International Journal of Scientific Research in Science and Technology
Available online at : www.ijsrst.com
Print ISSN: 2395-6011 | Online ISSN: 2395-602X
doi : https://doi.org/10.32628/IJSRST

Study of Josephson Tunneling Across a Bicrystal Superconductor Potential

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ARTICLEINFO

Article History:

Accepted: 01 July 2023
Published: 10 July 2023

Publication Issue
Volume 10, Issue 4
July-August-2023

Page Number
650-656

ABSTRACT

The mechanism of electrical transport through grain boundaries in high-temperature superconductors is still far from understanding. The high Tc grain boundaries (GB) junctions with mutually tilted C-axis have been fabricated with an order of magnitude lower GB meandering and up to a threefold increase of the Ic Rn - values as shown by Divin et.al. in the year 2002. A complete antiphase correlation has been low-frequency fluctuations of the resistance Rn and the critical current Ic have been observed in these junctions, thus showing that both quasiparticles and Cooper pairs tunnel directly through the same regions of the barrier as discussed by Liathi et. al. in the year 2006. Recently, they selected $YBa_2Cu3O7-x$ GB junctions with characteristic voltage IR up to 8 mV that have been fabricated on NdGaO3 bicrystal substrates. In this present paper, we studied Josephson tunneling across a bicrystal superconductor potential.

Keywords : Josephson Tunneling, Temperature, Superconductor.

I. INTRODUCTION

The junctions were patterned with widths in the range of 1-2 um from 60 nm thick YBa Cu_3O_{7-x} films. Meandrin of the $YBa_2Cu_3O_{7-x}$ grain-boundary in AFM image was less than 20 nm. Each junction was supplied with an integrated sinuous log-periodic Ag-antenna. They used solid-state oscillators and an optically pumped far-infrared gas laser as sources of monochromatic radiation in the frequency range 15 GHz to 6.3 THz.

The voltage responses ΔV (V) have been measured and the normalized responses $\Delta I(V)/\Delta I_c$ containing information on the amplitude and line width of Josephson oscillations being calculated[1-8]. Normalized responses $\Delta I(V)/\Delta I_c$ of low resistance $YBa_2Cu_3O_{7-x}$ Josephson junction to THz laser radiation was calculated and the variation of response with voltage is shown in Fig.1.

II. MATERIALS AND METHOD

The response demonstrates odd-symmetric responses at the voltage V = hf/2e, due to a frequency pulling of Josephson oscillations by THz radiation[9-14]. The amplitude of the normalized response at V ↲ hff/2e is proportional to the amplitude of Josephson oscillations at the frequency f. As it is seen from the Fig. 1, the amplitude of the Josephson oscillations is falling down in the THz range. Nevertheless, we succeeded in measurements of a response to laser radiation with the frequency 5.2 THz, which is above the frequency fph = 4.57 THz of the strongest IR optical phonon in $YBa_2Cu_3O_{7-x}$ as done by L. Genzel in 1998. The result of these measurements is that the ac Josephson effect is observed at the frequency range, where the dynamic conductivity σ(f) of the $YBa_2Cu_3O_{7-x}$ changes radically as shown by general in 1998[15-19]. We have calculated the fine structure of the I-V curves of two junctions and observed on the dependence of differential resistances DV/DI vs the junction voltage as shown in Fig.2. The two values thus observed show the same fine structures, but their visibility increases with the decrease of the junction resistance[20-23]. The most prominent structures in both the values are at the voltage V ↲ 9.5 mV, which gives the Josephson frequency of 4.5 THz in good agreement with the frequency of the strongest IR active optical phonon mode in $YBa_2Cu_3O_{7-x}$. This mode appears in the infrared spectra, when the polarisation of elecromagnetic wave is parallel to the C-axis of the $YBa_2Cu_3O_{7-x}$. Also, some in-plane polarized modes together with broadband free- carrier response in $YBa_2Cu_3O_{7-x}$ have been observed by C. Bernhard et al.[24] in 2002, but non of them is close to the frequency 4.6 THz, which can give the peculiarity on the (dl/dV) - V dependence at V ↲ 9.5 mV. Here we interpret the peculiarity at V J 9.5 mV as a result of shunting of Josephson oscillations by conductivity of $YBa_2Cu_3O_{7-x}$ enhanced electrodes dynamic at the frequencies close to the phonon frequency. For low resistance junctions the strength of the main peculiarity in the dV/DI values is larger, that it is an accordance with Volkov's result as calculated by A.F. Volkov[25] in the year 1972, where the effect of shunting of a Josephson junction by external frequency-dependent admittance was considered.

