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Effect of a temperature dependent effective quasiparticle mass on the surface impedance of $YBa_2Cu_3O_{7-x}$

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Abstract. The temperature dependent surface impedance $Z_{\mathrm{s}}(T)$ of single-crystalline $YBa_2Cu_3O_{7-x}$ (YBCO) was analyzed within the two-fluid model in terms of the fraction of paired charge carriers, $f_{\mathrm{s}}(T)$, and of the quasiparticle scattering time $\tau(T)$. The usual approach was extended by considering a temperature dependent effective quasiparticle mass $m^*(T)$, which results from a strong electron-phonon interaction. This effect must not be neglected in the description of high-temperature superconductors due to the large ratio of T_{c} to the Debye temperature T_{D}. The temperature dependence of the penetration depth, $\lambda(T)$, of high-quality YBCO crystals and films could be described with an electron-phonon coupling constant $\Lambda_0 = 4$, and using $f_{\mathrm{s}}(T) = 1 - (T/T_{\mathrm{c}})^{2.8}$ as an approximation of the BCS theory. Different trial phonon spectra were encountered in terms of their ability to reproduce the $\lambda(T)$-data. The scattering time $\tau(T)$ was described by the Bloch-Grüneisen formalism with $T_{\mathrm{D}} = 460$ K. Assuming an Einstein spectrum with $k_{\mathrm{B}}T_{\mathrm{c}}/\hbar\Omega_{\mathrm{ln}} = 0.24$, a residual resistivity $\rho_{\mathrm{r}} = 1.8\ \mu\Omega$cm and a fraction of unpaired quasiparticles $\varepsilon = 0.04$ at $T = 0$ K yielded a surprisingly good agreement of the model with $Z_{\mathrm{s}}(T)$-data measured at 87 GHz with a high-quality epitaxial YBCO film between $T = 4$ K and T_{c}. While an exact reproduction of the surface impedance asks for a rigorous theoretical computation, our analysis demonstrates that strong electron-phonon coupling is relevant for discussing the unconventional transport properties of YBCO.

PACS. 74.25.Nf Response to electromagnetic fields (nuclear magnetic resonance, surface impedance, etc.) – 74.20.De Phenomenological theories (two-fluid, Ginzburg-Landau, etc.) – 74.76.Bz High-T_{c} films

1 Introduction

Since the advent of the copper oxide superconductors with high transition temperatures $T_{\mathrm{c}} > 30$ K, many experiments revealed unconventional electronic properties. Among these there are measurements of the complex surface impedance $Z_{\mathrm{s}} = R_{\mathrm{s}} + \mathrm{i}X_{\mathrm{s}}$, with R_{s} the surface resistance, $X_{\mathrm{s}} = \mu_0\omega\lambda$ the surface reactance, and λ the penetration depth (μ_0 is the magnetic permeability of vacuum, and $\omega = 2\pi f$ is the circular frequency). Of special concern for a consistent theoretical understanding of the superconducting state is the temperature dependence of Z_{s} [1–4]. $Z_{\mathrm{s}}(T)$-data obtained with high-quality $YBa_2Cu_3O_{7-x}$ (YBCO) films and single-crystals displayed unconventional behaviour in the following respects: 1) Despite steady improvements of sample quality, the residual resistance $R_{\mathrm{res}} = R_{\mathrm{s}}(T = 0)$ remained higher by several orders of magnitude than typical values for conventional superconductors like Nb or Nb_3Sn. 2) The surface resistance R_{s} as well as the change of the penetration depth $[\lambda(t)/\lambda(0) - 1]$ often displayed power-law behaviour at low reduced temperatures $t = T/T_{\mathrm{c}} \ll 1$. This is qualitatively different from the exponential temperature dependence expected for superconductors with a gapped density of states, *e.g.*, in the framework of Eliashberg theory at weak electron-phonon coupling [5,6]. 3) At intermediate temperatures, $R_{\mathrm{s}}(t)$ has been observed to pass through a shallow maximum. The temperature at which this maximum occurred as well as its shape were found to depend on frequency, in accordance with the Drude model of metals [7]. 4) Approaching the transition temperature ($t \leq 1$), penetration depth data were reported to be consistent with a "3dim-XY" model, $\lambda^n(T) \propto (1 - t)$ with $n = 3$ [8]. Such a behaviour does not agree with the prediction of Ginsburg-Landau theory [9] with $n = 2$ which, however, has also been reported by some groups [10–12]. These observations were concluded to rule out a description of the surface impedance in the framework of conventional Eliashberg theory. Instead, unconventional coupling mechanisms were speculated with a possible d-wave symmetry of the order parameter, or two-band superconductivity with one band being gapless or very weakly gapped [1–4,13–15].

