Complex conductivity of FeSe$_{1-x}$Te$_x$ ($x = 0 - 0.5$) films

Hodaka Kurokawa$^1$, Sota Nakamura$^1$, Jiahui Zhao$^1$, Naoki Shikama$^1$, Yuki Sakishita$^1$, Yue Sun$^2$, Fuyuki Nabeshima$^1$, Yoshinori Imai$^3$, Haruhiisa Kitano$^2$, Atsutaka Maeda$^1$

$^1$ Department of Basic Science, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo, Japan
$^2$ Department of Physics, Aoyama Gakuin University, 5-10-1 Fuchinobe, Chuo-ku, Sagamihara, Japan.
$^3$ Department of Physics, Graduate School of Science, Tohoku University, 6-3 Aramaki-Aoba, Aoba-ku, Sendai, Miyagi, Japan

E-mail: kurokawa00128@gmail.com

Abstract. We measured the complex conductivity, $\sigma$, of the FeSe$_{1-x}$Te$_x$ ($x = 0 - 0.5$) films below $T_c$ which show a drastic increase of the superconducting transition temperature, $T_c$, when the nematic order disappears. Since the magnetic penetration depth, $\lambda$ (> 400 nm) of Fe(Se,Te) is longer than the typical thickness of the film (∼100 nm), we combined the coplanar-waveguide-resonator- and cavity-perturbation techniques to evaluate both the real and imaginary parts of $\sigma$. Films with the nematic order showed a qualitatively different behavior of the quasiparticle scattering time compared with those without the nematic order, suggesting that the nematic order influences the superconducting gap structure. On the other hand, the proportionality between the superfluid density, $n_s/m^*$ ($\propto \lambda^{-2}$), and $T_c$ was observed irrespective of the presence or absence of the nematic order. This result indicates that the amount of the superfluid has a stronger impact on $T_c$ of Fe(Se,Te) than the presence or absence of the nematic order itself.

1. Introduction

An iron chalcogenide superconductor, FeSe, has been intensively studied [1, 2, 3] because of its various intriguing properties: the potential ability for the high-transition-temperature superconductivity, the absence of the magnetic order under ambient pressure, and the exotic electronic states due to the extremely small Fermi surface. The superconducting transition temperature, $T_c$, can be largely enhanced above 40 K from 9 K [4] by the intercalation [5], the carrier doping using the electron-double-layer-transistor [6, 7], and the synthesis of a monolayer film [8, 9]. The nematic phase without the magnetic order in FeSe is ideal for studying the origin of the nematicity [10] and the relationship between the nematicity and the superconductivity [11]. Also, its small Fermi surface ($\epsilon_F < 10$ meV) can easily be tuned by the hydrostatic pressure [12], the chemical pressure by the isovalent substitution [13, 14, 15], and the in-plane lattice strain [16]. Since the changes in the Fermi surface influence all of the superconducting phase, the nematic phase, and the magnetic phase, various different techniques have been applied to investigate the electronic phase diagram and the exotic superconductivity of FeSe.

Among the above-mentioned techniques to control the electronic state, the chemical isovalent substitution is advantageous since experiments can be performed under the ambient pressure. The S-substitution shrinks the lattice of FeSe, corresponding to the positive chemical pressure.
With increasing S content, the nematic transition temperature, $T_{N}$, decreased, and $T_{c}$ once slightly increased and then decreased [17]. Although there were no significant changes in $T_{c}$ when the nematic order disappeared, some abrupt changes in the superconducting gap have been observed in the measurement of thermal properties [18] and the scanning tunneling microscopy/spectroscopy [19]. Thus, the nematic order or its fluctuation still may have some influences on the superconducting state. On the other hand, systematic investigations of Te-substituted FeSe, which is subjected to the negative chemical pressure, were fewer than Fe(Se,S) since the systematic synthesis of bulk Fe(Se,Te) had been hindered by the phase separation region until recently [20]. Although the superconducting gap structure of FeSe [21, 22] is distinctly different from Fe(Se,Te) [23], it is still the subject of importance how the superconducting gap evolves with increasing Te content.

