Universal relationship between the penetration depth and the normal-state conductivity in YBaCuO.

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Abstract

The absolute values of the conductivity in the normal state σ_n and of the low temperature penetration depths $\lambda(0)$ were measured for a number of different samples of the YBaCuO family. We found a striking correlation between σ_n and λ^{-2} regardless of doping, oxygen reduction or defects, thus providing a simple method to predict the superconducting penetration depth and to have an estimate of the sample quality by measuring the normal-state conductivity.

The superconducting penetration depth, $\lambda(0)$, is one of the most important electrodynamic properties of the high-temperature superconductors and provides direct information about the spectral weight of the superconducting condensate [1]. In the normal state the low frequency electrodynamics can be characterized by the absolute value of the conductivity $\sigma_n(\nu, T)$. At not too high frequencies, $\sigma_n(\nu, T)$ is in a good approximation a real function of frequency. Because $\lambda(0)$ and $\sigma_n(0, T)$ both involve a Fermi-surface averaging and depend on the same amplitude factors $e^2 N(0) v_{\mathrm{F}}^2$ [2], they may be expected to be connected to each other.

In order to investigate possible correlations experimentally, we have carried out

submillimeter-wave (100 GHz $<$ ν $<$ 1100 GHz) transmission experiments on different thin YBa$_2$Cu$_3$O$_{7-\delta}$ films. Optimally doped films on different substrates were obtained by laser ablation and by magnetron sputtering. One film was oxygen reduced after the measurement and then remeasured under identical conditions. Transmission experiments in the frequency range 100-1100 GHz were performed utilizing a set of backward-wave oscillators. The measurements were performed in a Mach-Zehnder interferometer arrangement [3] which allows both, the measurements of transmission and phase shift. The properties of the substrates were determined in separate experiments. Utilizing the Fresnel optical formulas for the complex transmission coefficient for a double layer system, the complex conductivity was determined from the observed spectra without any approximations. It is important to note, that the absolute values of the conductivity could be deduced directly from the experiment. The penetration depth was calculated from the conductivity data via $\lambda = c/\omega k$, with k being the imaginary part of the complex refractive index $k = Im[i(\sigma_1 + i\sigma_2)/\varepsilon_0\omega]^{1/2}$. This expression for λ gives the usual microwave result $\lambda = (\mu_0\omega\sigma_2)^{-1/2}$ in the limit $\sigma_1 \ll |\sigma_2|$ and reduces to the expression for the skin depth in the normal state ($\sigma_1 \gg |\sigma_2|$).

The submillimeter properties of YBa$_2$Cu$_3$O$_{7-\delta}$ films for a fixed frequency $\nu = 450\ GHz$ (15 cm^{-1}) are summarized in the Table 1. In addition, some details of the film preparation, the weight of the superconducting condensate ($\omega_{p,s}^2 = c^2/\lambda(0)^2$), and the effective scattering rate (Eq. 1) are given. The detailed submillimeter-wave data for the samples No.1,3,5 were published previously [5–7]. The data in Tab.1 are represented in the order of decreasing absolute values of the conductivities at 100 K. Comparing the conductivity column with the penetration depth column, the correlation between these two quantities becomes obvious. With the exception of the sample No.4, the penetration depth increases with decreasing conductivities. We note that the scattering of data for different samples may be connected with experimental difficulties in measuring the absolute values of conductivity and penetration depth. In addition, in spite of substantial progress in prepairing good quality YBaCuO films [4], the details of deposition process still may influence the experimental results.

To check the possible correlation between σ_n and λ in more detail, the normal state con-

ductivity and the superconducting penetration depth were analyzed on the basis of published data available up to now. The results of this analysis are summarized in Fig. 1. In order to simplify the analysis only results on YBaCuO based materials were considered. To compare the absolute values of the conductivity for different samples the characteristic temperature of $T=100$ K was chosen. It is well known [8] that the resistivity even of oxygen reduced or doped cuprates is to a reasonable approximation linear for temperatures between 100 K and 300 K. A linear temperature scaling was therefore used, if the results were reported at temperatures different from $T=100$ K. Taking into account the relatively strong scattering of the data for different samples, this procedure certainly introduces no substantial errors.

Fig. 1 represents the data as measured by different experimental methods. In addition to the thin film results by THz transmission technique [9–15], mutual inductance data [16,17] and single crystal data [18–22] are shown. The remarkable feature of Fig. 1 is that the majority of experimental points closely follows the dashed line, which is the best fit to our data according to the expression $\lambda(0)^{-2}/\mu_0 = \sigma_n/\tau$, with $1/\tau = 22$ THz. Fig. 1 thus suggest that the absolute value of the conductivity in the normal state is approximately proportional to the spectral weight of the superconducting condensate $\omega_{p,s}^2$ or to the inverse square of the penetration depth $\lambda(0)^{-2}$.

