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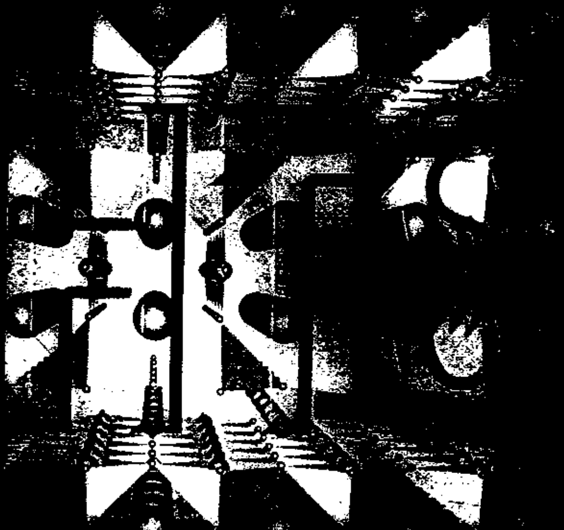

Editor

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Low Field and Deformation Effects of the Energy Gap of BSCCO Superconductors

S.K.J. Al-Ani[1], R.H. Yousif[2] and G.A. Al-Dahash[3]

[1]College of Science, University of Baghdad, Baghdad, Iraq
[2]Physics Department, College of Science, University of Baghdad, Baghdad, Iraq
[3]Department of Physics, College of Science, Babylon University, Hilla, Iraq

The energy gap 2Δ for BSCCO superconductor is measured by tunneling method. Its value at 20 K is found to be 22 meV. Higher temperature reflects lower 2Δ values. Low field and deformation effects on gap values have also been investigated. At no field and for undeformed samples the best fitting of 2Δ with BCS theory is limited to low temperature (up to 0.3 T_c) but at higher temperature up to T_c, the energy gap is shifted from BCS curve because of the very weak coupling of the Bi-compounds. The field effect is found to lower the 2Δ values too, whereas the deformation significantly enhances their levels.

I. INTRODUCTION

One of the most important properties of the BCS ground state is that the paired electrons are described by a single quantum wave function. The interaction between two degenerate electron configurations that differ in a pair state ($\uparrow$k+,$\downarrow$k-) changed to ($\uparrow$k′+,$\downarrow$k′-) in which the state (k) must be initially occupied and the state (k′) is empty, then the interval between k and k′ states is called the energy gap [1].

According to the BCS theory if temperature rises above absolute zero, Cooper's pairs are thermally broken up into two quasi-particles. Because an electron thermally in the state (p$\uparrow$) without partner in (-p$\downarrow$) from being available to form Cooper pairs, the pair interaction energy is diminished or the number of scattering events in which they may participate is lessened. This decreases the energy gap.

Blackmore [2] gives a highly exaggerated picture of the differences between the spectrum and the occupancy of the states in normal metal and those in superconductor (see Figs. 1 a, b and c).

