Maximum Josephson current and inhomogeneous superconductivity in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Abstract. The maximum Josephson current (MJC) is measured for a small thin stack of approximately 10 intrinsic Josephson junctions in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) single crystals with various carrier doping levels. By interlayer tunneling spectroscopy, tunneling spectra are also measured to obtain values for the superconducting energy gap $2\Delta/e$. It is found that the MJC decreases with decreasing doping by more than two orders of magnitude from almost $10^4$ A/cm$^2$ to less than $10^2$ A/cm$^2$. The anomalous decrease of two orders of magnitude in the MJC is inexplicable in terms of the Ambegaokar-Baratoff theory. It is explained only when the superconducting state is inhomogeneous. This leads to an astonishing implication that the superconducting state in BSCCO is inhomogeneous and phase-separated on a fine scale.

1. Introduction and conclusion

There is experimental evidence that the electronic states in high-$T_c$ superconductors (HTSC) are inhomogeneous when carriers are lightly doped [1]. It is of significant interest to know whether the superconducting (SC) state in high-$T_c$ cuprates is spatially inhomogeneous or not. While spectroscopic experimental results [2] suggest that the quasiparticle energy spectrum is likely to be spatially inhomogeneous, it is not fully confirmed that the superconducting state is inhomogeneous and the phase separation takes place in the sense of SC phase and nonsuperconducting (NSC) phase. Furthermore, it should be noticed that these experiments probed into only surfaces. Thus the inhomogeneous superconductivity as a bulk nature has yet to be proved.

In this paper, we report that the maximum Josephson current (MJC) observed experimentally decreases drastically as the doping level decreases, and that the MJC decreases nearly proportionally to the square of the $c$-axis conductivity $\sigma_c$. Based on the results and postulating that the doping level is nearly proportional to $\sigma_c$, we argue that the SC state in HTSC is essentially inhomogeneous as a bulk nature.

2. A model for inhomogeneous superconductivity

The term intrinsic Josephson junction (IJJ) refers to a superconductor/insulator/superconductor (SIS) structure formed in a layered crystal structure typically found in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$.
The Josephson current flows only when both sides of the junction are in the SC state. When one side of the junction is not in the SC state, the junction is resistive and no Josephson current flows. Then in the case of inhomogeneous SC state, there is a portion where the Josephson current flows, and also a portion where the Josephson current does not flow. When the IJJ is looked as a sheet on a macroscopic scale, the sheet is randomly fractionalized on a scale of the inhomogeneity of the superconductivity into SC and NSC regions. In this situation, the MJC decreases significantly and approximately proportionally to \( f^2 \), where \( f \) is the total areal fraction of the SC regions. If it is known experimentally that the observed MJC decreases nearly proportionally to \( f^2 \), then it follows that the inhomogeneous superconductivity really emerges in HTSC as a bulk nature.

3. Sample fabrication

Samples were small thin mesa structures fabricated on top of a cleaved surface of Bi\(_2\)Sr\(_2\)CaCu\(_2\)-O\(_{8+\delta}\) single crystals grown by the TSFZ method [4]. The mesa’s side length was 5, 10, or 20 \( \mu \)m and the thickness was typically 15 nm, which corresponds to a stack of 10 IJJs connected in series. The cross section of a sample is shown in the inset to Fig. 1. The samples were configured with three terminal electrodes. The electrode which directly touches the mesa is approximately 450 nm thick and intended to provide a heat flow channel for the suppression of self-heating effect in the case of interlayer tunneling spectroscopy (ITS) [5]. The other fabrication details were described elsewhere [5].

4. Results

Typical temperature \( T \) dependence of the \( c \)-axis resistivity \( \rho_c \) calculated from the mesa resistance is shown in Fig. 1. The filled squares in Fig. 1 show the \( T \)-dependent normal tunneling resistivity \( \rho_N = R_N S/t \), where \( R_N \) is the normal tunneling resistance, \( S \) is the mesa planar area and \( t \) is the mesa thickness. \( R_N \) was evaluated from the ITS results, as described later. From the comparison of \( \rho_c \) and \( \rho_N \), we can reasonably assume that \( \rho_N \) can be approximated by values for \( \rho_c \) at 300 K, though such values tend to be overestimated in the case of overdoped samples, as inferred from Fig. 1.

