Microwave–Enhanced Superconductivity and Transport Properties of Y–Ba–Cu–O Bicrystal Weak–Links

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***Abstract*—The effects of the tilt angle on microwave–enhanced transition temperatures and critical currents of YBCO bicrystal weak–links have been investigated. It was found that, with smaller grain boundary tilt angles (*e.g.* 24°), the enhancement was small, displaying essentially the same behavior as that manifested in intragranular regions. By contrast, when the tilt angle was increased from 36.8° to 45°, noticeable Tc enhancement was found to occur even at low input microwave powers. The results were compared to the temperature dependent critical current, in order to delineate possible correlations between the two physical parameters.**

I. INTRODUCTION

Since the first demonstration of Dimos et al. [1], YBCO bicrystal grain boundary weak–link (GBWL) has become one of the most extensively studied fields in high–Tc superconductivity research [2–6]. Even for the step–edge type junction devices developed later with the aid of rapidly maturing deposition techniques [7–9], the basic physics involved was, at least to some extent, inspired by the understanding acquired through the studies on GBWLs. However, despite the successes obtained thus far, there exist many fundamental issues to be clarified. For instance, the low frequency *1/f* noise exhibited in most superconducting quantum interference devices made of GBWLs is substantial [4–6]. On the other hand, in step–edge type junctions, the critical current–normal resistance product (IcRn), which ultimately determines the detection sensitivity of the devices, was usually too low as compared to the superconducting energy gaps of the materials [10–13]. In both cases, the detailed structure near the boundary area, as well as its effects on the device performance are believed to be crucial. As a result, to obtain a thorough understanding of the nature of GBWLs, and to find a way of manipulating their properties in a fully controllable manner, are undoubtedly the most important tasks to be surmounted before further improvements for devices of this kind become possible.

Very recently, we have observed, for the first time in high–Tc thin films, a substantial enhancement of the superconducting transition with ΔTc > 3 K when microwaves were irradiated onto such YBCO GBWLs [14]. Even more surprisingly, the enhancement was realized only when the weak–link boundary was crossed, and no enhancement could be unambiguously indentified in homogeneous regions of the same films. The mechanisms responsible for the phenomena, though they may have important physical implications on high–Tc superconductivity, are unfortunately far from transparent. In this paper, we report further evidences experimental obtained by measuring similar effects on YBCO films deposited on $SrTiO_3$ bicrystal substrates with various tilt angles. In addition, the scaling behavior of the temperature–dependent critical current Ic(T) across the same GBWLs were also studied to seek possible links and implications towards understanding the fundamental nature of the fascinating phenomena.

II. EXPERIMENTALS

The YBCO bicrystal GBWLs used in this study were fabricated by using the epitaxial YBCO films deposited *in–situ* onto $SrTiO_3$ bicrystal substrates with various tilt angles by a KrF excimer pulsed laser. The details of the film deposition parameters as well as the configuration of the microwave measurement setup were described elsewhere [14,15]. Briefly, the standard photolithographic method was applied to pattern the YBCO films into strips straddling the grain boundary to form the weak–links. The weak–link bridges typically have dimensions of 20 μm wide, 120 nm thick, and 60 μm long between each two voltage electrodes. The voltage electrodes were arranged such that both the intra– and inter–boundary properties could be probed simultaneously along the same bridge. For temperature

Manuscript received October 18, 1994.

Work supported in part by Chun–San Institute of Science and Technology and by the National Science Council of Taiwan, R.O.C. under Grant No. CS82–0210–D009–029 and NSC82–0212–M009–002.

