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Tunneling Measurements of the Zero-Bias Conductance Peak and the Bi-Sr-Ca-Cu-O Thin-Film Energy Gap

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We have examined the zero-bias conductance peak that is often found in high-temperature-superconductor tunnel-junction spectra. We have also measured the Bi-Sr-Ca-Cu-O thin-film energy gap. The zero-bias conductance peak can be explained in terms of quasiparticle tunneling, phase diffusion, and a supercurrent. The implications of this model are discussed.

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A number of tunneling techniques have been employed to determine several of the most important high-temperature-superconductor (HTS) properties. Despite these studies uncertainty remains over whether the HTS cuprates have a complete, BCS-like, energy gap; that is, a region near the Fermi energy (ε_F) with zero density of states. In addition, there is uncertainty over the cause and significance of the zero-bias conductance peak (ZBCP) that has been seen in HTS tunneling spectra by a number of researchers.[1-9] It has been suggested that the ZBCP in HTS tunneling spectra is due to localized magnetic states on the film surfaces,[2] or that it is due to an oxygen-poor surface layer that forms a barrier with a narrow conductive channel near ε_F.[3] The temperature (T) dependence of the ZBCP has been recorded by several researchers.[4-6] Kwo *et al.*[7] refer to the ZBCP of their experiment as a supercurrent feature, while Tsai *et al.*[8] comment that it was not observed consistently enough in their experiment to produce systematic results. In addition, tunneling experiments have been performed on HTS while using Nb (Ref. 5) or Pb (Ref. 8) (which we will call conventional materials) as a counterelectrode, and a ZBCP has been observed well above the critical temperature (T_c) of the conventional material. Lee *et al.*[5] suggested that the ZBCP probably was not due to a supercurrent, since it showed no response to an applied magnetic field. In this paper we show that zero-bias conductance peaks can be explained in terms of quasiparticle conductance, thermal noise which causes phase diffusion, and a supercurrent.

A detailed description of the squeezable electron tunneling (SET) junction experimental configuration has been published by Moreland and Hansma.[10] The SET junctions used in our experiment employed two 15 mm×3 mm×0.5 mm MgO substrates coated with 0.5-μm-thick Bi-Sr-Ca-Cu-O (BSCCO) films. The BSCCO was prepared by a coevaporation of SrF_2, CaF_2, Cu, and Bi onto MgO substrates, followed by a postanneal in flowing O_2 that had been bubbled through deionized water. A four-probe resistive technique was used to measure T_c which ranged from 75 to 84.5 K. While compositions were nominally $Bi_2Sr_2Ca_1Cu_2O_x$, the films were polycrystalline and sometimes showed evidence of the 2:2:2:3 phase in the resistance versus temperature profile. The films were masked, and two thin strips of SiO, each 1 μm thick, were deposited lengthwise along the edges of the films. The substrates were arranged perpendicular to each other, with the BSCCO films facing each other and separated by the SiO strips. The junction was placed into an electromagnetic squeezer, and lowered into liquid He at 4 K—the temperature at which all measurements were made. The squeezer was activated, placing a force on the substrates, which arched until the film surfaces touched and formed one or more point contacts. The magnetic field at the junction produced by the squeezer electromagnet was measured with a Hall probe, and was less than 10^{-4} T. Several measurements were made with the films clamped into the squeezer so tightly that the film surfaces touched without the squeezer being activated. In this case there was no squeezer-induced magnetic field, and the data did not differ from those taken with the squeezer activated. A voltage source was employed for junction biasing, lock-in techniques were used for data acquisition, and feedback was used to obviate drift of the ac amplitude. Details of this method are given by Hebard and Shumate.[11]

While tunneling spectra are usually reported in terms of conductance, it is conventional to report a supercurrent as displaying zero resistance. For consistency we report all data in terms of conductance. Since our minimum resolvable resistance was 10^{-2} Ω, our maximum resolvable conductance was 10^2 S. By infinite conductance we mean that the conductance was greater than 10^2 S.

