Microwave enhancement of superconductivity in $Bi_2Sr_2CaCu_2O_{8+\delta}$ break junctions

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Superconductor-insulator-superconductor (SIS) tunnel junctions have been used to investigate the enhancement of superconductivity in a single-crystal Bi2212 high-T_c superconductor in the presence of gigahertz-microwave radiation. When the microwave power is increased at constant temperature, the break-junction tunneling spectra show that the energy gap increases several times.

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It was long predicted by Eliashberg[1] that the energy gap 2Δ of a superconducting thin film should be enhanced by microwave irradiation. In his model, photons of frequency less than $2\Delta/\hbar$ excite quasiparticles from low-lying states to states of higher energy, thereby making additional pair states near the Fermi wave vector k_F available for occupancy. Eliashberg pointed out that there is a close relation between a change in the nonequilibrium distribution function $f(\epsilon)$ and the energy-gap parameter Δ, which is determined by a modified BCS gap equation at finite temperature T: $\Delta(T) = \lambda\int_{\Delta}^{\omega_D}\Delta[1-2f(\epsilon)]d\epsilon/(\epsilon^2-\Delta^2)^{1/2}$, where λ is the effective strength of the electron-phonon coupling and ω_D is the Debye frequency. Since pairs near k_F contribute most strongly to the pairing interaction, this redistribution of pair-state occupancy increases the condensation energy and leads to an enhancement of the gap while keeping the total number of excitations constant.

Several subsequent experiments[2–4] strongly supported the concept of gap enhancement. It was found that at a fixed temperature the energy gap increases with increasing radiation power and that at a fixed power the energy gap decreases with increasing temperature. Chang[5] and Chang and Scalapino[6] calculated the energy gap for a thin superconducting film which is part of a superconductor-insulator-superconductor (SIS) tunnel junction and driven out of equilibrium by microwave radiation. Entin-Wohlman[7] and Yu and Entin-Wohlman[8] derived the expression for the tunnel current between two dirty superconductors in the presence of microwave radiation, starting from the microscopic theory for a nonequilibrium superconductor. The above-mentioned theoretical calculations, based on BCS theory, taking into account the energy-dependent scattering rate and nonequilibrium phonons, predicted an enhancement of the energy gap of no more than 4%, whereas, for example, Kommers and Clarke,[4] using Al-Al_2O_3-Al tunnel junctions, measured a twofold increase in the energy gap of superconducting Al in the presence of 10-GHz microwave radiation at $T/T_c \approx 0.99$. Nevertheless, these calculations qualitatively agree with experiments.

It is to be noted that Dayem and Wiegan[9] and Fjordboge *et al.*[10] studied superconducting microbridges and point contacts and found that the critical current I_c could be enhanced by a microwave field. Very small bridges have a maximum relative I_c enhancement on the order of 10% in a temperature region down to $T/T_c=0.5$, whereas larger bridges, as compared to the coherence length, have very large relative I_c enhancement (several times) but only in a temperature region very close to T_c. Microwave field results in a larger gap and hence increases the critical current.

It is known that the symmetry and pairing mechanism of the superconductivity in high-T_c superconductors (HTSCs) up to now remain controversial. Since the mechanism responsible for superconductivity in HTSCs is still unresolved, an investigation of the density of states for quasiparticle excitations in copper oxide superconductors is essential. In particular, it would be interesting to study the influence of microwave radiation on the energy gap of HTSCs and to probe the validity of the Eliashberg model for these superconductors. This is especially relevant as there is reason to believe that $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) has a $d+s$ mixed pair state.[11–15] To our knowledge, the microwave gap enhancement in HTSCs has not been observed by tunneling. It should be noted that Galaktionov[16] showed that in the framework of the Eliashberg model, the enhancement of superconductivity by a high-frequency electromagnetic field may also occur in anisotropic superconductors and in HTSCs in particular. However, as a result of the gap anisotropy, both sides of a bell-shaped frequency dependence of the gap enhancement in HTSCs drop significantly faster than in the case of conventional superconductors. Among the HTSCs, Bi2212 has often been studied by the tunneling method. In this work we report the enhancement of the energy gap, as measured by tunneling, in Bi2212 single crystals irradiated with microwaves.

Although over the last few years, in order to measure tunnel spectra in Bi2212 a scanning tunneling microscope has often been used, we performed our experiments using break junctions fabricated from Bi2212 single crystals.[15] A mechanically controllable break junction is one of the better tunnel systems (see, e.g., Refs. 17–19). Breaking the crystal *in situ* at cryogenic temperatures and in high vacuum (or in an inert cryogenic fluid) guarantees two atomically clean surfaces, thereby minimizing surface contamination. The distance between these surfaces and hence the junction resistance can be mechanically controlled.