In advance of the systematic synthesis of bulk Fe(Se,Te), we have succeeded in growing the single-crystalline thin films of Fe(Se,Te) in the whole composition using a pulsed laser deposition technique [13, 24]. While $T_{N}$ of the Fe(Se,Te) films decreased by the Te substitution, $T_{c}$ was largely enhanced after the nematic order disappeared (Fig. 1 [a]) [15]. This enhancement of $T_{c}$ is in contrast to the Fe(Se,S) films [25] and bulk Fe(Se,Te) [20], indicating that the effect of nematicity on $T_{c}$ is complicated in these materials. Rather, the correlation between the carrier density and $T_{c}$ was observed by the magneto-transport measurements in the normal state [26]. However, the superconducting property of these films is yet to be fully understood. To clarify the effect of the Te substitution and the nematic order on the superconducting state, we investigated both the dynamics of the quasiparticle and the response of the superfluid in Fe(Se,Te) films.

In this paper, we report a systematic measurement of the complex conductivity, $\sigma$, of the FeSe$_{1-x}$Te$_{x}$ ($x = 0 - 0.5$) films below $T_{c}$. Since the magnetic penetration depth, $\lambda$, is several times as long as the typical thickness of the film ($\sim 100$ nm), the measurement technique used for bulk crystals cannot be applied. Thus, to evaluate both the real and imaginary parts of $\sigma$, we combined the coplanar-waveguide-resonator- and cavity-perturbation techniques. The quasiparticle scattering time, $\tau$, calculated from the real part of $\sigma$ increased at low temperatures as was observed in bulk FeSe [22] and FeSe$_{0.4}$Te$_{0.6}$ [28]. Besides, $1/\tau$ of the film with the nematic order showed a quantitatively different behavior from those without the nematic order, suggesting the change of the superconducting gap structure due to the nematic order. On the other hand, the proportionality between the superfluid density, $n_{s}(\propto \lambda^{-2})$, and $T_{c}$ was observed irrespective of the presence or absence of the nematic order. This result indicates that while the nematic order affects the superconducting gap structure, the amount of the superfluid has a stronger influence on $T_{c}$ of Fe(Se,Te) than the nematic order.

2. Sample

All the films were grown on CaF$_{2}$ substrates ($\sim 5 \times 5 \times 0.5$ mm$^{3}$) by a pulsed laser deposition method using a KrF laser. Details of the film growth were described elsewhere [21, 30].
thicknesses of the grown films were measured by a stylus profiler. The electrical resistivity was measured with a standard four-probe method using a physical property measurement system (Quantum Design, PPMS).

3. Experiments
To measure $\lambda$ of the FeSe$_{1-x}$Te$_x$ films, we fabricated the $\sim 5 \times 5$ mm$^2$ film into the coplanar waveguide resonator (Fig. 2 [a]) by Ar ion milling and focused ion beam (FIB). The Ar ion milling was used to fabricate the whole structure, and the 50 $\mu$m gap between the resonator and the microwave input/output port was etched using FIB. The width of the resonator, $w$, the gap between the resonator and the ground, $s$, and the length of the resonator, $l$, were designed to be 120 $\mu$m, 30 $\mu$m, and 6.2-9.9 mm, respectively. Figure 2 (b) shows the fabricated resonator on the FeSe$_{0.8}$Te$_{0.2}$ film. The resonator was mounted onto the printed circuit board, which was connected to the resonator by Al wirebonding. They are cooled down to 2 K using PPMS. The transmitted power was measured by a network analyzer (Keysight, N5222A).