In the following we would like to suggest rather simple arguments to understand this relation. Within the isotropic approximation the real part of the conductivity can be written as $\sigma_n = \varepsilon_0 \omega_{p,n}^2 \tau$, where τ^{-1} is the quasiparticle scattering rate and $\varepsilon_0 \omega_{p,n}^2$ is the spectral weight of the Drude peak. For a number of high temperature cuprates in the normal conducting state the characteristic scattering rate has been shown to increase linear in temperature following $\hbar/\tau \approx 2k_B T$ [23]. Assuming the value $\Delta = 2k_B T_C$ for the energy gap [24], one obtains the approximation for the ratio of mean free path to the coherence length, $\ell/\xi = \pi\tau\Delta/\hbar \approx 3$. As the scattering rate decreases even stronger than linearly below T_C [1], at low temperatures the high-T_C superconductors are in the clean limit and the spectral weight of a Drude peak $(\varepsilon_0 \omega_{p,n}^2 = ne^2/m^*)$ is expected to fully condense into the delta function at $T=0$K. This conclusion is supported by the Drude-analysis of the frequency dependent conductivity

of $YBa_2Cu_3O_{7-\delta}$ [5] and by a comparison of the conductivity spectral weights at infrared frequencies [25]. In the clean limit the following expression holds

$$\frac{1}{\mu_0\lambda(0)^2} = \varepsilon_0\omega_{p,s}^2 = \varepsilon_0\omega_{p,n}^2 = \sigma_n/\tau \tag{1}$$

The Eq.(1) thus suggests the possible explanation of the correlation in Fig. 1: obviously defects (doping, sample quality) and oxygen concentration change only the density of states at the Fermi-level, N(0), or the effective number of charge carriers, $\omega_{p,s}^2$ and $\omega_{p,n}^2$, and do not affect the effective scattering rate τ^{-1}. Theoretical calculations of the normal-state properties using spin-fluctuation scattering [26], Fermi-surface nesting [27] or phenomenological marginal Fermi-liquid approach [28] result in the quasiparticle scattering rate, which is not dependent on N(0), but is approximately proportional to temperature. Therefore, within a reasonable approximation, τ^{-1} may be supposed to be unsensitve to the level of defects. As long as the sample is in the clean limit, the complete Drude spectral weight $\omega_{p,n}^2$ condenses into the superconducting delta function retaining the correlation between the normal and the superconducting state given by Eq. (1).

Interestingly, the Ni- and Zn-doped samples of Ulm et al. [17] and the Pr doped samples of Brorson et al. [9] still follow the correlation of Fig.1, except for the samples with the highest doping levels (6% Ni, 40% Pr, or 4% Zn doping). The different behavior of heavily doped samples is probably due to the fact, that they are no more in the clean limit. Therefore a substantial portion of the "normal" spectral weight is not condensed into the delta function at low temperatures and the penetration depth $\lambda(0) = c/\omega_{p,s}$ is substantially higher than the value estimated from Eq. (1), $\lambda(0) = c/\omega_{p,n}$. In addition Fig. 1 shows that Zn doping has the strongest effect on the electrodynamic properties of high-T_C's compared to Ni or Pr. Similar conclusion has been drawn on the basis of the microwave data by Bonn et al. [29].

Although simple arguments, presented above, give an idea to understand the observed correlation, we cannot exclude other possible explanations. E.g. even the application of Fermi-liquid picture to high-temperature superconductors is still an intensively discussed problem [2,30]. Further on and especially concerning optimally doped YBCO films, the

extrinsic effects may also play an important role in determining the conductivity values. The influence of weak links on the surface impedance of granular superconductors was discussed in detail by Halbritter [31].

The scattering rate $1/\tau = 22$ THz, as deduced from the dashed line in Fig. 1, leads to the following expression at T=100 K: $\hbar/\tau = 1.7k_{\mathrm{B}}T$. This relation is similar to $\hbar/\tau \approx 2k_{\mathrm{B}}T$ [23] cited above. On the basis of the above presented discussion we may conclude, that the scattering rate $\hbar/\tau = 1.7k_{\mathrm{B}}T$ is to a good approximation independent of doping, oxygen depletion and defects. Hence, the proportionality between $\lambda(0)^{-2}$ and σ_n provides a simple possibility to characterize the superconducting properties of the YBaCuO samples by measuring the normal state conductivity by e.g. standard four point method. On the basis of data, presented in Fig.1 the penetration depth of a certain sample is given by the approximate expression

$$\lambda(0)[nm] = 190/\sqrt{\sigma_n(100K)[10^4\Omega^{-1}cm^{-1}]} = 19 \cdot \sqrt{\rho_n(100K)[\mu\Omega \cdot cm]} \qquad (2)$$

Eq. (2) describes 80% of all penetration depth data in Fig. 1 with deviations well below 25%. Finally it should be noted, that most points of Fig.1 represent thin-film data. The applicability of Eq. (2) for single crystals should be checked in more detail in further investigations.

