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Tunnel spectra of junctions involving BSCCO and other cuprates: Superconducting and charge-density-wave gapping

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ABSTRACT

We have calculated quasiparticle current–voltage characteristics $J(V)$ for non-symmetric CDWS–I–N tunnel junctions between a partially gapped charge-density wave (CDW) *s*-wave superconductor and a normal metal (I stands for an insulator), as well as for symmetric CDWS–I–CDWS junctions. Relevant parameters of CDWS are considered spatially inhomogeneous in accordance with experimental data for various cuprates, especially $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). The calculated dependences $G(V) = dJ(V)/dV$ demonstrate conspicuous dip-hump structures (DHSs) at low temperatures, T, and pseudogap shallow well at high $T > T_c$ above the critical temperature. In CDWS–I–N junctions, DHSs were shown to be observed for either one or both voltage polarities, depending on the CDW order parameter phase. Similar symmetric DHSs were found for CDWS–I–CDWS junctions. $J(V)$ for break-junctions made of BSCCO were measured. Qualitative agreement was reached between our theoretically calculated and experimental $G(V)$ dependences.

1. Introduction

The problem of the so-called pseudogap (PG) manifestations constitutes one of the major puzzles in the physics of high-T_c oxides. In particular, noticeable deviations from the normal-state behavior are observed in the temperature, T, dependence of the resistivity $\rho(T)$ far above the critical temperature T_c, reflecting changes in the electron density of states (DOS). Such a DOS depletion was observed in angle-resolved photoemission spectra (ARPES) and tunnel measurements. The majority of recent measurements show evidence that superconducting gap (SG) and the PG can be distinguished experimentally, thus seeming to be competing phenomena of different origins.

In addition to PG phenomena, other kinds of peculiarities were observed in cuprates and especially in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). We mean conspicuous dip-hump structures (DHSs) in tunnel current–voltage characteristics (CVCs) [1]. It is notable that in the S–I–N set-up, where S, I, and N stand for a high-T_c superconductor, an insulator, and a normal metal, respectively, the DHS might appear for either one bias voltage V polarity or both, depending on the specific sample. In symmetric S–I–S junctions, DHSs are observable (or not) at both CVC polarities simultaneously. A common interpretation of those observations is still lacking.

2. Theory

We present an idea that dip-hump and PG features, the latter both above and below T_c, are manifestations of the same phenomenon – the development of charge-density waves (CDWs) [2,3]. One should bear in mind that CDW modulations and the concomitant DOS depletion appear against the inhomogeneous background of the non-stoichiometric cuprate structure. Those inhomogeneities are well studied and revealed by scanning tunnel microscopy (STM), especially distinctly at BSCCO [1], $Bi_2Sr_2CuO_{6+\delta}$ [4] and $Bi_2Sr_{1.6}La_{0.4}CuO_{6+\delta}$ [5] surfaces. In particular, wide distributions of gaps were found [1], sometimes having a two-peak character [4], or a clear-cut discontinuity between patches in the apparent-gap map was observed [5].

To describe tunneling across junctions involving high-T_c oxides, we applied a standard theory using Green's functions and taking into account that the Fermi surface (FS) is gapped below T_c owing to the simultaneous existence of the CDW-caused, $\Sigma e^{i\varphi}$, and the superconducting, Δ, order parameters (OPs). (CVCs depend on the phase φ of the CDW OP but not on the superconducting OP phase.) Both OPs give rise together to the appearance of a combined gap $D = (\Sigma^2 + \Delta^2)^{1/2}$ on the nested (d) FS sections and

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the unique superconducting gap equal to Δ (therefore, we shall use this notation for both the superconducting OP and the SG) on the rest of the FS (n-section). The ratio μ between the initial DOS on the d section to the overall DOS is the control parameter of the problem, which is of the order of 0.1 for cuprates. The bare gap values Σ_0 and Δ_0, which describe the strength of the electron–hole (CDW) and Cooper pairings, respectively, constitute other relevant parameters. Both kinds of pairing are considered to be s-wave ones. It means that we do not pretend to reproduce the CVC details at small V exactly, since the superconducting OP Δ is believed to have a predominantly d-wave character [6], although the problem is far from being solved [7].

Due to the inhomogeneity of electronic properties, every parameter may fluctuate in space. Therefore, the resulting tunnel currents $J(V)$ and the differential conductivities $G(V) = dJ(V)/dV$ were calculated making allowance for the scatter of any relevant parameter of the problem. Calculations were carried out for CDWS–I–N and CDWS–I–CDWS configurations, where CDWS simulates the oxide.

3. Calculations, measurements and discussions

In Fig. 1a and b, the temperature evolution of $G(V)$ is displayed for CDWS–I–N junction with $\varphi = \pi$ and 0. Both kinds of CVCs may occur for this non-symmetric set-up with BSCCO electrodes. One sees how the DHS gradually evolves into a broad and shallow PG-like depression. Hence, both features should be considered inter-related. They manifest the CDW-induced FS gapping, competing with superconducting correlations. Averaging over the spread $\delta\Sigma_0$ is crucial to realize a smooth hump (humps) at $|eV| = D$ instead of the sharp peak (peaks). Here e is the elementary charge.

