SIN feature observed in intrinsic Josephson junction characteristics for overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Abstract. We have fabricated mesa structures made of 5 to 10 intrinsic Josephson junctions (IJJs) from overdoped and slightly overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) crystals and observed in their tunneling spectra a characteristics structure or a broad peak within the superconducting gap. We propose that this structure results from the inclusion of nonsuperconducting regions in the superconducting layer of IJJs. The cause of the structure is presumed to be the tunneling current through a superconductor/insulator/normal-metal (SIN) junction and the voltage drop due to the current flow in the normal regions after the tunneling through the SIN junctions. The broad peak located at a higher than $\Delta/e$ position reflects the current path through the normal region. All these features imply that the superconducting state is inhomogeneous. The experimental results are compared with numerical calculations based on a simple model to obtain a good agreement. From the comparison, it is concluded that the nonsuperconducting and superconducting regions coexist in overdoped BSCCO on a $\sim 50$ nm scale.

1. Introduction
The superconducting state of the high-$T_c$ superconductors (HTSC) is yet to be understood sufficiently. The scanning tunneling spectroscopy results on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ revealed inhomogeneous quasiparticle energy states on a fine scale [1]. It is likely that the result is directly related to the inhomogeneous superconducting state of the high-$T_c$ superconductors. Indeed, spectroscopic experimental results suggesting an inhomogeneous superconducting state have been observed [2]. However, the results are not sufficient to provide the intuitive understanding of the inhomogeneous superconducting state. Therefore, further studies on various aspects are necessarily to gain complete insight into the superconducting state of the high-$T_c$ superconductors.

The intrinsic Josephson junctions (IJJ) are naturally built in a layered crystal structure of HTSC [3], and they are the crystal structure itself, extending every nm in a superconducting crystal. Therefore, the characteristics of IJJs are regarded as a unique probe into the superconducting state of HTSC. We have fabricated mesa structures made of a few IJJs from a slightly overdoped or an overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) crystal and observed in their tunneling characteristics a shoulder-like structure or broad peak within the superconducting gap. We propose that this structure can result from inclusion of nonsuperconducting regions on a fine scale in the superconducting layer of IJJs. Although it may appear clear that this structure
reflects partial existence of superconductor/insulator/normal-metal (SIN) junctions in IJJs, the position of this broad peak is greater than $\Delta/e$, with $\Delta$ being the superconducting gap, and the interpretation is not straightforward. We argue that the structure derives from the partial existence of the normal state region in the superconducting layer when the normal regions are dispersed on a fine scale. In order to provide a semi-quantitative basis to this postulate, we have made a numerical model calculation to obtain a good agreement. The numerical results have also shown that the nonsuperconducting fraction is of the order of 50%, which is rather large. Therefore, the SIN-like structure in the IJJ tunneling characteristics implies that the superconducting state in HTSC is inhomogeneous on a fine scale.

2. Experimental current-voltage curves

For the observation of the current-voltage ($I-V$) characteristics (CVC), we have fabricated small mesa structures 7.5 to 15 nm thick (5 to 10 IJJs) and 5 to 10 $\mu$m on a side on a cleaved surface of a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO) crystal. BSCCO crystals used were grown by the TSFZ method or by the self-flux method. A Au and Ag thin film electrode was evaporated on a cleaved surface immediately after the cleavage in vacuum. By annealing in an oxygen atmosphere, the mesas were made overdoped or slightly overdoped to have a $T_c$ of 80 to 86 K. By photolithography and Ar ion milling techniques, we fabricated square mesas 5 to 10 $\mu$m on a side made of 5 to 10 IJJs with nearly regular CVC in which the number of the resistive branches corresponds to the number of IJJs ($N$). The other fabrication processes were detailed elsewhere [4]. Figure 1 shows the CVC observed for a mesa made of 8 IJJs with a lateral size of 10 $\mu$m. In this mesa, the $I_c$ values are almost the same for all IJJs except the one which is in contact with the electrode and has a lower $I_c$. $T_c$ is 86 K for this sample and the doping level lies in a slightly overdoped region.

