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Bi-Sr-Ca-Cu-O thin-film energy gap as a function of temperature and force applied to squeezable-electron-tunneling junctions

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Tunneling-spectroscopy measurements have been performed on Bi-Sr-Ca-Cu-O squeezable-electron-tunneling (SET) junctions. Two distinct features have been seen in the current-voltage [$I(V)$] and conductance-voltage [$G(V)$] characteristics. One of these features has the appearance of an energy-gap signature, while the other may be due to switching to the voltage state of a grain-boundary junction that is in series with the SET junction. The latter feature can mimic the energy-gap signature in $I(V)$ and $G(V)$ characteristics. These two features respond very differently to changes in temperature and the force applied to the SET junctions.

The Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity has been highly successful in explaining the properties of conventional superconductors such as Pb and Nb. The results of a number of experiments, however, suggest that this theory may not be adequate for describing the new class of cuprate high-critical-temperature superconductors (HTS). A lack of consistency in the conclusions of different researchers, who have often used similar experimental techniques to study the same fundamental property, has rendered the development of a comprehensive theory problematic. One important property, that has been reported with contradictory results, is the temperature dependence of the gap voltage ($2\Delta/e$). While some researchers have reported that the HTS energy gap has a BCS-like temperature dependence,[1-3] the results of others suggest that the gap has little or no dependence on temperature.[4-6] In addition, the dependence of Δ on the force applied to point-contact junctions is uncertain.[7,8] We report that these discrepancies may be due in part to the interpreting of two distinct types of features as the gap signature. These two features display very different responses to changes in temperature and the force applied to point-contact junctions.

We have performed tunneling-spectroscopy measurements using squeezable-electron-tunneling (SET) junctions, and we have measured the effects of changes in temperature and the force applied to the junctions on the current-voltage [$I(V)$] and conductance-voltage [$G(V)$] characteristics. The SET junction configuration is shown in Fig. 1. MgO substrates were coated with thin films, about 0.5 μm thick, of Bi-Sr-Ca-Cu-O. Two strips of SiO, each about 1 μm thick, were evaporated lengthwise along the edges of the Bi-Sr-Ca-Cu-O films. The substrates were arranged perpendicular to each other, with the Bi-Sr-Ca-Cu-O films facing each other and separated by the SiO strips. This configuration was placed into an electromagnetic squeezing apparatus which, when activated by having a current passed through it, applied a variable and controllable force to the substrates and pressed the surfaces of the Bi-Sr-Ca-Cu-O films together to form one or more point contacts. The junctions were cooled by being lowered into liquid He, and they were heated by being lifted out of the liquid He and reaching a new equilibrium temperature. Four-point measurements were made with a current and a voltage lead connected to each film.

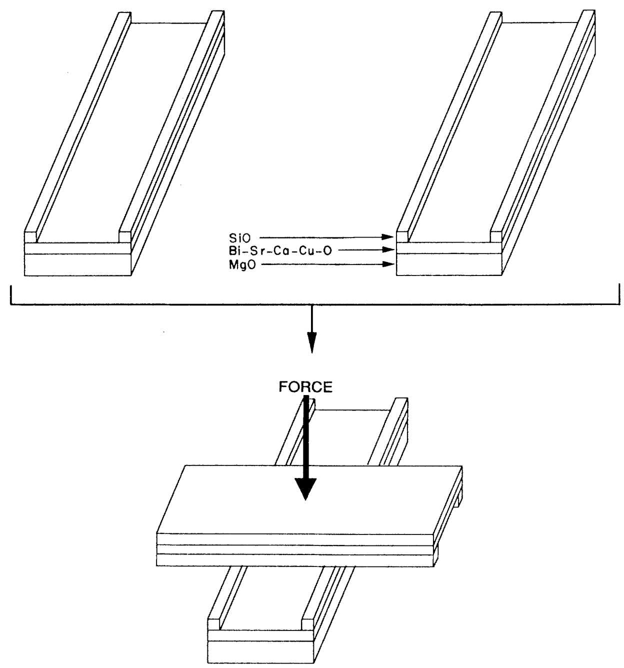

FIG. 1. Thin-film Bi-Sr-Ca-Cu-O SET junction configuration. The figure is not to scale. 1-μm-thick SiO spacers are deposited onto Bi-Sr-Ca-Cu-O thin films grown on MgO substrates. The substrates are placed perpendicular to each other, with the Bi-Sr-Ca-Cu-O films facing each other and separated by the SiO spacers. A force is applied to the substrates until the film surfaces make contact.

