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# Novel Interface-engineered Junction Technology for Digital Circuit Applications

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**Abstract**

Interface-engineered junctions with $YbBa_2Cu_3O_7$ as the counter electrode were demonstrated. The junctions exhibited excellent Josephson characteristics with a Josephson critical current ($I_c$) ranging from 0.1 mA to 8 mA and a magnetic field modulation of the $I_c$ exceeding 80% at 4.2 K while maintaining complete *c*-axis orientation of the counter-electrode layer. The $1\sigma$ spreads in $I_c$ for junctions with an average $I_c$ of 1-2 mA were 5-8% for 16 junctions within a chip, and 9.3% for a 100-junction array. Our $dI/dV$ measurements suggest that a theoretical approach taking into account both a highly transparent barrier and the proximity effect is required to fully understand the junction characteristics.

*Keywords* : Interface-engineered junctions, Josephson effect, $YbBa_2Cu_3O_7$, current transport mechanism

## I. Introduction

Uniformity and reproducibility of junction characteristics constitute the major challenge concerning the present high-$T_c$ Josephson junction technology for digital circuit applications. Recently developed interface-engineered junctions (IEJs) seem to be highly promising in this regard [1,2]. However, the electric properties of IEJs are extremely sensitive to the substrate temperature for the counter-electrode deposition, and the $I_c$ value appropriate for the fabrication of SFQ (single flux quantum) circuits can be obtained only at a relatively low substrate temperature range. This temperature range conflicts with the requirement for the complete *c*-axis oriented growth of the counter-electrode layer with minimum sheet inductance $L_s$, when sputter-deposited $YBa_2Cu_3O_7$ (YBCO) is utilized as the counter electrode [3]. This trade-off problem between $I_c$ and $L_s$ could be solved if $YbBa_2Cu_3O_7$ (YbBCO) were adopted as the counter electrode, because it can grow with complete *c*-axis orientation in a far wider temperature range than is possible with other 123 compounds [4].

This paper describes our successful fabrication of IEJs with YbBCO as the counter electrode together with some discussion concerning the current transport mechanism within the junctions.

## II. Junction fabrication

The YBCO and YbBCO films used in the present work were grown on $SrTiO_3$ substrates in a 200 mTorr mixture of 70% Ar and 30% $O_2$ using an off-axis sputtering system. An epitaxial $SrTiO_3$ or $CeO_2$ film sputtered in the same chamber was used for interlayer isolation. The substrate temperature for the base YBCO layer was fixed at 780 ℃.

Ramp-edge structures were produced using a photoresist mask reflowed after patterning, together with Ar-ion milling with substrate rotation during etching. We adopted the two-step etching technique to obtain a clean ramp-edge surface [5]. The

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resultant ramp edges had a taper of 20° independent of the edge orientation in a wafer.

After etching, the samples were heated to the temperature for the subsequent counter-electrode deposition and maintained at that temperature for 10 min. An activated oxygen flux from an ECR plasma source was supplied during the annealing process in order to suppress the fatal decomposition of the ramp-edge surface. Then, a 300-nm-thick YbBCO counter-electrode layer was deposited at a substrate temperature ranging from 650 ℃ to 730 ℃. The junction width was fixed at 4 μm.

## III. Junction characteristics

Fig. 1 summarizes the substrate-temperature dependences of the junction critical currents ($I_c$) at 4.2 K averaged over 16 junctions in a chip and the volume fraction of $a$-axis oriented grains in the YbBCO counter-electrode layers estimated from the X-ray (200) diffraction intensity relative to (004).

All junctions in Fig. 1 exhibited RSJ-like characteristics with some hysteresis in their $I$-$V$ characteristics at 4.2 K. The magnetic field modulation of $I_c$ amounted to almost 100% for junctions with $I_c$ of less than 0.1 mA and was more than 80% even for junctions with $I_c$ of several mA. We also confirmed that the crossover from a small junction regime to a large junction one took place when the junction width exceeded four times the Josephson penetration depth.

The sheet inductance of a superconducting wiring layer is extremely sensitive to the quality of the film, and the inclusion of $a$-axis oriented grains with a volume fraction exceeding 10% results in a fatal increase in the inductance value. Our empirical criterion for the volume fraction is 1%. In the case of YbBCO, this criterion is fulfilled at substrate temperatures above 650 ℃, as seen in Fig. 1. This is in striking contrast to YBCO, for which a $c$-axis oriented film with sufficient quality is obtained only above 750 ℃.