The Bi2212 single crystals were grown by a KCl-solution-melt free growth method.[20] The preparation and characterization of Bi2212 single crystals are described in detail elsewhere.[15] In this work we have used two slightly underdoped *as grown* single crystals of $Bi_{2.22}Sr_{1.55}Ca_{1.17}Cu_{2.01}O_{8+\delta}$ with $T_c=84$ K and transition width $\Delta T_c=1.5$ K. The dimensions of the investigated crystals were $\simeq 1$ mm $\times 1$ mm $\times 3$ μm. A four-probe contact configuration with symmetrical positions of the low-resistance contacts (<1 Ω) on both *ab* surfaces of the sample was used. The temperature dependence of the resistance of the present samples is essentially the same as those we reported previously.[15]

For the tunneling measurements, the crystal was cooled to 4.2 K in a variable-temperature cryostat and the tunnel junction was then fabricated *in situ* using a mechanical break-junction technique. The differential conductance dI/dV was measured simultaneously with the four terminal *I-V* characteristic using a 1 μA ac modulation and phase-sensitive detection. A calibrated Cernox resistor, mounted on the heater block of the variable-temperature insert, allowed the temperature to be controlled to better than ± 0.1 K. An Allen-Bradley carbon resistance thermometer placed close to the sample allowed the sample temperature to be measured. In addition, microwave heating of the sample can be monitored via the decrease in the measured value of dI/dV at $V>2\Delta/e$. An Agilent E8257D was used to inject microwaves via a semirigid coaxial cable, the bared end (over roughly $\lambda/4$) of which was placed within a few millimeters of the tunnel junction. The maximum power at the sample, taking into account losses in the coaxial cable, was estimated to be $\simeq 0.5$ mW (at 24 dB and 40 GHz).

Figure 1 shows the effect of increasing microwave power at 40 (a) and 7.5 GHz (b) on the differential conductances dI/dV as a function of the bias voltage V for the (a) 1- and (b) 5-kΩ-resistance (at $V>2\Delta/e$) break junctions at 4.2 K (sample 2 was placed directly in liquid helium). For the investigated SIS tunnel junctions, the voltage distance between the two conductance gap peaks is equal to $4\Delta/e$. The sharp peak at zero-bias voltage in the zero-power curve in Fig. 1(a) is caused by the Josephson effect, which can be suppressed by a magnetic field.[11,15] This curve also shows small gaplike features within the gap near zero-bias voltage.[15] As the microwave power increases, the two main maxima of the curves corresponding to 2Δ move to higher voltages, broaden, and diminish in amplitude. It is clear that microwave power increases the superconducting gap. The Josephson and small gaplike features vanish even at low power.

It should be pointed out that with increasing temperature, as a consequence of the energy-gap decrease, the main gap structure also broadens and diminishes. However, in the case of SIS tunnel junctions, the gap peaks shift to *lower voltages* with increasing temperature due to the suppression of the superconducting gap. At high power, a new broad maximum appears within the gap, the amplitude of which first increases and then subsequently decreases and broadens with increasing microwave power. The value of dI/dV at $V\simeq 200$ mV (and consequently the temperature) remains unchanged for microwave powers of up to 12 dB. At the highest power available at 40 GHz, the tunnel junction starts to be heated by the microwave radiation which can be seen both in the decrease of dI/dV at $V\simeq 200$ mV and in the sample temperature monitored by the Allen-Bradley resistance thermometer.

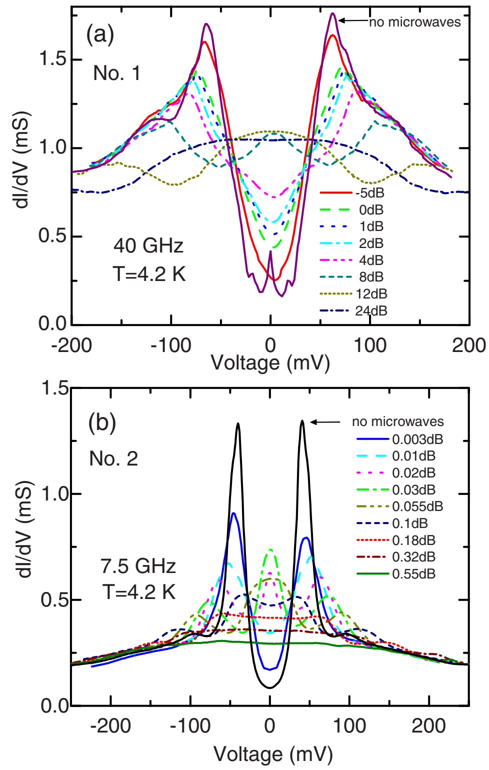

FIG. 1. (Color online) Differential conductance dI/dV for samples 1 and 2 as a function of the bias voltage V for the (a) 1- and (b) 5-kΩ-resistance break junctions at 4.2 K for different microwave power levels at (a) 40 and (b) 7.5 GHz.