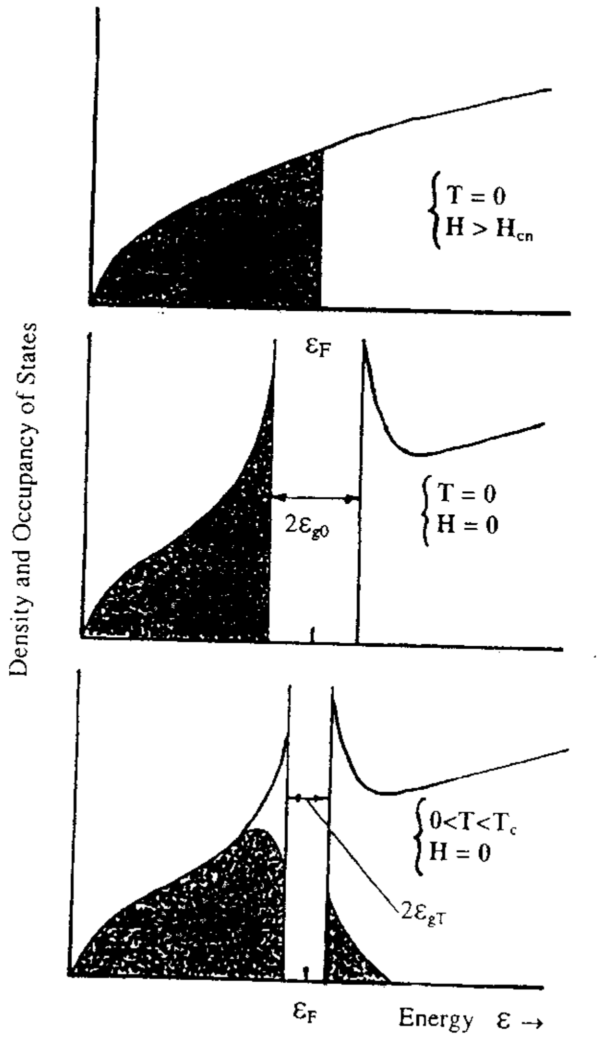

Fig. 1. A visualization of the difference between the spectrum of states for a normal and for a superconductor at very low temperature.

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Fig. 1(a) shows no superconductivity at T = 0K, with ($H>H_{co}$). The Fermi- Dirac occupancy factor is unity up to energy E_{fo} and zero for any higher energy. Fig. 1(b) represents the superconductivity ground state (BCS) at T=0K, which shows a zero density of states for energies within $\pm E_{go}$ on either side of Fermi energy. At T=0K all electrons are in Cooper pairs. Fig. 1(c) gives the situation for $T < T_c$. Here the superconducting energy gap E_{gT} is smaller than E_{go}, where all electrons are still not in the superconducting state. when the When the temperature $T > T_c$ the energy gap and the number of paired electrons both go to zero.

II. EXPERIMENTAL TECHNIQUE

A. The SIN tunnel junction

The superconductor-insulator-normal metal (SIN) tunnel junction was prepared by vapour depositing Al_2O_3 on superconductor pellet in vacuum, and vapour-depositing aluminum on top of aluminum oxide. The oxide layer was represented as an insulating layer sandwiched between the superconductor and normal metal (aluminum).

Now, SIN became a tunnel junction as in Fig. 2 · in the superconductor, there was an energy gap centered at the Fermi level. At absolute zero, no current can flow until the applied voltage is $V=E_g/2e$.

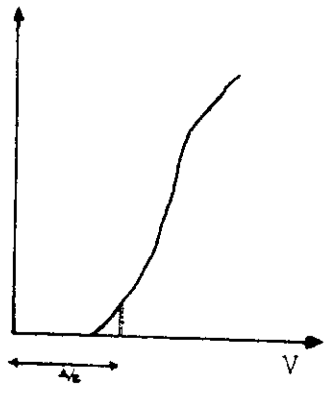

Fig. 2. I-V characteristic for SIN junction

The energy gap (E_g) corresponds to the state with formation of two electrons. The current starts when $eV=\Delta$. At finite temperature, there is a small current flow even at low voltages. This is because of electrons in the superconductor that are thermally excited across the energy gap.

B. Sample preparation

The samples were prepared by the solid state reaction method using highly pure powders of $(BiO)_2$ CO_3, $SrCO_3$, CaO, CuO, PbO, and Al_2O_3 with 99.9% purity. Three types of superconductor systems were obtained: Bi-Sr-Ca-Cu-O, Bi-Pb-Sr-Ca-Cu-O, and Bi-Al-Sr-Ca-Cu-O.

The appropriate amount of the reactant materials had been weighed using a sensitive four-digit balance type STANTON. They were mixed in agate mortar for two hours adding acetone to the mixture during the process of grinding to get a more homogenized mixture. The above process was repeated again by adding further amount of acetone to the mixture, the grinding was continued further for one hour. The mixture was then dried in an oven at (60°C) for (30min) to prevent the possibility of contamination of the mixture on the surface of the agate mortar. The mixture was put in a ceramic crucible and then in the tube furnace whichwas connected with programmable controller (type Eurothrem 816P). Calcination of the mixture was done at (800°C) for 16 hours with heating and cooling rate about (1°C/min). The produced powder was black. For better homogeneity, the mixed powder was then repeated by adding acetone and further grinding was adopted for one hour.