When the films first contacted each other, the differential conductance-voltage characteristic [$G(V)$] varied smoothly and continuously through zero bias. When the force to the substrates was increased, $G(V)$ increased for all values of V, and a ZBCP was observed when $G(0)$ reached about 5 μS. The ZBCP is charac-

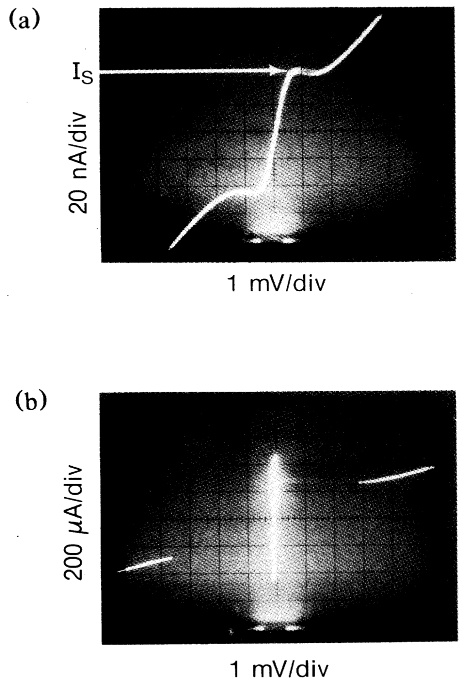

FIG. 1. Low-bias $I(V)$ curves showing ZBCPs at 4 K. (a) $G(0)=100$ μS, and $I_s=44$ nA. (b) $G(0)=\infty$, and $I_s=470$ μA.

terized by an almost linear increase in current with increasing voltage up to a particular current I_s. Beyond I_s the current increases much less rapidly with voltage; that is, the conductance drops dramatically. A further increase in the force resulted in a continuous increase in both $G(0)$ and I_s. By applying enough force we achieved $G(0)=\infty$ in about 50% of the junctions. The force could be varied, and I_s repeatedly raised and lowered by more than an order of magnitude, with $G(0)=\infty$. A supercurrent was evidenced by both infinite conductance and a hysteretic switching between the zero-voltage and voltage states. Figure 1 shows photographs of the low-bias current-voltage $[I(V)]$ characteristics of two typical junctions: one having a ZBCP with a finite $G(0)$, the other with $G(0)=\infty$. By placing a cable from a microwave source into the top of the He Dewar we attempted to couple microwaves to the junctions. The supercurrents of YBCO-YBCO,[12] Nb-Nb,[13] and BSCCO-BSCCO SET junctions could be quenched with microwaves. With extensive variations in the power and frequency of the microwave radiation, it has been possible to resolve Shapiro steps with YBCO-YBCO and Nb-Nb SET junctions, but not with BSCCO-BSCCO SET junctions. The difficulty in resolving Shapiro steps is probably due to a poor coupling of the radiation to the junctions. It is also possible that the junctions responded chaotically to the radiation.

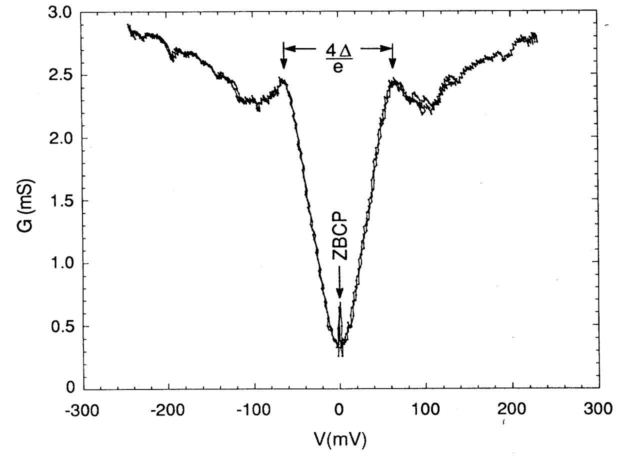

FIG. 2. $G(V)$ curve at 4 K. Conductance peaks corresponding to the energy gap and the ZBCP are indicated by arrows.