$I(V)$ characteristics were recorded by computer and by photographing an oscilloscope display. For $G(V)$ measurements an ac signal was added to the slowly ramped dc bias. Details of the SET junction configuration,[9] and the data-acquisition technique,[10] have been reported.

While the conclusions of different researchers, regarding the effect of changes in temperature and force applied to point-contact junctions, have not been consistent, the $I(V)$ characteristics can often be grouped into one of two distinct categories, as exemplified by Figs. 2(a) and 2(b). Figure 2(a) displays a smooth $I(V)$ characteristic, which has a local maximum in the slope as indicated by the arrow. This type of curve is typical of quasiparticle-tunneling characteristics. In Fig. 2(b) the $I(V)$ curve is characterized by a sharp break in its slope, and in this case the curve is hysteretic. This type of feature is typical of the switching of a series junction, and we will call it a switching feature, and the voltage at which it occurs, the switching voltage.

$G(V)$ characteristics for these two types of $I(V)$ characteristics are shown in Figs. 3(a) and 3(b) [in the case of Fig. 3(b) the switching was not hysteretic]. In Fig. 3(a) there is a relatively low conductance that rises with voltage, below the voltage that is taken to be $2\Delta/e$ (indicated by the arrows). At $2\Delta/e$ there is an overshoot in the conductance. At higher voltages the conductance rises less abruptly with voltage or, in some spectra, levels off. This type of feature has been described by Kirtley as being a high-quality gap signature,[11] and we will call such a feature the gap signature. Figure 3(b) displays several

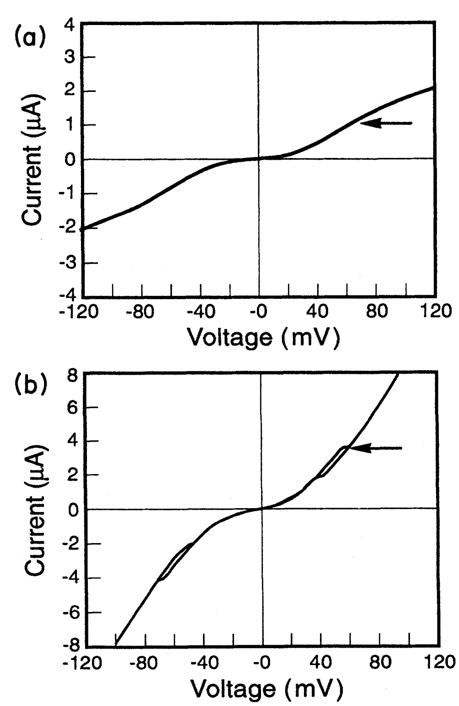

FIG. 2. Digitized current-voltage characteristics taken from oscilloscope traces. (a) The gap signature is indicated by the arrow. (b) The hysteretic switching feature is indicated by the arrow.

