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Measuring the microwave response of superconductors: broadband Corbino and resonant stripline techniques

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Abstract **– Superconducting materials are of great interest both for the fundamental understanding of electrons in solids as well as for a range of different applications. Studying superconductors with microwaves offers a direct experimental access to the electrodynamic response of these materials, which in turn can reveal fundamental material properties such as the superconducting penetration depth. Here we describe two different techniques to study superconductors at microwave frequencies: the broadband Corbino approach can cover frequencies from the MHz range up to 50 GHz continuously but is limited to thin-film samples whereas the stripline resonators are sensitive enough to study low-loss single crystals but reveal data only at a set of roughly equidistant resonant frequencies. We document the applicability of these two techniques with data taken on an ultrathin TaN film and a single crystal of the heavy-fermion superconductor $CeCu_2Si_2$, respectively.**

I. INTRODUCTION

Superconductivity belongs to the most intensively studied phenomena of solid state physics. This research is driven both by the interest to gain fundamental understanding of electronic properties of solids and the aim to establish new applications of superconductors or to improve the existing ones. Both fields require experimental techniques to measure the characteristic material properties that characterize a superconductor. While certain “static” approaches like measuring the dc resistivity, the dc magnetization, or the specific heat are routine approaches in the material development and characterization of superconductors, electrodynamic experiments are much less common. In this contribution, we first motivate why microwave studies are particularly helpful in superconductivity research and then we present two complementary techniques, the broadband Corbino approach and the multi-frequency stripline resonators, that we have implemented successfully to study different types of superconductors using microwaves.

A. Optical response of superconductors

Though microwave experiments are technically performed in a very different manner compared to conventional optics, the actual outcome is rather similar: one probes the electrodynamics of the sample under study. Therefore, we briefly review the optical response of superconductors with a special focus on microwave frequencies [1].

The crucial energy scale of the optical response of a superconductor is the superconducting energy gap Δ that in the case of a weak-coupling BCS superconductor is related to the critical temperature T_c via $2\Delta = 3.53\ k_B\ T_c$. With typical T_c of the order of a few K, the energy gap is found in the range of μeV to meV, i.e. up to THz frequencies. This means that at microwave frequencies one operates well within the superconducting energy gap and therefore probes the response of the superconducting ground state of the material.

At these frequencies, two types of charge carriers contribute to the electrodynamics: firstly, there are the Cooper pairs that constitute the superconducting condensate, the fundamental manifestation of superconductivity. Secondly, there are thermally excited quasiparticles that are lossy (i.e. Ohmic with respect to conduction) like conventional metallic electrons, but that do now show up in dc resistance measurements because they are short-circuited by the loss-less Cooper pairs. Microwave measurements probe both kinds of electrons: the quasiparticles determine the real part σ_1 of the complex conductivity $\sigma = \sigma_1 + i\ \sigma_2$ whereas the Cooper pairs dominate the imaginary part σ_2. In particular, σ_2 exhibits a $1/\omega$ frequency dependence ($\omega = 2\pi f$), which can be explained via Kramers-Kronig transform of the $\delta(\omega)$-peak of the Cooper pairs in σ_1. The magnitude of the $1/\omega$ dependence directly depends on the Cooper pair density, which in turn is related to the superconducting penetration depth.

B. General aspects of optical and microwave measurements

Optical measurements are contact-less and usually only demand a sample significantly bigger than the wavelength, i.e. typically of size of order mm and with at least one flat surface. Compared to other spectroscopic techniques, these requirements can often be met rather easily. However, in the case of conducting samples, the crucial question is whether the sensitivity of a particular optical technique is sufficient to resolve the features of interest. In particular for superconductors, this is a stringent restriction as the optical reflectivity of a bulk superconductor is very close to unity and therefore is extremely difficult to study even with state-of-the-art optical spectrometers of the relevant spectral range, i.e. typically at THz and/or infrared frequencies. At microwave frequencies, the situation is in principle even more difficult, as the lower frequency of the employed radiation directly means reflectivity yet closer to unity. However, because of the rather long wavelength of microwave radiation, typically of order cm, the employed experimental techniques do not follow optical routines, but are intrinsically different ones where the sample as well as the guides for the microwave radiation are smaller than the wavelength. I.e. although the fundamental physics of the microwave response of superconductors follows the theory of "optics of superconductors", the experiments are rather different than a conventional optics approach.

II. MICROWAVE MEASUREMENTS ON SUPERCONDUCTORS

A very well established and very versatile technique to study the microwave properties of conducting materials are cavity resonators [2]. Here, a three-dimensional conducting cavity has dimensions of order of the wavelength, and the sample under study acts as a small perturbation. The major disadvantages of this technique are that it is usually operated only at a single frequency (i.e. one does not gain any spectral information) and that it is difficult to obtain quantitative information due to the - in general - poorly defined geometry (whereas relative information, e.g. as a function of temperature, is obtained easily).