1051-8223/95$04.00

dependent resistance, R(T), measurements, standard four—probe configuration with a dc current of 100 μA was practiced. Microwaves were irradiated to the samples via an antenna with a fixed frequency of 12.4 GHz. The antenna tip was directed longitudinally along the bridge to obtain the maximum possible uniformity of irradiation. The temperature was monitored and controlled by two separate diode thermometers attached near the sample with careful shielding. No variations in temperature (within a resolution of 0.03 K) were observed even when the maximum output power (18 dBm in this case) was applied.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the typical resistive transitions measured on the same bridge in two different regions. The solid curve represents the typical results for regions without crossing the GBWLs. The sharpness of the transition (see the blow—up plot in the transition region shown in Fig. 1(b)) as well as the low normal state resistance indicate the generally high quality of the YBCO films obtained by the PLD process. In contrast, as can be seen from both Fig. 1(a) and 1(b), when the GBWL is crossed, not only is the normal state resistance an order of magnitude higher, but a typical weak—link transition tail is clearly evident. To further elucidate that the observed transition tail is indeed manifestated by the Josephson phase slippage effect instead of arising from effects such as stoichiometric inhomogeneity, the current—voltage characteristics (IVCs) of the GBWLs were measured. The typical resistively—shunted junction behaviors were evident. As an example, we show in Fig. 2 the results of IVCs measured under irradiation of a 12.4 GHz microwave. The microwave—induced Shapiro steps occurred at the predicted fixed voltages $Vn=nh\nu/e$ (as indicated by the arrows shown in Fig. 2), again, demonstrate a solid manifestation of the Josephson effect. It is noted that, when measured in regions without crossing the grain boudary, the IVCs are essentially inert to microwave irradiations.

With the clear distinctions between the properties of intra— and inter—boundary regions described above, we proceed to show the results of microwave—enhanced superconductivity obtained in GBWLs with different tilt angles, θ. The results are shown in Fig. 3(a), 3(b), and 3(c) for $\theta = 24^\circ$, $\theta = 36.8^\circ$, and $\theta = 45^\circ$, respectively. It is clear from Fig. 3 that, although the basic features of the microwave enhancement are essentially the same for the three cases, the detailed responses to the nominal input microwave power level are quite different when θ was varied. For instance, in the case of $\theta = 24^\circ$, essentially no enhancement is evident and the behavior is very similar to that observed in intra—boundary regions (Fig. 3(d)). Whereas, when $\theta = 45^\circ$, significant enhancement is realized, even when the minimum microwave power (5 dBm) is applied. As has been discussed previously [14], the fact that the entire superconducting transition was enhanced to well over its equilibrium Tc and occurred only in the weak—link region, it could not be explained by either the mechanism of fluctuations or the effects of redistribution nonequilibrium quasiparticle alone.

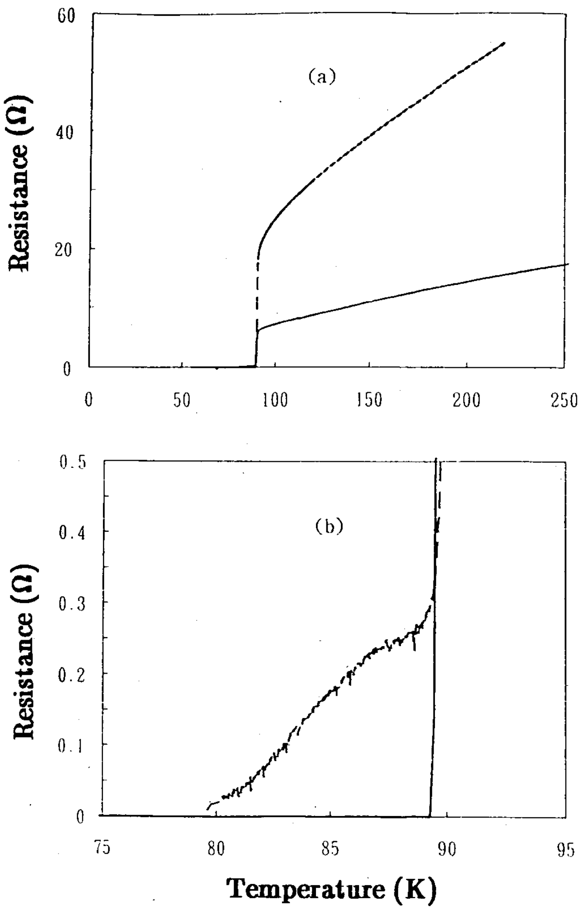

Fig. 1. (a) The resistive transitions of a θ=36.8° GBWL measured with (dashed curve) and without (solid curve) crossing the boundary weak-link. (b) The enlarged plot near the transition region of (a), showing the clear manifestation of the Josephson phase slippage effects when boundary was acrossed.