As can be seen in Figs. 1(a) and 1(b), the peak-to-peak separations of the two main maxima of the $dI/dV(V)$ curves are different for two single crystals with the same T_c. This is a consequence of a spatial inhomogeneity of the superconducting gap in Bi2212, which was reported in a number of the scanning tunneling microscope studies (see, e.g., Ref. 21 and references therein).

In Figs. 2(a) and 2(b) we plot values of 2Δ as a function of microwave power at $T=4.2$ K extracted from the separation of the gap peaks in the $dI/dV(V)$ curves for samples 1 and 2 at frequencies of 40 and 7.5 GHz, respectively (the raw data can be seen in Fig. 1). Here, we have used $dI/dV(V)$ curves measured at a constant temperature. Since the spacing between the main maxima on the $dI/dV(V)$ curves equals $4\Delta/e$, it is evident that the magnitude of the energy gap 2Δ is enhanced with the microwave power. Before sample heating occurs, the gap is enhanced by a factor of 2.5 in sample 1 with 40-GHz microwave radiation, while for sample 2 with 7.5-GHz microwave radiation, the gap is increased five times. The data in Fig. 2(b) show that a microwave induced enhancement of the energy gap at the lower frequency is considerably larger than that observed in $Al\text{-}Al_2O_3\text{-}Al$ tunnel junctions.[4] In addition, the stimulation effect changes with the frequency more steeply than for conventional superconductors, in agreement with Ref. 16. It is seen that the data in Figs. 2(a) and 2(b) can be fitted quite well (dashed lines) to curves of the form $2\Delta=2\Delta_0+a(P/P_0)-b(P/P_0)^2$, where a and b are constants and $2\Delta_0$ is the gap in the absence of microwave irradiation.

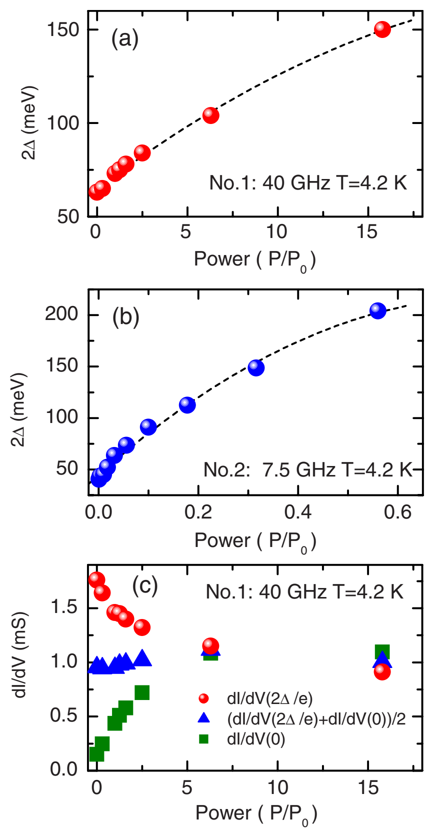

FIG. 2. (Color online) (a) and (b) 2Δ as a function of microwave power at $T=4.2$ K for samples 1 and 2 at frequencies of 40 and 7.5 GHz, respectively. (c) Amplitudes of the gap maxima in $dI/dV(V)$ curves at $V=2\Delta/e$ and the magnitudes of the zero-bias conductance dI/dV as a function of 40-GHz microwave power for sample 1 extracted from Fig. 1(a).

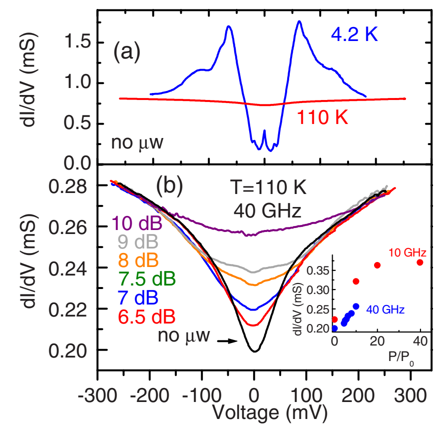

FIG. 3. (Color online) (a) Differential conductance $[dI/dV(V)]$ curves at $T=4.2$ and 110 K for a tunnel break junction on crystal 1 without microwave irradiation. The curve at 110 K has been shifted vertically in order to correct for the change in the junction resistance with temperature. (b) dI/dV as a function of the bias voltage V for the same break junction at 110 K for a different power level of the 40-GHz microwave radiation. The appropriate values of power are indicated. The inset in (b) shows the magnitude of the zero-bias conductance dI/dV as a function of microwave power at frequencies of 40 and 10 GHz at $T=110$ K for sample 1.

