Angular scaling of the microwave magnetodissipation in $Bi_2Sr_2CaCu_2O_{8+x}$

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We report measurements of the surface resistance at 21 GHz as a function of the magnetic field H and of the field orientation ϑ with respect to the (a,b) planes, for different temperatures, on epitaxial $Bi_2Sr_2CaCu_2O_8$ films. We find clear experimental evidence for the angular scaling of the microwave surface resistance, at all the temperatures investigated, with no need for specific hypothesis on the origin of the dissipation. The scaling is perfect over four decades of the magnetic field. The angular scaling function is identified with the quasi-two-dimensional, thin-film formula.

High-T_c superconductors (HTCS's) present strikingly anisotropic features, both in the normal and superconducting state. Among the HTCS's, $Bi_2Sr_2CaCu_2O_8$ is the most representative compound between the strongly anisotropic cuprates. The extreme properties of $Bi_2Sr_2CaCu_2O_8$ have been investigated both theoretically and experimentally, and several reports dealt with the anisotropic features of the dissipative properties such as resistivity,[1-5] critical currents,[6,7] and microwave dissipation.[8-11] In the last few years, the scaling approach to the angular properties of the layered superconductors was largely followed, substained by several theoretical works.[12,13] Historically, most of the theoretical effort in the study of the anisotropic superconductors was spent obtaining well-defined expressions for the angular (and, eventually, temperature) dependence of some critical field, such as the first critical field H_{c1}, and the upper critical field H_{c2}.[14-17] However, the huge values of H_{c2} (and, by contrast, the ambiguous determination of H_{c1}) in the cuprate superconductors did not allow a proper comparison between the experimentally obtainable results and the models. The scaling approach[12,13] overcame these difficulties. In fact, it was demonstrated that in an anisotropic superconductor the thermodynamical quantities depend on the angle ϑ between the magnetic field H and the (a,b) planes only through the reduced field $h=H/H_{c2}(\vartheta)$, at least for fields $H \gg H_{c1}$. As a consequence, measurements of the angular dependence of such quantities should provide the angular behavior of H_{c2}. A slightly different situation arises for the transport properties: these were argued to depend on the magnetic field through the same reduced field h, at least in the absence of the Lorentz force, but no demonstration has been given up to now. It is then interesting to search for the scaling properties of dissipation-related quantities. In this sense, $Bi_2Sr_2CaCu_2O_8$ is a good model system to study the (possible) scaling properties, because it does not exhibit any experimentally detectable Lorentz force.[2,6] It has been previously shown that in $Bi_2Sr_2CaCu_2O_8$, dc resistivity[3] and critical currents[7] scale through an appropriate angular scaling function, but no detailed high-frequency investigation was performed along this path, the investigation being limited to some parameters of the experimental curves.[11] The most common approach to the angular dependence of the high-frequency dissipation in $Bi_2Sr_2CaCu_2O_8$ has been carried out up to now only by including the effects of the anisotropy in some specific model for the dissipation.[10] In this paper, we present experimental evidence for the angular scaling of the entire magnetic curves of the microwave surface resistance in $Bi_2Sr_2CaCu_2O_8$ *without any assumption on the specific origin of the dissipation.*

The experiment has been performed on two epitaxial $Bi_2Sr_2CaCu_2O_{8+x}$ films, by a microwave technique. The 1 cm×1 cm films have been grown by liquid phase epitaxy[18] on $LaGaO_3$ and $NdGaO_3$ substrate (samples I and II, respectively). Thickness was about 1 μm, and the mosaic spread was less than 0.15°, according to x-ray diffraction. The dc resistivity transition widths (10–90 %) were 4 and 7 K, respectively, with midpoints at 81.8 and 84.9 K. We have employed a cavity technique: the sample replaced a narrow wall of a silver-coated rectangular cavity, resonant at 21 GHz in the TE_{011} mode. In this configuration the microwave current density flowed in the (a,b) planes. The microwave dissipation has been measured by detecting the power reflected by the tuned cavity. The variation of the reflected power with the field at fixed temperature, $\Delta P_r(H)$, is proportional to the variation of the surface resistance. More details on the experimental apparatus and the microwave technique have been given elsewhere.[8]

The temperature was measured by a Pt sensor, and was stabilized within ±0.02 K during the fixed-temperature measurements. Because one set of angular measurements takes more than 10 h, and a resonant system is used, the long-time stabilization of the temperature is a crucial requirement of the experimental apparatus. The magnetic field could be rotated thus varying the angle ϑ with respect to the (a,b) planes. In our apparatus ϑ was also the angle between H and the microwave current density.

