Determination of density of states of thin high-$T_c$ films by FET type microstructures

T.M. Mishonov and M.V. Stoev

Department of Theoretical Physics, Faculty of Physics, University of Sofia St. Kliment Ohridski, 5 J. Bourchier Boulevard, BG-1164 Sofia, Bulgaria

(Dated: September 5, 2018)

A simple electronic experiment with a field effect transistor type microstructure is suggested. The thin superconductor layer is the source-drain channel of the layered structure where an AC current is applied. It is necessary to measure the second harmonic of the source-gate voltage and third harmonic of the source-drain voltage. The electronic measurement can give the logarithmic derivative of the density of states which is an important parameter for fitting of parameters of the band structures.

PACS numbers: 74.78.-w, 71.20.-b, 74.78.Bz, 73.50.Lw

I. INTRODUCTION

The importance of density of states (DOS) for the physics of high-$T_c$ cuprates was discussed in many papers. The purpose of this work is to suggest a simple electronic method for determination of DOS. The proposed experiment requires the preparation of field-effect transistor (FET) type microstructure and require standard electronic measurements. The FET controls the current between two points but does so differently than the 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 to the gate terminal (potential relative to either source or drain). It causes the electrons flow to change it’s width and thus controls the voltage between the source and the drain. If the negative voltage applied to the gate is high enough, it can remove all the electrons from the gate and thus close the conductive channel in which the electrons flow. Thus the FET is blocked.

The system, considered in this work is in hydrodynamic regime, which means low frequency regime where the temperature of the superconducting film adiabatically follows the dissipated Ohmic power. All working frequencies of the lock-ins say up to 100 kHz are actually low enough. The investigations of superconducting bolometers show that only in MHz range it is necessary to take into account the heat capacity of the superconducting film. As an example there is a publication, corresponding to this topic as well as the references therein. In this work we propose an experiment with 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), but in principle they can be also used for determination of the density of states. An analogous experimental research has been already performed for investigation of thermal interface resistance. The suggested experiment can be done using practically the same experimental setup, only the gate electrodes should be added to the protected by insulator layer superconducting films.

II. DETERMINATION OF LOGARITHMIC DERIVATIVE OF DENSITY OF STATES BY ELECTRONIC MEASUREMENTS

The purpose of this work is to suggest a simple electronic experiment, determining 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 demonstrate already the properties of the bulk phase. The numerical value of this parameter

$$\nu'(E_F) = \frac{\partial \nu(\epsilon)}{\partial \epsilon},$$

will ensure the absolute determination of hopping integrals.

We propose a field effect transistor (FET) from Tl:2201 Fig. 1 to be investigated electronically with lock-in at second and third harmonics. Imagine a strip of Tl:2201 and between the ends of the strip, between the source (S)
and the drain (D) is applied an AC current

\[ I_{SD}(t) = I_0 \cos(\omega t). \]  

(2)

For low enough frequencies the ohmic power \( P \) increases the temperature of the film \( T \) above the ambient temperature \( T_0 \)

\[ P = R I_{SD}^2 = \alpha(T - T_0), \]  

(3)

where the constant \( \alpha \) determines the boundary thermoresistance between the Ti:2201 film and the substrate, and \( R(T) \) is the temperature dependent source-drain (SD) resistance. We suppose that for thin film the temperature is almost homogeneous across the thickness of the film. In such a way we obtain for the temperature oscillations

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

(4)

As the resistance is weakly temperature dependent

\[ R(T) = R_0 + (T - T_0)R_0', \quad R_0'(T_0) = \frac{dR(T)}{dT} \bigg|_{T_0}. \]  

(5)

A substitution here of the temperature oscillations from Eq. (4) gives a small time variations of the resistance

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

(6)

Now we can calculate the source-drain voltage as

\[ U_{SD}(t) = R(t) I_{SD}(t). \]  

(7)

Substituting here the SD current from Eq. (2) and the SD resistance from Eq. (4) gives for the SD voltage

\[ U_{SD}(t) = U_{SD}^{(1f)} \cos(\omega t) + U_{SD}^{(3f)} \cos(3\omega t). \]  

(8)

The coefficient in front of the first harmonic \( U_{SD}^{(1f)} \approx R_0 I_0 \) is determined by the SD resistance \( R_0 \) at low currents \( I_0 \), while for the third harmonic signal using the elementary formula \( \cos^3(\omega t) = (3 \cos(\omega t) + \cos(3\omega t))/4 \) we obtain

\[ U_{SD}^{(3f)} = \frac{U_{SD}^{(1f)}}{4\alpha} I_0^2 R_0'. \]  

(9)

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

\[ \alpha = \frac{U_{SD}^{(1f)}}{4U_{SD}^{(3f)}} I_0^2 R_0'. \]  

(10)

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

At known \( \alpha \) we can express the time oscillations of the temperature substituting in Eq. (4)

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

(11)

In this approximation terms containing \( I_0^4 \) are neglected and also we consider that shift of the average temperature of the film is small.