In about 25% of the samples the $G(V)$ characteristic displayed an energy-gap feature, often with a ZBCP, and sometimes with $G(0)=\infty$. We emphasize that $G(0)$ is the conductance of the ZBCP. The background zero-bias conductance, the conductance at ± 10 mV, was always less than 15% of $G(150\text{ mV})$. As pointed out by Kirtley,[9] a high-quality gap feature is characterized by low conductance below the gap voltage, a conductance overshoot at the gap edge, and symmetry in voltage in the positions of the overshoots. Our $G(V)$ figures that show the energy-gap feature display these characteristics. Figure 2 shows $G(V)$ with both the ZBCP and the gap features. Values for $2\Delta/e$ for different junctions varied from 46 (± 4) to 64 (± 4) mV.

There is a functional relationship between $G(0)$ and I_s. Figure 3 shows $G(0)$ as a function of I_s. The data are taken from ten samples. Three distinct regions are indicated by the vertical dashed lines and the letters inside the figure. In region A, which covers values of I_s from about 10 nA to 5 μA, $G(0)$ is roughly proportional to I_s, is equal to the high-bias conductance $G(150\text{ mV})$ to within an order of magnitude, and ranges from about 5 μS to 10 mS. In region B these relationships change dramatically. With a small increase in I_s from 5 to 20 μA, $G(0)$ changes from about 10 mS to ∞, and rises rapidly above $G(150\text{ mV})$ with increasing I_s. In region C, which includes all values of I_s greater than 20 μA, $G(0)=\infty$, while $G(150\text{ mV})$ rises very little with increasing I_s. We now present an explanation of this relationship between $G(0)$ and I_s in terms of quasiparticle excitations (region A), phase diffusion (region B), and a supercurrent (region C).

It is the tunneling of thermally excited quasiparticles that explains the behavior in region A of Fig. 3. It has been shown experimentally,[14] and by our computer simulations of $I(V)$, that for BCS materials the quasiparticle current increases nearly linearly with voltage until a voltage of about 4 times $k_BT/2e$ is reached. A further in-

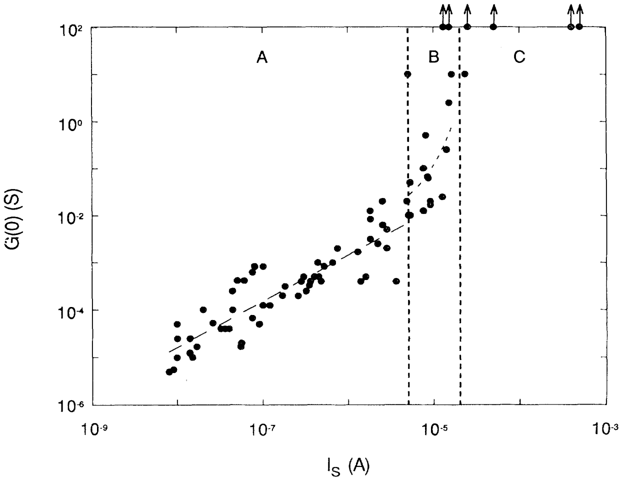

FIG. 3. $G(0)$ as a function of I_s. Region A: quasiparticle tunneling, $k_BT_{\text{eff}} \gg E_J$. A least-squares-error power-law fit to our data for $G(0) < 10$ mS is indicated by the long-dashed line, and is given by $G(0)=1.034\times10^{3}I_s^{0.98}$. $I_sR(150$ mV) ranged from 190 to 440 μV in this region. Region B: quasiparticle tunneling and phase diffusion, $k_BT_{\text{eff}} \approx E_J$. A least-squares-error exponential fit to our data for 10 mS $\leq G(0) \leq 10^{2}$ S is indicated by the short-dashed line and given by $G(0)=5.837\times10^{-3}\exp(3.055\times10^{5}I_s)$. Here $I_sR(150$ mV) ranged from 530 to 830 μV. Region C: pair tunneling, $k_BT_{\text{eff}} \ll E_J$. Here $I_sR(150$ mV) ranged from 1.2 to 2.0 mV.