Figure 2(a) shows the CVC measured by the short-pulse method on 300 ns time scale for the same sample in Figure 1. The voltages were normalized to represent the single junction voltage $V$. The linear portion above $\sim$70 mV represent the normal tunneling resistance. The self-heating due to the injection of quasiparticle current, which is usually characterized by the downward bending of the CVC, is suppressed within this current range. The important feature in this CVC is that there is a shoulder-like structure within the superconducting gap $2\Delta$. Since this structure is frequently observed in the CVC for BSCCO mesas, it is thought that the structure is closely related to the intrinsic nature of the BSCCO superconductor. The cause of this structure is not necessarily obvious. The distribution of the tunneling conductances or the gap values does not lead to this kind of structure in the case of a series stack of tunnel junctions; they simply result in a broader conductance peak. A hetero-junction with different $\Delta$ values leads to a structure within the gap. In this case, however, the position of the structure corresponds to the difference of the two gaps. As is clear in Fig. 1, there is no signature which indicates existence of such a
large difference in the gap values. We presume that the structure within the gap originates from the SIN junction, which is formed locally in the IJJ structure. Since this structure is observed in mesas made of slightly overdoped and overdoped BSCCO, the structure is thought to imply a physically distinct nature of BSCCO. We argue that this implies the existence of fractional nonsuperconducting regions in BSCCO. In the case of SIN junctions, the peak in the $dI/dV−V$ curve is located at $\Delta/e$, whereas in Figure 2 the shoulder structure is seen to be located at a higher than $\Delta/e$ position. Namely, the higher than $\Delta/e$ position of the broad peak reflects the current path through the normal region, which shift the tunneling spectra to higher voltages by an amount of the voltage drop within the normal region. This result indicates that the nonsuperconducting and superconducting regions coexists in overdoped BSCCO.

3. Model and numerical calculations
In order to provide a semi-quantitative basis to the above argument, we have made model calculation. Figure 3 shows the model and parameters for the numerical calculations. The model consists of a part of a single IJJ, of which the layer is composed of superconducting (S) regions and nonsuperconducting (N) regions, as schematically represented in Fig. 3(a). In this model, the current flows from the superconducting top layer to the superconducting region of the bottom layer through two paths. One is the Josephson current $I_J$ through the SIS junction part, and the other is the current $I_N$ through the SIN junction part, where $I_J$ and $I_N$ are the current per unit area. The latter current flows through the SIN junction and then N region before flows into the S region. Therefore, the voltage between the top S layer and the bottom
\(I_N-V\) curves as a function of the parameter \(r = R_L/R_T\). As \(r\) increases, the current flows through the SIN junction decreases, because the bias between the junction decreases due to the voltage drop in the N region. Equivalently, the voltage curve shifts to higher voltages as the current increases, and the shift increases as \(r\) increases.

\[I_N(x) = W \int_x^L I_{SIN}(V - V_N(x))dx, \quad V_N(x) = \int_0^x R_L I(x)dx. \quad (1)\]

\(R_L\) is the sheet resistance in the N region. The quasiparticle currents \(I_{SIN}\) and \(I_{SIS}\) are obtained using s-wave superconducting order parameter \(\Delta\) and the quasiparticle relaxation time \(\Gamma(E)\) and
the density of states $N(E)$.

$$N(E) = \text{Re} \frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}$$  \hspace{1cm} (2)

$$I_{SIS}(V) = \frac{1}{R_T} \int_{-\infty}^{\infty} N(E)N(E - eV)[f(E - eV) - f(E)]dE,$$  \hspace{1cm} (3)

$$I_{SIN}(V) = \frac{1}{R_T} \int_{-\infty}^{\infty} N(E)[f(E - eV) - f(E)]dE,$$  \hspace{1cm} (4)

where $f(E)$ is the Fermi-Dirac distribution function and $\Gamma = \Gamma_0 \tan^2(E/\Delta)$, which reflects the energy dependence of the quasiparticles[5], and $R_T$ is the tunneling resistance for the area $WL$. We employed this type of superconducting gap parameter in order to reproduce the superconducting peak in Fig. 2 The current through the SIN junction is $I_N = I(0)$. The total current is $I = I_N + fI_J$, where $I_J = WLIS_{SIS}$, i.e., $f$ is the ratio of the S area to the N area, and $f/(1 + f)$ reflects the fraction of the superconducting area. In the numerical calculation, we use $f$ and $r = R_L/R_T$ as parameters. The normalized CVC for $I_N(V)$ and $I_S(V)$ and their $dI/dV$ curves are shown in Fig. 4 in the case of $2\Delta = 50$ meV and $\Gamma_0 = 6$ meV. Figure 5 shows the CVC for $I_S$ as a function of $r$, reflecting that the current is suppressed as the sheet resistance $R_L$ increases. It also indicates that the curve shifts to higher voltages as the current increases.

