Effect of Microwave-Enhanced Superconductivity in $YBa_2Cu_3O_7$ Bi-crystalline Grain Boundary Weak-links

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Abstract

We have studied systematically the effect of microwave irradiation on the temperature dependent resistivity *R(T)* and the current-voltage (*I-V*) characteristics of $YBa_2Cu_3O_{7-x}$ (*YBCO*) bicrystalline grain boundary weak-links (GBWLs), with grain boundary of three different tilt angles. The superconducting transition temperature, T_C, has significant enhancement upon microwave irradiation. The microwave enhanced T_C is increased as a function of incident microwave power, but limited to an optimum power level. The GBWLs of 45° tilt boundary has shown to be most sensitive to the microwave irradiation power, and the GBWLs of 36.8° tilt boundary has displayed a moderate response. In contrast, no enhancement of T_C was observed in the GBWLs of 24° tilt boundary, as well as in the uniform films. Under the microwave irradiation, the *R(T)* dependence is hysteretic as the transition taken from superconducting state to normal state and vice versa. Mechanisms associated with the redistribution of nonequilibrium quasiparticles under microwave irradiation are discussed.

1. Introduction

The enhancement of superconductivity by microwave irradiation has been observed in a wide range of conventional superconductors and structures made thereof [1-9]. The fascinating phenomena of microwave induced enhancements of superconductivity has excited a considerable amount of investigations to find the operating mechanisms.

Eliashberg and colleagues [13] proposed the first microscopic theory to link the microwave-enhanced effects to the nonequilibrium processes of the quasiparticles induced by the electromagnetic fields. At finite temperatures, some of the quasiparticles are excited from the low-lying energy state near the edge of the energy gap to the higher-energy states and reach to a new nonequilibrium steady state. Since the low-lying quasiparticles are more effective in inhibiting paring correlation than the higher energy ones, with the total number of quasiparticles being preserved, the microwave induced redistribution of excited quasiparticles would lead to an increase of the energy gap. As a consequence, the critical temperature and the critical current are enhanced, in agreement with the BCS theorem. Later, calculation by Chang and Scalapino has shown that [14] not only the redistribution of quasiparticles causes the gap enhancement, but a net decrease in the total number of quasiparticles plays an important role. Aslamazov and Larkin have pointed out that [15], the nonequilibrium state occurs locally and the resultant enhancement is associated with gap oscillations in the weakly-coupled regions. Only if the constriction size, *a*, is smaller than coherence length (ξ) but larger than a characteristic length $\eta = \xi(T)(1-T/T_c)^{1/4}$, there is superconductivity enhancement. They showed that the effective cooling of electrons trapped in the region of the contact which has a lower value of the gap may result in an increase of critical current.

We report in the article, for the first time to our knowledge, the microwave-enhanced superconducting transition temperature in $YBa_2Cu_3O_{7-x}$ (YBCO) grain boundary weak-links (GBWL), with grain boundary of various tilt angles. The experimental results have demostrated significant enhancement of superconducting transition temperature ($\Delta T_c > 2$ K as compared to a few tens of mK obtained in conventional superconductors) when the GBWL's were irradiated by an $f = 12.4$ GHz microwave with appropriate incident powers. The GBWLs of 45° tilt boundary has shown to be most sensitive to the microwave irradiation power, and the GBWLs of 36.8° tilt boundary has displayed a moderate response. On the contrast, the GBWLs of 24° tilt boundary as well as the uniform film have shown no enhancement on the T_c. Mechanisms associated with the redistribution of nonequilibrium quasiparticles under microwave irradiation will be discussed. We note that the present observations are fundamentally different from the enhancements manifested by the photoinduced hole doping effects, recently reported in under-optimized HTSC systems [16].

2. Experimental

The $YBa_2Cu_3O_{7-x}$ grain boundary weak-links studied in this work were fabricated from the YBCO epitaxial films deposited onto the $SrTiO_3$ bicrystal substrates by KrF excimer pulsed laser. There different misorientation angle of $SrTiO_3$ bicrystal substrates was used. The details of the thin film deposition conditions has been described previously[17]. Briefly, the substrate temperature was held at 770°C using a CW CO_2 laser as the heating source. The oxygen partial pressure was kept in the range of 0.2-0.3 Torr during deposition with a laser energy density of 2-4 J/cm^2 and a repetition rate of 3-5 Hz. At the end of deposition, the CO_2 laser is shut off, resulting in a fast quench from 770°C to room temperature by taking less than 1 minute. The films obtained are nearly perfect *c*-axis oriented in crystalline structure.

