Penetration depth and flux-flow resistivity measurements of $\text{BaFe}_2(\text{As}_{0.55}\text{P}_{0.45})_2$ single crystals

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Abstract

We measured the surface impedance of $\text{BaFe}_2(\text{As}_{0.55}\text{P}_{0.45})_2$ single crystals under finite magnetic fields by using a microwave technique. We found that the penetration depth increased as $\lambda(T) = \lambda(0) + A \times T^n$ with an exponent of $n \approx 1.7$ in the temperature region of $0.1 < T/T_c < 0.2$. The observed fractional exponent can be understood by considering that this material has gaps with lines of nodes and nodeless gaps with large anisotropy. The flux-flow resistivity showed an almost H -linear dependence and a remarkably rapid enhancement in the low- H region; $\rho_f/\rho_n \approx \alpha H/H_{c2}$ with a gradient of $\alpha > 2.5$. Such a behavior is similar to that of $\text{SrFe}_2(\text{As,P})_2$. By comparing these with results of 111-materials and $\text{SrFe}_2(\text{As}_{0.7}\text{P}_{0.3})_2$, it has been clarified that the gap anisotropy dominates the gradient α of iron-based materials.

Keywords: microwave surface impedance; flux-flow resistivity; iron-based superconductor; $\text{BaFe}_2(\text{As,P})_2$; single crystal

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1. Introduction

Since the discovery of the superconducting transition of $\text{LaFeAsO}_{1-x}\text{F}_x$ [1], iron-based superconductors (Fe-SCs) have attracted a lot of attention. The Fe-SCs have multiple sheets of the Fermi surface formed mainly by Fe(3d) orbital, and both the amplitude and the sign of the superconducting gap vary significantly on different sheets, making multiple-band effects strong in these materials. Based on an experimental fact that the magnetically ordered phase exists next to the superconducting phase in the phase diagram, pairing mechanisms based on spin-based fluctuations had been suggested theoretically [2, 3]. According to such a spin-fluctuation scenario, there are possibilities of a sign-change of superconducting order parameters on different Fermi surface sheets (so-called “ $s^\pm$ -wave”). Because of (i) the multiple-band nature, (ii) a rich variety of gap structures, and (iii) possibilities of sign-change of order parameters, it can be said that Fe-SCs belong to a new category of SCs.

To investigate such novel SCs, one of the most important problems is to clarify the superconducting gap structure closely related to the pairing mechanism. In addition to typical measurements for investigating gap structures, such as the temperature dependence of the penetration depth, $\lambda(T)$, it has been known that the flux-flow resistivity as a function of applied field, $\rho_f(H)$, is also sensitive to low-energy excitations. Specifically, $\rho_f(H)$ of conventional s -wave SCs behaved as $\rho_f/\rho_n \approx \alpha H/H_{c2}$ with a gradient $\alpha \approx 1$, where ρ_n and H_{c2} are the normal state resistivity and the upper critical field, respectively [4]. Such an H -linear dependence was well explained by assuming that the vortex core is a cylinder with the normal state inside [5]. On the other hand,

for single-band SCs with an anisotropic gap, such as p -wave [6], d -wave [7], and anisotropic s -wave [8] gaps, $\rho_f(H)$ increased more rapidly in the low- H region; $\alpha > 1$. Theoretically, the calculation by Kopnin and Volovik, who treated quasi-particle bound states inside the vortex core, suggested that the gradient, α , becomes larger than unity when the gap function is anisotropic [9]. Furthermore, $\rho_f(H)$ of two-band SCs, such as MgB_2 [10] and Y_2C_3 [11], also increased rapidly at low- H s, and a parallel-circuit model succeeded to explain those behaviors [12].