In conclusion, we have measured the conductivity and the penetration depth of a variety of YBaCuO samples and compared our results to published data. We have plotted the low temperature penetration depth as a function of the normal-state conductivity, where the absolute values for both parameters were available on the same sample. In this plot we observe a correlation $\lambda^{-2} \backsim \sigma_n$. This observation allows the estimate of the penetration depth of a given YBaCuO sample by measuring its normal state conductivity. In the normal conducting state we find universal scattering rate $\hbar/\tau = 1.7k_{\mathrm{B}}T$ independent of defects, oxygen concentration and doping.

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No.	T_C [K]	Preparation	Substrate	d [nm]	σ_n [$10^4\Omega^{-1}\mathrm{cm}^{-1}$]	λ [nm]	$\omega_{p,s}^2$ [eV^2]	τ^{-1} [THz]	Ref.
1	89.5	magnetron sputt.	NdGaO$_3$	81	1.51	152	1.71	22.8	[4]
2	91.3	magnetron sputt.	LaAlO$_3$	90	1.0	204	0.952	19.1	
3	85.9	laser ablation	MgO	85	0.80	243	0.671	16.8	[5]
4	89	magnetron sputt.	NdGaO$_3$	75	0.64	215	0.857	26.9	
5	56.5	No.1 reduced	NdGaO$_3$	81	0.60	279	0.509	17.0	[6]
6	91	laser ablation	NdGaO$_3$	70	0.38	292	0.464	24.6	

Table 1. Submillimeter-wave properties of YBa$_2$Cu$_3$O$_{7-\delta}$ films at $\nu = 450$ GHz. The normal state conductivity σ_n and the superconducting penetration depth λ are given at temperatures 100 K and 6 K respectively. The spectral weight of the superconducting condensate $\omega_{p,s}^2$ and the effective scattering rate $1/\tau$ were calculated using Eq. (1).

Figure caption.

Fig. 1. Low temperature ($T \lesssim 10$ K) penetration depth λ of different YBCO samples as a function of the normal-state conductivity σ_n at $T=100$ K. Dashed line is drawn according to the expression $\lambda(0)^{-2}/\mu_0 = \sigma_n/\tau$ using $1/\tau = 22$THz. The characters in the symbols correspond to:

Rhombs - single crystal data:

B - Basov et al. [18] and Zhang et al. [19]; K - Kitano et al. [20]; K1 - Kamal et al. [22]; S - Sonier et al. [21].

Circles - optimally doped $YBa_2Cu_3O_{7-\delta}$ films:

closed circles - this work, Table 1; B - Brorson et al. [9]; D - Dähne et al. [13]; F - Fiory et al. [16]; L - Ludwig et al. [11]; N - Nagashima et al. [12] (λ is taken at $T=40$ K); N1 - Nuss et al. [14]; V - de Vaulchier et al. [15].

Squares - oxygen reduced $YBa_2Cu_3O_{7-\delta}$ films:

closed square - this work, Table 1; L - Ludwig et al. [11].

Down triangles - doped $YBa_2Cu_3O_{7-\delta}$ films:

B - Brorson et al. [9] (20%, 30%, and 40% Pr - doped films); F - Feenstra et al. [10] ($DyBa_2Cu_3O_{7-\delta}$); U - Ulm et al. [17] (2%, 4% and 6% Ni doped and 2% and 4% Zn doped films). Dotted lines are guide to the eye. Arrows indicate the increasing doping direction.
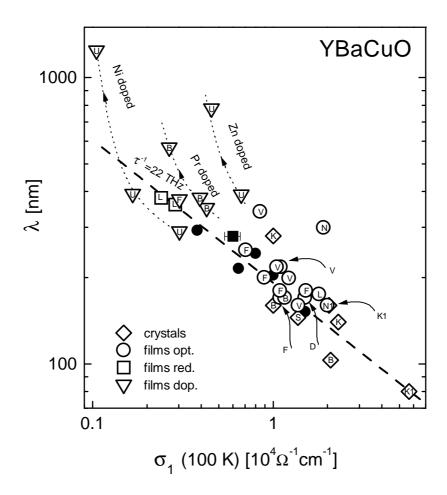
Fig. 1, Pimenov et al.