In low resistance junctions, we reach the case of strong coupling of THz Josephson oscillations with optical phonons, which is reflected in the appearance of subharmonic structures at Vn hfph/2en, where n = 1,2,3 in (dl/dV) - V dependence values. Tentatively we can assign the features in the (dV/DI)-V values at V ↲ 7.4 mV and 11.8 mV with two adjacent optical phonon modes in $YBa_2Cu_3O_{7-x}$ at 3.4 THz and 5.7 THz respectively.

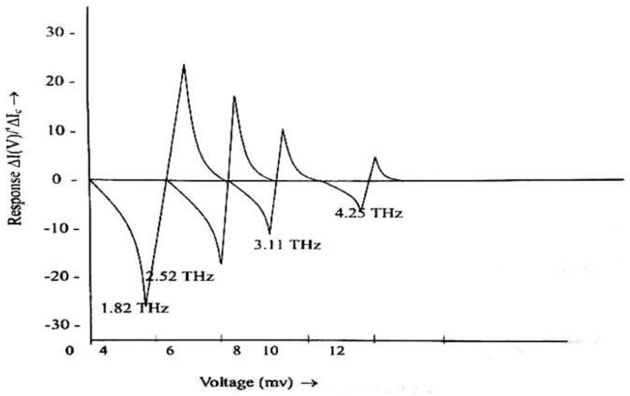


Fig.1 : Normalized responses $\Delta I(V)/\Delta I_c$ of $YBa_2Cu_3O_{7-x}$ Josephson junction to THZ radiation

1. JOSEPHSON EFFECT IN GB SUPERCONDUCTOR BARRIER

Among many different types of high - T_c Josephson junctions, the grain-boundary junction (GB) is considered to be the most promising for its application potential such as superconducting quantum interference devices (SQUID's). It is also fundamental interests to study its weak link behaviours and the nature of the GB coupling. In general, the current voltage characteristics of GB junction have been found to be well described by the resistively shunted junction model. The critical current across a boundary, which is usually much less than the critical currents of the films on both sides of the junction, is attributed to the presence of a normal or insulating barrier along the grain boundary.

Superconductor-insulator-superconductor (SIS) junctions and some of the high quality superconductor-metal-superconductor (SNS) junctions made of conventional superconducting films was made by H. Akoh et al.[26] in the year 1990, gives I_cR_n, products about 1 mV, which is much smaller than their bulk superconducting gap voltage (2Δ - 30 to 60 mV). A low I_cR_n, value implies that the energy gap at the GB interface is reduced. Some microscopic studies done in the year 1991 by Chisholm and Pennycook[27] indicated that the consequence of the dislocation arrangement alosn a GB causes the local superconductivity to be suppressed. In the year 1993, Moeckly et. al[28] and E. Samelli[29] considered the local oxygen deficiency or disorder in the region of the GB to be the main region for the considerably weakened pair potential at the interface. We vary the junction parameters in a wide range by changing the misorientation angle, oxygen content and fabrication process and found the results indicate that the Josephson coupling behaviour of these junctions can be explained in terms of the conventional theory of proximity effect. The reduced gap at the GB is found to be linearly dependent on the oxygen content of the sample. The grain boundary junction are generally made of laser ablated or RF sputtered epitaxial $YBa_2Cu_3O_9$ films grown on $SrTiO_3$. The misorientation angles of the substrates are 24^0 or 36^0 to the plane direction. The junction pattern with four- probe geometry are defined by the standard photolithography technique, then followed by wet etching with EDTA or dilutes HNO_3. In general the laser ablated films have higher T_c and higher critical current densities at 4.2 K than those of the sputtered films. In addition, the critical current densities of 24^0 GB junctions are higher than those of 36^0 GB junction about a factor 5. The narrow-west junctions seem to have lower critical current densities, presumably due to some degradation on the edge.

