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ORIGINAL PAPER

Broadband Microwave Measurements of Overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ Films Using Corbino Geometry

E. Farber · N. Bachar · D. Lavi · H. Castro · Y.-J. Chen · K.H. Wu · J.Y. Juang

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Abstract The surface impedance of $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ thin films was measured using the Corbino spectroscopy method. This special geometry, in which the sample dimensions are well defined by a ring pattern, is ideal for broadband high frequency reflection measurements. Using the complex reflected signal, S_{11}, measured by a vector network analyzer, one can find the surface impedance of the thin film, from which the complex conductivity can be deduced. In the current work we present the three-standard approach for calibration of the Corbino method and demonstrate the benefits of this approach in measuring superconducting $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ thin films up to 20 GHz and down to 6 K. For the data analysis the well-known generalized two-fluid model was implemented, taking into account a film thickness which is much smaller than the normal state skin depth and superconducting penetration depth.

Keywords Superconductor · Microwave · Corbino

E. Farber (✉) · N. Bachar · D. Lavi
Laboratory for Superconductivity and Optical Spectroscopy, Ariel University Center of Samaria, Ariel 40700, Israel
e-mail: e.farber@ariel.ac.il

N. Bachar
School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel

H. Castro
Physics Department, National University of Colombia, Bogota, Colombia

Y.-J. Chen · K.H. Wu · J.Y. Juang
Department of Electrophysics, National Chiao Tung University, Hsinchu 300, Taiwan

1 Introduction

Microwave measurements of the surface impedance, $Z(T,\omega)$, in high-T_c superconductors reflect the quasiparticle and Cooper pair electrodynamics. Surface impedance is perhaps the most important technical parameter determining the application potential of superconductors for high frequency passive and active devices [1]. From a microscopic aspect, high precision measurements of $Z(T,\omega)$ advance our understanding of pairing symmetry in these materials [2, 3]. The surface impedance real part is related to quasiparticle excitations, while the imaginary part indicates superfluid density.

In the current research we used the Corbino method in a wide frequency range up to 20 GHz, in contrast to a resonance method where a small frequency bandwidth is employed. This method was used to measure Ca-doped YBCO thin films grown by off-axis DC sputtering. The films were overdoped and known to have an increased critical current due to their large-angle grain boundaries [4], and therefore can be good candidates for microwave applications.

2 Experimental Method and Calibration

Overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ c-axis oriented thin films with $T_c = 88$ K were grown to a thickness of 1000 Å using off-axis magnetron sputtering.

The Corbino method implemented in the current research to measure the surface impedance of these films is a broadband method in contrast to the widely used microwave cavities, which are implemented around a single base frequency. Scheffler and Dressel reviewed the use of the Corbino method to measure the real and imaginary parts of the conductivity in UPd_2Al_3 [5]. The Corbino method was implemented by a semi-rigid cable, 1.5 meter long and 2.2 mm

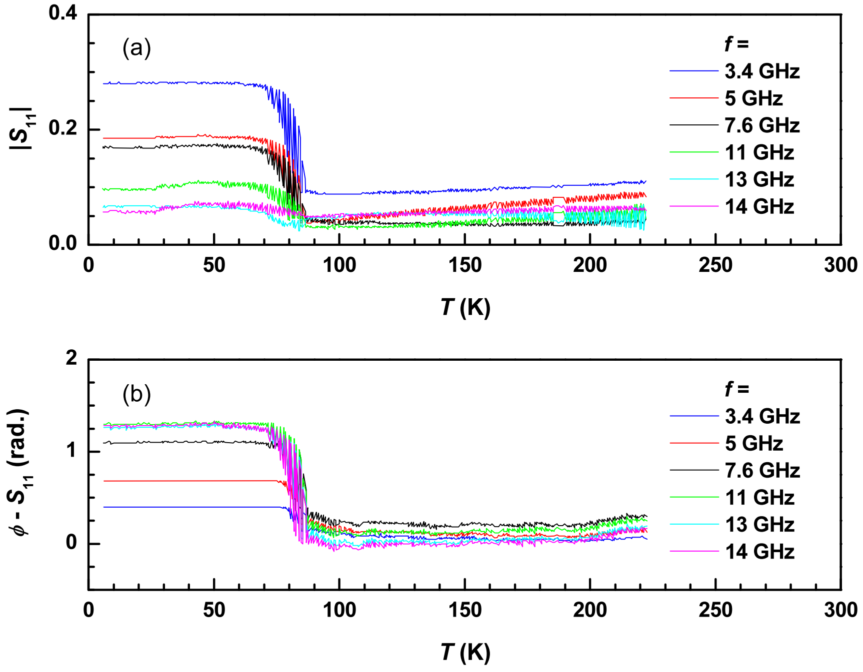

Fig. 1 (**a**) Uncalibrated magnitude of S_{11} and (**b**) phase of S_{11} for overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ films as a function of temperature

