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Determination of the density of states in high-T_c thin films using FET-type microstructures

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Abstract. A simple electronic experiment using a field-effect-transistor–type microstructure is suggested. The thin superconductor layer forms the source-drain channel of a layered structure across which an AC current is applied. It is found necessary to measure the second harmonic of the source-gate voltage, and the third harmonic of the source-drain voltage; these electronic measurements then give the logarithmic derivative of the density of states, which is an important consideration when fitting parameters of the band structure.

PACS. 74.78.-w Superconducting films and low-dimensional structures – 71.20.-b Electron density of states and band structure of crystalline solids – 74.78.Bz High-Tc films – 73.50.Lw Thermoelectric effects

1 Introduction

The importance of the density of states (DOS) in the physics of high-T_c cuprates has been discussed in many papers [1–10] The purpose of the present work is to suggest a simple electronic method for determination of the DOS. The proposed experiment requires the preparation of a field-effect transistor (FET)-type microstructure, and involves standard electronic measurements. The FET controls the current between two points, although in a different manner than when using a bipolar transistor. The FET relies on an electric field to control the shape, and hence the conductivity, of a "channel" in a semiconductor material. The shape of the conducting channel in a FET is altered when a potential difference is applied across the gate terminal (this potential being relative to either the source or the drain). This causes the flow of electrons to change in width, and thus controls the voltage between the source and the drain. If the negative voltage applied to the gate is sufficiently high, it can remove all of the electrons from the gate, and hence close the conductive channel in which the electrons flow, blocking the FET.

The system considered in this work operates in a hydrodynamic regime; that is, a low-frequency regime wherein the temperature of the superconducting film adiabatically follows the dissipated ohmic power. All of the working frequencies of the lock-ins (up to, say, 100 kHz) are low enough to lie within this regime. Investigations on superconducting bolometers have shown that it is only necessary to take into account the heat capacity of the superconducting film when operating in the MHz range. See, for example, reference [11] and references therein. In the present work, we propose an experiment involving a FET for which we need to measure the second harmonic of the source-gate voltage and the third harmonic of the source-drain voltage. Other, higher harmonics will be present in the measurements (e.g. from the leads), which can in principle also be used for a determination of the density of states. An analogous experiment has already been performed for investigation of thermal interface resistance [12]. The experiment suggested here can be performed using essentially the same experimental set-up, equipment and a FET sample.

2 Determination of the logarithmic derivative of the density of states by electronic measurements

This paper aims to suggest a simple electronic experiment by which to determine the logarithmic derivative of the density of states by electronic measurements, using a thin film of the material Tl:2201. The thickness of the samples should be typical for the investigation of high-T_c films, say 50–200 nm. Such films are sufficiently thick to exhibit the properties of the bulk phase. The numerical value of the parameter

$$\nu'(E_F) = \frac{d\nu(\epsilon)}{d\epsilon}, \tag{1}$$

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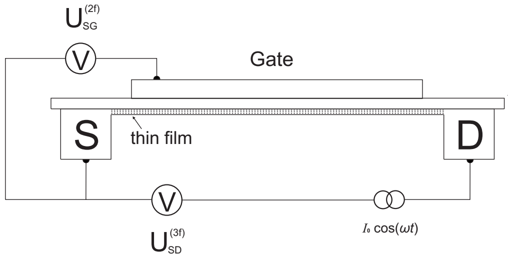

Fig. 1. Schematic illustration of a field-effect transistor (FET). The current $I(t)$ flowing between the source (S) and the drain (D) has a frequency ω. The electrons, as they run through the transistor, create a voltage U_{SG} between the source (S) and the gate (G). The source-gate voltage should be measured at doubled frequency 2ω, while source-drain voltage U_{SD} at tripled frequency 3ω.

gives the possibility for the absolute determination of the hopping integrals.