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The microscopic quantities are usually deduced from the surface impedance within the two-fluid model. Recent extensions of this model were successful in reducing the number of free parameters needed to describe experimental data, namely by extending the normal-state properties to the quasiparticle states below T_c [16]. However, the source of the apparently unconventional temperature dependence of the pair density $f_s(T)$ remained unexplained. In the present paper we suggest a further extension of the two-fluid model by fixing $f_s(T)$ to conventional BCS-like behaviour and by accounting for a temperature dependent effective quasiparticle mass. This feature is relevant for strongly coupled and hence for high temperature superconductors, as argued in relation to the discussion of an unconventional isotope effect [17]. Our model allows to describe various features of measured surface impedance data, completely based on conventional approaches, with merely two free parameters. At the same time, the model provides a natural explanation of the different Z_s-data of single crystals and epitaxial films. The general two-fluid formalism is outlined in Section 2. Extensions of the two-fluid model are discussed in Section 3 in terms of the temperature dependent scattering time $\tau(T)$ and effective mass $m^*(T)$. The model is applied to describe the published $\lambda(T)$-data typical for single-crystals [16]. Surface impedance data of a high-quality epitaxial YBCO film measured at 87 GHz and analyzed previously [13] are simulated in Section 4.

2 Two-fluid model of the surface impedance

Since the electrodynamics of YBCO fall into the local ($\lambda \gg$ coherence length ξ_0) and clean (mean-free path $\ell \gg \xi_0$) limit, the surface impedance can be described in terms of the two-fluid model [1]. Denoting the fraction of paired charge carriers by f_s and the fraction of quasiparticles by f_n, the complex conductivity σ_S of a superconductor is:

$$\sigma_S(t) = \sigma_1(t) - \mathrm{i}\sigma_2(t) = \frac{ne^2}{m^*(t)}\left[\frac{f_n(t)}{1/\tau(t)+\mathrm{i}\omega} + \frac{f_s(t)}{\mathrm{i}\omega}\right], \tag{1}$$

with n the quasiparticle density at the Fermi level, e the electronic unit charge, and m^* and τ the effective mass and the scattering time of the quasiparticles respectively. The temperature dependence has been made explicit in equation (1). Assuming a complete condensation of quasiparticles into pairs, $f_n(0) = 0$, and neglecting the temperature dependence of the effective mass, we obtain $\omega\tau$ and f_n as

$$\omega\tau(t) = \frac{\sigma_1(t)}{\sigma_2(0) - \sigma_2(t)}, \tag{2a}$$

$$f_n(t) = 1 - f_s(t) = \left\{1 + [\omega\tau(t)]^2\right\}\left[1 - \frac{\sigma_2(t)}{\sigma_2(0)}\right] \cdot \tag{2b}$$

The real and imaginary parts of $\sigma_S(t)$ can be extracted from the measured temperature dependences of the surface resistance and the surface reactance by

$$\sigma_S(t) = \frac{\mu_0\omega}{[X_s^2(t) + R_s^2(t)]^2} \times \left\{2R_s(t)X_s(t) - \mathrm{i}\left[X_s^2(t) - R_s^2(t)\right]\right\}. \tag{3}$$

Finally, the penetration depth in the adiabatic limit, $\omega\tau(t) \ll 1$, is related to the microscopic quantities introduced in equation (1) by

$$\lambda^2(t) = \frac{m^*(t)}{\mu_0 e^2 n f_s(t)} \cdot \tag{4}$$

The unconventional temperature dependence of $\lambda(t)$ mentioned in Section 1 was attributed to a power-law behaviour $f_s(t) \propto t^\alpha$, $\alpha = 1$–2, in accordance with an order parameter that changes sign along lines in momentum space. Furthermore, a steep drop of the scattering rate $\tau^{-1}(t)$ between $t = 1$ and $t = 0.1$ by more than two orders of magnitude was reported [18]. The increase of $\tau(t)$ and the simultaneous decrease of the quasiparticle fraction $f_n(t)$ were found to cause a maximum in $\sigma_1(t)$ which also explained the extremal behaviour of the surface resistance at intermediate temperatures. As argued, *e.g.*, in reference [19], the observed temperature dependences of τ and f_n could not be explained within BCS theory. Rather, different mechanisms were considered, based on magnetic pair interactions, strong quasiparticle correlations, and granularity [1,3,13–15].