Then, $\lambda$ was calculated from the resonance frequency as follows. For the half-wavelength coplanar resonator,

$$f_c = \frac{1}{2\sqrt{LC}}$$

(1)

where $L$ is the inductance per unit length and $C$ is the capacitance per unit length. Here, using an electromagnetic simulation software (WIPL-D), we confirmed that the coupling between the resonator and the input port had negligible effects on $f_c$. For a superconductor,

$$L = L_m + L_k,$$  

(2)

where $L_m$ is the magnetic inductance and $L_k$ is the kinetic inductance which corresponds to the response of the superfluid [31]. $L_k$ is a quadratic function of $\lambda$ as

$$L_k = \frac{\mu_0 g(s, w, d)}{dw} \lambda^2,$$

(3)

where $\mu_0$ is the vacuum permeability, $g(s, w, d)$ is a geometrical factor, $d$ is the thickness of the film [31, 32]. From eq. (1), eq. (2), and eq. (3), $\lambda$ is expressed as

$$\lambda = \sqrt{\frac{dw}{g\mu_0} \left( \frac{1}{4f_c^2 C} - L_m \right)}.$$

(4)

All parameters in eq. (1) can be determined from the shape of the resonator ($d, w, s$) and the measurements of $f_c$ and $C$. The length was measured by an optical microscope (Keyence,
VHS-6000), and $C$ was measured using an impedance analyzer (Hewlett-Packard, 4192A) in the frequency range, 10-1000 kHz. The measured $C$ was in good agreement with the calculated $C$ assuming that the relative permittivity of CaF$_2$ is 6.5. The obtained $\lambda(T)$ was extrapolated to 0 K assuming that $\lambda(T) = \lambda_0 + AT^n$, where $\lambda_0$ is the penetration depth at 0 K, $A$ and $n$ are constants.

The dynamics of the quasiparticle in the Fe(Se,Te) films was measured using the cavity perturbation technique. For a thin film ($d < \lambda$), the cavity perturbation formula for the analysis of a bulk crystal cannot be applied. In such a case, the measured quantity is the effective surface resistance, $Z_{\text{eff}}(Z_s,d)$, where $Z_s$ is the surface impedance. The formulas of $Z_{\text{eff}}$ corresponding to the various situations have been derived [35, 37, 38], which depend on the configuration of the electromagnetic field and the sample.

A flake of the FeSe$_{1-x}$Te$_x$ films was cut from the coplanar resonator after the measurement of $\lambda$. The flake ($\sim 0.5 \times 0.5$ mm$^2$) was mounted onto the sapphire rod at the center of the cavity resonator (Fig. 2(c)). The TE$_{011}$ mode (44 GHz) of the resonator was used, and the magnetic field of the TE$_{011}$ mode was perpendicular to the film. In this configuration, at low temperatures, $Z_{\text{eff}}$ can be expressed as

$$ Z_{\text{eff}} = -\frac{i}{2} Z_s \cot \left( \frac{\omega \mu_0 d}{2Z_s} \right), $$(5)

where $\omega$ is the angular frequency [38]. Experimentally, the effective surface resistance, $R_{\text{eff}}$, is determined by

$$ R_{\text{eff}} = G \left( \frac{1}{2Q_{\text{sample}}} - \frac{1}{2Q_{\text{blank}}} \right), $$$(6)$

where $G$ is the geometric factor, $Q_{\text{sample}}$ is the quality factor of the cavity with the sample, $Q_{\text{blank}}$ is the quality factor of the cavity without the sample. Here, we have confirmed that the effect of the CaF$_2$ substrate was negligible by the measurement of the substrate alone. Also, the effective surface reactance, $X_{\text{eff}}$ is

$$ X_{\text{eff}}(T) = G \left( \frac{f_{c,\text{sample}}(T) - f_{c,\text{sample}}(T_0)}{f_{c,\text{sample}}(T_0)} - \frac{f_{c,\text{blank}}(T) - f_{c,\text{blank}}(T_0)}{f_{c,\text{blank}}(T_0)} \right) + X_{\text{eff}}(T_0), $$$(7)$

where $f_{c,\text{sample}}$ is the resonance frequency with the sample and $f_{c,\text{blank}}$ is the resonance frequency without the sample.

