The electric field effect in a superconducting film device

1993 J. Phys.: Condens. Matter 5 L597

(http://iopscience.iop.org/0953-8984/5/46/002)

J. Phys.: Condens. Matter 5 (1993) L597–L600. Printed in the UK

LETTER TO THE EDITOR

The electric field effect in a superconducting film device

Keshav N Shrivastava

School of Physics, University of Hyderabad, PO Central University, Hyderabad-500 134, India

Received 8 September 1993

Abstract. Upon the application of an electric field in a superconducting film device, the drain–source resistivity increases and when the polarity of the electric field is reversed, it decreases; the oxygen ions move from the occupied to the empty sites thereby creating a finite dipole moment owing to pinning which contributes to the carrier concentration and hence to the conductivity of the system. The resistivity is quantized and depends inversely on the dipole moment. The calculated results are in good agreement with the experimental measurements in a $YBa_2Cu_3O_{7-\delta}$ film device.

Recently, Mannhart *et al* [1] have found that the density of mobile carriers in a superconductor can be changed by the application of an electric field. Thus the critical current density of $YBa_2Cu_3O_{7-\delta}$ films can be controlled by an electric field. Changes of relative conductivity of the order of one in 10^4 have been produced earlier by Glover III and Sherrill [2] but the recent results [3] are much larger in magnitude. The carrier densities in the high-temperature superconductors are about 100 times less than in the low-transition-temperature superconductors, but even then field effects have been measured in films [4–7].

The effect of the electric field on the oxygen ions is to change their position in the basal plane, so the coordination of Cu^{2+} ions changes. Relaxation effects owing to the motion of the oxygen ions have been observed [8]. An activation energy of 0.97 ± 0.03 eV has been measured [9] for oxygen ions by tracer diffusion. Several measurements [10–17] show that permanent electrical dipole moments are present in $YBa_2Cu_3O_{7-\delta}$. The dipole moment calculated [18] for the planar oxygen atoms is about $0.003e$ Å thereby showing that the lattice is polarizable by the application of an electric field. Since many oxygen ion sites are vacant, the negatively charged oxygen ions jump from the occupied sites to the empty sites upon application of a small electric field. The experimental work of Mannhart *et al* shows that the drain–source resistance increases when a gate voltage of +10 V is applied and decreases when a gate voltage of −10 V is applied.

In this letter, we report the mechanism of the change of resistivity upon the application of an electric field in a polarizable superconducting device near the onset temperature. As the system is cooled, this resistivity approaches zero. We find that in the case of a finite electric dipole moment, the resistivity is quantized.

We assume that there are vacancies of oxygen ions, so when the electric field $|\boldsymbol{E}|$ is applied, the system develops an electric dipole moment,

$$\boldsymbol{p} = -e\sum_i \boldsymbol{r}_i \tag{1}$$

0953-8984/93/460597+04$07.50

where $\boldsymbol{r}_i$ is the radius vector of the ith ion. The potential energy of the ion due to the dipole moment is given by

$$V^{(1)} = -\boldsymbol{E} \cdot \langle \boldsymbol{p} \rangle. \tag{2}$$

The quadratic polarization effects give rise to a change in energy expressed by the usual second-order perturbation theory,

$$V^{(2)} = -\sum_n \frac{\langle 0|\boldsymbol{E} \cdot \boldsymbol{p}|n\rangle\langle n|\boldsymbol{E} \cdot \boldsymbol{p}|0\rangle}{E_n - E_0}. \tag{3}$$

The change in energy due to the electric field is then given by the sum of the previous two terms,

$$V = -|\boldsymbol{E}|\left[\langle p\rangle + \sum_n \frac{\langle 0|\boldsymbol{E} \cdot \boldsymbol{p}|n\rangle\langle n|p|0\rangle}{E_n - E_0}\right]. \tag{4}$$

