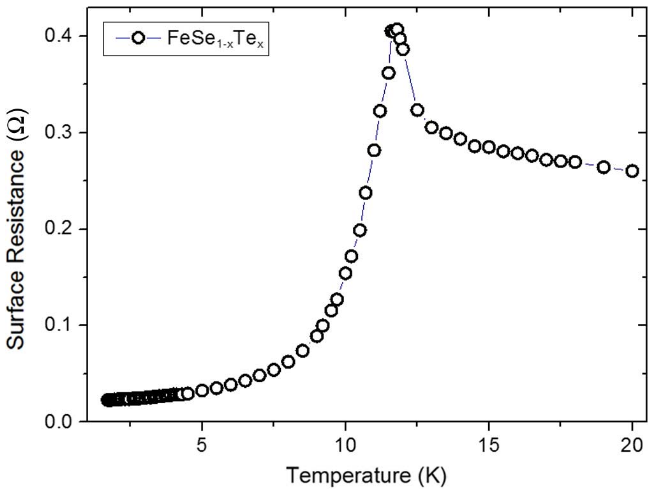

Fig. 1. Surface resistant of the sample $\mathrm{FeSe_{1-x}Te_x}$ $(\mathrm{x} = 0.7)$. Noticed that a peak appeared near the transition temperature.

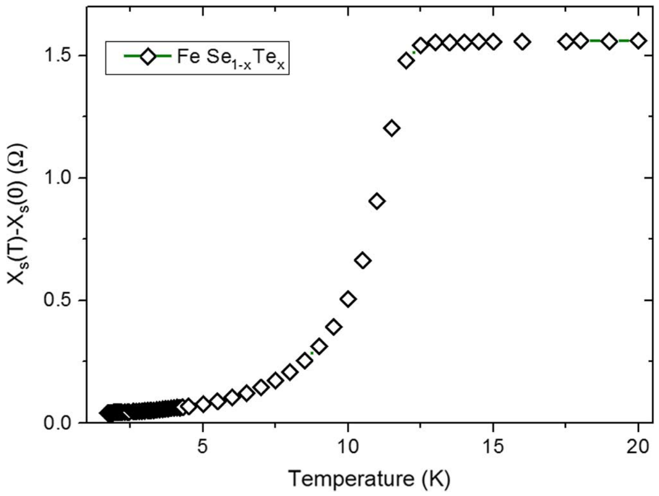

Fig. 2. Relative surface reactance of sample $\mathrm{FeSe_{1-x}Te_x}$ $(\mathrm{x} = 0.7)$.

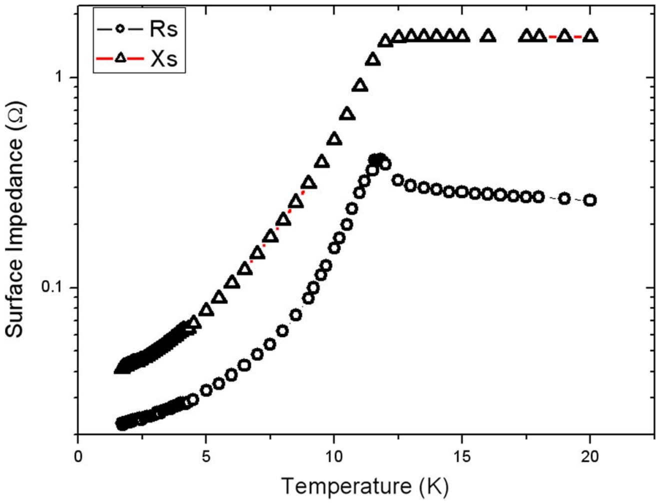

Fig. 3. Surface impedance of the sample $\mathrm{FeSe_{1-x}Te_x}$ $(\mathrm{x} = 0.7)$. Noticed that R_s was not equal to X_s above T_c.

and quality factor of the resonator were measured by a vector network analyser (Agilent N5230C) for both thin film and also the same substrate with no film on it.