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The angular accuracy was 0.1°. The maximum attainable field was 14 kG. The experimental procedure was the following: the temperature was fixed and stabilized, then field sweeps were performed and the microwave losses were measured as a function of the magnetic field. For the same temperature, field sweeps at several angles were repeated. Sample I was measured at several temperatures. The data here presented refer to the temperature region in which the magnetic dissipation did not show hysteretic behavior.

The experimental field sweeps at selected angles for sample I at 70.4 K are reported in Fig. 1. The data are presented as $\Delta P_r(H)=P_r(H)-P_r(0)$, that is by subtracting the (temperature-dependent) background. The absorption is highly anisotropic, reducing by a factor of ~ 3 from the orthogonal orientation ($\vartheta=90°$) to $\vartheta=1°$. However, the most interesting feature appears in the log-lin plot (main panel): all the curves are parallel to each other, which means that a normalization of the magnetic field through an angle-dependent function $f(\vartheta)$ should make all the curves collapse one on top of the other. In other words, the transformation $H\rightarrow H/f(\vartheta)$ represents the scaling procedure.

Several scaling functions were proposed in the past, such as the simple $|\sin\vartheta|$ law, based on the idea that a highly layered material could be "magnetically transparent" to the component of the field parallel to the layers.[19] Different scaling functions can be obtained from early theories on the angular behavior of the upper critical field, according to the scaling approach. Considering the effective-mass model,[20] appropriate for an anisotropic (but continuous) material, the scaling function can be written as

$$f_{3D}(\vartheta)=\frac{1}{\sqrt{\sin^2\vartheta+\varepsilon^{-2}\cos^2\vartheta}}\ , \quad (1)$$

where $\varepsilon=H_{c2\parallel}/H_{c2\perp}$ is the anisotropy ratio. From the thin-film formula,[14] appropriate for a stack of separated superconducting layers whose (finite) thickness is less than the out-of-plane coherence length, one obtains

$$f_T(\vartheta)=\frac{1}{2\varepsilon^{-2}\cos^2\vartheta}\left[\sqrt{\sin^2\vartheta+4\varepsilon^{-2}\cos^2\vartheta}-|\sin\vartheta|\right]\ . \quad (2)$$

with the same meaning of the symbols.

Instead of applying a specific function in the examination of the data, we decided to leave $f(\vartheta)$ as a free scaling parameter, and then to examine the characteristic features of the obtained point-defined function. A typical scaling is presented in Fig. 2 (inset). As it is clearly visible, a perfect scaling takes place even for low angles. By contrast, the simple $|\sin\vartheta|$ scaling[19] (main panel) breaks down even for angles as far as 7° from the $H\parallel(a,b)$ configuration. Thus, it can be considered a good approximation for large angles only. We stress that our sensitivity in the measurements and in the scaling procedure is high enough to state that the obtained scaling is different from the $|\sin\vartheta|$ law.

In Fig. 3 we report the scaled curves for the temperatures under investigation, in the entire accessible field range. Every curve is the superposition of seven field sweeps, taken at seven different angles. As it can be seen, at all temperatures investigated, angular scaling takes place. This figure represents the main experimental result of this paper, demonstrating the angular scaling for the high-frequency dissipation in $Bi_2Sr_2CaCu_2O_8$. As it is apparent, the scaling is perfect over the entire accessible field range, from very low fields (~ 1 G) up to 14 kG, spanning a four-decades interval.

We stress that the scaling is applied directly to the raw experimental data: neither a model for the dissipation nor a model for the detailed type of anisotropy is assumed. By contrast, it is possible to obtain information about the possible details of the dissipation and the anisotropy from the features of the scaling here presented.

First of all, it is noteworthy that the scaling takes place

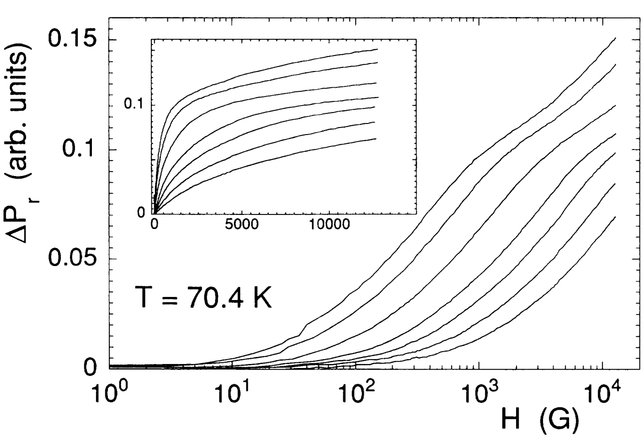

FIG. 1. Microwave dissipation at 70.4 K, sample I, for several angles between the field direction and the (a,b) plane. From top to bottom: $\vartheta=90°$, 37°, 17°, 7°, 4°, 2°, 1°. All the curves are parallel to each other on a log scale for the field (main panel), which indicates that a scaling $H\rightarrow H/f(\vartheta)$ is taking place.