**Figure 3.** (a) The resonance frequency as a function of temperature of the resonator shown in Fig. 2(b). The inset is the resonance spectrum at 2 K. (b) Te content versus $T_c$, zero and $\lambda_0$. (c) $\lambda_0^2$ versus $T_c$, zero of the FeSe$_{1-x}$Te$_x$ ($x = 0 - 0.5$) films. The data of bulk FeSe$_{1-x}$Te$_x$ ($x > 0.5$) [28, 31, 33] and FeSe [21, 27] are also shown.
To obtain $Z_s$ by solving eq. (3), eq. (1) and eq. (2), we determined $G$ and $X_{\text{eff}}(T_0)$ as follows. At low temperatures where $\sigma_1 << \sigma_2$,

$$X_{\text{eff}}(T) = \frac{1}{2} \mu_0 \omega \lambda \coth \left( \frac{d}{2 \lambda} \right)$$

from eq. (2) and $X_s \approx \mu_0 \omega \lambda$. Thus, $X_{\text{eff}}(T)$ can be calculated by substituting $\lambda(T)$ measured by the coplanar resonator into eq. (8). Here, $X_{\text{eff}}(T_0)$ was obtained using eq. (8) and $\lambda(T_0)$ measured by the coplanar resonator. On the other hand, $G$ was determined by the curve fitting which satisfies $X_{\text{eff}}^{\text{coplanar}}(T) \approx X_{\text{eff}}^{\text{cavity}}(T)$ in the temperature range, $0.2 - 0.5T_c$. After we determined $G$ and $X_{\text{eff}}(T_0)$, we numerically solved eq. (3) and obtained $Z_s$.

4. Results and Discussions

Figure 1 (b) shows the temperature dependence of the resistivity of the FeSe$_{1-x}$Te$_x$ ($x = 0.1 - 0.5$) films. $T_c$ increased almost twice from $x = 0$ to $x = 0.2$, which is consistent with the previous report [13]. Then, $T_c$ gradually decreased with increasing Te content. Also, the resistivity at $T_c\text{,onset}$ changed from $\sim 100 \mu \Omega \text{ cm}$ at $x = 0$ to $\sim 400 \mu \Omega \text{ cm}$ at $x = 0.5$, which was the typical value for these films, [23].

Fig 2 (a) shows the resonance spectrum and the temperature dependence of the resonance frequency, $f_c$, of the FeSe$_{0.6}$Te$_{0.4}$ film, respectively. We calculated $\lambda$ using eq. (1) from $f_c$ in each film. Figure 3 (a) shows Te content versus $T_c\text{,zero}$ and $\lambda_0$. The negative correlation between $T_c$ and $\lambda_0$ seems to exist irrespective of the presence or absence of the nematic order. Then, we plotted $T_c$ as a function of $\lambda_0^{-2}$ (Fig. 3 [b]). $T_c$ has a positive correlation with $\lambda_0^{-2}$, which corresponds to the superfluid density, $n_s$. The observed correlation between $T_c$ and $n_s$ is consistent with the relationship between $T_c$ and the carrier density of the Fe (Se,Te) and Fe(Se,S) films in the normal state [20]. These results indicate that $n_s$ (carrier density) plays a more crucial role in determining $T_c$ of the Fe(Se,Te) films than the presence or absence of the nematic order or its fluctuation. Of note, the trend between $T_c$ and $\lambda_0^{-2}$ were similar to that of the bulk Fe(Se,Te) [23, 24], while the discrepancy existed in FeSe [21, 27], the origin of which is unclear at present.

Then, we show the result of the measurement of the dynamics of the quasiparticle using the cavity perturbation technique. In Figs. 1 (b),(c), the temperature dependence of $Q^{-1}$ and $f_c$ of the FeSe$_{0.6}$Te$_{0.4}$ film was shown as a representative. The peak in $Q^{-1}$ around $T_c$ is considered to originate from a drastic change of the electromagnetic field around the film [28]. Figure 2 (a) shows the temperature dependence of $Z_s$ of the FeSe$_{0.6}$Te$_{0.4}$ film. Below 0.75 $T_c$, $R_s$ and $X_s$ were calculated using eq. (3). Above $T_c$, $Z_s$ was obtained from the equation, $R_s = X_s = \sqrt{\mu_0 \omega \rho_{dc}/2}$, where $\rho_{dc}$ is the dc resistivity of the film at $T_c$. Figures 2 (b) and (c) show $R_s$ and $X_s$ of the

![Figure 4](image_url)