Alternatively, as proposed by Aslamazov and Larkin [16], the superconducting contacts or weak—link structures effectively represent a potential well for electrons, leading to an energy diffusion—induced cooling effect when subject to microwave irradiation. As a

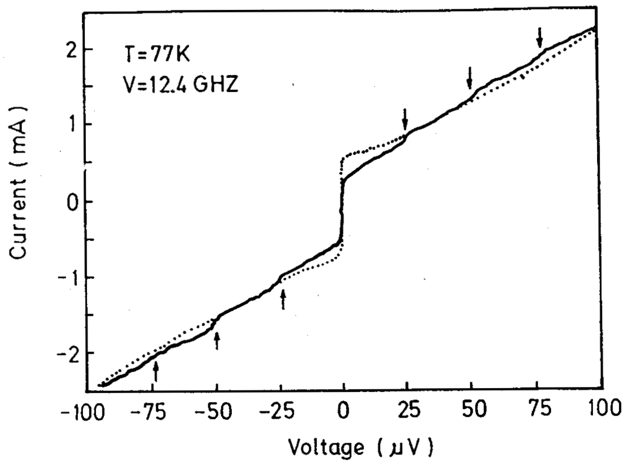

Fig. 2. The typical cross—boundary IVC of the θ=36.8 ° GBWL taken at 77 K, showing the effects of microwave irradiation. The steps indicated by the arrows on the solid curve correspond exactly to the Shapiro steps expected from weak—link Josephson junctions. The dashed curve represents the results obtained in the absence of microwave, displaying a typical RSJ type behavior.

result, the critical parameters of the structure can be strongly enhanced, depending on the frequency and power of the incident microwave. The effects become most significant when the dimension of the structure is within the constraint condition, $\xi_0 > a > \xi(T)(1-t)^{1/4}$. Where ξ_0, a, $\xi(T)$, and t are the BCS coherence length, the dimension of the conducting filament, the temperature dependent Ginzburg—Landau coherence length, and the reduced temperature, respectively. The results, shown in Fig. 3, may thus reflect the detail geometrical structure of the boundary weak—links. If this is indeed the case, one would expect to see some variations in the transport properties, as the nature of the weak—link is very sensitive to the dielectric regions existing within 5—20 nm from boundary interface [17].

Figure 4 shows the temperature scaling behavior of the boundary critical current Ic(T), to reveal the nature of weak—link junctions. Indeed, though the Ic(T) for the three θ values studied here are basically describable by the form $Ic(T) \approx (1-T/Tc)^2$, a relation usually found in superconductor/normal/superconductor (SNS) junctions, they are different in details. In particular, in the case of θ=24° (Fig. 4(a)), unlike those of θ=36.8° and θ=45° (Fig. 4(b) and 4(c)), the data clearly deviate from the power—law behavior within a narrow temperature span, implying that the 24° junction may have stronger