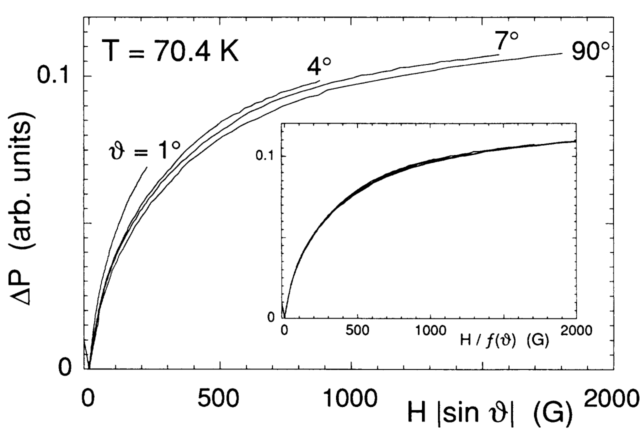

FIG. 2. Plot of some of the data of Fig. 1 versus the orthogonal field component: the $|\sin\vartheta|$ scaling (Ref. 19) breaks down even for relatively large ($\vartheta=7°$) deviations from the $H\parallel(a,b)$ configuration. Inset: all data from Fig. 1, versus the scaled field $H/f(\vartheta)$ as proposed in the text. As can be seen, all the data collapse onto a single curve. The abscissa axes are limited to 2000 G in order to emphasize the details of the scaling.

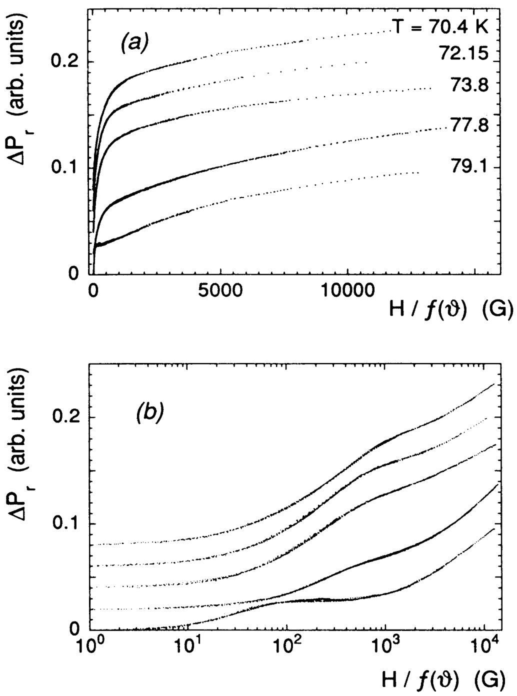

FIG. 3. Scaled data for different temperatures over the accessible field range: (a) lin-lin scale; (b) log-lin scale. Each curve consists of the collapse of seven different curves (for the same angles as those in Fig. 1). All the data belong to sample I except for the curves at 77.8 K (sample II). The curves are artificially offset vertically to avoid crowding.

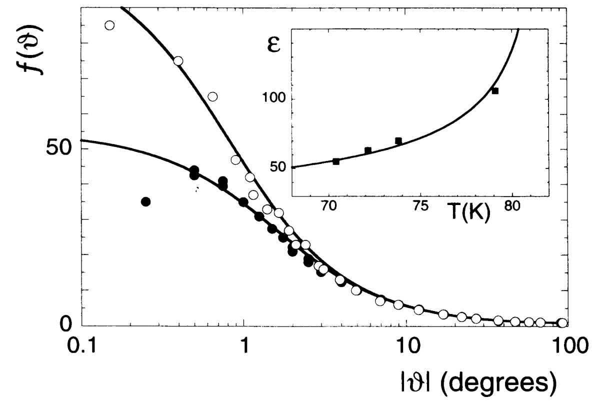

FIG. 4. Scaling functions $f(\vartheta)$ for $T=70.4$ K (full dots) and 79.1 K (empty circles). Continuous lines are the fits by Eq. (2) with ε as a free parameter. Apart from orientations very close to $\vartheta=0°$, not reported, the quasi-2D prediction is fully verified. It is to be noted that the anisotropy *increases* with increasing temperature, consistent with the prediction for the quasi-2D, thin-film case. In the inset, we plot the ε data vs T for sample I (full squares). The continuous line is the best fit with the thin-film prediction, with $T_c=82$ K, in reasonable agreement with the dc resistive transition data.