Based on the results described above, we have investigated the flux-flow resistivity of several Fe-SCs systematically in order to clarify how the novel features of Fe-SCs described above influence on $\rho_f(H)$. Here, we first summarize the obtained results for LiFe(As,P) [13, 14], $\text{NaFe}_{0.97}\text{Co}_{0.03}\text{As}$ (Co-Na111) [15], and $\text{SrFe}_2(\text{As}_{0.7}\text{P}_{0.3})_2$ (P-Sr122) [16]. Each $\rho_f(H)$ of Fe-SCs increased almost linearly with H at low- H regions; $\rho_f/\rho_n \approx \alpha H/H_{c2}$. As for the gradient, however, observed α s were quite different from each other. Specifically, LiFeAs (Li111), which has nodeless gaps with a small anisotropy [17], showed $\alpha^{\text{Li111}} \approx 1.4$ [13]. Since a small amount of phosphorus substitution blurs the gap anisotropy, α of $\text{LiFeAs}_{0.97}\text{P}_{0.03}$ (P-Li111) became slightly smaller than that of Li111; $\alpha^{\text{P-Li111}} \approx 1.3$ [14]. On the other hand, Co-Na111, which is considered to be a gapless SC with isotropic electronic structures, the gradient became almost unity; $\alpha^{\text{Co-Na111}} \approx 1$ [15]. In contrast to the nodeless Fe-SCs described above, P-Sr122 is considered to have a highly anisotropic gap structure composed by gaps with lines of nodes and deeply-warped nodeless gaps, and $\rho_f(H)$ increased rapidly at low- H ; $\alpha^{\text{P-Sr122}} \geq 2.5$ [16]. These results suggest that $\rho_f(H)$ of Fe-SCs is governed by the gap anisotropy, and

there is a tendency that the gradient α of Fe-SCs also becomes larger when the superconducting gap is more anisotropic, as well as the case of single-band SCs which was well explained by the Kopnin-Volovik model.

To make this gap anisotropy scenario more convincing, we focused on $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ system. This material is a representative of the Fe-SCs with nodal gaps [18, 19, 20, 21, 22], and it is known that single crystals with high quality can be obtained [23, 24]. Therefore, $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ is adequate for investigating the flux-flow of Fe-SCs with lines of nodes.

In this paper, we report the results of the surface impedance measurements of $\text{BaFe}_2(\text{As}_{0.55}\text{P}_{0.45})_2$ single crystals under finite magnetic fields. The temperature dependence of the penetration depth indicated that this material has a highly anisotropic gap structure, and the observed field dependence of the flux-flow resistivity can also be understood by considering such a highly anisotropic gaps in a consistent manner. These results seem to support the gap anisotropy scenario.

2. Experimental

Details of the sample preparation of $\text{BaFe}_2(\text{As}_{0.55}\text{P}_{0.45})_2$ (P-Ba122) single crystals were reported previously [24], and the critical temperature of $T_c = 22$ K, the dc-resistivity of $\rho_{\text{dc}}(T > T_c) = 13.8 + 0.0582 \times T^{1.49} \mu\Omega\text{cm}$, and the residual resistivity ratio (RRR) of $\text{RRR} \equiv \rho_{\text{dc}}(300 \text{ K})/\rho_{\text{dc}}(0 \text{ K}) \approx 15$ were equal to those described in Ref.24 within errors of the measurement. The residual resistivity of $\rho_{\text{dc}}(0) = 13.8 \mu\Omega\text{cm}$ is comparable to that of $\text{BaFe}_2(\text{As}_{0.59}\text{P}_{0.41})_2$ [23] where the quantum oscillation was observed [25], suggesting that the quality of our samples is high. In order to measure the

surface impedance, single crystals were cut into a small piece whose typical dimensions are $a \times b \times c = 0.5 \times 0.5 \times 0.2 \text{ mm}^3$.

The microwave surface impedance was measured by using a cavity perturbation technique [26] with a cylindrical oxygen-free Cu cavity resonator, which has the Q -factor of $Q > 2.6 \times 10^4$, operated at $\omega/2\pi \approx 44 \text{ GHz}$ in TE_{011} mode. Both the external magnetic field up to 8 T and the microwave magnetic field were applied parallel to the c -axis of the sample. Therefore, we investigated the in-plane vortex motion. The surface impedance, $Z_s = R_s - iX_s$ (R_s and X_s are the surface resistance and the surface reactance, respectively), was related to the resonant frequency and the Q -factor of the resonator as $R_s = G(1/2Q_s - 1/2Q_b)$ and $X_s = G(1 - \omega_s/\omega_b) + C$, where G and C are constants defined by the size and the shapes of the sample and the resonator, and subscripts s and b denote numbers measured with- and without the sample. The magnitude of Z_s was determined by assuming the Hagen-Rubens limit, $R_s = X_s = (\mu_0\omega\rho_{\text{dc}}/2)^{1/2}$, above T_c , where μ_0 is the vacuum permeability. Well below T_c , X_s is related to the penetration depth as $X_s(T) = \mu_0\omega\lambda(T)$. As for the mixed state, Coffey and Clem calculated Z_s induced by the vortex motion [27]. Since the effects of the flux creep and the thermal fluctuations are negligibly small at low- T regions, the Coffey-Clem model leads to the relation

$$R_s - iX_s = -i\mu_0\omega\lambda\sqrt{1 + \frac{\rho_f}{\mu_0\omega\lambda^2} \left(1 - \frac{\omega_{\text{cr}}}{\omega}\right)^{-1}}, \quad (1)$$

where $\omega_{\text{cr}}/2\pi$ is the crossover frequency characterizing the crossover between the resistive response ($\omega > \omega_{\text{cr}}$) and the reactive response ($\omega < \omega_{\text{cr}}$). Consequently, we can obtain $\rho_f(T, H)$ and $\omega_{\text{cr}}(T, H)$ from $R_s(T, H)$ and $X_s(T, H)$ by solving Eq.(1).