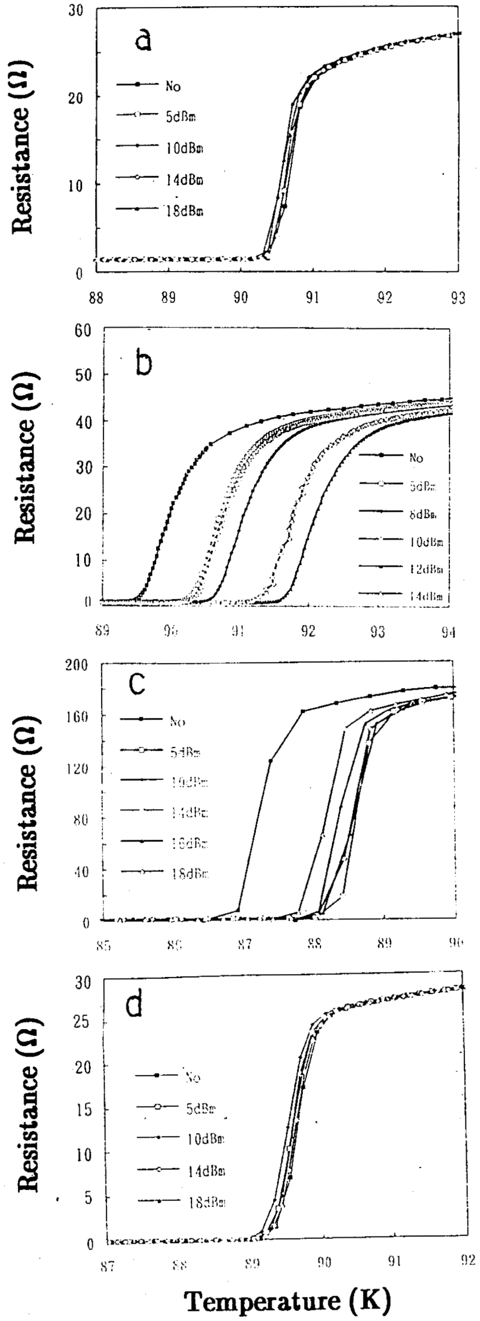

Fig. 3. The microwave—enhanced R(T) results for (a) θ=24°, (b) θ=36.8°, and (c) θ=45°, respectively. The intra—boundary results for θ=36.8° bridges are also shown in (d) for comparison. It is evident that the enhancements are significant only when the junctions are sufficiently weakly coupled.

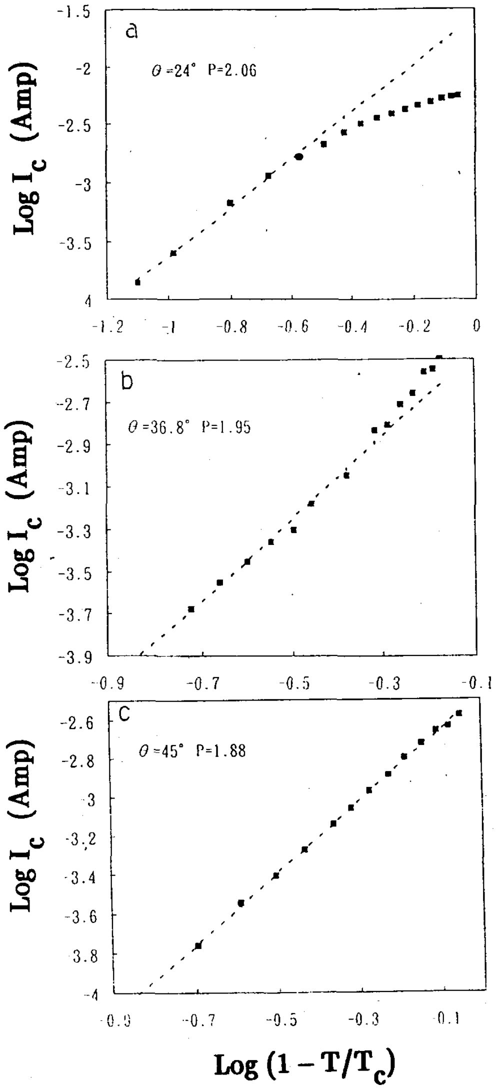

Fig. 4. The cross-boundary Ic(T) results plotted in *log–log* scales as a function of reduced temperatures for the corresponding GBWLs shown in Fig. 3.

coupling effects. Indeed, both the R(T) and IVC's results of the 24° junction showed a much less pronounced weak–link behavior as compared to the others. It seems still too early to draw a definite conclusion on the actual mechanisms responsible for the observed results reported here and further assertions may have to rely on deeper analyses of the boundary structures. The present results have, however, indicated a new direction of research towards the understanding of high–Tc superconducting grain boundary junctions, both from theoretical and practical points of view.

IV. SUMMARY

We have demonstrated a series of new results on microwave–enhanced superconductivity, realized by investigating the effects of the tilt angle of the bicrystal boundaries. By correlating the effects with the details of the boundary structures, we find that both the Ic(T) scaling laws and the enhanced transition temperatures appear to display consistent and close correlation.

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