3 Extensions of the two-fluid model

Assuming the scattering of quasiparticles as a result of an ordinary electron-phonon interaction, Trunin [3] and Fink [16] could reproduce surface resistance data by extending the Bloch-Grüneisen formalism for the normal-state conductivity to the quasiparticles below T_c. They replaced the constant low-frequency limit of the quasiparticle conductivity $\sigma_{dc} = ne^2\tau/m^*$ by

$$\sigma_{dc} = \frac{ne^2\tau(t)f_n(t)}{m^*(0)} = \frac{f_n(t)}{\rho(t)} = \frac{1 - f_s(t)}{\rho_r + \rho_i(1)t^5 g(t)}, \tag{5}$$

where the total resistivity $\rho(t) = \rho_r + \rho_i(t)$ is the sum of a residual $[\rho_r = \rho(0)]$ and an intrinsic term $[\rho_i(t) = \rho(t) - \rho_r]$, and $g(t)$ is related to the Bloch-Grüneisen integral [16,20]. This approach yielded a reasonable explanation of $\tau(t)$ in YBCO films and single-crystals. However, the temperature dependence of f_s remained an empirical input parameter, deduced from measured penetration depth data.

Following the same rational, we propose a further refinement of the two-fluid model within conventional strong-coupling theory [21]. It is well-known that the coupling constant Λ of strongly coupled Eliashberg superconductors becomes temperature dependent due to electron-phonon corrections to the quasiparticle energies [22–24]. Consequently, the effective quasiparticle mass $m^* = m_0(1 + \Lambda)$ becomes temperature dependent, too (where m_0 is the unrenormalized electron mass). As argued in the following, this effect significantly alters the temperature dependence of the penetration depth and of the surface resistance.

The following treatment is based on simplifying assumptions in order to demonstrate the impact of a temperature dependent effective mass on $Z_s(T)$. However, the conclusions of the model remained correspondingly valid if more realistic approaches (including anisotropy, realistic phonon spectra, possible two-band behaviour and non-s wave symmetry of the pair state) were encountered. We assume for simplicity that an isotropic electron-phonon interaction is described by the characteristic function $\alpha^2(\Omega)F(\Omega)$, where Ω is a phonon frequency, $F(\Omega)$ is the phonon density of states, and $\alpha^2(\Omega)$ is the electron-phonon coupling. Under these conditions $\Lambda(t)$ is given by:

$$\Lambda(t) = 2\int_0^\infty \mathrm{d}\Omega \left[\frac{\alpha^2(\Omega)F(\Omega)}{\Omega} G\left(\frac{k_\mathrm{B}T}{\hbar\Omega}\right)\right] \tag{6}$$

where k_B is the Boltzmann constant, $\hbar$ is the reduced Planck's constant, and $G(x)$ is the Grimvall function [22]

$$G(x) = \int_0^\infty \frac{\mathrm{d}z}{\coth^2(z)} \frac{1}{1-(2zx)^2}\,. \tag{7}$$

The resulting temperature dependence of the effective mass turns out to be:

$$m^*(t) = m^*(0)\left[1 + \frac{\Lambda(t) - \Lambda_0}{1+\Lambda_0}\right], \tag{8}$$

where $\Lambda_0 = \Lambda(t=0)$. A precise computation of $m^*(t)$ requires the knowledge of the real electron-phonon interaction [23,24]. However, a useful approximation can be obtained assuming an Einstein spectrum centered at the characteristic phonon frequency Ω_ln [5,14,15]:

$$\alpha^2(\Omega)F(\Omega) = \frac{\Lambda_0}{2}\,\frac{\Omega}{\Omega_\mathrm{ln}}\delta(\Omega - \Omega_\mathrm{ln}), \tag{9a}$$

$$\Omega_\mathrm{ln} = \exp\left[\frac{2}{\Lambda_0}\int_0^\infty \ln(\Omega)\frac{\alpha^2(\Omega)F(\Omega)}{\Omega}\mathrm{d}\Omega\right]. \tag{9b}$$