The weak-link bridge was patterned by photolithography into a geometry of 20 μm in width, 1200Å in thickness and 60 μm in length of two voltage electrodes crossing boundary. The standard four-probe arrangement was used to determine the electrical behavior of the YBCO weak-links. To improve the contact resistance, gold pads were evaporated on the contact electrodes. The sample was mounted to sample holder which was cooled in the closed cycle system. The pulsed current method was applied to prevent heating from long time running in the normal state, which may suppress the critical values. The microwave energy is irradiated to the sample via an antenna, with a fixed frequency of 12.4 GHz. Careful shielding of the thermometer and electrical circuit was ensured to prevent the microwave heating on thermometers and the pick-up voltage in a feedback circuit which may result in a lower bath temperature. No temperature change (within a resolution of ± 0.03K) was observed even when the maximum output power up to 18dBm was applied.

3. Results and Discussion

Fig. 1 shows the $R(T)$ dependence of the transition from the superconducting to normal state (S $\rightarrow$ N) of a GBWLs of 36.8° tilt boundary. As shown in Fig. 1, the critical superconducting transitions are shifted to higher temperatures under appropriate microwave power, with the main features of normal state resistance not affected by the microwave irradiation. Further, the enhancement appears to be dependent on the incident microwave power and reaches the maximum at an optimal power P_{opt}. At incident power $P > P_{opt}$ the transition cease to shift to higher temperatures and moves back to lower temperatures. The numerical value given here for P is labeled for the output power from microwave generator. One might compare this result with those observed photoinduced T_c enhancement in under-optimized HTSC systems [16]. What is immediately noted is that the microwave-induced T_c enhancement can only be observed during GBWLs are being irradiated by microwave,

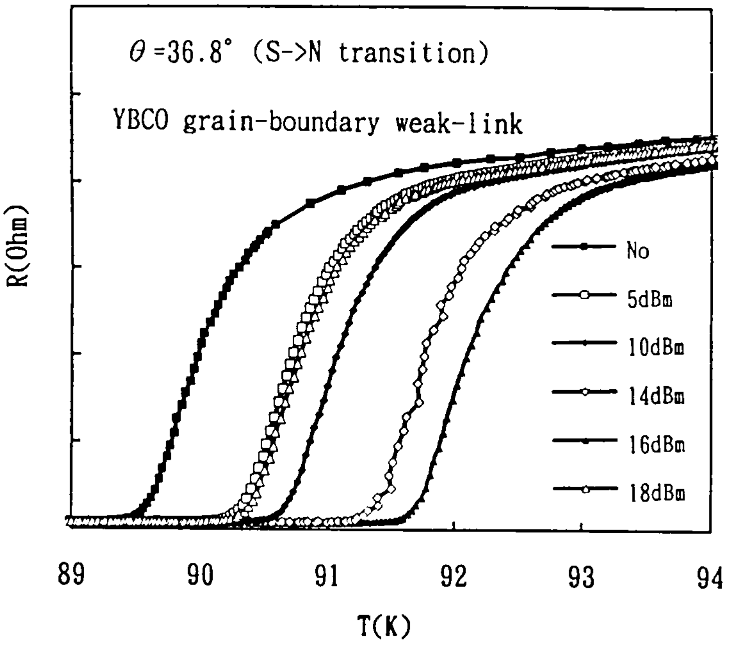

Fig. 1: The temperature dependent resistance, $R(T)$, of YBCO grain boundary weak-links under microwave irradiation in a variety of powers levels.