Figure 4. (a) Temperature dependence of $\Delta Q^{-1}(T)$ and (b) $f_c(T)$ of the FeSe$_{0.6}$Te$_{0.4}$ film.
FeSe$_{1-x}$Te$_x$ ($x = 0 - 0.5$) films as a function of reduced temperature. The real part of the complex conductivity, $\sigma_1$, was calculated from $\sigma_1 = 2\omega\mu_0 R_S X_S/(R_S^2 + X_S^2)^2$. When calculating $\sigma_1$, we subtracted residual resistance from $R_S$ which was estimated from the linear extrapolation of $R_S$ to 0 K. Assuming the two-fluid model and Drude-like single-carrier normal fluid, the quasiparticle scattering time, $\tau$, can be expressed as

$$\omega\tau = \frac{\tilde{\sigma}_1}{1 - \tilde{\sigma}^2},$$

where $\tilde{\sigma} = \sigma_1 + i\sigma_2 = \mu_0\omega\lambda_0^2(\sigma_1 + i\sigma_2)$ is the dimensionless conductivity \[28\]. Here, we should be careful this single-carrier treatment because Fe(Se,Te) is actually a multi-band superconductor. Since FeSe has highly anisotropic gaps in both hole and electron pockets \[24\], while FeSe$_{1-x}$Te$_x$ ($x > 0.5$) has nodeless gaps in both pockets \[24\], $\tau$ of the electron pocket is expected to show similar temperature dependence to that of the hole pocket in Fe(Se,Te). Hence, in eq. (6), we assumed that the temperature dependence of $\tau$ in both pockets could be represented using a single $\tau$ as a first approximation.

The decrease in $1/\tau$ at low temperatures was observed in all films (Fig. 1 (a)), which indicates the rapid suppression of the inelastic scattering of the electron. It was consistent with the result of bulk FeSe \[27\] and FeSe$_{0.4}$Te$_{0.6}$ \[28\]. Besides, the slope of $1/\tau$ seems to be different among these films as shown in Fig. 1 (a). To obtain more insights, we performed the curve fitting with $1/\tau = aT^n + b$, where $a$, $b$, $n$ are some positive constants. Figure 1 (b) shows $n$ of each film as a function of the maximum temperature used for the curve fitting, $T_{\text{fitmax}}$. $n$ showed a different behavior among these films when we decreased $T_{\text{fitmax}}$. While $n$ was nearly 1 in $x = 0, 0.1$ film below $T_{\text{fitmax}} = 0.5T_C$, $n$ tended to increase with lowering $T_{\text{fitmax}}$ in the other films. Also, in the bulk FeSe \[27, 49\], which is in the nematic phase as the same as $x = 0, 0.1$ films, $n$ was nearly equal to 1. In the bulk FeSe$_{0.4}$Te$_{0.6}$ \[28\], which do not show the nematic order, $n$ increased over 2 with decreasing $T_{\text{fitmax}}$. As was pointed out by Li et al. \[39\], the $T$-linear behavior ($n = 1$) in $1/\tau$ may be the consequence of the gap structure with the line nodes or deep gap minima \[39, 101, 102\]. On the other hand, the $n > 2$ behavior could be the sign of the nodeless superconducting gap since the exponential decrease of $1/\tau$ is expected in the nodeless superconductor \[12, 13\]. Hence, considering the change in $n$ in the samples with different Te content, we consider that the superconducting gap structure changes from the line nodes or deep

Figure 5. (a) Temperature dependence of the surface impedance of the FeSe$_{0.6}$Te$_{0.4}$ film. The dotted lines are guides for the eye. The surface impedance above $T_C$ (purple dots) was determined from $\rho_{dc}$. (b) The surface resistance and (c) the surface reactance of the FeSe$_{1-x}$Te$_x$ ($x = 0 - 0.5$) films as a function of the reduced temperature.
minima in the nematic phase to the nodeless outside the nematic phase. The result is consistent with those of other measurement techniques claiming that bulk FeSe has the line nodes or the deep minima while bulk FeSe\(_{1-x}\)Te\(_x\) (\(x > 0.5\)) shows nodeless superconducting gap \([23]\).