The black powder produced from the calcination was ground with acetone by more than one stage for (30 minutes), dried in an oven, and then pressed as pellets using cylindrical die. The die has a stainless steel cylinder of (0.5 cm) radius. The pellet was pressed by a hydraulic press (SPECEC Ltd., U.K.) under a pressure of 10 $tons/cm^2$.

C. Deformation technique

By using a hydraulic press from SPECEC limited U.K. the influence of the applied pressure on T_c (onset) and T_c (offset) was investigated. Three ranges of hydrostatic pressure were applied on the superconducting pellets; (Below 20 MPa) as a low level , (40-50 MPa) as a medium level and high level pressure which exceed 60 up to 100 MPa.

D. Resistivty measurement

The resistivity of superconducting sample was measured by using four-probe technique. The pellets were cut into a rectangular shape of 10 mm length and as 5 mm in its width by using a fine cutting saw. Now , if a current (I) passes through the sample and V is the voltage drop across the electrodes, the resistivity (ρ) is measured by the usual relationship

$$\rho = \frac{V}{I}\frac{tw}{L}$$

III. Results

The superconductive tunneling technique was used for measuring the energy gap of four types of Bi-Sr-Ca-Cu-O compounds. Besides, this technique was found be useful in studying the influence of the temperature and magnetic field on width of the energy gap for these samples which listed in Tables I and II.

Table I. Variation of energy gap with temperature.

Sample	T= 20 K	T = 50 K	T = 65 K
	Δ (meV)	Δ (meV)	Δ (meV)
$Bi_2Sr_2Ca_2Cu_3O_{10}$	11.0±0.5	8.0±0.5	6.2±0.5
$Bi_2Sr_2Ca_2Cu_3O_8$	7.5±0.5	5.0±0.5	4.0±0.5
$Bi_4Sr_3Ca_3Cu_4O_{10}$	11.0±0.5	7.5±0.5	6.0±0.5
$Bi_{1.65}Pb_{0.35}Sr_2Ca_2Cu_3O_{10}$	13.5±0.5	10.0±0.5	7.6±0.5

Table II. Variation of energy gap with magnetic field at 20K.

Sample	H= 0 T	H = 0.4 T	H = 0.9 T
	Δ (meV)	Δ (meV)	Δ (meV)
$Bi_2Sr_2Ca_2Cu_3O_{10}$	11.0±0.5	9.1±0.5	7.0±0.5
$Bi_2Sr_2Ca_2Cu_3O_8$	7.5±0.5	6.0±0.5	4.7±0.5
$Bi_4Sr_3Ca_3Cu_4O_{10}$	11.0±0.5	9.5±0.5	8.0±0.5
$Bi_{1.65}Pb_{0.35}Sr_2Ca_2Cu_3O_{10}$	13.5±0.5	11.0±0.5	9.0±0.5

A. Effect of temperature on energy gap

The 2223-Bi system has $\Delta = (11.0\pm0.5)$ meV at 20K. It drops to (5.0±0.5) meV and (4.0 ± 0.5) meV at 50K and 65K, respectively. These results show that the inverse relation between energy gap and temperature refers to change in density of superelectron state with temperature. This means that.at T_c(onset) the density of superelectron state will be increased to the highest density of state at absolute zero. Therefore, the sample will have a maximum energy gap at absolute zero because all electrons are coupled as Cooper pairs. On the other hand, the effect of temperature on energy gap can be explained as follows:

An electron in the state (P↑) without a partner in (-P↓) prevents the pair state (P↑, -P↓) to from Cooper pairs and the pair interaction energy is diminished; the number of scattering events in which they may participate is lessened [3]. This decrease in the pair interaction energy means a decrease in the energy gap. As the temperature rises, the number of quasi-particles increases and the energy gap continues to fall, until finally a temperature is reached where the energy gap is zero, which is the critical temperature T_c

B. Effect of magnetic field on energy gap

The effect of magnetic field on the energy gap is listed in Table II. From this table, one can observe that an almost similar behaviour for the value of the energy gap was obtained. However the variation of the energy gap with magnetic field is not unique for all the samples. It is seen that the energy gap has more dependence on temperature than the magnetic field. The increase of temperature could change the entropy of the system to have more energy to break the Cooper pairs while the effect of the magnetic field was only to perturb the density of states and not to break the pairs.