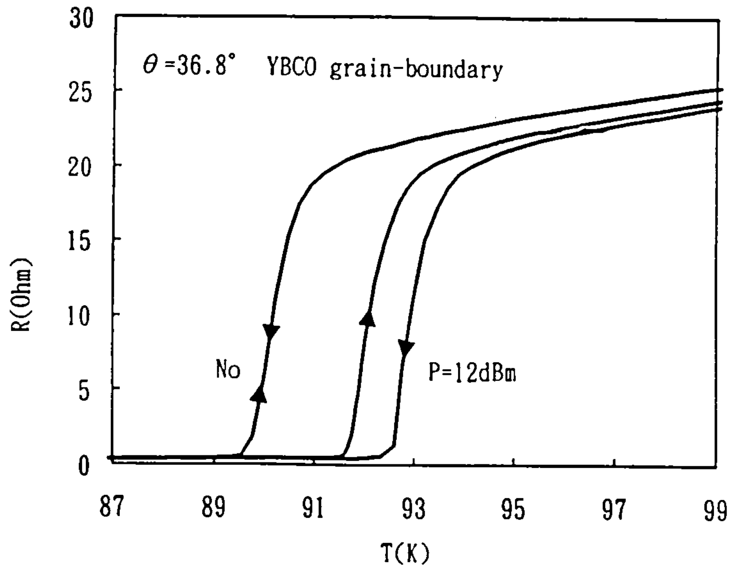

Fig. 2: The plot of the temperature hysteresis effect of the *R*(*T*) behavior under microwave irradiation.

while the photoinduced T_c enhancement remains persistent when the illumination was turned off.

As shown in Fig.1, the resistance near the superconducting transition is also significantly reduced. The *R*(*T*) curve deviating from usual normal state linearity was much more pronounced with increasing incident power and reaches the maximum value at P_{opt}, though the deviations are already evident for high T_c cruprates in the absence of microwave irradiation. Moreover, as incident power $P > P_{opt}$ the deviations were suppressed. The fact that the power dependence of both the T_c enhancement and excess-conductance changes in accordance with each other indicates the underlying physical mechanisms giving rise to the phenomena must be closely related. One might associate the T_c enhancement and excess-conductance as simply due to thermal fluctuations. However, according to the fluctuation theory, the enhancement of superconducting transition temperature originating from fluctuations should not exceed the "bulk" value of the system. Apparently, herein, the interpretation simply by fluctuations does not agree with the "large" T_c enhancement observed in our GBWL samples.

As shown in Fig. 2, the critical transitions under microwave irradiation are hysteretic, with the transition from normal state to superconducting state (N → S) occuring at higher temperatures than that of the S → N ones. We have checked the same measurements with no external microwave applied and no transition hysteresis were evident. Thus the results should be entirely originating from the microwave-induced effects. In Fig. 3, we summarize the power dependence of T_c enhancement of two different cases. Where the T_c is defined as the temperature at which 5 % of the normal state resistance remains. The T_C defined in this way is apt to the main transition of the microbridge, to be distinguished from the T_{CO} encountered with phase slippage effect, as will be described later. As can be seen immediately, the typical T_C enhancements (≈3K at optimal case) obtained here is remarkable, as compared to the values of a few tens of mK to 100 mK typically observed in conventional superconductors. The fact that the microwave-enhanced T_C's are all well above the equilibrium value of the system, again, indicates that conventional fluctuation theorem alone is inadequate to explain the results.

The mechanism that might be able to account for the T_C enhancement in YBCO grain boundary weak-links is the microwave-induced nonequilibrium dynamics of the redistributed quasiparticles derived for similar phenomena observed in conventional superconductors [2-9]. The essence of this theoretical scenario was that the redistributed quasiparticles in high-lying energy states, driven by the microwave field, have higher recombination rate, resulting in a more effective pairing, and could effectively increase a net reduction in the quasiparticle density. This, in turn, increase the averaged magnitude of the superconducting energy gap, leading to enhancements of both T_C and excess-conductance, in consistence with the results observed here.

In the framework of the nonequilibrium quasiparticle dynamics, the transition hysteresis is explainable as: more energy is required to break up "well-ordered" pair from cool side [1]. As a consequence, the transition from S → N should be characterized by an abrupt jump as indeed usually being observed. Such a signature, however, is hardly evident in the present case. Thus, in order to understand the intriguing results observed, we propose here a qualitative interpretation based on the notion of fluctuation-aided nonequilibrium quasiparticle redistribution. Here, the ever-existent fluctuations are regarded as the background needed for the realization of microwave-triggered quasiparticle redistribution. Within the context of this crude