The variations of the temperature lead to variation of the work function of the film according to the well-known formula from the physics of metals

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

(12)

where the logarithmic derivative of the density of states \( \nu'(\epsilon) \) taken for the Fermi energy \( E_F \) has dimension of inverse energy, the work function \( W \) has dimension of voltage. \( T \) is the temperature in Kelvins and \( k_B \) is the Boltzmann constant. For an introduction see the standard text books on statistical physics and physics of metals.\(^{13,14}\) Substituting here the temperature variations from Eq. (11) gives

\[ W = -\frac{\pi^2 k_B^2}{6e} \nu' \frac{1}{\nu} T_0 \left[1 + \frac{R_{SD}I_0^2}{\alpha T_0^2} \cos(2\omega t)\right] + O(I_0^4). \]  

(13)

where \( O \)-function again marks that the terms having \( I_0^4 \) are negligible.

The oscillations of the temperature creates AC oscillations of the source-gate (SG) voltage. We suppose that a lock-in with a preamplifier, having high enough internal resistance is switched between the source and the gate. In these conditions the second harmonics of the work-function and of the SG voltage are equal

\[ U_{SG}^{(2f)} = -\frac{\pi^2 k_B^2}{6e} \nu' \frac{1}{\nu} T_0 R_{SG} I_0^2. \]  

(14)

\[ U_{SG}(t) = U_{SG}^{(2f)} \cos(2\omega t) + U_{SG}^{(4f)} \cos(4\omega t) + \ldots \]

Substituting \( \alpha \) from Eq. (10) we have

\[ U_{SG}^{(2f)} = -\frac{4\pi^2 k_B^2}{6e} \nu' \frac{U_{SD}^{(3f)}}{\nu} \frac{T_0}{I_0} \frac{R_{SG}^2}{R_0} \frac{\epsilon}{\nu}. \]  

(15)

From this equation we can finally express the pursued logarithmic derivative of the density of states

\[ \frac{d \ln \nu(\epsilon)}{d \epsilon} \bigg|_{E_F} = \nu' = -\frac{3\epsilon}{2\pi^2 k_B} \frac{I_0 U_{SG}^{(2f)}}{U_{SD}^{(3f)}} \frac{dR}{dT}. \]  

(16)

In such way the logarithmic derivative of the density of states can be determined by fully electronic measurements with a FET. This important energy parameter can be used for absolute determination of the hopping integrals in the generic LCAO model. The realization of the experiment can be considered as continuation of already
published detailed theoretical and experimental investigations and having a set of complementary researches we can reliably determine the LCAO parameters.

**Acknowledgements** One of the authors (TM) is thankful to J. Bok, P. Bernstein and J.P. Maneval for the stimulating discussions.

* E-mail: mishonov@phys.uni-sofia.bg
† E-mail: martin.stoev@gmail.com

1. J. Friedel, *J. Phys.: Condens. Matt.* 1, 7757 (1989);
2. J. Labbe and J. Bok, *Europhys. Lett.* 3, 1225 (1987);
3. J. Bouvier and J. Bok, *J. Superconductivity* 10, 673 (1997);
4. J. Bouvier and J. Bok, *Physica C364-365*, 471 (2001);
5. J. Bouvier and J. Bok, *Physica C288*, 217 (1997);
6. R. S. Markiewicz, *J. Physics.: Condens. Matt.* 2, 665 (1990);
7. R. S. Markiewicz, *J. Phys. Chem. Solids* 58, 1179-1310 (1997);
8. D. M. Newns, C. C. Tsuei and P. C. Pattnaik, *Phys. Rev.* 52, 13611 (1995);
9. C. C. Tsuei, C. C. Chi, D. M. Newns, P. C. Pattnaik and Däumling, *Phys. Rev. Lett.* 69, 2134 (1992);
10. T. M. Mishonov, J. O. Indekeu and E. S. Penev, *J. Phys.: Condens. Matter* 115, 4429-4456 (2003).
11. T.M. Mishonov, N. Chénne, D. Robes and J.O. Indekeu, “Generation of 3rd and the harmonics in a thin superconducting film by temperature and isothermal nonlinear current response” *Eur. Phys. J. B* 26, 291-296 (2002); [cond-mat/0109478](https://arxiv.org/abs/cond-mat/0109478)
12. N. Chénne, T.M. Mishonov, and J.O. Indekeu, “Observation of a sharp lambda peak in the third harmonic voltage response of YBaCuO film” *Eur. Phys. J. B* 32, 437-444 (2003); [cond-mat/0110632](https://arxiv.org/abs/cond-mat/0110632)
13. L. D. Landau and E. M. Lifshitz, *Statistical Physics*, Part 1, Chapter 5, (Pergamon, New York, 1977);
14. I. M. Lifshitz, M. Y. Azbel and M. I. Kaganov *Electron Theory of Metals* (Consultants Bureau, New York, 1973);