Figure 1. \( T \)-dependence of \( \rho_c \) and \( \rho_N \) (filled squares) for a Bi2212 small mesa. The inset shows the cross section of a sample.

Figure 2. Oscilloscope image of an \( I - V \) characteristics for a sample in Fig. 1. X-axis: 100 mV/div. Y-axis: 0.5 mA/div.
Figure 3. $I - V$ characteristics for a single IJJ for the sample in Fig. 1 by short-pulse technique.

Figure 4. $dI/dV - V$ characteristics for a single IJJ for the sample in Fig. 1 by short-pulse technique.

Figure 2 show the oscilloscope image for the current-voltage ($I - V$) characteristics for the sample shown in Fig. 1. In this photograph, definitely nine voltage branches are seen and the mesa is regarded as a stack of 9 IJJs connected in series. The MJC is evaluated from this characteristics to be approximately 1 mA for most of constituent junctions.

Values for $2\Delta_{SG}$ were obtained from short-pulse ITS measurements. Figures 3 and 4 show a set of $I - V$ curves and a set of corresponding $dI/dV - V$ curves for the same sample, respectively. The values for $\rho_N$ shown in Fig. 1 were evaluated from $I$ and $V$ values in Fig. 3 at high biases. Values for $2\Delta_{SG}$ at low temperatures are easily evaluated in Fig. 4 as half the peak separation, giving a value of $2\Delta_{SG}$=60.8 meV in this case. We estimate the influence of self-heating on $2\Delta_{SG}$ values to be no greater than 3% [6] in this short pulse ITS.

The characteristics shown in Figs. 1 to 4 are typical ones observed for small thin mesas of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. For various samples with different carrier doping levels, the characteristics changed systematically. Generally, it is observed that, as the doping level is decreased, $\rho_c$ and $2\Delta_{SG}$ become larger and, in particular, $J_c$ decreases dramatically. Figure 5 shows the plots for $J_c$ vs $\rho_c$ for various samples with different doping levels. It is seen that $J_c$ decreases by almost two orders of magnitude when the doping level is decreased. This is the central result of the present study. The result is combined with the short-pulse ITS data to give an argument that the superconducting state in HTSC is inhomogeneous.

5. Discussion
In the Ambegaokar-Baratoff (AB) theory [8], the MJC $I_c$ is given by

$$I_c = \frac{\pi\Delta_{SG}}{2eR_N}\tanh\frac{\Delta_{SG}}{2k_B T}$$

and at low temperatures it reduces to $I_c = \pi\Delta_{SG}/2eR_N$. Therefore, $J_c = I_c/S = \pi\Delta_{SG}/2eR_NS \simeq \pi\Delta_{SG}\sigma(300K)t_0/2e$ is obtained if we assume $\rho_N \sim \rho_c(300K)$, where $t_0$ is the unit IJJ thickness. Since values for $\Delta_{SG}$ and $R_N$ were obtained experimentally, $J_c$ based on the AB theory is evaluated straightforwardly. Figure 6 shows this evaluation as compared with
Figure 5. Plots for $J_c$ vs $\rho_c$ for various samples with different doping levels.

Figure 6. Plots of observed $J_c$ vs $\sigma_c x$ and comparison with the AB theory.

the experimentally observed $J_c$ values. It is clearly seen that the actual $J_c$ values are one to two orders of magnitude smaller than the AB theory values. There is also a tendency that the difference decreases with increasing doping.

The explanation for this large difference in $J_c$ values is difficult within the framework of conventional homogeneous superconductivity. If the $d$-wave order parameter is rotated within the CuO$_2$ plane from layer to layer, $J_c$ can be reduced significantly. However, this is not likely when we take into account the coincidence of the order parameter principal axis and the crystal lattice axes. Furthermore, we have spectroscopic experimental evidence against it [7]. Thus, the significant difference between the AB theory and the observed results is almost inexplicable within the framework of homogeneous superconductivity. The only conceivable cause for this reduced MJC is the inhomogeneous superconductivity like a model described in the preceding section. In this model, $J_c$ decreases nearly proportionally to $f^2$, where $f$ is reasonably assumed to be approximately proportional to the carrier doping level and then $f \propto \sigma_c$. Then it follows that $J_c \propto \sigma_c^2$. The data in Fig. 6 seems to support this model quite well in spite of crudeness of this model.

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