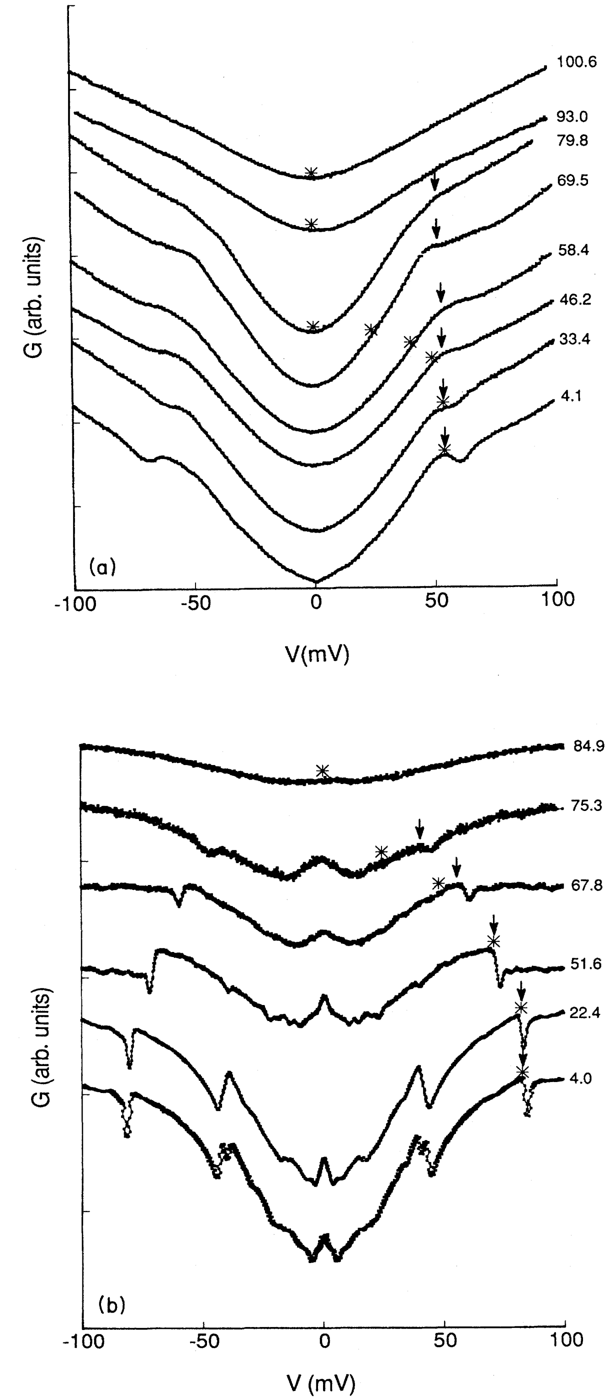

FIG. 3. Conductance-voltage characteristics as a function of temperature in Kelvins as indicated by the number to the right of each spectrum. (a) Energy gap (arrows) of a Bi-Sr-Ca-Cu-O thin film, and the BCS gap (asterisks) of a superconductor with $T_c = 75$ K and a 4-K gap of 55 mV. (b) Switching feature (arrows), and the BCS gap (asterisks) of a superconductor with $T_c = 77.6$ K and a 4-K gap of 82 mV. In this figure there is also a zero-bias-conductance peak. In addition to being offset for clarity, the 51.6-, 67.8-, 75.3-, and 84.9-K conductance values were multiplied by factors of 3, 5, 8, and 8, respectively, to emphasize the switching features.

features including a peak in the conductance at zero bias, which can occur with either a switching feature or a gap signature. We have previously modeled the zero-bias-conductance peak, and have explained it as being due to the tunneling characteristics of the SET junction point contact.[12,13] We will not refer to it further in this paper. In Fig. 3(b), there is a relatively low conductance, which rises with voltage, below a voltage that could be taken to be $2\Delta/e$. At this voltage there is a drop in the conductance. This drop is followed by a fairly rapid return to the previous conductance. Beyond this the conductance continues to rise with voltage or levels off. The important difference between the appearance of these two characteristics is the shape of the feature that could be considered the gap signature. In the case of a high-quality gap signature there is a conductance overshoot, while in the case of a switching feature there is a sharp drop in the conductance.

In the 4-K curve of Fig. 3(b) there are two switching features, one at about 40 mV, the other at about 82 mV. Although switching features were sometimes seen alone, they were often accompanied by other similar features at different voltages. While in Fig. 3(b) the 82-mV feature occurs at about twice the voltage of the 40-mV feature, this relationship was not always found.

The temperature dependence of these two types of features is also shown in Fig. 3. The characteristics taken at different temperatures have been offset for clarity, and the temperature in Kelvins is indicated to the right of each curve. In Fig. 3(a) the arrows indicate the location of the gap signature, while the asterisks indicate the calculated BCS value of the gap for the temperature indicated next to the curve. The BCS gap is determined from the measured 4-K gap of 55 mV and the resistively measured critical temperature (T_c) of 75.0 K. This value of the energy gap yields $2\Delta/k_BT_c=8.5$. As indicated by the arrow pointing toward the 79.8-K curve, there is weak evidence of superconductivity above the measured T_c. It is possible that T_c at the point of contact of the SET junction was higher than 75 K. The gap voltage in this figure displays no temperature dependence.

In Fig. 3(b) the temperature dependence of one of the switching features is indicated by the arrows. This feature was chosen for emphasis because it is visible up to 75.3 K. The asterisks indicate the calculated BCS gap voltage for the appropriate temperature assuming the measured T_c of 77.6 K and a 4-K gap of 82 mV, the switching voltage at 4 K. Changes in temperature had little effect on the switching feature until the temperature reached about 50 K. Beyond this the switching occurred at lower voltages as the temperature was raised.