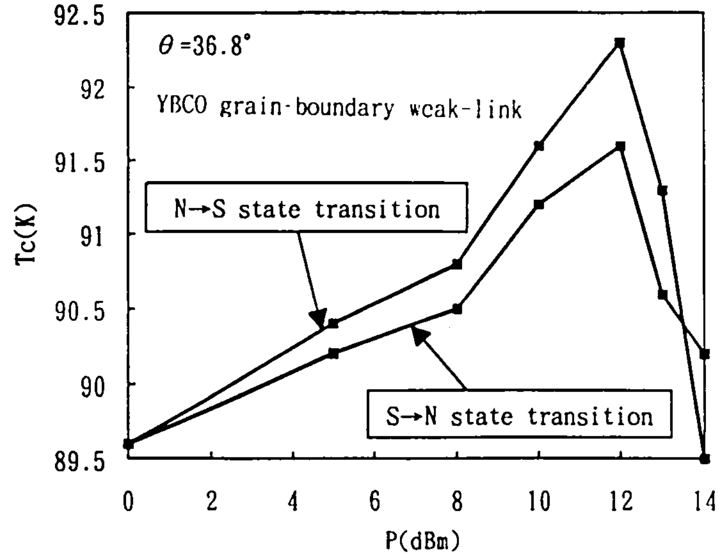

Fig.3: The microwave power dependence of T_C enhancement, for the resistive transition from normal (N) to superconducting (S) state ($N \rightarrow S$) and ($S \rightarrow N$).

picture, a qualitatively consistent interpretation for all the results presented here can be obtained as follows. In the circumstances, the Cooper pairs in the superconducting state below T_C are much well-defined, making it hard to turn on quasiparticle excitations by the driving microwaves, even with the same extent of fluctuation background assumed. On the other hand, when the temperature is approaching T_C from the normal state region, the fluctuating quasiparticles are very easy to be excited and re-distributed. As a result, the T_C enhancement occurs at higher temperature in N → S transition than that of S → N one's. The functional dependence of $\Delta T_C(P)$ (see Fig.3) may also lend further support to the above argument.

To further elucidate the mechanisms underlying these phenomena other peculiar features originating from microwave irradiation were investigated systematically. Perhaps the most important one to be noted is that the enhancement can only be realized when cross boundary configuration were practiced. No microwave-induced enhancement was observed in intra-regions despite of the fact that essentially the same bridge dimensions in the same films were used. This strongly suggests that the microwave induced enhancement occurs only in weak-links and not in homogeneous regions. It is contradicting to the experimental results observed in conventional superconductors as asserted by Eliashberg's theory, of which microwave enhancement of superconductivity can exist in a 'uniform structure' only. As have been pointed out by Aslamazov and Larkin that [15], the nonequilibrium state occurs locally and the resultant enhancement is associated with gap oscillations in the weakly-coupled regions. Only if the constriction size, a, is smaller than coherence length (ξ) but larger than a characteristic length $\eta = \xi(T)(1-T/T_C)^{1/4}$, there is superconductivity enhancement. In order to interpret the results of no enhancement of I_C at $T \approx T_C$, the constraint of $\xi > a > \eta = \xi(T)(1-T/T_C)^{1/4}$ is needed to be regarded.

Furthermore, we have performed studies on the GBWLs of 24° and 45° tilt boundary, respectively. Fig.4 shows the effect of the microwave power on the $R(T)$ behavior of a GBWLs of 45° tilt boundary, measured as the transition taken from the superconducting to normal state (S → N). We notice that, as revealed in Fig.4, the transitions can be shifted to an optimal higher temperature upon a microwave power comparative lower than that for optimal case in GBWLs of 36.8° 's. Moreover, when incident power $P > P_{opt}$ the enhancement is ceased and the transition systematically drops back to lower temperatures as P increased. In contrast, the GBWLs of 24° tilt boundary is insensitive to the microwave irradiation, as shown in Fig.5. It corroborates that no enhancement effect upon microwave irradiation was also observed in case of the uniform film.

The relation between tilt angles of GBWL's and the sensitivity of $\Delta T_C(P)$ is summarized as follows. To the microwave power, the GBWLs of 45° tilt boundary are seen to be the most sensive, the 36.8° 's displays moderrate respone, and the 24° 's is inert. This implies a correlation between GBWLs junction properties and the microwave enhancement of superconductivity. A systematic study on this scheme is