5. Conclusion
In conclusion, we measured the complex conductivity of the FeSe\(_{1-x}\)Te\(_x\) (\(x = 0 - 0.5\)) films below \(T_C\) combining the coplanar-waveguide-resonator- and cavity-perturbation techniques. In the presence of the nematic order, the dynamics of the quasiparticle was qualitatively different from the samples without the nematic order. The difference indicates that the nematic order strongly affects the formation of nodes or gap minima in its superconducting gap structure. On the other hand, the proportionality between \(T_C/\tau\) of FeSe\(_{1-x}\)Te\(_x\) was found irrespective of the presence or absence of the nematic order, suggesting that the amount of the superfluid has a more direct influence on \(T_C\) of Fe(Se,Te) than the nematic order itself.

References
[1] Liu X, Zhao L, He S, He J, Liu D, Mou D, Shen B, Hu Y, Huang J and Zhou X J 2015 Journal of Physics Condensed Matter 27 183201
[2] Böhmer A E and Kreisel A 2018 Journal of Physics Condensed Matter 30 023001
[3] Kreisel A, Hirschfeld P J and Andersen B M 2020 Symmetry 12 1402
[4] Hsu F C, Luo J Y, Yeh K W, Chen T K, Huang T W, Wu P M, Lee Y C, Huang Y L, Chu Y Y, Yan D C and Wu M K 2008 Proceedings of the National Academy of Sciences 105 14262–14264
[5] Burrard-Lucas M, Free D G, Sedlmaier S J, Wright J D, Cassidy S J, Hara Y, Corkett A J, Lancaster T, Baker P J, Blundell S J and Clarke S J 2013 Nature Materials 12 15–19
[6] Shiojai J, Ito Y, Mitsuhashi T, Nojima T and Tsukazaki A 2016 Nature Physics 12 42–46
[7] Shikama N, Sakishita Y, Nabeshima F, Katayama Y, Ueno K and Maeda A 2020 Applied Physics Express 13 083006
[8] Wang Q Y, Li Z, Zhang W H, Zhang Z C, Zhang J S, Li W, Ding H, Ou Y B, Deng P, Chang K, Wen J, Song C L, He K, Jia J F, Ji S H, Wang Y Y, Wang L L, Chen X, Ma X C and Xue Q K 2012 Chinese Physics Letters 29 037402
[9] Xiang Y Y, Wang F, Wang D, Wang Q H and Lee D H 2012 Physical Review B 86 134508
[10] Fernandes R M, Chubukov A V and Schmalian J 2014 Nature Physics 10 97–104
[11] Glashvrenner J K, Mazin I I, Jeschke H O, Hirschfeld P J, Fernandes R M and Valentí R 2015 Nature Physics 11 953–958

Figure 6. (a) The inverse of the quasiparticle scattering time of the FeSe\(_{1-x}\)Te\(_x\) (\(x = 0 - 0.5\)) films as a function of the reduced temperature. \(1/\tau\) of FeSe (grown by the vapor transport) \([27]\) and FeSe\(_{0.4}\)Te\(_{0.6}\) (grown by the flux method) \([28]\) are also shown. (b) The exponent, \(n\), in the equation, \(1/\tau = aT^n + b\), determined from curve fitting. The maximum temperature for the fitting was varied from 0.25\(T_c/\tau\) to 0.5\(T_c/\tau\). The orange circles and blue squares are 1/\(\tau\) of the bulk FeSe \([27, 39]\). The pink triangles are 1/\(\tau\) of the bulk FeSe\(_{0.4}\)Te\(_{0.6}\) \([28]\).
[12] Margadonna S, Takabayashi Y, Ohishi Y, Mizuguchi Y, Takano Y, Kagayama T, Nakagawa T, Takata M and Prassides K 2009 Physical Review B 80 064506

[13] Fang M H, Pham H M, Qian B, Liu T J, Vehstedt E K, Liu Y, Spinnu L and Mao Z Q 2008 Physical Review B 78 224503

[14] Mizuguchi Y, Tomioka F, Tsuda S, Yamaguchi T and Takano Y 2009 Journal of the Physical Society of Japan 78 074712