III. SURFACE IMPEDANCE MEASUREMENT

The surface resistance (see Fig. 1) is determined by the expression as

$$R_s = \left(Q^{-1}_{with\ sample} - Q^{-1}_{without\ sample}\right)/A_s \tag{1}$$

The coefficient of inclusion [15] $A_s = 9.5 \times 10^{-4}\ \Omega^{-1}$ was determined by the size of the sample and calibrated using values of the sample resistivity at $T \geq T_c$. The lower calculated value, namely $A_s = 2.9 \times 10^{-4}\ \Omega^{-1}$ obtained by using CST 2009, can be explained by a small sample thickness.

Relative surface reactance $\Delta X_s(T)$ (see Fig. 2) can be derived by the expression

$$\Delta X_s(T) = -\frac{2\Delta f(T)}{A_s f_0} \tag{2}$$

where f_0 is the center frequency of the resonator and $\Delta f_0(T)$ is the frequency shift which have been taking into account the resonance frequency change of the resonator without the sample.

Using the known value of the field penetration depth reported in [16] $\lambda(0) = 560\ \mathrm{nm}$ at $T = 0$ K, we are able to find the absolute value of the surface reactance by using the following expression

$$X_s(T) = X_s(0) + \Delta X_s(T) \tag{3}$$

and the surface impedance of the film can be obtained as showed in Fig. 3

IV. DISCUSSION

The obtained $\mathrm{X_s(T)}$ and $R_s(\mathrm{T})$ in Fig. 3 indicate at least two peculiarities, namely, (i) X_s exceeds R_s considerably at $T \rightarrow T_c$, although in general case R_s and X_s should be equal, i.e., $R_s = X_s$ in normal state when normal skin-effect takes place whereas $X_s = \sqrt{3}R_s$ at anomaly skin-effect; (ii) a peak in $R_s(T)$ takes place near T_c. One of reasons of a great excess of X_s in comparison with R_s can be attributed to a very small thickness of the film under test as against with the field penetration depth. The observed effect near T_c is similar outwardly to radiofrequency size effect in cuprate HTS samples [16]. However in the given case a ratio of the film thickness to the field penetration depth is less than 1 in a whole temperature interval of study and such an explanation is evidently misdescription.

The obtained values of R_s and X_s should be considered as effective meanings depending on the film thickness (see e.g. [17]). The approach to accurate analysis of impedance properties of very thin samples in this case has not been developed when microwave fields have the same direction on opposite faces of the film. As far as we know, an only exception is a work [18]. We obtained the strong experimental dependence of effective meaning of $\Delta X_s(T)$ (see Fig. 2), but on the other hand the corresponding theory [18] contradicts this fact. In the given situation we used

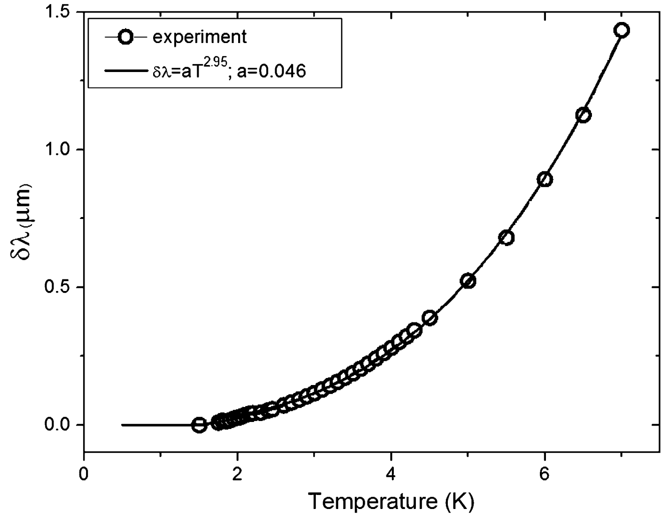

Fig. 4. The field penetration depth change in $\mathrm{FeSe_{1-x}Te_x}$ $(\mathrm{x} = 0.7)$ as a function of temperature. The solid line correspondents to the expression (5).

a fact of weak dependence of X_s and hence λ on temperature within the interval lower than $T_c/3$.