**Figure 6.** $I$–$V$ and $dI/dV$–$V$ curves calculated based on the present model with $r = 0.3$ and $f = 2$.

**Figure 7.** $I$–$V$ and $dI/dV$–$V$ curves calculated based on the present model with $r = 0.3$ and $f = 1$.

Figures 6 and 7 show the numerical results for two typical sets of parameters. In Fig. 6, where $r = 0.01$ and $f = 2$, the CVC is similar to the experimental result shown in Fig. 2.
with respect to the structure within the superconducting gap. Therefore, this implies that the characteristic structure in the gap is explicable if we assume that the superconducting layers in BSCCO contain nonsuperconducting regions. The position of the in-gap structure is higher than $\Delta/e$ for the SIN junction conductance peak, although it is lower than the experimental result. This is considered to reflect the existence of the normal regions in the superconducting layers of BSCCO. Figure 7, in which $r = 0.2$ and $f = .1$, shows a numerical result in the case of a large fraction of N regions, which contrasts to the result shown in Fig. 6. As is clear, the $dI/dV$-V curve represents the V-shaped conductance within the gap and the superconducting peak becomes less significant. The result can be compared with tunneling result for an underdoped BSCCO [2]. Thus it is found that the model shown in Fig. 3 explain the experimental result rather reasonably.

4. Discussion
The reasonable agreement of the numerical result with the experimental results implies that the superconducting state in BSCCO can be inhomogeneous even in the overdoped region. The fraction of the nonsuperconducting regions is estimated as large as 33% in the simulation. In order to estimate the length scale of the N regions, we take a value of $R_N = 6 \, \text{k}\Omega$, which corresponds to the value of $\rho_{ab} = 1.0 \times 10^{-3} \, \Omega\text{cm}$. It is presumed that a lower resistivity will render the local area superconductive so that $\rho_{ab}$ in the N regions is rather large. As a tunneling conductance, we take a value of $\rho_c = 2 \, \Omega\text{cm}$, which corresponds to a value of $R_T = 30 \, \Omega\text{cm}$ for a 1 $\mu\text{m} \times 1\mu\text{m}$ square. It should be noticed that $R_L$ does not depend on the dimension, while $R_T$ depends on the area. Therefore, if $r = R_L/R_T$ is determined, then the length scale for $L$ and $W$ is determined. In the present case, the value of $r = 0.3$ leads to $L = W = 55 \, \text{nm}$. If we take a value of $\rho_{ab} = 0.1 \, \Omega\text{cm}$, then the length scale is 5.5 nm. These values indicate that the N regions and S regions coexist on a fine scale. The value estimated here roughly corresponds to the length scale of the S regions in a deeply underdoped BSCCO [2]. As for the case for Fig. 3, where $r = 6$, we obtain $L = W = 224 \, \text{nm}$ in the case of $\rho_{ab} = 1 \times 10^{-3} \, \Omega\text{cm}$ and $L = W = 22.4 \, \text{nm}$ in the case of $\rho_{ab} = 1 \times 10^{-1} \, \Omega\text{cm}$. The present estimates depend on the value for $\rho_{ab}$ in the N regions. However, it is concluded that inhomogeneous nonsuperconducting state of a length scale of 5 to 50 nm can be a reason for the characteristic structure in the gap region in the tunneling characteristics of IJJs.

5. Conclusions
We have observed a characteristic structure in the tunneling characteristics for small mesas made of intrinsic Josephson junctions in a slightly overdoped and overdoped BSCCO high-$T_c$ superconductor. It is shown that the structure is caused by the inclusion of nonsuperconducting regions in the superconducting layers of IJJs. The numerical calculations provide an estimate for the length scale of 5 to 50 nm.

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