Theoretical approaches to describe YBCO within Eliashberg theory revealed $\Lambda_0 = 3 \div 4$ and $\Psi \equiv k_\mathrm{B}T_\mathrm{c}/\hbar\Omega_\mathrm{ln} \approx 0.3-1$ as typical parameters. However, taking into account the breakdown of the Migdal theorem resulted in a much smaller coupling constant $\Lambda_0 \approx 1.5$ [25], which approaches the range of validity of the scaled BCS theory.

Figure 1 displays the dependence of the reduced effective mass $m^*(t)/m^*(0)$ on the normalized temperature $\Psi \times t$ for different values of Λ_0 calculated by equations (6–8). Due to the simple Einstein spectrum, the temperature dependence of m^* is determined by the Grimvall function $G(\Psi t)$, which scales like t^2 for $(\Psi t) \ll 1$ [23]. As Λ_0 vanishes, the electron-phonon correction of the quasiparticle energies becomes negligible, and $m^*(t)$ approaches the constant $m^*(0)$ in accordance with expectation. Similar results for $m^*(t)$ can be obtained with a Debye spectrum:

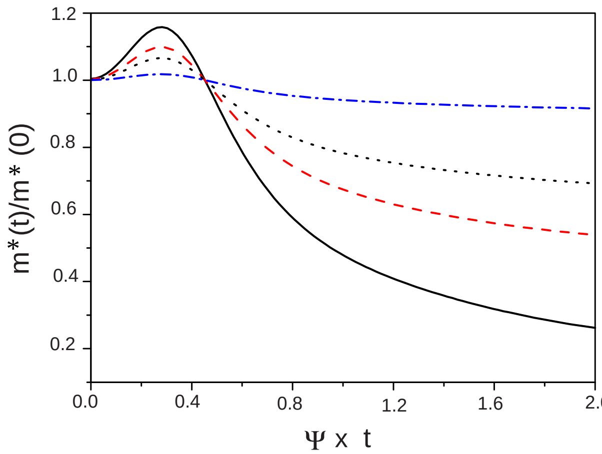


Fig. 1. Reduced effective mass $m^*(t)/m^*(0)$ as a function of the normalized temperature $\Psi \times t = k_\mathrm{B}T/\hbar\Omega_\mathrm{ln}$ assuming an Einstein spectrum centered at Ω_ln for $\Lambda_0 = 4$ (solid curve), 1 (dashed), 0.5 (dotted), 0.1 (dash-dotted).

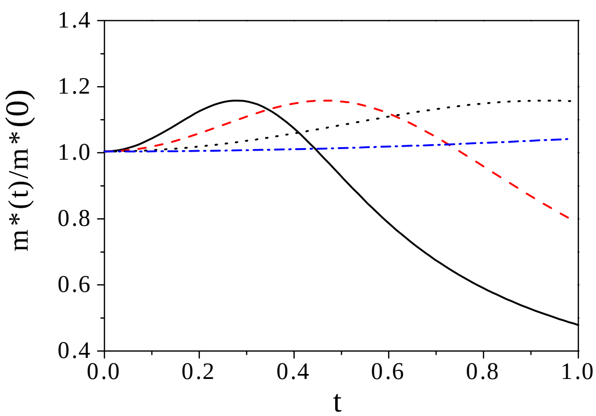


Fig. 2. Temperature dependence of the reduced effective mass $m^*(t)/m^*(0)$ assuming an Einstein spectrum with $\Lambda_0 = 4$ and $T_\mathrm{c} = 90$ K for $\Psi = 1$ (solid curve), 0.6 (dashed), 0.3 (dotted), 0.1 (dash-dotted).

$$\alpha^2(\Omega)F(\Omega) = \frac{\Lambda_0}{2}\left(\frac{\Omega}{\Omega_\mathrm{D}}\right)^2 \theta(\Omega_\mathrm{D} - \Omega) \tag{10}$$

with Ω_D the Debye frequency which corresponds, for YBCO, to a Debye temperature $T_\mathrm{D} = 460$ K [16]. This spectrum yields an effective mass initially increasing like $(T/T_\mathrm{D})^2 \log(T_\mathrm{D}/T)$ at $T/T_\mathrm{D} \ll 1$. Figure 2 shows $m^*(t)$ for different values of Ψ, calculated under the assumption of the Einstein spectrum, $\Lambda_0 = 4$ and $T_\mathrm{c} = 90$ K. The maximum of $G(x)$ at $x \approx 0.26$ is transferred to an extremal temperature dependence of m^* for $\Psi \geq 0.25$. It is thus expected to occur for strong-coupling superconductors like YBCO and other cuprates.