If supposed that the expression $X_s(T) = 2\pi f \mu_0 \lambda(T)$ is correct, we can derive $\Delta\lambda(T)$ and compare it with a number of various temperature dependence laws. One can see in Fig. 4, that a temperature law

$$\Delta\lambda(T) = aT^{2.95} \tag{4}$$

where $a = 46\ \mathrm{nm}$ describes the temperature dependence of the field penetration depth for temperature interval 1.7 K to 7 K very well. The other laws give less satisfactory results.

The authors of a work [18] presented an experimental study of the field penetration depth, $\lambda(T)$, in single crystals of $\mathrm{Fe_{1.03}(Te_{0.63}Se_{0.37})}$. Our result in a power law is altered from that in [19] by the higher power. It can show “a clear signature of multi-gap superconductivity and a failure of the clean limit s-wave (including $\mathrm{s}^{\pm}$) pairing” in $\mathrm{FeSe_{1-x}Te_x}$ $(\mathrm{x} = 0.7)$. In addition, the obtained result on a temperature law $\Delta\lambda(T)$ see expression (5)) coincides well with one for optimally doped single crystals $\mathrm{Ba(Fe_{0.926}Co_{0.074})_2As_2}$ [20]. At the same time, it is worth comparing our data with the expectations in unconventional superconductors with nodes in the gap. In the clean superconductors with line nodes, the thermally excited quasiparticles near the gap nodes give rise to the T-linear temperature dependence of $\Delta X(T)$ at low temperature, as observed in $\mathrm{YBa_2Cu_3O_{7-\delta}}$ crystals with d-wave symmetry [21], [22]. In the d-wave case, the relation

$$\delta\lambda(T)/\lambda(0) \approx \frac{\ln 2}{\Delta_0} k_B T \tag{5}$$

is expected [22], where Δ_0 is the maximum of the energy gap. This linear temperature dependence leads to an estimation of $2\Delta_0/k_B T_c \approx 4$. However, our data is about 1, which is quite different.

V. CONCLUSION

Thus X-band microwave impedance measurements of a high quality epitaxial thin film of $\mathrm{FeSe_{1-x}Te_x}$ $(\mathrm{x} = 0.7)$ has been carried out. The results show a clear signature of multi-gap superconductivity. For the greater certainty in conclusion concerning properties of the studied superconductor, it is important to investigate the thickness dependence of impedance properties of this kind pnictides samples and to develop the accurate approach to analysis of the microwave properties of very thin samples.