The uniformity of the junction characteristics was investigated either for 16 individual junctions within a chip or using a 100-junction array pattern. The 1σ spread obtained for 16 junctions fabricated at 680 ℃ ranged from 5.4% to 8.4% for three independent runs. The average $I_c$ values for these three chips were 1.3 mA, 1.4 mA and 1.7 mA, respectively. The spread became slightly worse for a 100-junction array and amounted to 9.3%, as shown in Fig. 2. Although these results are not yet satisfactory, a reasonable reproducibility of the junction characteristics at this stage of development is encouraging. Further improvement in the uniformity and the reproducibility of junction characteristics would be possible by the tighter control of the process conditions.

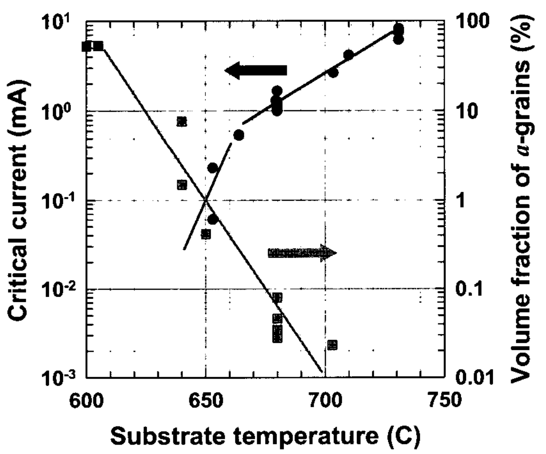


Fig. 1. Substrate-temperature dependence of $I_c$ at 4.2 K averaged over 16 IEJs in a chip and the volume fraction of $a$-axis oriented grains in the counter-electrode laver.

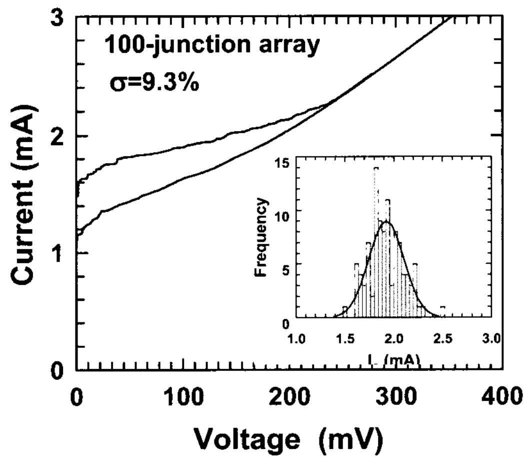


Fig. 2. $I$-$V$ characteristics observed for a 100-junction array at 4.2 K. The inset shows the histogram of the $I_c$ values of the junctions in the array derived from the $I$-$V$ curve.

Fig. 3 shows $I_cR_n$ values as a function of the Josephson critical current density ($J_c$) on various wafers processed at various substrate temperatures. Similar data obtained for our previous YBCO junctions are also plotted for comparison [3]. It is apparent that there is no significant difference between these two types of junctions, indicating that the characteristics of IEJs are essentially independent of the counter-electrode materials.

We noticed that, in many cases, the $I_cR_n$ values approximately scaled with the square root of $J_c$ as long as the junctions were processed under the same conditions. Such behavior can be clearly seen for the junctions in the $J_c$ region below $10^5$ A/cm$^2$ in Fig. 3. This scaling behavior, however, is not universal in the sense that the $I_cR_n$ versus $J_c$ curves for junctions processed under different conditions never lie on the same line. Another interesting point to note is that the $I_cR_n$ values seem to saturate at around 3 mV even in the extremely high $J_c$ region.

The scaling of $I_cR_n$ with the square root of $J_c$ has been confirmed for various types of high-$T_c$ Josephson junctions, and is often ascribed to the existence of different transport channels for Cooper pairs and quasiparticles; that is, Cooper pairs transfer by direct tunneling while quasiparticles can also flow by resonant tunneling [6,7]. In fact, we confirmed that junctions with low $J_c$ (<1x10$^4$ A/cm$^2$) and high

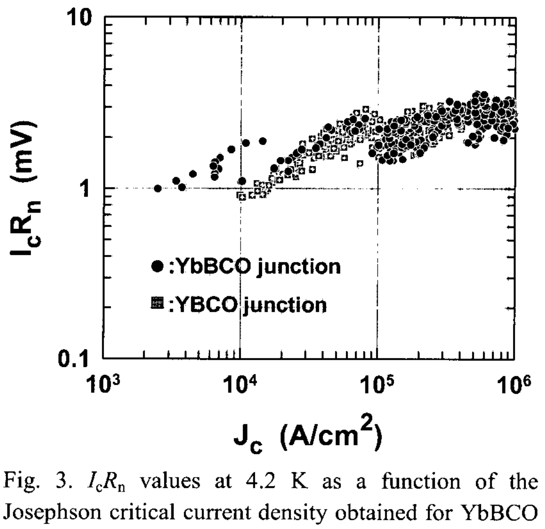


Fig. 3. $I_cR_n$ values at 4.2 K as a function of the Josephson critical current density obtained for YbBCO junctions (black circles). Similar data for our previous YBCO junctions are also plotted for comparison.