We propose a FET from Tl:2201 (Fig1) to be electronically investigated, with lock-in at the second and third harmonics. Let us consider a strip of Tl:2201, and between the ends of the strip (the source (S) and the drain (D)), apply an AC current

$$I_{\mathrm{SD}}(t) = I_0\cos(\omega t). \tag{2}$$

For sufficiently low frequencies, the ohmic power P causes the temperature of the film T to rise above the ambient temperature T_0, where

$$P = RI_{\mathrm{SD}}^2 = \alpha(T - T_0), \tag{3}$$

and the constant α determines the boundary thermoresistance between the Tl:2201 film and the substrate, and $R(T)$ is the temperature-dependent source-drain (SD) resistance. We assume that for thin films, the temperature is almost homogeneous across the film's thickness. In this way, we obtain for the temperature oscillations

$$(T - T_0) = \frac{RI_{SD}^2}{\alpha} = \frac{RI_0^2}{\alpha}\cos^2(\omega t). \tag{4}$$

Since the resistance is weakly temperature dependent,

$$R(T) = R_0 + (T - T_0)R_0{}', \quad R_0{}'(T_0) = \left.\frac{dR(T)}{dT}\right|_{T_0}. \tag{5}$$

Substituting in the temperature oscillations from equation (4) leads to a small time variation in the resistance:

$$R(t) = R_0\left(1 + \frac{R_0'}{\alpha}I_0^2\cos^2(\omega t)\right). \tag{6}$$

We can now calculate the source-drain voltage as

$$U_{\mathrm{SD}}(t) = R(t)I_{\mathrm{SD}}(t). \tag{7}$$

Substituting in the SD current from equation (2) and the SD resistance from equation (6) gives the SD voltage as

$$U_{\mathrm{SD}}(t) = U_{\mathrm{SD}}^{(1f)}\cos(\omega t) + U_{\mathrm{SD}}^{(3f)}\cos(3\omega t). \tag{8}$$

The coefficient of the first harmonic $U_{\mathrm{SD}}^{(1f)} \approx R_0 I_0$ is determined by the SD resistance R_0 at low currents I_0, while for the third-harmonic signal, the elementary formula $\cos^3(\omega t) = (3\cos(\omega t) + \cos(3\omega t))/4$ can be used to obtain

$$U_{\mathrm{SD}}^{(3f)} = \frac{U_{\mathrm{SD}}^{(1f)}}{4\alpha}I_0^2 R_0'. \tag{9}$$

From this formula, we can express the boundary thermoresistance by electronic measurements as

$$\alpha = \frac{U_{\mathrm{SD}}^{(1f)}}{4U_{\mathrm{SD}}^{(3f)}}I_0^2 R_0'. \tag{10}$$

Application of the method requires fitting of $R(T)$, and numerical differentiation at a working temperature T_0; linear regression is probably the simplest method if we only need to know one point.

At known α, we can express the time oscillations of the temperature by substituting in equation (4), i.e.

$$T = T_0 + \frac{RI_0^2}{2\alpha}(1 + \cos(2\omega t)) \approx T_0\left(1 + \frac{R_{\mathrm{SD}}I_0^2}{2\alpha T_0}\cos(2\omega t)\right). \tag{11}$$

Under this approximation, terms containing I_0^4 are neglected and the shift from the average temperature of the film is considered to be small.

The variations in the temperature lead to variations in the work function of the film, according to a formula well known from the physics of metals:

$$W(T) = -\frac{\pi^2}{6e}\frac{\nu'}{\nu}k_B^2 T^2, \quad \nu'(E_F) = \left.\frac{d\nu}{d\epsilon}\right|_{E_F}, \tag{12}$$

where the logarithmic derivative of the density of states $\nu(\epsilon)$ (taken at the Fermi energy E_F) has dimensions of inverse energy, the work function W has dimensions of voltage, T is the temperature in kelvins, and k_B is Boltzmann's constant. For an introduction, consult standard textbooks on statistical physics and on the physics of metals.[13,14]. Substituting in the temperature variations from equation (11) gives

$$W = -\frac{\pi^2 k_B^2}{6e}\frac{\nu'}{\nu}T_0^2\left[1 + \frac{R_0 I_0^2}{\alpha T_0}\cos(2\omega t)\right] + \mathcal{O}(I_0^4), \tag{13}$$

where $\mathcal{O}$-function indicates that the terms involving I_0^4 are negligible.