The variation of 2Δ with microwave power qualitatively resembles the behavior predicted and observed in Refs. 1 and 4–8 for the gap in conventional BCS superconductors under nonequilibrium conditions. However, there are striking differences with previously published work on conventional superconductors. First, we do not observe an additional structure in the $dI/dV(V)$ curves in Fig. 1 due to photon-assisted tunneling at voltages $\pm 2\Delta/e \pm n\hbar\omega/e$ (here $\hbar\omega \simeq 165$ μV at 40 GHz and $\simeq 30$ μV at 7.5 GHz). It is possible that the blurred edges of the energy gap in HTSCs prevent the observation of such fine structure. Indeed, at low frequencies with respect to the gap voltage $V=2\Delta/e$, the I-V characteristics of conventional superconducting tunnel junctions showed a small smoothing as a microwave power was applied. A smearing of such curves as well as a step structure at high frequencies has always been found to be symmetrical above and below the gap voltage with no change in the main maximum position in dI/dV curves. In our case, as can be seen in Fig. 1, the symmetry with respect to $V=2\Delta/e$ is absent in the dI/dV curves, and the gap maximum shifts toward higher voltages at increasing power. Second, the main maxima on the curves in Fig. 1 corresponding to 2Δ broaden and diminish at high power, which was not found for conventional superconductors in the above cited works. Finally, the nonzero conductances dI/dV at zero-bias voltage and the appearance of the broad maximum within the gap in Fig. 1 at high power are the most prominent discrepancies with respect to the BCS model for the quasiparticle density of states, which may be linked to the peculiarity of the HTSC gap parameter. It seems likely that the diminution in the amplitude of the main maxima at $2\Delta/e$, the increase in the zero-bias conductance, and the emergence of the maximum within the gap are connected to one another.

The conductance of the tunnel junction is directly proportional to the quasiparticle density of states. According to the sum rule, the appearance of excitations within the gap should correspond to a decrease in the density of states at the gap boundary. Figure 2(c), where we plot the amplitudes of the main maxima in $dI/dV(V)$ curves at $V=2\Delta/e$ and the magnitudes of the zero-bias conductance dI/dV extracted from Fig. 1(a), confirms this hypothesis. The total density of quasiparticle excitations, $dI/dV(2\Delta/e)+dI/dV(0)$, is conserved to within experimental error [for convenience, we plot in Fig. 2(c) half of the sum].

It is known that in HTSCs, a pseudogap (an incomplete depletion in the quasiparticle density of states) exists in the electronic excitation spectra below a temperature $T^* > T_c$ or in a magnetic field above an upper critical field at $T < T_c$. As can be seen from Fig. 2(c), the amplitude of the peaks in $dI/dV(V)$ at $V=2\Delta/e$, together with the zero-bias conductance dI/dV, tends to saturate with increasing radiation power. It seems very likely that such a behavior of the tunnel conductance is a consequence of the gradual transformation of the superconducting gap to the pseudogap, as observed in tunneling experiments with increasing temperature.[22] Due to the heating of the superconducting sample by the high-power microwave radiation, it is not possible to separate the effects of microwaves and temperature for the transformation of the superconducting gap to the pseudogap. However, we were able to study the effect of the microwave radiation on the pseudogap at higher temperatures. Figure 3(a) shows the zero microwave power $dI/dV(V)$ curves at $T=4.2$ and 110 K for the tunnel break junction on crystal 1 in order to compare the amplitudes of the gap features. Since at $T=110$ K we are well above the critical temperature for superconductivity ($T_c=84$ K), therefore in the normal state, we attribute the observed minima around zero bias to the pseudogap.[22] In Fig. 3(b) we show the effect of increasing microwave power at 40 GHz on the differential conductances dI/dV as a function of the bias voltage V for the same break junction at 110 K. As in Fig. 1, the value of dI/dV at $V\simeq 200$ mV, and consequently the temperature, remains unchanged. As can be seen from the dI/dV characteristics, the minimum dI/dV around zero-bias voltage diminishes with increasing microwave power as well in the case of the superconducting gap prior to being saturated. At high power of the microwave radiation, the pseudogap can be closed. These data clearly show that the behaviors of the normal-state pseudogap and the superconducting gap with microwave radiation are qualitatively similar.

Finally, it should be pointed out that high quality Bi2212 Josephson tunnel junctions are formed intrinsically in Bi2212 crystals. Many experiments on the dependence of the *I-V* characteristics of these intrinsic junctions are reported and discussed in the literature. However, although such spectroscopic studies have given spectra similar to what the break-junction technique shows, only the effect of microwave power on the Josephson critical current in intrinsic Josephson junctions with unchanged gap voltage was studied (see, e.g., Ref. 23). The effect of microwave stimulation has not been studied. In contrast to these experiments, we studied the influence of microwave radiation on the energy gap after suppression of the Josephson current in a break junction that is a variant of a tunnel point contact.

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