Therefore, different new experimental techniques have been devised. These can be roughly divided into two classes: firstly, truly broadband techniques that cover the full frequency dependence. Here two approaches have been applied to the study of superconductors, namely the Corbino approach [3,4] and the bolometric approach [5]. The main difference in their capabilities is that the Corbino approach reveals phase information (giving amplitude and phase of the response) but has a rather poor sensitivity, whereas the bolometric approach is very sensitive but does not reveal phase information. The second family is based on resonators that can be operated at several frequencies. While our approach below is based on one-dimensional transmission line structures, namely superconducting stripline resonators [6,7], a three-dimensional resonator with a dielectric resonator in its core has recently also been established successfully [8].

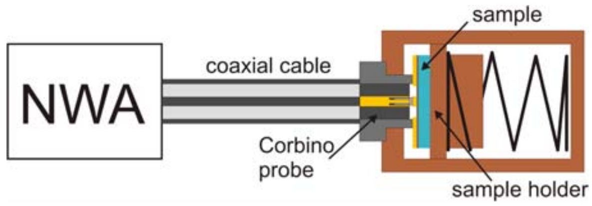

Fig. 1. Scheme of a Corbino spectrometer. The network analyzer (NWA) measures the reflection coefficient of the microwave signal that travels in the coaxial cable and is reflected by the sample.

III. BROADBAND CORBINO SPECTROSCOPY

In Corbino spectroscopy, the flat sample terminates the open end of a coaxial cable (schematically shown in Fig. 1). In this way, the sample reflects the microwave signal traveling in the coax, and the reflection coefficient S_{11}, which can conveniently be measured with a network analyzer, then directly yields the impedance Z_L of the sample via the following relation (with Z_0 = 50 Ω the characteristic impedance of the coaxial cable):

$$Z_L = Z_0 \frac{1+S_{11}}{1-S_{11}} \tag{1}$$

While this approach is commonly used at room temperature and in particular in the study of dielectrics [9], it is much more difficult for the case of superconductors. This is due to the elaborate calibration procedure that has to be applied to correct for the strongly temperature-dependent transmission properties of the coaxial cable [3,4]. Different groups have come up with different schemes how this challenge can be met most successfully. It turns out that the best approach can differ drastically depending on the particular goal. In contrast to groups that concentrate on detailed studies of a single sample (or a selected few) [10], we have focused on a procedure that allows a high throughput combined with rather low temperature. Presently, we operate a Corbino spectrometer with one cooldown per day, base temperature of 1.1 K (in a ^{4}He cryostat), frequency range 45 MHz to 50 GHz, and two samples measured during each cooldown. With this rate, we can easily study extended sets of samples. Current examples are NbN and TaN thin films as a function of deposition parameters. Ultrathin films of these materials with thicknesses about 5 nm or even smaller are interesting both for applications in superconducting single-photon detectors [11,12] as well as for understanding of the so-called superconductor-to-insulator transition (SIT) [13,14]. The

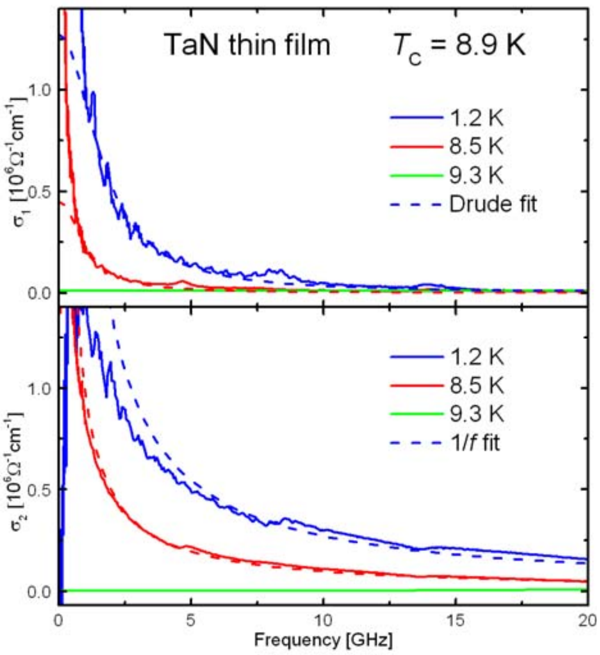

Fig. 2. Microwave conductivity spectra of a TaN thin film, measured with a Corbino spectrometer.

typical critical temperatures of these materials are of order 5 K to 10 K, and as a result the energy gap is located in the THz frequency range, much higher than accessible with Corbino spectroscopy. However, for such ultrathin films, THz transmission measurements are easily possible and can directly determine the energy gap, whereas these studies usually have difficulties to resolve quasiparticle dynamics at the low-frequency limit of their spectral range [1,15]. Therefore, the combination of Corbino spectroscopy at GHz frequencies and THz transmission measurements is an ideal match to study the complete charge dynamics in superconductors, if the materials are available as very thin films.