We studied the above experimental results done by different workers, and we noted the resistance versus temperature curves for each junction. For most samples, the current-voltage curves are studied at T = 4.2K. I_c and R_n of various samples can be directly obtained from their corresponding current voltage curve. It is found in general that I_c increases with decreasing temperature while R is essentially temperature independent. The value of the I_c R_n product is directly related to the pair potential of the superconductors adjacent to the interface of the junction. A stronger coupling behaviour is expected for the boundary with a lower tilt angle. It has been shown by Gross et al[30] in the year 1990 that this foot is caused by the grain boundary, and can be accounted for by the thermally activated Josephson phase slippage across a boundary with a suppressed superconducting gap parameter at both sides of the interface as shown in graph 2.

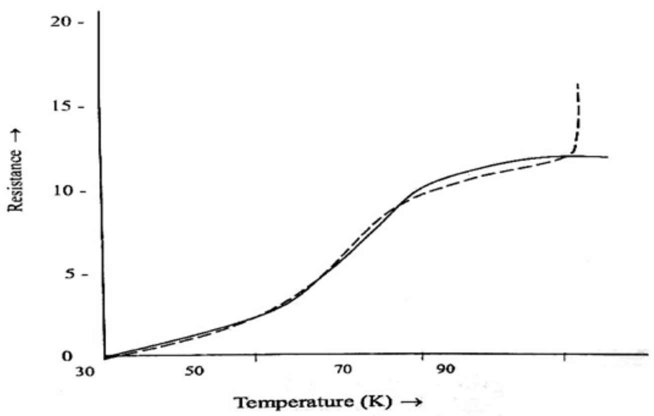


Fig. 2 : Experimental R/Rn dependence of a 360 title-angle Josephson junction and curves computed from AH model

According to the theory of Ambegaokar and Halperin[31] in the year 1969, also known as AH model, the effect of thermal fluctuation on the I-V characteristics of Josephson junctions with a small capacitance is expected to be present over a wide temperature range. This is particularly true for the high-T_c. grain boundary Josephson junctions. This is due to a combination of a high critical temperature and a reduced energy gap at the interface of the grain boundary. The AH model predicts, that the resistance R caused by thermally activated phase slippage is given by $R/R_n = [I_0(r_0/2)]^{-2}$, where I_0 is the modified Bessel function, r_o is the ration of the Josephson coupling energy $hI_c/2e$ to the thermal energy K_BT, and R_n is the normal junction resistance. Assuming that the temperature dependence of Ic can be written as $I_{AH}(l-(T/T_C))^n$, then we have $R/R_o = [I_oC(1-(T/T_c))]^{-2}$, where C is a constant proportional to I_{AH}. We used this expression to fit the long resistance tail of the foot curve is plotted shown as dashed line in graph 1. The calculated values of I_{AH} correlate well with the values of I_c measured at 4.2 K is shown in graph 3.

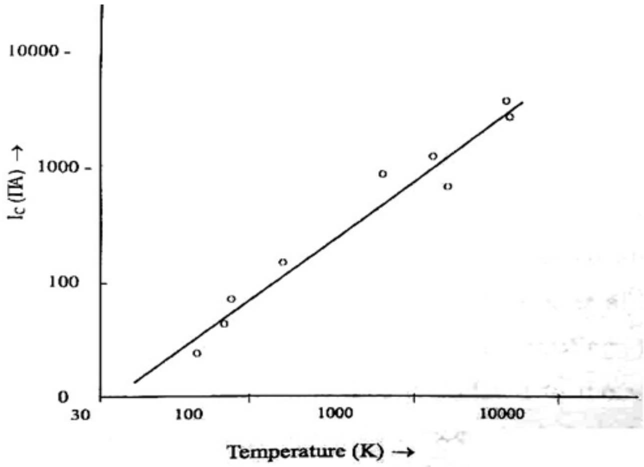


Fig.3 : The correlation of the calculated values of I_{AH} with the values of I_c measured at 4.2 K.