In order to determine the penetration depth from equation (4), the temperature dependent pair fraction must be known in addition to $m^*(t)$. As a first guess, we have approximated $f_\mathrm{s}(t)$ dependence as $f_\mathrm{s}(t) = 1 - t^{2.8}$, in

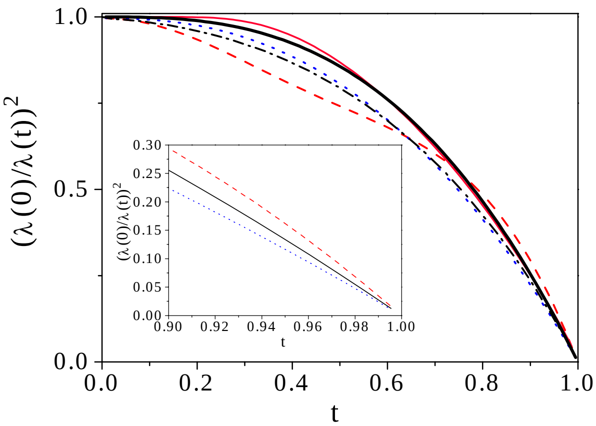


Fig. 3. Temperature dependence $[\lambda(0)/\lambda(t)]^2$ for $f_s(t) = 1 - t^{2.8}$ (bold solid curve) and $\Lambda_0 = 4$ for an Einstein spectrum with $\Psi = 0.3$ (dotted) and $\Psi = 0.6$ (dashed), and for a Debye spectrum with $T_D = 460$ K (dash-dotted). The thin solid curve represents the BCS prediction evaluated as reported in the text. The inset magnifies the region $0.9 < t < 1$ (the BCS curve and the Debye spectrum were omitted for clarity).

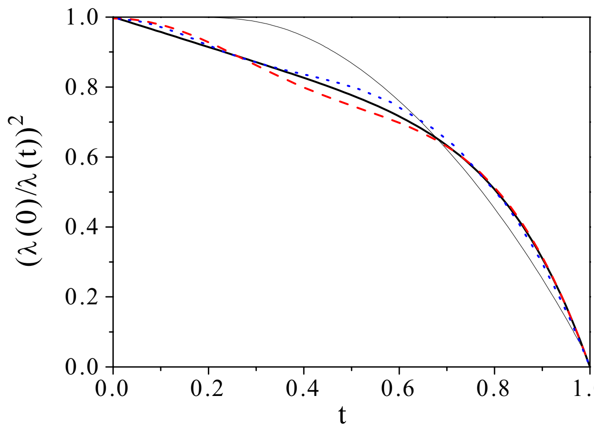


Fig. 4. Temperature dependence of $[\lambda(0)/\lambda(t)]^2$ for the Einstein spectrum with $\Psi = 0.68$ (dashed curve) and the step spectrum (dotted) according to equation (11), with the parameters given in the text. The bold curve represents the data reported by Fink [15], the BCS prediction is indicated by the thin solid curve.