The CVCs of a symmetric CDWS–I–CDWS structure for different T are demonstrated in Fig. 2. As T increases, DHSs at $|eV| = \Delta + D$ smooth out, the coherent peaks at $|eV| = 2\Delta$ approach each other and the finite-T zero-V peak emerges. The latter is well known for S–I–S junctions [8]. The zero-V peak is broadened by the $\delta\Sigma_0$ spread as compared to the homogeneous case. Above T_c, the zero-V feature disappears although dielectric gapping survives up to much higher CDW-transition critical temperatures, which are also scattered together with Σ_0.

The CVC of a BSCCO break junction was measured and is displayed in Fig. 3 together with a theoretical fitting curve. Both

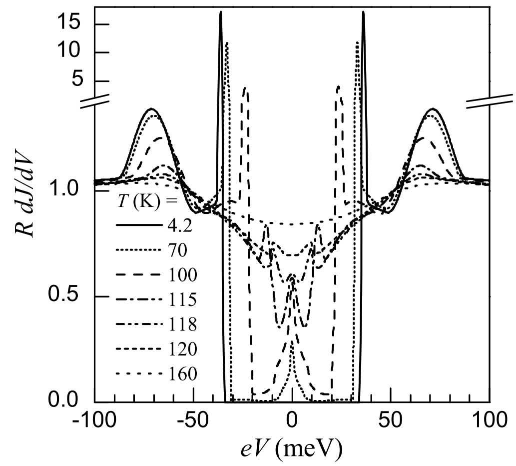

Fig. 2. The same as in Fig. 1, but for a symmetric tunnel junction between CDWSs. The parameter $\varphi = \pi$ in both electrodes. All other parameters are the same as in Fig. 1.

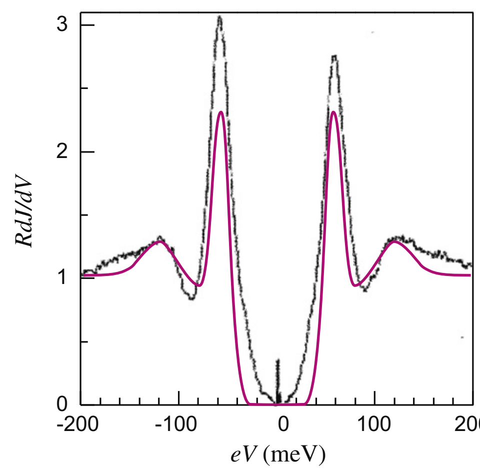

Fig. 3. The measured $RdJ/dV(V)$ for a BSCCO break junction (thin curve) is displayed together with a theoretical fitting bold curve. Here $\Delta_0 = 30 \pm 15$ meV, $\Sigma_0 = 90 \pm 35$ meV, $\mu = 0.08$, and $T = 4.2$ K.

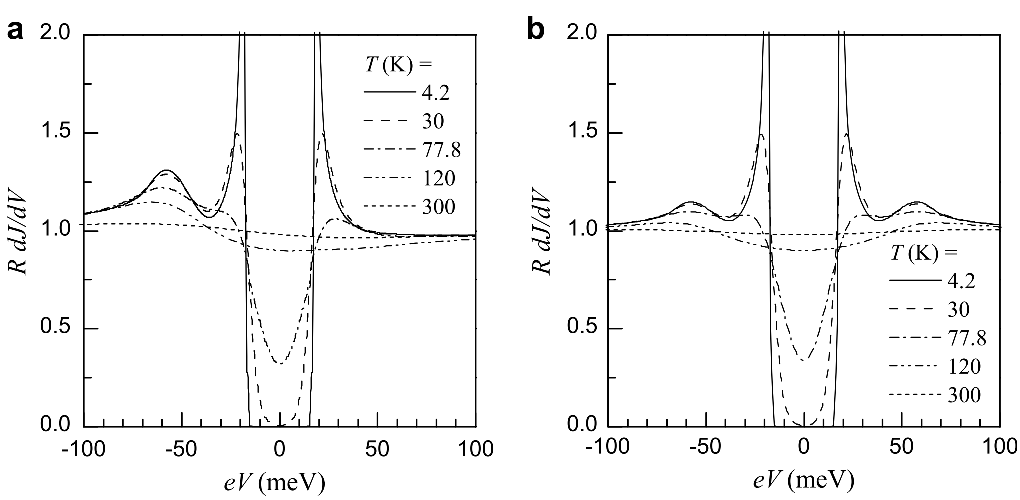

Fig. 1. Temperature evolution of the dimensionless differential conductance RdJ/dV versus bias voltage V for a non-symmetric CDWS–I–N tunnel junction (CDWS stands for inhomogeneous partially gapped charge-density-wave superconductor, I for an insulator, and N for a normal metal). Here, J is the quasiparticle current, R is the junction resistance and $e > 0$ the elementary charge. The CDWS parameters are (see explanations in the text): $\Sigma_0 = 50 \pm 20$ meV, $\Delta_0 = 20$ meV, $\mu = 0.1$, and $\varphi = \pi$ (panel a) and 0 (panel b).

superconducting and DHS features are well reproduced by our theory.

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