The oscillations in the temperature create AC oscillations in the source-gate (SG) voltage. We assume that a lock-in with a preamplifier, with sufficiently high internal resistance, is switched between the source and the gate. Under these conditions, the second harmonics of both the work function and the SG voltage are equal, i.e.

$$\begin{aligned} U_{\mathrm{SG}}^{(2f)} &= -\frac{\pi^2 k_B^2}{6e}\frac{\nu'}{\nu}T_0^2\frac{R_0 I_0^2}{\alpha T_0}, \\ U_{\mathrm{SG}}(t) &= U_{\mathrm{SG}}^{(2f)}\cos(2\omega t) + U_{\mathrm{SG}}^{(4f)}\cos(4\omega t) + \ldots \end{aligned} \tag{14}$$

Substituting in α from equation (10), we have

$$U_{\mathrm{SG}}^{(2f)} = -\frac{4\pi^2 k_B^2}{6e}\frac{\nu'}{\nu}\frac{U_{\mathrm{SD}}^{(3f)}}{I_0}\frac{T_0}{R_0'}. \tag{15}$$

From this equation, we can finally express the sought-for logarithmic derivative of the density of states,

$$\left.\frac{d\ln\nu(\epsilon)}{d\epsilon}\right|_{E_F} = \frac{\nu'}{\nu} = -\frac{3e}{2\pi^2 k_B^2}\frac{I_0}{T_0}\frac{U_{\mathrm{SG}}^{(2f)}}{U_{\mathrm{SD}}^{(3f)}}\frac{dR}{dT}. \tag{16}$$

By this method, the logarithmic derivative of the density of states can be determined solely by electronic measurements using a FET. This important energy parameter can be used for an absolute determination of the hopping integrals in the generic Linear Combination of Atomic Orbitals (LCAO) model. The realisation of this experiment could be regarded as a continuation of previously published, detailed theoretical and experimental investigations, and by having a set of complementary studies, we can reliably determine the LCAO parameters.

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References

1. J. Friedel, J. Phys.: Condens. Matt. **1**, 7757 (1989)
2. J. Labbe, J. Bok, Europhys. Lett. **3**, 1225 (1987)
3. J. Bouvier, J. Bok, J. Superconductivity **10**, 673 (1997)
4. J. Bouvier, J. Bok, Physica C **364, 365**, 471 (2001)
5. J. Bouvier, J. Bok, Physica C **288**, 217 (1997)
6. R.S. Markiewicz, J. Physics.: Condens. Matt. **2**, 665 (1990)
7. R.S. Markiewicz, J. Phys. Chem. Solids **58**, 1179 (1997)
8. D.M. Newns, C.C. Tsuei, P.C. Pattnaik, Phys. Rev. **52**, 13611 (1995)
9. C.C. Tsuei, C.C. Chi, D.M. Newns, P.C. Pattnaik, Däumling, Phys. Rev. Lett. **69**, 2134 (1992)
10. T.M. Mishonov, J.O. Indekeu, E.S. Penev, J. Phys.: Condens. Matter **115**, 4429 (2003)
11. T.M. Mishonov, N. Chéenne, D. Robes, J.O. Indekeu, Eur. Phys. J. B **26**, 291 (2002), e-print `arXiv:cond-mat/0109478`
12. N. Chéenne, T.M. Mishonov, J.O. Indekeu, Eur. Phys. J. B **32**, 437 (2003), e-print `arXiv:cond-mat/0110632`
13. L.D. Landau, E.M. Lifshitz, *Statistical Physics*, Part 1, (Pergamon, New York, 1977), Chap. 5
14. I.M. Lifshitz, M.Y. Azbel, M.I. Kaganov, *Electron Theory of Metals* (Consultants Bureau, New York, 1973)