crease in voltage bias increases the current, but at a much lower rate; that is, the conductance drops. In our experiment at 4 K, $k_BT/2e=172$ μV, while $I_sR(0)$ $[R(V)=1/G(V)]$ has a mean value of about 640 μV, or 3.72 times $k_BT/2e$, for all of region A. We emphasize, however, that if the BSCCO gap were BCS-like, that is, completely devoid of quasiparticle states, there would be virtually no quasiparticle excitations above the gap at 4 K, since the value of Δ/e that we measured was 23–32 mV, $k_BT/e=345$ μV, and for low-bias quasiparticle tunneling between BCS superconductors $I(V)$ depends on the gap predominantly through the term $\exp(-\Delta/k_BT)$.[15] Our simulations of $I(V)$ show that the quasiparticle tunneling current would be immeasurably small if the gap were BCS-like.[13] Results of tunneling experiments measuring the conductance below the HTS gap imply that the gap may not be complete, since the low-bias conductance is anomalously high. While the excess low-bias conductance could be caused by a leakage current, the peak structure at zero bias due to quasiparticle tunneling would be reduced or eliminated by a leakage. When the conductance due to quasiparticle tunneling falls above I_s (above $V \approx 4k_BT/2e$), a large shunt conductance would prevent the measured conductance from falling to a very low level. In fact, if the shunt conductance were very high, only the shunt conductance would be measured when the quasiparticle conductance fell dramatically, and only a high zero-bias conductance with no peak would be detected.

Detailed analyses of phase diffusion have been reported.[16] Phase diffusion is the thermally excited slippage of the junction phase that occurs when the thermal energy k_BT is comparable to the Josephson coupling energy of the junction, $E_J=\hbar I_c/2e$ (I_c is the junction critical current). When phase diffusion occurs the junction phase (ϕ) is not constant, and the average voltage $[V_{\text{ave}}=(\hbar/2e)\langle d\phi/dt\rangle]$ is nonzero. It is common to define the ratio $\Gamma=k_BT/E_J$. For $\Gamma \gg 1$ the thermal noise is so much larger than E_J that the junction is effectively always in the voltage state; while for $\Gamma \ll 1$ the thermal noise is too small to cause phase diffusion, and $V=0$ for $|I|<I_c$. As Γ approaches 1 from below, phase diffusion occurs, and a nonzero average voltage, less than that of the voltage state, is detected for a range of $|I|<I_c$. For $\Gamma \approx 1$ a nonzero voltage is measured for $|I| \neq 0$. In addition to causing phase diffusion, noise can reduce I_s to a value below I_c. We have measured I_s, which is probably somewhat smaller than the ideal I_c, and increases and decreases with I_c. We use I_s to estimate Γ. If additional noise is present, the effective temperature (T_{eff}) is higher than the thermodynamic temperature of the junction. Phase diffusion occurs for $\Gamma \approx 1$ only if we define Γ in terms of T_{eff}; that is, $\Gamma=k_BT_{\text{eff}}/E_J$. Although the junction temperature is 4 K, the room-temperature equipment may be adding a noise current to the junction, so we expect phase diffusion to occur at a higher I_s than would be the case if all of the noise were 4-K thermal noise. We, therefore, calculate I_s from $\Gamma=1$ for $T_{\text{eff}}=4$ K (giving $I_s=168$ nA) and for $T_{\text{eff}}=300$ K (giving $I_s=12.6$ μA). We expect phase diffusion to occur for I_s between these values. Finally, one can consider phase diffusion in terms of the lifetimes τ_{zvs} and τ_{vs} for the junction remaining in the zero-voltage and voltage states, respectively. Both lifetimes depend on bias current and I_c. For a given bias current τ_{zvs} increases exponentially, and τ_{vs} decreases exponentially, with increasing I_c. The relevant points for the interpretation of our data are that for $\Gamma \gg 1$ there will be no evidence of a supercurrent—only quasiparticle tunneling will contribute to $G(0)$ as in region A of Fig. 3. For $\Gamma \approx 1$ there will be quasiparticle tunneling plus a contribution to $G(0)$ from pair tunneling through phase diffusion. Since τ_{zvs} and τ_{vs} both vary exponentially with I_c, with a small increase in I_s, τ_{zvs} becomes significantly greater than τ_{vs} for measurable bias currents, and $G(0)$ rises to ∞. This explains the behavior in region B. When $\Gamma \ll 1$, I_s has increased to the point where $\tau_{\text{zvs}} \gg \tau_{\text{vs}}$ for measurable bias currents, and $G(0)=\infty$. This is the case in region C. Since in our experiment all data were taken at 4 K, we varied Γ by changing the pressure to the junction, thereby varying I_s (either by increasing the junction area, or by reducing the barrier width, or both).