The current, j, is related to the electric field $\boldsymbol{E}$ through the conductivity, σ per unit length, as

$$j = \sigma E. \tag{5}$$

The flux is quantized in units of $\phi_0 = hc/2e$, so $nj\phi_0/c$ with $n = 1, 2, 3, \ldots$, an integer, represents the current in terms of energy. We have taken current in units of e/s, ϕ_0 in terms of G cm^2 and c is the velocity of light in cm s^{-1}. Here e is the electronic charge, so $j\phi_0/c$ is measured in erg. Accordingly $n\sigma|E|\phi_0/c$ represents the energy of a flux quantized system with electric field $\boldsymbol{E}$, so

$$-\frac{n\sigma|E|\phi_0}{c} = -|\boldsymbol{E}|\left[\langle p\rangle + \sum_n \frac{\langle 0|\boldsymbol{E} \cdot \boldsymbol{p}|n\rangle\langle n|p|0\rangle}{E_n - E_0}\right]. \tag{6}$$

Therefore we can write the conductivity as

$$\sigma = \frac{c\langle p\rangle}{n\phi_0}\left[1 + \sum_n \frac{\langle 0|\boldsymbol{E} \cdot \boldsymbol{p}|n\rangle\langle n|p|0\rangle/\langle p\rangle}{E_n - E_0}\right]. \tag{7}$$

When the sign of $\boldsymbol{E}$ is changed the second term in the above changes sign, so for one direction of $\boldsymbol{E}$ we have

$$\sigma_+ = \sigma_0(1 + \gamma) \tag{8}$$

whereas for the direction of $\boldsymbol{E}$ reversed we get

$$\sigma_- = \sigma_0(1 - \gamma). \tag{9}$$

Thus the ratio of the conductivity for the two directions of $\boldsymbol{E}$ is

$$\frac{\sigma_+}{\sigma_-} = \frac{1 + \gamma}{1 - \gamma}. \tag{10}$$

Similarly, the ratio of resistivity for the two directions of the electric field is $(1-\gamma)/(1+\gamma)$ where

$$\sigma_0 = \frac{c\langle p\rangle}{n\phi_0} \tag{11}$$

$$r = \sum_n \frac{\langle 0|\boldsymbol{E}\cdot\boldsymbol{p}|n\rangle\langle n|p|0\rangle/\langle p\rangle}{E_n - E_0}. \tag{12}$$

The conductivity is the inverse of resistivity, so

$$\rho+ = 1/\sigma_+ \qquad \rho_- = 1/\sigma_-. \tag{13}$$

We now compare our theory with the experimental results [1]. At $\simeq 90$ K, the increase in the drain–source resistance upon the application of a gate voltage of +10 V is 0.11 kΩ while the decrease in the same resistance upon reversing the gate voltage to -10 V is 0.18 kΩ, so the ratio $\rho_+/\rho_- = 0.61$, when compared with the calculated conductivity expression (10), gives $(1-\gamma)/(1+\gamma) = 0.61$, and so $\gamma = 0.24$ indicating that there is a 24% correction to the energy of the system due to the second-order dipole moment. When the sign of $\boldsymbol{E}$ changes, the sign of γ also changes, so the resistivity is either increased or reduced depending upon the direction of the electric field. This feature of experimental measurements is also fully in accord with the expressions (8) and (9). The quantized resistivity

$$\rho_+ = \rho_0(1+\gamma)^{-1} \tag{14a}$$

$$\rho_- = \rho_0(1-\gamma)^{-1} \tag{14b}$$

has a prefactor of $\rho_0 = n\phi_0/c\langle p\rangle$, so when $\langle p\rangle = 0$, the system has infinite resistivity, i.e. it becomes an insulator. Thus for our theory a non-zero $\langle p\rangle$ is needed. This requirement is met in a polarizable material where $\langle\sum_i \boldsymbol{r}_i\rangle \neq 0$. Once the system is polarized, the polarization decays unless there are pinning centres. In this way pinning becomes necessary to hold the dipole moments.