in the microwave regime: the microwaves probe the whole surface of the sample, and consequently if the total dissipation arises from several mechanisms, they are simultaneously observed in the resulting $P_r(H)$ curves. In principle, it would be expected to have a different angular behavior for each mechanism. Our result does not support this view: the existence of the scaling is a constraint for any proposal of a dissipative mechanism for the surface resistance, because a dissipation model *must* contain the indication that the angular dependence of the dissipation is given simply by an appropriate normalization of the field, $H \rightarrow H/f(\vartheta)$: it must then be expressed in the form $P_r(H,\vartheta)=P_r[H/f(\vartheta)]$. Moreover, $f(\vartheta)$ is the same in a very extended field region. This is a hint to search for a unified description of the high-frequency dissipation, from low to quite high fields, in $Bi_2Sr_2CaCu_2O_8$. We also note that the scaling takes place in samples grown on different substrates, so that it does not seem to be affected by the microscopic details (pinning centers, defects, impurities). This fact suggests that the dissipation is due to intrinsic factors, instead of sample-dependent details. This is only a qualitative argument, and in order to prove it, several different samples should be tested.

Secondly, the analysis of the angular scaling functions we have obtained, provides information on the anisotropy. To this aim we shall examine more closely the angular functions obtained from the scaling. The scaling functions at two temperatures for sample I are reported in Fig. 4. There exists an anomalous dissipation, more evident at lower temperatures, close to $\vartheta=0°$, which causes a depression of $f(\vartheta)$. This feature has already been found in $Bi_2Sr_2CaCu_2O_8$ in the measurements of the high-current-density resistivity,[1] critical currents,[7] and surface resistance,[9] but up to now it is still unexplained. A detailed experimental characterization of this effect has been given previously.[9] However, such anomalous dissipation does not affect the scaling. For our purposes, the relevant effect is the deformation of the scaling function in the range $|\vartheta|<0.5°$, and consequently, we will compare the theoretical scaling function to the data for $\vartheta \geq 0.5°$ only. The second important feature is that the scaling function increases its height with increasing temperature: the anisotropy *increases* with the temperature. This experimental fact rules out a description of the anisotropy in terms of effective-mass model, because in the latter ε does not depend on T. By contrast, in the Tinkham thin-film formula ε *does* depend on T, and diverges at T_c with power $\frac{1}{2}$, $\varepsilon \sim (1-T/T_c)^{-1/2}$. We would have obtained satisfying fits also with Eq. (1), but the increase of ε with the temperature is not consistent with the effective-mass model.

We then fit the scaling functions obtained experimentally by Eq. (2), with ε as a free parameter (we must leave ε free because of the anomalous dissipation at $\vartheta=0°$). The fits are very satisfying in the range $\vartheta \geq 0.5°$. The resulting anisotropy ratio values increase with T, as predicted by the thin-film model. In Table I we report the values of the anisotropy ratio ε obtained from the fits of the angular scaling functions, showing the T dependence. As expected for $Bi_2Sr_2CaCu_2O_8$, large values of ε have been obtained. The inset of Fig. 4 shows the comparison between the ε data for sample I and the thin-film predic-

TABLE I. Data for the anisotropy ratio ε as a function of the temperature, as obtained from the scaling procedure. ε increases with T, revealing the 2D nature of $Bi_2Sr_2CaCu_2O_8$.

	T (K)	ε
Sample I	70.4	55
	72.15	63
	73.8	70
	79.1	106
Sample II	77.8	26

tion.

In principle, the anisotropic properties of the dissipation may depend on the intrinsic anisotropy of the material and on the orientational structure of the pinning centers. However, our result that the experimental data exhibit scaling behavior through a scaling function related only to the intrinsic anisotropy seems to indicate that the effects of the pinning are isotropic. A similar conclusion can be drawn by the observation that columnar defects induced in $Bi_2Sr_2CaCu_2O_8$ do not vary the shape of the angular dependence of the critical currents.[21]

We remark that the scaling procedure takes place only if *the same* scaling function applies in the field range under study: we expect a breakdown of the scaling for T extremely close to T_c, where the divergence of the out-of-plane coherence length gives rise to a dimensional crossover,[4] and the corresponding $f(\vartheta)$ is found to depend on the field strength.[5]

In conclusion, we have performed measurements of the microwave dissipation at 21 GHz in two $Bi_2Sr_2CaCu_2O_8$ epitaxial films, as a function of the magnetic field for several field orientations. The measurements were repeated at different temperatures. All the angular measurements collapse over the corresponding orthogonal-field curve by an experimentally determined scaling function, without any need for a dissipation model. This result represents experimental evidence for the scaling of the dissipation, even in the high-frequency limit. From the existence of the angular scaling, some constraints on the possible dissipation mechanisms are given. The angular scaling function is identified with the thin-film formula, which predicts increasing anisotropy with increasing temperature, as observed. Our results strongly support the scaling approach[13] in $Bi_2Sr_2CaCu_2O_8$, also for the transport properties at high frequency.

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