We have also recorded the gap and switching voltages as the force to the junctions was increased at 4 K. An increase in this force increased the overall conductance of the junction. The gap voltage displayed at most a weak dependence on the changes in force applied to the junction. For one junction when the conductance, at which the gap signature was measured, was changed from 0.185 to 9.25 mS, the gap voltage changed from 58 ± 4 to 60 ± 4 mV; that is, it did not change within experimental resolution. The switching feature, however, had a strong dependence on the force applied to the junction. In one junction when the conductance at which the switching feature occurred was changed from 1.59 to 1.9 mS, the voltage at which the feature appeared changed from 55 ± 4 to 94 ± 4 mV.

The response of the switching feature to changes in temperature and force applied to the junction, as well as its shape in the $I(V)$ and $G(V)$ characteristics, suggest that it may be due to switching to the voltage state of a grain-boundary junction that is in series with the SET junction. A series grain-boundary junction would have no voltage across it until its critical current was reached. At this current it would switch to the voltage state, and the total voltage measured across the grain-boundary junction and the SET junction would jump to a higher value. As a result, the total conductance (the conductance measured across the two junctions) would drop. After a grain-boundary junction has switched to the voltage state it will have a finite conductance. As a result the total conductance abruptly rises but not to the value that it had before the switching. If the conductance of the SET junction, the grain-boundary junction, or both continue to rise with voltage, however, the total conductance will continue to rise. Switching at a higher voltage, such as that shown in Fig. 3(b) at 82 mV on the 4-K characteristic, could be caused by switching to the voltage state of the boundaries of the grains that border the grain to which the SET junction makes contact.

Tsai, Kubo, and Tabuchi have reported the temperature dependence of the critical current of a Y-Ba-Cu-O/Y-Ba-Cu-O crack junction.[8] An increase in temperature had little effect on the critical current of their junction until the temperature reached a value of about 40 K—the resistively measured T_c of their sample was 90 K. As the temperature was raised further the critical current fell at an increasing rate as the temperature approached T_c (except for a tailing off above about 70 K). They noted in their paper that their result was similar to the temperature dependence of an ideal point-contact junction. If a series grain-boundary junction had a similar temperature dependence the switching feature would occur at about the same voltage until the temperature reached a value of about 50% of T_c. As the temperature was further increased, the critical current of the grain-boundary junction would fall at an increasing rate with increasing temperature, and there would be less voltage measured across the SET junction when the switching occurred, the exact value of the voltage depending on the SET junction conductance. This temperature dependence of the switching voltage could mimic the temperature dependence of the BCS gap voltage.

The characteristics that were used in Fig. 3(b) were chosen because of the sharp voltage dependence of their switching features, which clearly distinguished them from gap features. The switching feature, however, was sometimes smoother and could, as a result, resemble a gap signature. In addition, if the time constant on the lock-in amplifier that was used to measure the ac amplitude was too high or, equivalently, the dc bias was ramped too quickly, then the switching feature would become rounded and would resemble a gap signature. An asymmetry in the conductance and voltage at which the feature is seen in the $G(V)$ characteristic is an indication that this has occurred. We believe that this switching feature has been detected before, and has been mistaken for a gap signature. Recent $G(V)$ characteristics, taken with better junctions than were previously available, show good gap features and, as stated above, suggest that the gap may be independent of temperature.[4,5]

Barone has listed a number of phenomena that can cause structure in the $I(V)$ and $G(V)$ characteristics.[14] These structures can lead to confusion over the value of the energy gap. Hysteretic switching, as shown in Fig. 2(b), indicates that such features may sometimes be due to switching to the voltage state of series grain-boundary junctions as described here.

In summation, two distinct phenomena have been observed in current-voltage and conductance-voltage characteristics of SET junctions. One of these features has the appearance of an energy-gap signature, while the other does not. The latter feature may be due to switching to the voltage state of a grain-boundary junction that is in series with the SET junction. The gap signature displays little or no dependence on temperature, while the switching feature has a temperature dependence similar to that of an ideal point contact. As a result, the switching feature appears to have a temperature dependence similar to that of a BCS energy gap. In addition, the gap signature is far less sensitive to changes in force applied to the junction than the switching feature. These two features have been seen previously in tunneling experiments, although they have not been reported for the same experiment. Both have been taken to be the gap signature. We have detected both features in the same experiment, and we believe that the interpreting of both of these features as a gap signature has contributed to the confusion over the temperature dependence and pressure sensitivity of the energy gap of Bi-Sr-Ca-Cu-O and possibly of other high-critical-temperature superconductors.

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