Several authors have seen a ZBCP above the T_c of one of the electrodes, when that electrode was made of a conventional material. One possible explanation is that a proximity-effect coupling was achieved across the conventional-material–HTS interface, and the conventional material was superconducting at the elevated temperature. This effect has been reported for UBe_{13}-Ta junctions.[17] It is also possible that the tunneling occurred through a grain boundary in the HTS rather than through the barrier between the HTS and the conventional material. In this case any gap feature was at twice the gap parameter of the HTS rather than at the gap parameter of the HTS plus the gap parameter of the conventional material. In addition, Lee *et al.*[5] have stated that they did not think that the ZBCP was associated with a supercurrent, because it showed no magnetic field dependence. One possible explanation of this is that the ZBCP was in region *A* of Fig. 3, where quasiparticle tunneling dominates. The quasiparticles would not respond to a magnetic field with a modulation of I_s. Another possible explanation is that the actual junction area was so small that the maximum flux linking the junction was much less than the magnetic flux quantum (Φ_0).

In conclusion, we have been able to achieve a good coupling between BSCCO films in HTS SET junctions. A supercurrent has been easily and repeatedly achieved. With $G(0)=\infty$ we have been able to reversibly change I_s by more than an order of magnitude. A high-quality gap feature has been seen repeatedly in the $G(V)$ characteristic, and a supercurrent has been seen in combination with the gap feature. We have shown that the zero-bias conductance peak can be explained in terms of quasiparticle tunneling, phase diffusion, and a supercurrent. There are several important implications of the model that we use to explain the ZBCP. First, as with low-temperature superconductors, for any junction to exhibit zero resistance it must have an E_J greater than or about equal to $k_B T_{\text{eff}}$. If a junction fabrication technique that gives finite $G(0)$ is developed, and if $G(0)=\infty$ is to be achieved at the same T_{eff}, then the barrier must be reduced to increase I_c. This has been achieved for low-temperature superconductors, but with HTS it may prove to be a serious obstacle, especially when grain boundaries, which are difficult to control, are used as junction barriers. Second, BSCCO SET junctions exhibit a relationship between the Josephson coupling energy and noise energy that is qualitatively the same as that exhibited by BCS superconductor junctions. At low coupling only a quasiparticle current is detected. When the coupling becomes large enough, phase diffusion becomes apparent. When the coupling is larger than the noise energy, a supercurrent is detected. Finally, the size of I_s for quasiparticle tunneling suggests that these materials do not have a complete BCS-like gap. Thermal excitations at 4 K could not excite a detectable number of quasiparticles over a complete gap of 46–64 mV.

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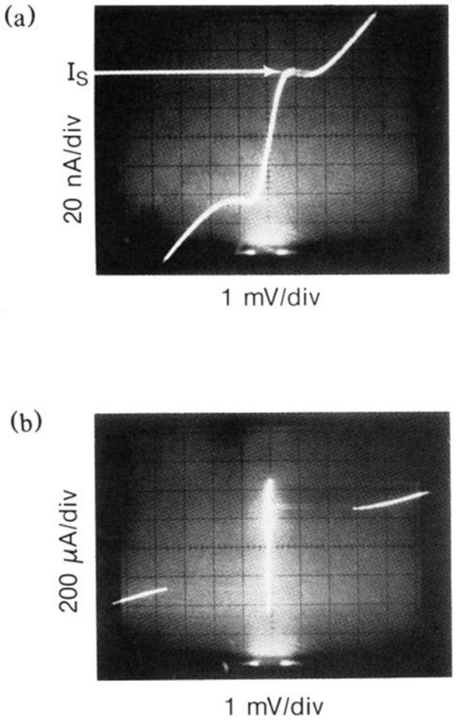

FIG. 1. Low-bias $I(V)$ curves showing ZBCPs at 4 K. (a) $G(0)=100$ μS, and $I_s=44$ nA. (b) $G(0)=\infty$, and $I_s=470$ μA.