accordance with a numerical evaluation [26] of the BCS penetration depth assuming $\lambda(0) = 150$ nm, $T_c = 90$ K, $\xi_0 = 2$ nm, and $\ell = 10$ nm. Figure 3 displays the results for $[\lambda(0)/\lambda(t)]^2 = f_s(t)m^*(0)/m^*(t)$ for Einstein spectra with $\Lambda_0 = 4$ and $\Psi = 0.3$ (dotted curve) and $\Psi = 0.6$ (dashed curve). The results for a constant effective mass (bold solid curve) and for the BCS prediction (thin solid curve) are shown for comparison. With increasing coupling strength, a shoulder occurs as a result of the extremal behaviour of $m^*(t)$. In accordance with the definition of $\Omega_{\ln}$, the Einstein spectrum with $\Psi = 0.3$ agrees well with a Debye spectrum at $T_D = 460$ K (dash-dotted). The low-temperature variation of $[\lambda(0)/\lambda(t)]^2$ reflects the quadratic dependence of $m^*(t)$ which is significantly steeper than the variation of $f_s(t)$ alone. This conclusion remains valid even if the Gorter-Casimir temperature dependence $f_s(t) = 1 - t^4$ was employed, which is known to reproduce the strong-coupling behaviour of conventional superconductors quite well. The inset to Figure 3 magnifies the effect of $m^*(T)$ on $\lambda^{-2}(t)$ close to T_c. Strong electron-phonon coupling (*e.g.*, $\Psi = 0.6$) can obviously account for deviations from the Ginsburg-Landau critical exponent $n = 2$ without needing to consider unconventional behaviour.

The relevance of the shape of the phonon spectrum for the explanation of the experimental $\lambda^{-2}(t)$-dependence is demonstrated in Figure 4. Typical data for YBCO single-crystals (Ref. [16], bold curve, $[\lambda(0)/\lambda(t)]^2 \approx 1 - 3t/7 - 4t^6/7$) are known to deviate from the BCS theory (thin solid curve). In contrast, much better agreement is found with our model under the assumption of an Einstein spectrum with $\Psi = 0.68$ (dashed curve). Even better agreement can be achieved with a more realistic step spectrum

$$\alpha^2(\Omega)F(\Omega) = \frac{\Lambda_0}{2\ln(\Omega_u/\Omega_l)}\theta(\Omega - \Omega_l)\theta(\Omega_u - \Omega) \quad (11)$$

using $\hbar\Omega_l/k_B = 60$ K and $\hbar\Omega_u/k_B = 460$ K (dotted curve). According to the definition of $\Omega_{\ln}$ by equation (9b), this spectrum corresponds to $\Psi = 0.54$. It is noted that any value of $\Psi \geq 0.2$ can be obtained by adjusting Ω_u below $\hbar\Omega_u/k_B = 1\,000$ K, which is considered reasonable for YBCO [5,15], and by replacing $\Omega_{\ln}$ by [5]:

$$\langle\Omega\rangle = \frac{2}{\Lambda_0}\int_0^\infty \alpha^2(\Omega)F(\Omega)\mathrm{d}\Omega.$$

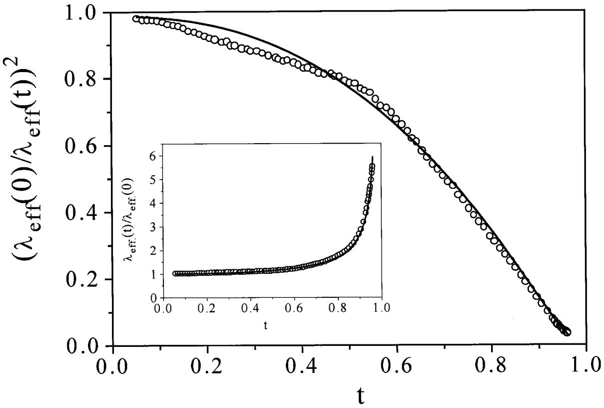
4 Modeling the surface impedance of YBCO films

The significance of the proposed two-fluid model can be further illustrated by applying it to the analysis of the experimental data of the temperature dependent surface impedance, measured on a typical high-quality epitaxial YBCO film at 87 GHz (“sample A” in Ref. [13]) by a copper cavity technique. The surface impedance was simulated according to the local relation:

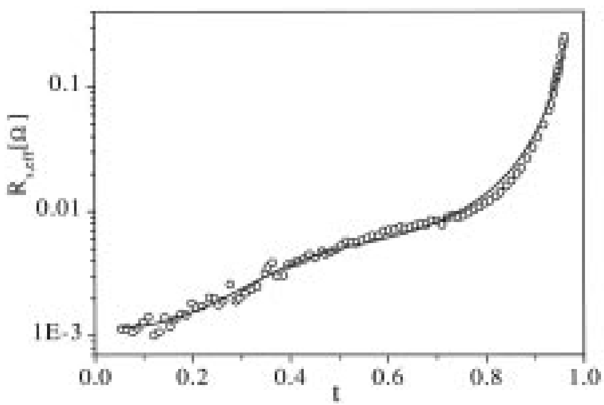
$$Z_s(t) = \sqrt{\frac{\mathrm{i}\mu_0\omega}{\sigma_S(t)}} \quad (12)$$

with $\sigma_S(t)$ given by equation (1). The temperature dependence of the scattering rate and of the effective mass were determined by equations (5, 8). In order to take into account a finite residual resistance R_{res}, a small fraction of inherently unpaired quasiparticles, ε, was assumed. The previous assumption $f_n(t)+f_s(t) = 1$ was correspondingly replaced by the more general approach $f_n(t)+f_s(t)+\varepsilon = 1$, with $0 < \varepsilon \ll 1$, yielding:

$$R_S(T = 0) = \frac{1}{2}\mu_0^2\omega^2\lambda^3(0)\frac{\varepsilon}{\rho_r}\cdot \quad (13)$$



(a)



(b)

Fig. 5. Effective data for $[\lambda_{\rm eff}(0)/\lambda_{\rm eff}(t)]^2$ (a), $\lambda_{\rm eff}(t)/\lambda_{\rm eff}(0)$ (inset to Fig. 5a), and for $R_{\rm s,eff}(t)$ (b), measured at 87 GHz with the epitaxial YBCO film referred to as "sample A" in reference [13] (symbols). The lines represent the best fit of the extended two-fluid model.

It should be noted that the existence of a finite fraction $\varepsilon > 0$ of unpaired charge carriers is a common phenomenon for conventional superconductors [2]. For instance, the values of $R_{\rm res} = 10{-}1$ nΩ measured at $f = 1.5$ GHz for Nb samples with $\rho_{\rm i}(T = 300\,{\rm K})/\rho_{\rm r} = 100$ correspond to $\varepsilon \approx 0.03$ [27]. The relationship between $\lambda(t)$ and the pair fraction $f_{\rm s}(t)$, and, hence, the results described in the previous sections, remained unaffected by setting $\varepsilon > 0$. In order to account for the finite film thickness d, $R_{\rm s}$ and λ were replaced by their effective values [28]

$$R_{\rm s,eff}(d) = R_{\rm s,\infty}\left\{\coth\left[\frac{d}{\lambda(t)}\right] + \frac{d/\lambda(t)}{\sinh^2[d/\lambda(t)]}\right\} \quad (14a)$$

$$\lambda_{\rm eff}(d) = \lambda_\infty \coth[d/\lambda(t)]. \quad (14b)$$

The model parameters were fixed at $d = 350$ nm, $T_{\rm c} = 91.6$ K (as obtained by inductive measurements), $\rho_{\rm i}(1) = 65$ $\mu\Omega$cm (as deduced from $R_{\rm s}(T)$-measurements above $T_{\rm c}$), $\lambda(0) = 160$ nm [13] and $T_{\rm D} = 460$ K [16]. The pair fraction was approximated by $f_{\rm s}(t) = 1 - t^{2.8}$ as before. However similar agreement between model and $Z_{\rm s}$-data was not limited to the weak-coupling expression for $f_{\rm s}(t)$ but applied similarly well to $f_{\rm s}(t) = 1 - t^4$ expected for strong coupling.

For simplicity, only an Einstein spectrum with $\Lambda_0 = 4$ was assumed, leaving only parameter Ψ as the free one to simulate $\lambda(t)$, and $\rho_{\rm r}$ and ε as additional parameters required to simulate $R_{\rm s}(t)$. However, the residual fraction ε is fixed by $R_{\rm res}$ and $\rho_{\rm r}$ according to equation (13). The measured $Z_{\rm s,eff}(t)$-data were fitted by least-squares procedure assuming errors of 0.1% and 10% for the $\lambda_{\rm eff}(t)$- and $R_{\rm s,eff}(t)$-data respectively. The best fit to the penetration depth, shown in Figure 5a, was achieved with $\Psi = 0.246 \pm 0.003$, which is consistent with the assumed Debye temperature for a coupling strength $\Lambda_0 = 4$. The best fit to the $R_{\rm s}$-data, shown in Figure 5b, was obtained with $\rho_{\rm r} = 1.8 \pm 0.2$ $\mu\Omega$cm and $\varepsilon = 0.041 \pm 0.005$. These values could be easily explained by granularity [29–31] or by residual magnetic scattering [32]. In spite of the simplicity of our model, the agreement between the measured surface impedance data and theoretical results is surprisingly good.