3. Results and discussions

Figure 1 shows the temperature dependence of the surface impedance measured under several magnetic fields. A good agreement between the T -sweep data and the H -sweep data indicates that vortices are uniformly distributed in the region of the sample where the microwave field penetrates even in the H -sweep measurements. By fitting the data taken under zero field with a function $\delta\lambda(T) \equiv \lambda(T) - \lambda(0) \propto T^n$, we obtained $n = 1.75 \pm 0.05$ for the fitting range of $0.1 < T/T_c < 0.2$. Such an exponent is larger than $n \approx 1.13$ for $\text{BaFe}_2(\text{As}_{0.67}\text{P}_{0.33})_2$ reported by Hashimoto *et al.* [18]. This disagreement is probably due to the fitting range. They measured the penetration depth down to $T = 0.005T_c$ and observed the almost T -linear dependence for $0.05 < T/T_c < 0.15$, suggesting the existence of nodal lines in the gap structure. Since our measurements were conducted down to $T \approx 0.075T_c$, we cannot know the exact temperature dependence below $0.075T_c$. However, in the inset of figure 1, $\lambda(T)$ shows a small upturn below $(T/T_c)^{1.75} < 0.012$, suggesting that an exponent n below $T < 0.08T_c$ may be smaller than 1.75. In fact, a double-logarithmic plot (not shown in this paper) shows that n becomes closer to unity. Thus, even in our data, the lowest temperature data might be $\propto T$. Anyway, what we would like to stress here is that our data is expressed by a larger n than the data, for example, in Ref.18, in the same temperature region, and this is not due to the impurity scattering effects. For most SCs including Fe-SCs, the T -dependence with an exponent of $n \approx 2$ usually suggests that the gapless state induced by strong pair-breaking effects is realized in the material [28, 29]. As for the P-doped 122 systems, the deviation from the T -linear dependence at lower temperatures have been observed,

and the data were well fitted by a relation, $\delta\lambda(T) \propto T^2/(T + T^*)$, where T^* is the crossover temperature characterizing the crossover from the linear- to the quadratic temperature dependence [20, 22]. According to Hashimoto *et al.* [18], a deviation from the T -linear dependence was seen at temperatures below $0.05T_c$ in $\text{BaFe}_2(\text{As}_{0.67}\text{P}_{0.33})_2$ for the sample whose residual resistivity was $\rho_{dc}(0) \approx 30 \mu\Omega\text{cm}$. Since $\rho_{dc}(0)$ of our $\text{BaFe}_2(\text{As}_{0.55}\text{P}_{0.45})_2$ single crystal is smaller than that of $\text{BaFe}_2(\text{As}_{0.67}\text{P}_{0.33})_2$ in Ref.18, such a deviation from the T -linear dependence by the pair-breaking effects should be observed at much lower temperatures than the temperature range of our measurement. Thus, it is hard to understand the observed exponent of $n \approx 1.75$ in the relatively higher temperature region by the pair-breaking scenario. A possible origin of the fractional exponent we observed was suggested by Mishra *et al.* [30]. Focusing on the multiple-band nature of iron-based materials, they reproduced a fractional exponent by considering the combination of a gap with lines of nodes and a nodeless gap with large anisotropy. Inspired by the Mishra's model, we calculated the temperature dependence of the penetration depth of P-Ba122 by using an extended version of the Chandrasekhar and Einzel's model [31] to two-band SCs, and succeeded in reproducing $\delta\lambda(T)$ of P-Ba122 [32]. Thus, we confirmed that in P-Ba122, similarly to P-Sr122 [16], the observed $\lambda(T)$ with a fractional exponent can be understood by assuming that the material has both gaps with lines of nodes and nodeless gaps with large anisotropy. In other words, the observed T -dependence with a fractional exponent indicates that the gap structure of P-Ba122 are highly anisotropic.