The energy in (2) is repulsive but that in (3) may be attractive. Since the second term is only about 24% of the first term, we assume that for a polar material (4) is repulsive. This means that the transition temperature of the BCS superconductor is reduced upon application of an electric field.

Unlike the microwave absorption [19, 20] the present effect of the electric field is not caused by weak links, but weak links and vacant oxygen sites increase the dipole moments and hence increase the conductivity or the carrier concentration. It will be of interest to study the problem of flux flow, in which case the linear electric field shifts the vortices. Similarly, the problem of flux-lattice melting [21] in an electric field may be of interest for the development of superconducting devices. Since ϕ_0 in (11) is quantized, the conductivity is also quantized. The conductance per square quantized in units of e^2/h has also been considered by Levy *et al* [22] who found the variation of conductance with gate voltage.

In conclusion, we find that there is a change in the drain–source resistivity of a superconducting film upon the application of an electric field. This change in resistivity is caused by an electric dipole moment, which we have calculated up to second order in the perturbation theory. The flux-quantized resistivity requires the existence of vacant oxygen sites and pinning centres in the system. The calculated results are in reasonable agreement with the experimental measurements performed by Mannhart *et al* [1] on a thin film of $YBa_2Cu_3O_{7-\delta}$.

References

[1] Mannhart J, Schlom D G, Bednorz J G and Müller K A 1991 *Phys. Rev. Lett.* **67** 2099

[2] Glover R E III and Sherrill M D 1960 *Phys. Rev. Lett.* **5** 248

[3] Xi X X, Doughty C, Walkenhorst A, Kwon C, Li Q and Venkatesan T 1992 *Phys. Rev. Lett.* **68** 1240

[4] Hebard A F, Fiory A T and Eick R H 1987 *IEEE Trans. Magn.* **MAG-23** 1279

[5] Fiory A T, Hebard A F, Eick R H, Mankiewich P M, Howard R E and O'Malley M L 1990 *Phys. Rev. Lett.* **65** 3441

[6] Kabasawa U, Asano K and Kobayashi T 1990 *Japan. J. Appl. Phys.* **29** L86

[7] Xi X X and Venkatesan T 1993 *APS News* (3) **2** 44

[8] Rybalchenko L F, Fisun V V, Bobrov N L, Yanson I K, Bondarenko A V and Obolenskii M A 1991 *Sov. J. Low Temp. Phys.* **17** 105

[9] Rothman S J, Routhbort J L and Baker J E 1989 *Phys. Rev.* B **40** 8852

[10] Testardi L R, Moulton W G, Mathias H, Ng H K and Rey C M 1988 *Phys. Rev.* B **37** 2374

[11] Muller V, Hucho C, Maurer D, DeGroot K and Rieder K H 1990 *Physica* **165** 1271

[12] Mihailovic D and Poberaj I 1992 *Physica* C **185** 781

[13] Kurtz S K, Bhalla A and Cross L E 1991 *Ferroelectrics* **117** 261

[14] Bussmann-Holder A, Bishop A R, Migliori A and Fisk Z 1992 *Ferroelectrics* **128** 105

[15] Muller V, Hucho C, DeGroot K, Winau D, Maurer D and Rieder K H 1989 *Solid State Commun.* **72** 997

[16] Conradson S D, Raistrick I D and Bishop A R 1990 *Science* **248** 1394

[17] Müller K A 1990 *Z. Phys.* B **80** 193

[18] Baetzold R 1988 *Phys. Rev.* B **38** 11 304

[19] Shrivastava K N 1987 *J. Phys. C: Solid State Phys.* **20** L789

[20] Shrivastava K N 1993 *Solid State Commun.* **85** 227

[21] Shrivastava K N 1990 *Phys. Rev.* B **41** 11 168

[22] Levy A, Falck J P, Kastner M A, Gallagher W J, Gupta A and Kleinsasser A W 1991 *J. Appl. Phys.* **69** 4439