REFERENCES

[1] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono*, J. Am. Chem. Soc.*, vol. 130, p. 3296, 2008.
[2] A. S. Sefat, A. Huq, M. A. McGuire, R. Jin, B. C. Sales, and D. Mandrus*, Phys. Rev. B*, vol. 78, p. 104505, 2008.
[3] G. Cao, S. Jiang, X. Lin, C. Wang, Y. Li, Z. Ren, Q. Tao, J. Dai, Z. Xu, and F.-C. Zhang*, Phys. Rev. B*, vol. 79, p. 174505, 2009.
[4] A. S. Sefat, R. Jin, M. A. McGuire, B. C. Sales, D. J. Singh, and D. Mandrus*, Phys. Rev. Lett.*, vol. 101, p. 117004, 2008, 10.
[5] F.-C. Hsu, J.-Y. Luo, K.-W. Yeh, T.-K. Chen, T.-W. Huang, P. M. Wu, Y.-C. Lee, Y.-L. Huang, Y.-Y. Chu, D.-C. Yan, and M.-K. Wu*, Proc. Natl. Acad. Sci. USA*, vol. 105, p. 14262, 2008.
[6] I. I. Mazin, D. J. Singh, M. D. Johannes, and M. H. Du*, Phys. Rev. Lett.*, vol. 101, p. 057003, 2008.
[7] S. B. Zhang, Y. P. Sun, X. D. Zhu, X. B. Zhu, B. S. Wang, G. Li, H. C. Lei, X. Luo, Z. R. Yang, W. H. Song, and J. M. Dai*, Supercond. Sci. Technol.*, vol. 22, p. 015020, 2009.
[8] U. Patel, J. Hua, S. H. Yu, S. Avci, Z. L. Xiao, H. Claus, J. Schlueter, V. V. Vlasko-Vlasov, U. Welp, and W. K. Kwok*, Appl. Phys. Lett.*, vol. 94, p. 082508, 2009.
[9] R. Khasanov, K. Conder, E. Pomjakushina, A. Amato, C. Baines, Z. Bukowski, J. Karpinski, S. Katrych, H.-H. Klauss, H. Luetkens, A. Shengelaya, and N. D. Zhigadlo*, Phys. Rev. B*, vol. 78, p. 220510(R), 2008.
[10] J. K. Dong, T. Y. Guan, S. Y. Zhou, X. Qiu, L. Ding, C. Zhang, U. Patel, Z. L. Xiao, and S. Y. Li*, arXiv:0906.3852*.
[11] K. Hashimoto, T. Shibauchi, T. Kato, K. Ikada, R. Okazaki, H. Shishido, M. Ishikado, H. Kito, A. Iyo, H. Eisaki, S. Shamoto, and Y. Matsuda*, Phys. Rev. Lett.*, vol. 102, p. 017002, 2009.
[12] Y. Han, W. Y. Li, L. X. Cao, S. Zhang, B. Xu, and B. R. Zhao*, J. Phys.: Condens. Matter*, vol. 21, p. 235702, 2009.
[13] Y. Han, W. Y. Li, L. X. Cao, X. Y. Wang, B. Xu, B. R. Zhao, Y. Q. Guo, and J. L. Yang*, arXiv:0911.5282v1*.
[14] J. J. Wingfield, J. R. Powell, C. E. Gough, and A. Porch*, IEEE Trans. Appl. Supercond.*, vol. 7, p. 2009, 1997.
[15] N. Cherpak, A. Barannik, Y. Filipov, Y. Prokopenko, and S. Vitusevich*, IEEE Trans. Appl. Supercond.*, vol. 13, p. 3570, 2003.
[16] E. V. Izhyk, A. Y. Kirichenko, and N. T. Cherpak*, Pis'ma v ZhTF*, vol. 15, no. 7, 1989.
[17] M. Hein*, High-Temperature Superconductor Thin Films at Microwave Frequencies*, ser. Tracts in Mod. Phys.. Berlin, Germany: Springer-Verlag, 1999, vol. 155.
[18] *Handbook of Superconducting Materials*, D. A. Cardwell and D. S. Ginley, Eds. : IoP Publishing Ltd., 2003, vol. II, Characterization, Application and Cryogenics.
[19] H. Kim, C. Martin, R. T. Gordon, M. A. Tanatar, J. Hu, B. Qian, Z. Q. Mao, R. Hu, C. Petrovic, N. Salovich, R. Giannetta, and R. Prozorov*, arXiv:1001.2042 v1*.
[20] A. Barannik, N. Cherpak, N. Ni, M. A. Tanatar, S. Vitusevich, K. Torokhtii, V. Skresanov, P. C. Canfield, and R. Prozorov, “Microwave impedance properties of single crystal $\mathrm{Ba(Fe_{1-x}Co_x)_2As_2}$,” presented at the 7th International Kharkov Symposium on Physics and Engineering of Microwaves, Millimeter and Submillimeter Waves Proceedings, Kharkov, Ukraine, June 2010, B10.
[21] W. N. Hardy, D. A. Bonn, D. C. Morgan, R. Liang, and K. Zhang*, Phys. Rev. Lett.*, vol. 70, p. 3999, 1993.
[22] R. Prozorov and R. W. Giannetta*, Supercond. Sci. Technol.*, vol. 19, p. R41, 2006.