5 Discussion and conclusion

The surface impedance $Z_{\rm s}(t)$ of a typical high-quality YBCO film [13] at $f = 87$ GHz could be described with the two-fluid model accounting for a temperature dependent quasiparticle scattering time $\tau(t)$ and an effective mass $m^*(t)$, which are related to conventional strong coupling electron-phonon interaction, and with $f_{\rm s}(t)$ fixed in agreement with the BCS approach. Such a procedure seems to be justified because in the full Eliashberg formalism the temperature dependence of the coupling strength mainly affects the renormalization function (which is strictly related to m^*) rather than the gap function (which is strictly related to $f_{\rm s}$) [5,33]. In general, a strong electron-phonon interaction could be expected to affect also the temperature variation of $f_{\rm s}$. It is tempting to assume that a more realistic form of $f_{\rm s}(t)$ could be deduced from measurements of the out-of-plane (c-axis) penetration depth $\lambda_{\rm c}$. In fact, charge transfer along the c-axis was considered to be related to tunneling or impurity assisted hopping [34, 35] and thus to be independent of electron-phonon interaction. Therefore, the out-of-plane value of the effective mass $m^*_{\rm c}$ should be independent of temperature. Given that the fraction of paired charge carriers $f_{\rm s,c}$ still reflects strong coupling, the expression $f_{\rm s,c}(t) = [\lambda_{\rm c}(0)/\lambda_{\rm c}(T)]^2$ could be assumed as simplest approximation. The observation that, for $t < 0.5$, the penetration depth for c-axis transport comes close to the BCS result [36] is a striking support of our model assumption.

A strictly linear temperature dependence of the penetration depth at $t \ll 1$ could not be obtained with a simple Einstein spectrum (Fig. 3). However, as was firstly pointed out by Eliashberg [33], it can be simulated with more realistic phonon spectra having a finite density of states at low frequencies [37] (see dotted line in Fig. 4 as a first step of this approximation). In such case, the penetration depth can be definitely factorized by equation (4), with $m^*(t)$ which controls the low-temperature behaviour of $\lambda(t)$ [37]. The results obtained with the two-fluid model and reported in reference [16] were concluded to remain valid, in the adiabatic limit $\omega\tau \ll 1$, if the quantities $y(t)$ ($y = f_s, f_n, \tau$) were modified by the formula $y^*(t) = y(t)m^*(0)/m^*(t)$. Furthermore, the subtle differences of $\lambda(t)$ between single-crystals and epitaxial films, which could be reproduced with the same value of Ψ, can be explained in terms of different phonon spectra, which depend on the presence of the strain and the defects which are present in typical films but absent in high-purity single-crystals.

In conclusion, the temperature dependence of the effective quasiparticle mass, which can be neglected in classical superconductors due to the low transition temperature and, hence, low ratio T_c/T_D, was found to explain many of the unconventional electronic properties of the high-T_c/T_D materials, including the observation of exponential temperature dependence of Z_s [2], which is inconsistent with a pure d-wave symmetry of the order parameter. The extended two-fluid model could also account for the empirical power law-behaviour of the scattering time $\tau(t)$ at low temperatures $t \ll 1$ without unconventional pairing assumption. The parameters required to fit the $\lambda(T)$-data measured at 87 GHz with a simple Einstein spectrum and $f_s(t) = 1 - t^{2.8}$ where $\Lambda_0 = 4$, $\Psi = 0.25$, and $\lambda(0) = 160$ nm. Considering a Bloch-Grüneisen temperature dependence of the quasiparticle scattering with a Debye temperature $T_D = 460$ K, which is consistent with $\Psi = 0.25$, it was possible to describe the temperature dependent surface resistance, which demonstrates the reasonable value of the residual resistivity $\rho(0)$. The residual resistance R_{res} was attributed to a small fraction (few percent) of quasiparticles that remained unpaired even at the lowest temperatures. This conclusion is satisfied with the R_{res}-values obtained for conventional superconductors of the highest purity.

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