At any fixed R of the tail region, the normalized width $\Delta T/Tc = (T_c-T)/Tc$ of the resistive transition is scaled as a square root of Rn according to the AH model. The plot $\Delta T/T_c$ versus R_n clearly demonstrated in a wide parameter range of each of the two tilt angles, as shown in graph-3. The different slopes are directly related to different coupling energies for two tilt angles. This result provides further evidence that the width of the resistive transition tail of GB junction is needed with a weakened Josephson coupling energy, which becomes weaker for higher tilt-angle grain-boundary junctions. Furthermore, our result that I_CR_n increases with J_c is quite consistent with the scaling behavior reported by Russek et al[32] in 1990. The strength of the Josephson coupling in a proximity effect junction is directly related to the value of the order parameter at the interface which is reduced from its values far away from the interface by a factor $b/\xi(T)$; b is the extrapolation length of the order parameter in non superconducting region and E(T) is the temperature-dependent Ginzburg-London coherence length. For the conventional metallic superconductors, $b/\xi(T)$ can be very different for superconductor- insulator-superconductor (SIS) and superconductor- normal metal - superconductor (SNS) junctions. On the other hand, for high T_c superconductors, Deutscher and Muller[33] in 1987 point out that the difference between SIS and SNS junctions becomes very small as the zero temperature coherence length approaches the lattice spacing. As a matter of fact, their critical current densities have a similar temperature dependence near the critical temperature because the superconducting order parameter decay length is of the same order of $\xi(0)$ in both the normal and the insulating region. According to Ambegaokar and Baratoff[34] in 1963, the critical current density of a Josephson junction is given by.

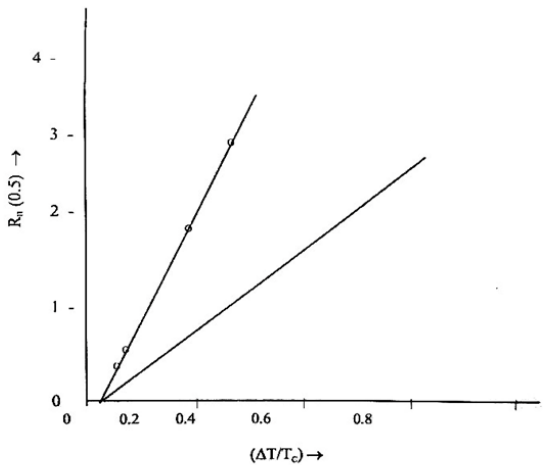


Fig. 4 : The linear dependence of $\Delta T/T_c$ Vs R_n for the grain boundary junction with two different angles.

$J_c(T) = (\pi\Delta(T)/2eR_n) \tanh[\Delta((T)/2K_BT_C]$

The reduced energy gap $\Delta(T) = \Delta_i(0)(1-(T/T_C))$ in this expression have the value $JC(T) = [\pi \Delta_i^2(0)/4eR_nK_BT_C]\ (1-(T/T_C))^2$ for T close to T_C when R_n in Fig. 4. is normalized with respect to, we find that all data points collapse into a single straight line as shown in Fig.5.

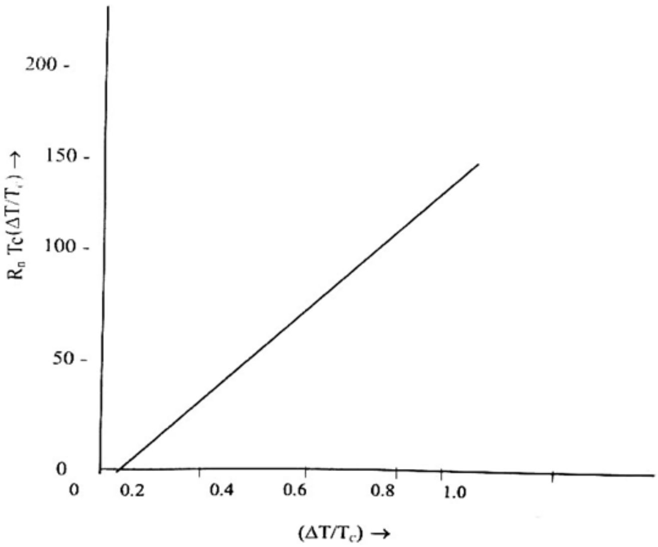
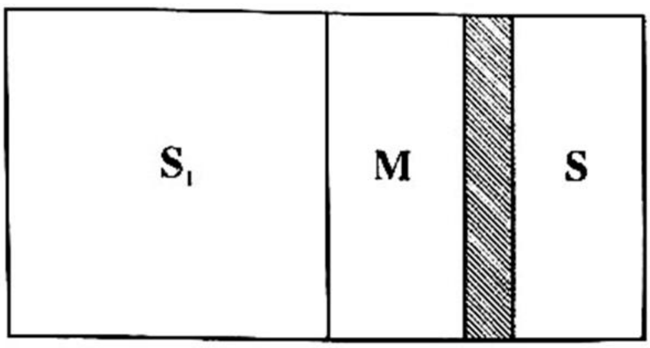


Fig. 5 : The scaling behavior of the normalized width of resistive transition as a function of normal junction resistance for several GB junctions.