(0.085″) in diameter, with a characteristic impedance of 50 Ω and a cutoff frequency of 61.7 GHz. The semi-rigid cable was connected at one end to an HP 8510C vector network analyzer and at the other end to the sample holder. The sample holder was made of a modified V-101F connector. The cable and its sample holder were inserted into an ARS-DE202 closed cycle cryocooler.

A superconducting, gold-coated film was used to terminate the coaxial transmission line. An 800 nm thick gold layer was evaporated onto the film with a homemade rotating disk-shaped mask, in order to create the Corbino inner and outer contact geometry. The inner contact diameter is approximately 0.3 mm, while the outer contact diameter is about 1.9 mm. Above T_c the conductivity of gold is much larger than the conductivity of the superconducting material in our frequency range. Below T_c, the conductivity of gold is smaller than the conductivity of the superconducting material, but the resistivity of the contacts is still very small and therefore can be neglected. The substrate of the superconducting film is held from the back by a loaded spring. The outer gold ring on the superconducting film is connected directly to the V-101F connector, while the inner gold point contact is connected to a pogo pin mounted on the central semi-rigid cable conductor.

The thin film surface impedance is analyzed by using the S_{11} parameter, $S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0}$, where Z_L is the load impedance terminating the transmission line and Z_0 is the characteristic impedance of the transmission line. It can be defined by the ratio of voltage to current across the Corbino disk, which depends on the dimensions of the Corbino disk. Assuming a transverse electromagnetic (TEM) mode, S_{11} can be related to the film surface impedance, $Z_s = \frac{2\pi(1+S_{11})}{\ln(\frac{b}{a})(1-S_{11})} Z_0$, assuming $Z_L = Z_s \ln(b/a)/2\pi$, where a and b are the inner and outer radii of the Corbino disk, respectively [5].

One of the main problems in this type of measurement results from the fact that the measured S_{11} is a combination of various reflections in the system, like those from the microwave connectors and other mismatched impedances along the RF path. Moreover, since the semi-rigid cable connects the network analyzer at room temperature and the sample in the cryocooler, a special calibration and error handling model had to be applied in order to deal with sample independent errors [6, 7].

The actual reflection coefficient S_{11a} and measured coefficient S_{11m} are related by $S_{11m} = E_D + \frac{E_R S_{11a}}{1 - E_S S_{11a}}$ where E_R, E_D, and E_S are three complex coefficients measured in the calibration process [7]. These coefficients are obtained by using the well-known three-standard calibration process: open, short, and 50 Ω. In the present study 30 Ω NiCr thin film was used.

3 Experimental Results and Discussions

Figure 1 shows the complex reflection coefficient of the overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ thin film before the calibration procedure was implemented. It clearly shows a large change in amplitude and phase of S_{11} when a superconducting gap opens at $T_c = 88$ K for these overdoped thin films. These changes in amplitude and phase are larger by

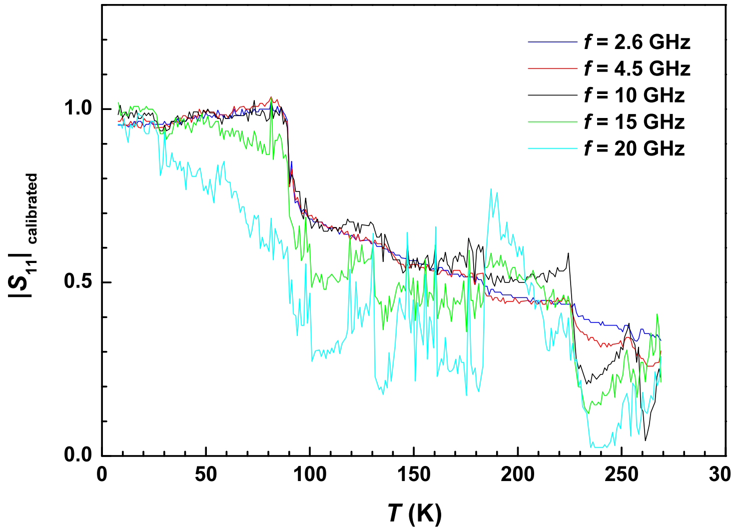

Fig. 2 Magnitude of calibrated S_{11}, for various frequencies, as a function of temperature for the overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ films