C. Energy gap of deformed samples

As mentioned above, the deformation level caused by 44 MPa is appreciable. Three different types of superconducting samples were prepared as SIN-tunnel function so as to measure the energy gap by tunneling method. Table III shows the energy gap for deformed and undeformed samples at different temperatures. The results showed the energy gap increases due to deformation but decreases with increasing temperature for undeformed samples (Table IV).

Table III. Variation of energy gap at different temperature.

Sample	Undeformed	Deformed		
	T = 20K	T = 20K	T = 50K	T = 65K
	Δ (meV)	Δ (meV)	Δ (meV)	Δ (meV)
2223	11.0±0.5	17.5±0.5	14.0±0.5	13.0±0.5
2212	7.5±0.5	12.5±0.5	9.5±0.5	7.5±0.5
2223-$Pb_{0.35}$	13.5±0.5	16.0±0.5	11.0±0.5	9.0±0.5

Table IV. Variation of energy gap at different magnetic field at 20K.

Sample	Undeformed	Deformed		
	H = 0 T	H = 0 T	H = 0.4 T	H = 0.9 T
	Δ (meV)	Δ (meV)	Δ (meV)	Δ (meV)
2223	11.0±0.5	17.5±0.5	12.25±0.5	7.5±0.5
2212	7.5±0.5	12.5±0.5	9.5±0.5	6.0±0.5
2223-$Pb_{0.35}$	13.5±0.5	16.0±0.5	12.5±0.5	11.5±0.5

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H = 0.9 T
Δ (meV)
7.5±0.5
6.0±0.5
11.5±0.5

Chakravarty et al [4] suggested an interlayer tunneling mechanism between CuO layers. The deformation stress, however, could vary the localization of Cooper pairs in CuO layers and thus can enhance the energy gap. The BCS theory gives, $2\Delta=(3\pm0.5)\ k_BT_c$. In this work the value of $2\Delta/k_BT_c$ was calculated for 2223-B compounds before 44 MPa. The values are (2.4±0.5) and (3.4 ±0.5) before and after deformation, respectively.

The curve of $2\Delta(T)/2\Delta(0)$ vs T/T_c for $\Delta(20K)$ was fitted with BCS curve (Fig. 3). At low temperature the agreement is reasonable with BCS theory but at higher temperature there is a shift from the BCS theory (for both deformed and undeformed cases). It is due to the easy variation of the density of superelectron state as temperature increases up to T_c because of weak coupling. As a result some part of samples will not superconduct and therefore the energy gap will decrease at a rate higher than that due to BCS theory.

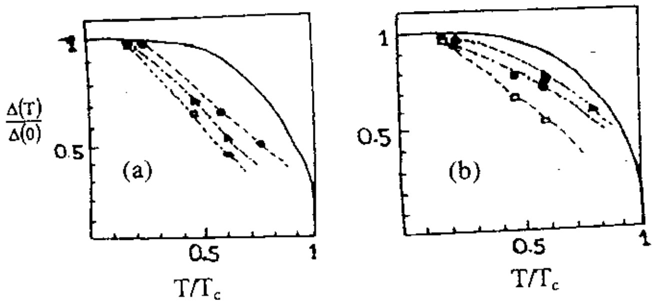

Fig. 3. Comparison of energy gap with BCS theory (a) before deformation (b) after deformation.

Schlesinger et al [5] measured the energy gap as $8\ kT_c$ by using energy gap of $YBa_2Cu_3O_7$ (Δ=14 meV). For Ta, V, Pb and Nb they showed a large deviation from BCS theory. Finally, this decrease in the energy gap is attributed to a decrease in the pair interaction energy as temperature increases.

IV. CONCLUSION

The work highlights the followings:

(a) The energy gap of 2223-Bi system is 2Δ=22 meV at 20K and increases to 35 meV at 20K after deformation by 44 MPa.

(b) Increasing the temperature from 20K to 50K and 65K leads to a decrease in the energy gap (2Δ) from (11±0.5) meV to (8±0.5) meV and to (6.2±0.5) meV for 2223-Bi system. The magnetic field has the same effect on the energy gap.

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