If a conductive thin sample is studied in Corbino spectroscopy and if the microwave fields and current density are uniform through the sample thickness (which usually is the case for conductive thin films of thickness up to several tens of nm), the complex conductivity of the sample can directly be calculated from the sample impedance Z_L as follows:

$$\sigma = \frac{\ln(a_2 / a_1)}{2\pi d Z_L} \qquad (2)$$

Here d is the thickness of the sample and a_1 and a_2 are the inner and outer diameters of the Corbino disk, respectively.

In Fig. 2 we show typical microwave spectra, both real and imaginary parts of the conductivity, for a TaN film of thickness 5 nm. For temperatures above the critical temperature T_c = 8.9 K, the real part σ_1 is frequency independent and the imaginary part σ_2 basically vanishes, as expected for a conventional metal at GHz frequencies. Below T_c, σ_1 rises strongly upon cooling. Our frequency range is well below the energy gap, and therefore σ_1 is not suppressed yet compared to the normal-state value even for the lowest temperature of 1.2 K [16]. The detailed frequency dependence reflects the density of states in the superconducting state and can phenomenologically be fitted with the Drude formula over a substantial frequency range [16]. Also σ_2 increases strongly upon cooling below T_c, and its characteristic $1/f$ frequency dependence gives direct access to the Cooper pair density and the penetration depth [1,16]. Corbino spectroscopy at ^{4}He temperatures is thus well suited to study thin films of superconductors with T_c of 1.5 K and higher.

Considering that for many spectroscopic studies one desires the photon energy in a similar range as the thermal energy, we have also implemented a Corbino setup at ^{3}He temperatures [17]. Here the requirements for the calibration of the microwave coaxial cable in principle are even more stringent, but since in our laboratory we have a ^{4}He Corbino spectrometer well established, we limit our ^{3}He spectrometer to the temperature range 0.45 K to 2.0 K, and we can use the overlap in temperature with the ^{4}He setup for additional calibration purposes.

All our studies mentioned so far, as well as Corbino experiments on superconductors by other groups [10,16-21], are limited to thin-film samples (thickness of a few tens of nm or less). The reason is the limited sensitivity of Corbino spectroscopy [4]. But this is no restriction if the superconductor of interest can be prepared as thin films with the same material properties as the more commonly studied bulk samples or if the particular properties of interest only become manifest in thin films, like the SIT.

IV. SUPERCONDUCTING STRIPLINE RESONATORS

Many unconventional superconductors, which are the topic of present research, are not available as thin film samples and as such not accessible with microwave Corbino spectroscopy. Many of these are ternary, quaternary, or even more complex intermetallics, and growth of high-quality thin films is extremely demanding [22-24]. Furthermore, T_c of unconventional superconductors is often suppressed if the mean free path of the conduction electrons is reduced, and then the small thickness of thin films can be an intrinsic limitation to superconductivity in these materials. To still be able to study these materials with microwaves as a function of frequency, we have developed a resonant technique for bulk samples that can be operated at numerous, roughly equidistant frequencies.

The general idea is that in a transmission line structure based on a stripline (also called triplate) one of the ground planes, which surround the signal-carrying center strip, can be formed by the conducting bulk material of interest. To be sensitive to low-loss samples, the stripline is created as a one-dimensional transmission line resonator, which has a fundamental frequency typically between 1 GHz and 3 GHz (depending on sample size) and which can easily be excited at numerous harmonics, i.e. one obtains a set of data at roughly equidistant frequencies, spanning a range up to approximately 15 GHz at present. Particular care has to be taken in the choice of the center conductor material: here, the density of the microwave currents are an order of magnitude larger than in the ground planes, and therefore the overall losses of the stripline first of all depend on the center conductor. If we want to study a superconductor as ground plane, this means that the center conductor has to be fabricated from a thin film of an even "better" superconductor, i.e. one with even lower microwave losses at low temperatures. In general, such very low losses can be achieved if the resonator is operated at temperatures well below T_c, i.e. materials with a high T_c are desirable. However, the materials should be conventional *s*-wave superconductors, as superconductors with nodes have much higher losses at low temperatures due to the larger amount of thermally excited quasiparticles. This restriction excludes the high-T_c cuprate superconductors, which are *d*-wave, from this application. Therefore, we fabricate our stripline resonators either from Nb or Pb thin films [25].