This scaling feature can be associated with the previous expression of TAPS, in which the width $\Delta T/T_c$ should be scaled as $C^{-0.5}$ at any fixed R/R_n. This demonstrations that the reduced energy gap at the grain boundary (GB) induces a lower Josephson coupling energy and causes the larger resistive transition width observed for the high T_c Josephson junction. It is true that more data for GB junctions of different angles are needed to firmly establish this new scaling behaviour, which, however, is beyond our current capability. In the year 1993, Tolpygo et al reported the R(T) curve develops a foot after intensive e-beam writing. They showed the T_c decreases and the foot resistance increases. It seem that the oxygen deficiency rather than structural disorder is the main cause of weakening the Josephson coupling. The graph ΔT versus R_n is plotted from AH model. However, the reduced order parameter $\Delta_i(0)$ does not scale with $\Delta(0) \sim K_BT_C$ as expected. Instead it is found that the calculated $\Delta_i(0)$ is roughly linear with $(T_{Cmaax} - T_c)^{½}$ as shown in Fig.5.

2. JOSEPHSON TUNNELING IN SUPERCONDUCTOR S-N-I-S BARRIER:

The properties of the Josephson junctions S_1-N-I-S and S_1NS which contain high T_c film, the properties of such junctions depend on a number of parameters, such as the thickness L, and the ratio of the energy gap r.



S-M-I-S system. S_1 is a high T_c film, M is a normal metal, semimetal, I an insulator and S another superconductor

By varying such parameters, one can change the properties of the junction in the desired direction. It is also interesting to study the properties of the S-S-I-S junction. Even if $T > T_c$, its properties will be different from those of the S-N-I-S system. The high T_c oxides make it possible to prepare Josephson junctions operating at high temperatures. However, in high currents, it is better to use the junction in the low temperature region and thereby take advantage of the large energy gaps in the oxides.

III. CONCLUSIONS

Recently, the Josephson current observed in the systems S-N-I-S (where S_1S are superconductors, I an insulator and N is the normal metal) or S-N-S is also due to the proximity effect. These systems have been studied theoretically by different authors. For example, in the former system, the

Josephson effect occurs between S and N (superconductor and normal metal barrier), the superconducting state in N is induced by the proximity effect. Recently, Moreland, Ono et al(36) in 1989, the proximity effect in the presence of high T_c films was observed experimentally. These authers observed the Josephson current in the system of superconductor- Normal metal-Insulator potential barrier S_1-N-I-S_2, where S_1 = Y-Ba-Cu-O film, N = Ag or An and S_2 = Pb. The use of high Tc films allow one to vary T and, consequently on the coherence length, over a range which is large compared to the conventional superconductors. Moreover, the amplitude of the Josephson current depends on the relation between the energy gap, Δ(T), and T. In the presence of a high Tc superconductor, there is a large temperature interval where Δ(T) >> T, which also appears to be an important factor. We will now study the properties of Josephson junctions containing both high T_c films. The S_1-N-I-S and S_1-N-S system are considered. We will consider the S-N-I-S system assuming the thickness of the N-film L << $hv_F/2\Delta T$. In other words, the thickness normal film is small relative to the coherence length ξ. For example, for Ag or Au, the Fermi velocity is nearly equal to 1.8 x 10^8 cm-1, which corresponds the normal thickness $1.5 \times 10^4/T$ A^0. Therefore, if T < 5 K, this condition holds up to < 10^3 A^0. The Josephson current can be calculated in both the S_1-N-I-S and S_1-N-S system when the cooper pairs penetrates into it, the Josephson current can be calculated from the expression.

$$J_m = (ie/m^*)T\sum_{w}\int dp\,(V_X - V)G(X,Z';p,w)]$$

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