Next, we work on the flux-flow resistivity. As shown in figure 2, we deter-

mined the T -dependence of the upper critical field from the onset of $R_s(T)$ and $X_s(T)$. The obtained slope of $-\mu_0 dH_{c2}/dT|_{T=T_c} = 1.53$ T/K was consistent with that reported by a specific heat study [33], and we estimated $H_{c2}(0)$ to be 23.6 T by using the WHH formula [34]. The H -dependence of the flux-flow resistivity of P-Ba122 measured at $T/T_c \approx 0.09$ is shown in figure 3, where vertical and horizontal axes are normalized by the normal-state resistivity obtained by extrapolating $\rho_{dc}(T > T_c)$ to the low- T region and by the upper critical field, respectively. For comparison, the same plots for P-Sr122 ($T/T_c \approx 0.08$) [16], Li111 ($T/T_c \approx 0.1$) [13], and Co-Na111 ($T/T_c \approx 0.09$) [15] are also shown. We already confirmed that the difference in the measurement temperature of $T/T_c \approx 0.01$ did not change their behaviors dramatically. The flux-flow resistivity of P-Ba122 increased almost linearly with H in the low- H region; $\rho_f/\rho_n \approx \alpha H/H_{c2}$, and such an almost linear H -dependence is generally seen among Fe-SCs [13, 14, 15, 16]. Focused on the gradient of $\rho_f(H)$, $\alpha^{\text{P-Ba122}}$ was much larger than that of Li111 ($\alpha^{\text{Li111}} \approx 1.4$), P-Li111 ($\alpha^{\text{P-Li111}} \approx 1.3$), and Co-Na111 ($\alpha^{\text{Co-Na111}} \approx 1$), and was similar to that of P-Sr122 ($\alpha^{\text{P-Sr122}} > 2.5$). Based on well-known results in conventional SCs and cuprates, there are two possible origins for the rapid enhancement of $\rho_f(H)$. The first origin is due to the multiple-band nature and the other is due to the gap anisotropy. If the former origin dominates the gradient α of Fe-SCs, $\rho_f(H)$ of all Fe-SCs is expected to show a similar H -dependence because the multiple-band nature is common to all Fe-SCs. However, the observed $\rho_f(H)$ of Fe-SCs showed a large variety in the value of the gradient depending on materials. Therefore, it is natural to consider that the α -value of Fe-SCs is dominated by the gap anisotropy. By consid-

ering a highly anisotropic gap structure of P-Ba122 indicated by the $\lambda(T)$ measurement described above, large α -value of P-Ba122 is qualitatively consistent with the gap anisotropy scenario that α becomes larger when the gap structure is more anisotropic. However, in the range of this paper, we cannot discuss quantitatively. One of the reasons is that even changing Ba to Sr dramatically alters the band structure [35]. The other reason is that the doping level is different (45% in P-Ba122, 30% in P-Sr122). More detailed studies, in particular, the band structural studies for $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ and $\text{SrFe}_2(\text{As}_{1-x}\text{P}_x)_2$ will be necessary.

4. Conclusions

We measured the surface impedance of $\text{BaFe}_2(\text{As}_{0.55}\text{P}_{0.45})_2$ single crystals under finite magnetic fields. The penetration depth increased as $\lambda(T) = \lambda(0) + A \times T^n$ with an exponent of $n \approx 1.7$ at $0.1 < T/T_c < 0.2$, indicating that this material has a highly anisotropic gap structure. On the other hand, the magnetic-field dependence of the flux-flow resistivity showed a rapid enhancement at low fields. Such a rapid enhancement can be understood by considering a highly anisotropic gap structure, even in quantitatively consistent manner with the $\lambda(T)$ data.

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Fig.1. The temperature dependence of (a) the surface resistance and (b) the surface reactance measured at fixed magnetic fields. Open circles are data measured by sweeping fields. The inset shows the penetration depth as a function of $(T/T_c)^{1.75}$ obtained from zero-field data.

Fig.2. The temperature dependence of the upper critical field, $H_{c2}(T)$, determined from the onset of $R_s(T)$ (black squares) and $X_s(T)$ (red circles). The Blue line is the T -linear dependence fit to the data.

Fig.3. The flux-flow resistivity of P-Ba122 (blue solid circle) as a function of magnetic fields. For comparison, same plots of P-Sr122 (open square), Li111 (gray solid circle), and Co-Na111 (open circle) are also depicted. The dotted line is Bardeen-Stephen's prediction, $\rho_f/\rho_n = H/H_{c2}$.

figure 1

figure 2

figure 3