While we originally implemented this technique to study unconventional metals, such as heavy fermions with their peculiar microwave properties [26-31], it turned out that this technique is also well capable to study bulk superconductors if their T_c is lower than that of the stripline material [7]. After test measurements on the conventional elemental superconductors Ta and Sn [7], we now apply it to the unconventional heavy-fermion superconductor $CeCu_2Si_2$ [32]. While $CeCu_2Si_2$ was long believed to be a *d*-wave superconductor [33], recent studies instead suggest that it is a two-gap *s*-wave superconductor [34]. This question is of particular interest as it is related to the possible pairing mechanism for superconductivity, which is thought to be of magnetic nature in $CeCu_2Si_2$ [35]. One possibility to address whether a superconductor has an order parameter with nodes or not is measure the temperature dependence of its penetration depth. This can be done with microwaves.

So far, no microwave studies on $CeCu_2Si_2$ have been reported. One difficulty here is the rather low T_c of around 0.6 K. While this temperature can be reached with ^{3}He cryostats, a detailed study of the penetration depth requires a base temperature of order $T_c/10$ or lower, i.e. one has to employ a ^{3}He/^{4}He dilution refrigerator. Here, another advantage of our stripline probe comes into play: its physical dimensions are much smaller than the fundamental wavelength, as this one-dimensional resonator can be shaped as a meander. As a result, the typical mounting of resonator and sample amounts to just a few cm^3, a volume that can easily be incorporated in a commercial dilution refrigerator. Furthermore, the microwave signals are guided from the room-temperature electronics to the cryogenic probe and back via coaxial cables, which is much more generic than waveguides that are often used for three-dimensional cavity resonators. Therefore, the stripline resonator is a widely applicable, very sensitive technique to study the microwave response of superconductors. In contrast to many other resonator approaches, here it is rather simple to obtain data at several different frequencies, i.e. spectral information. While for addressing the penetration depth, which in this range basically is frequency independent, a single resonator frequency might be sufficient, there are other questions of interest, such as the quasiparticle dynamics, where data as a function of frequency are crucially required. These frequency dependences are usually broad, and therefore the rather restricted spectral resolution of order 1 GHz is sufficient, whereas the truly broadband Corbino approach has a much better frequency resolution that can also reveal narrow spectral structures.

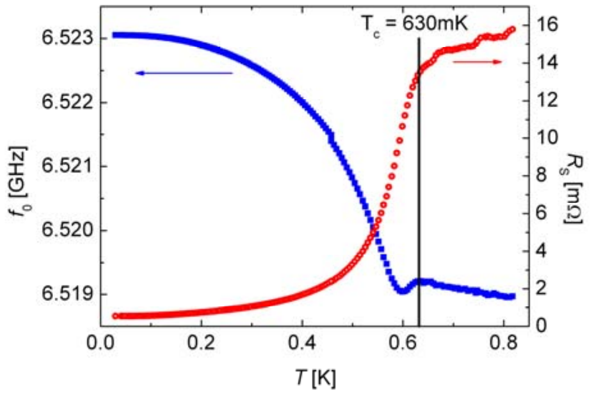

Fig. 3. Temperature dependence of stripline resonator frequency f_0 and sample surface resistance R_s measured on a $CeCu_2Si_2$ single crystal sample.

As a demonstration for mK measurements using a stripline resonator, in Fig. 3 we show data obtained on a $CeCu_2Si_2$ single crystal. When cooled below T_c, the surface resistance R_s decreases strongly due to the reduction of microwave losses. At the same time, the resonator frequency f_0 increases because of the decreasing penetration depth. Above T_c, in the metallic heavy-fermion state, both R_s and f_0 are also temperature dependent, even for these low temperatures below 1 K. This indicates that the electronic conduction is governed by intrinsic scattering mechanisms (in contrast to impurity scattering), and it shows promise for future studies of the microwave response of heavy fermions in the normal state of $CeCu_2Si_2$, an interesting field of study on its own [26-31].

V. CONCLUSIONS

We have discussed why microwave measurements on superconductors are powerful tools to understand their electrodynamics and to obtain detailed information about fundamental characteristics of superconductivity, such as the temperature-dependent penetration depth. In recent years, several groups have developed new techniques for cryogenic microwave spectroscopy. While the Corbino approach is particularly popular and offers the possibility to cover a very large frequency range completely, it is limited to the study of very thin films. As an alternative, we have established a rather different technique, which are stripline resonators where the bulk sample of interest is one ground plane of the stripline. With these two approaches available, we can cover a very large range of superconducting materials and address their microwave properties both for fundamental research as well as for materials optimization for applications.

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