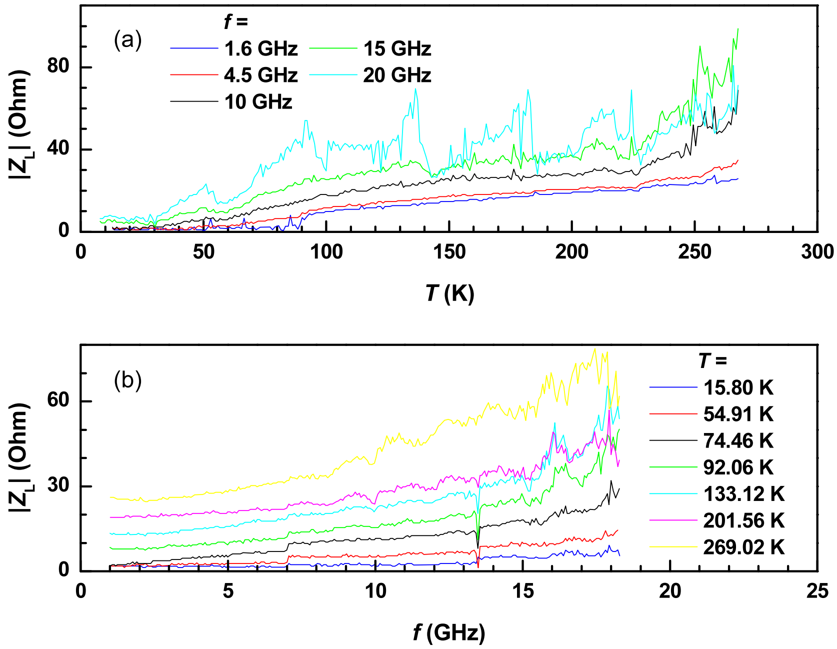

Fig. 3 Magnitude of surface impedance, after calibration, for overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ films (**a**) as a function of temperature and (**b**) as a function of frequency

a factor of two than those observed for optimally doped $YBa_2Cu_3O_{7-\delta}$ thin films grown with the same method [7].

Figure 2 shows the reflection coefficient after calibration. One can clearly see the reflection from the superconducting thin film below T_c, i.e., $|S_{11}| = 1$. In this case the phase shift equals 180 degrees. Above 15 GHz the calibration is poor, which leads to noisy measurement.

Figure 3 shows the magnitude of the surface impedance as a function of temperature and frequency and the decrease of the surface impedance as a function of temperature for various frequencies. Once the frequency is lowered, the surface impedance decreases as expected. The surface impedance as a function of frequency shows a linear dependence below T_c, indicating a reactive-inductance frequency dependence as expected. These results are consistent with the two-fluid model with $\sigma_1(\omega) \sim$ constant and $\sigma_2(\omega) \sim 1/\omega$, where $\omega\tau \ll 1$ in our frequency range. When using the two-fluid model analysis applied in the superconducting state, it is assumed that the scattering rate is frequency independent.

Above T_c the contribution to $Z_s(\omega)$ comes mainly from the substrate; therefore, the overall magnitude increases, starting from the lowest frequency.

The complex conductivities were deduced from the complex impedance from which the superconducting penetration depth and the normal state skin depth were calculated [8, 9]. The penetration depth shows a behavior which is almost frequency independent, consistent with surface impedance frequency dependence, indicating $\omega\tau \ll 1$ where the normal state skin depth shows the well-known $\omega^{1/2}$ behavior.

4 Conclusions

Corbino broadband microwave measurements were implemented to measure overdoped $Y_{0.9}Ca_{0.1}Ba_2Cu_3O_{7-\delta}$ thin films. Reflection measurements reveal a larger change in S_{11} in comparison to optimally doped films, which can be attributed to a larger impedance in the superconducting state due to Ca doping. We observed a larger phase shift in comparison to optimally doped films, which is presumably due to a larger density of carriers in the overdoped regime. The surface impedance in the superconducting phase shows a linear frequency dependence, where the penetration depth is frequency independent, indicating a large scattering rate due to Ca doping.

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