$R_n$ far exceeding 10 Ω exhibited nonlinear *I-V* characteristics at high bias voltages that could be explained well by the contribution from inelastic tunneling conduction via a couple of localized states. This seems to suggest that the conventional tunneling scheme offers a good starting point for understanding the Josephson characteristics in IEJs, though the existence of an additional normal conducting or reduced-$T_c$ layer adjacent to the tunnel barrier would be required to account for the temperature dependence of $I_c$ of these junctions that deviates considerably from the Ambegaokar-Baratoff theory [8].

The situation of high-$J_c$ junctions, however, seems to be further complicated. Fig. 4 depicts the *dI/dV* profiles observed for a junction with $J_c$ of 5.5x10$^4$A/cm$^2$ in a weak magnetic field at various temperatures. Although profiles in the close vicinity of zero voltage are affected by the residual superconducting current, we can see a clear dip structure with its minimum at zero voltage together with a slight change in curvature at around 28 mV in the *dI/dV* curve observed at 4.2 K. It seems reasonable to ascribe these features to the remnant of a highly smeared-out superconducting gap structure.

A curious point seen in Fig. 4 is that the differential conductance at high voltages increases gradually with decreasing temperature. Such behavior is certainly beyond the scope of the conventional tunneling picture. Moreover, we can see a number of small step-like structures below 15 mV. We have confirmed that this structure is

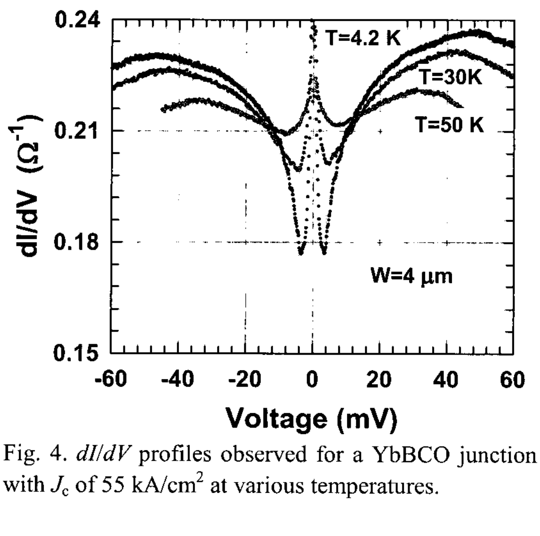


Fig. 4. *dI/dV* profiles observed for a YbBCO junction with $J_c$ of 55 kA/cm$^2$ at various temperatures.

reproducible among junctions.

These experimental results together with extremely high $J_c$ values far exceeding $10^5$ A/cm$^2$ in IEJs strongly suggest that the conventional tunneling model based on the transfer Hamiltonian approach is inadequate and a more general approach including the concept of multiple Andreev reflections (MAR) would be required to fully describe the junction characteristics [9,10]. It is well known that MAR processes produce the subharmonic gap structures (SGS) and a considerable amount of excess current in *I-V* characteristics. The step-like structures seen in Fig. 4 may have some relation with SGS, though we have not obtained any direct evidence.

One problem that makes the situation of IEJs more complicated is the existence of a thin normal conducting or reduced-$T_c$ layer adjacent to the barrier with a finite transparency. A recent theoretical analysis has revealed that the proximity effect between the superconducting and the normal layers induces additional structures in the *I-V* characteristics depending on the actual structure of individual junctions [11]. This makes it difficult to precisely compare the experimental data with the theory at present.

## IV. Summary

We have shown that IEJs with a sputter-deposited YbBCO counter-electrode layer are advantageous for digital circuit applications because of their excellent Josephson characteristics with $I_c$ appropriate for the construction of SFQ circuits, reasonable uniformity and reproducibility in the junction characteristics, and the low sheet inductance of the wiring layer. However, the current transport mechanism in the junctions is still mysterious. Further investigations are required in order to advance this technology.

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