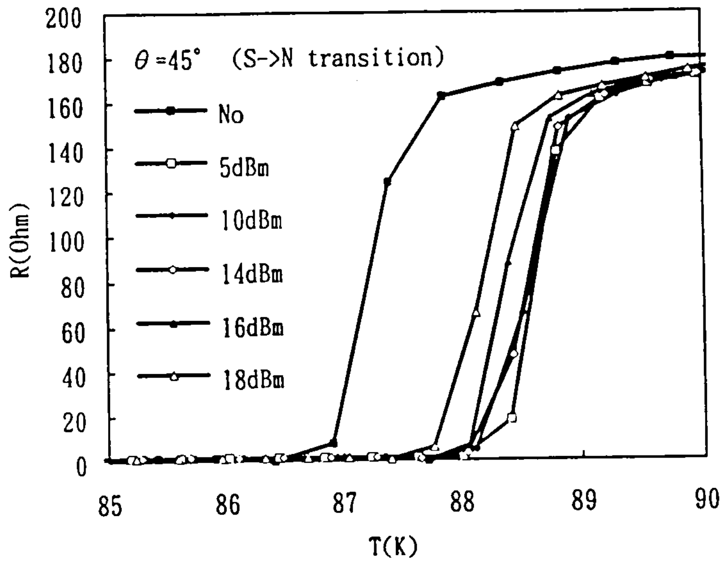

Fig. 4: The *R*(*T*) curve of YBCO grain boundary weak-links of 45° tilt boundary under microwave irradiation in a variety of powers levels.

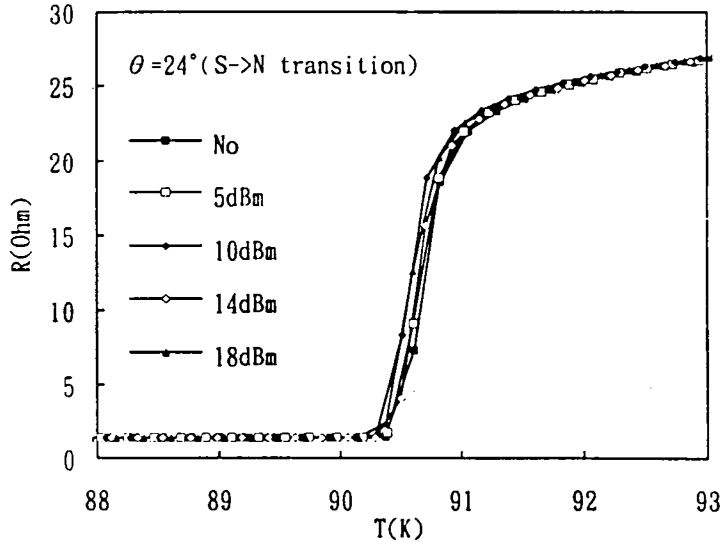

Fig. 5: The *R*(*T*) curve of YBCO grain boundary weak-links of 24° tilt boundary. No enhancement is observed under under microwave power levels.

under progress, to ascertain to what extent of the physical constraint in GBWLs play a role for the observation of T_C enhancement under microwave irradiation.

In conventional superconductors, the observation of T_C enhancement was always accompanied with observations of enhancement in I_C and energy gap in the *I-V* characteristics. To check if, indeed, similar effects occur in the YBCO weak-link, we have performed the *I-V* measurements at a variety of fixed temperatures and incident powers. For the temperature range $T < T_{CO}$, the experimental results showed that under the microwave irradiation the I_C was depressed, accompanying with current steps in the *I-V* characteristics. That is, no enhancement of I_C was observed in the YBCO weak-links. However, when the *I-V* measurements were performed at $T \approx 0.99 T_{CO}$, shape of V(I) curve changed from parabolic to hyperbolic with an invaried ohmic linearity at higher current part, indicating an opening of energy gap. Detailed descriptions of the particular features is given in Ref[20].

In ending, we would like to emphasize that the microwave induced enhancement of superconducting properties was observed repeatedly for at least 3~ 4 runs each in three weak-links.

4. Conclusion

In conclusion, we have presented the microwave induced enhancement of superconductivity in YBCO grain-boundary weak-links; in which remarkable enhancement of T_C were observed. The temperature dependent resistance curves shows anomalous hysteresis behavior as the transition taken from superconducting state to normal state and vice versa. Compared the microwave enhanced $\Delta T_C(P)$, the strength of sensitivity of three different tilt anglar GBWLs upon the microwave irradiation have shown a systematic variations: the GBWLs of 45° tilt boundary is most sensitive, the 36.8° 's displays a moderrate respone, and the 24° 's is inert to the microwave powers. The correlation between GBWLs junction properties and the microwave enhancement of superconductivity implies the geometrical constraint is needed to be regared for the enhancement effect. Mechanisms associated with the redistribution of nonequilibrium quasiparticles under microwave irradiation is being worked out.

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