[15] Imai Y, Sawada Y, Nabeshima F and Maeda A 2015 Proceedings of the National Academy of Sciences 112 1937–1940

[16] Mizuguchi Y, Tomioka F, Tsuda S, Yamaguchi T and Takano Y 2009 Journal of Physics: Conference Series 1975 (2021) 012009

[17] Watson M D, Kim T K, Haghighirad A A, Blake S F, Davies N R, Hoesch M, Wolf T and Coldea A I 2015 Physical Review B 92 121108

[18] Sato Y, Kasahara S, Taniguchi T, Xing X, Kasahara Y, Tokiwa Y, Yamakawa Y, Kontani H, Shibauchi TW and Matsuda Y 2018 Proceedings of the National Academy of Sciences 115 1227–1231

[19] Hanaguri T, Iwaya K, Kohsaka Y, Machida T, Watashige T, Kasahara S, Shibauchi T and Matsuda Y 2018 Science Advances 4 eaar6419

[20] Terao K, Kashiwagi T, Shizu T, Klemm R A and Kadowaki K 2019 Physical Review B 100 224516

[21] Kasahara S, Watashige T, Hanaguri T, Kohsaka Y, Yamashita T, Shimoyama Y, Mizukami Y, Endo R, Ikeda H, Aoyama K, Terashima T, Uji S, Wolf T, Von Löhneysen H, Shibauchi T and Matsuda Y 2014 Proceedings of the National Academy of Sciences 111 16309–16313

[22] Sprau P O, Kostin A, Kreisel A, Böhm A E, Taufour V, Canfield P C, Mukherjee S, Hirschfeld P J, Andersen B M and Davis J C 2017 Science 357 75–80

[23] Hanaguri T, Niitaka S, Kuroki K and Takagi H 2010 Science 328 474–477

[24] Imai Y, Sawada Y, Nabeshima F, Asami D, Kawai M and Maeda A 2017 Scientific Reports 7 46653

[25] Imai Y, Akiike T, Hanawa M, Tsukada I, Ichinose A, Maeda A, Hikage T, Kawaguchi T and Ikuta H 2010 Applied Physics Express 3 043102

[26] Imai Y, Tanaka R, Akiike T, Hanawa M, Tsukada I and Maeda A 2010 Japan Journal of Applied Physics 49 023101

[27] Watanabe K, Yoshida K, Aoki T and Kohjiro S 1994 Japanese Journal of Applied Physics 33 5708

[28] Clem J R 2013 Journal of Applied Physics 113 013910

[29] Jacob M V, Mazierska J, Ledenyov D and Krupka J 2003 Journal of the European Ceramic Society 23 2617–2622

[30] Klein N, Chaloupka H, Müller G, Orbach S, Piel H, Roas B, Schultz L, Klein U and Peiniger M 1990 Journal of Applied Physics 67 6940–6945

[31] Peligrad D N, Nebendahl B, Kessler C, Mehring M, Dulčić A, Požek M and Paar D 1998 Physical Review B 58 11652–11671

[32] Baranik A A, Cherpak N T, Kharchenko M S, Wu Y, Luo S, He Y and Porch A 2014 Low Temperature Physics 40 492–499

[33] Li M, Lee-Hone N R, Chi S, Liang R, Hardy W N, Bonn D A, Girt E and Broun D M 2016 New Journal of Physics 18 082001

[34] Hirschfeld P J, Putikka W O and Scalapino D J 1993 Physical Review Letters 71 3705–3708

[35] Özcan S, Turner P J, Waldram J R, Drost R J, Kes P H and Broun D M 2006 Physical Review B 73 064506

[36] Quinlan S M, Scalapino D J and Bulut N 1994 Physical Review B 49 1470–1473

[37] Hashimoto K, Shibauchi T, Kasahara S, Ikeda K, Tonegawa S, Kato T, Okazaki R, Van Der Beek C J, Konczykowski M, Takeya H, Hirata K, Terasima T and Matsuda Y 2009 Physical Review Letters 102 207001

[38] Sun Y, Park A, Pyon S, Tanegai T and Kitamura H 2017 Physical Review B 96 140505