Charge-density-wave features in tunnel spectra of high-$T_c$ superconductors

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Abstract.
Tunnel conductances $G(V) = dJ/dV(V)$, where $J(V)$ is the quasiparticle current and $V$ is the voltage, have been calculated for nonsymmetric (CDWS-I-N) and symmetric (CDWS-I-CDWS) tunnel junctions (N, I, and CDWS stand for a normal metal, insulator, and electronically inhomogeneous CDW superconductor, respectively). The CDWS inhomogeneity was shown to be responsible for the appearance of smooth but conspicuous dip-hump structures (DHSs) in $G(V)$ at $T \ll T_c$. At higher $T$, the DHS transforms into a broad pseudogap depletion in the density of states. Good qualitative agreement was obtained between theoretically calculated and experimental $G(V)$ dependences.

1. Introduction
The problem of coexistence and interplay between different order parameters in solids is well known and principally important [1, 2]. Recently, the interest to this problem has been revived, in particular, on the basis of findings in the realm of superconductivity, including high-$T_c$ oxides [3]. Here, coupled charge and lattice distortions (charge density waves, CDWs) were observed coexisting with superconductivity [4]. Below, we want to attract the readers’ attention to those tunnel spectroscopic studies, which support the validity of those results found by other methods and unequivocally demonstrate that CDWs and Cooper pairing coexist at all temperatures, $T$, below the critical temperature of superconducting transition, $T_c$, and that CDWs survive above $T_c$, although a true phase transition into a CDW state is not seen against a thermally blurred normal spectral background.

We made calculations of tunnel current-voltage characteristics, taking into account both the CDW phenomenon and the well-documented intrinsic inhomogeneity of the materials [5]. Our theory shows that low-$T$ features of the differential conductance $G(V) = dJ/dV$, where $V$ is the voltage and $J$ is the quasiparticle current, transform into a famous pseudogap (PG) depletion in the electronic density of states (DOS) at higher $T$. Nevertheless, one can identify PG only at $T > T_c$, where superconducting effects do not interfere with CDW ones. We suppose an isotropic pairing both for CDWs and superconductivity and, hence, do not pretend to adequately...
describe the intra-gap region ($|eV| < \Delta$), since the complex behavior of the superconducting order parameter (SOP) testifies to a major role played by the $d_{x^2-y^2}$ contribution [6] (see however opposite opinions [7,8]). Here, $\Delta$ is the superconducting gap and $e > 0$ is the elementary charge. We have also carried out break-junction experiments at low $T$, which are well reproduced by the theory.

2. Basic formulation

The partial gapping approach [9] was used in a self-consistent form [10]. Nesting conditions are fulfilled only for certain ($i = 1, 2$) Fermi surface (FS) sections ($d$), which can be associated with a dielectric (CDW) order parameter (DOP) and become gapped below some temperature $T_d \geq T_c$, while the rest of the FS ($i = 3$) remains ungapped ($n$) down to $T_c$. The degree of this gapping is described by a parameter $\mu = N_d(0)/[N_d(0) + N_n(0)]$ ($0 < \mu < 1$), where $N_d(0)$ and $N_n(0)$ are the DOSs at the $d$ and $n$ FS sections. On the other hand, strong mixing of the four-particle interaction results in the extension of the SOP over the whole FS [9,11]. Such a partitioning of the FS has been recently confirmed for BSCCO by photoemission spectroscopy [12].

The mean-field Hamiltonian of the CDW superconductor (CDWS) includes the interaction terms responsible for the dielectric and superconducting gappings of the FS. If there had been no CDW gapping, the superconductor would have been characterized by a BCS behavior with a zero-$T$ SOP $\Delta_0^d$ and the critical temperature $T_c^d = \frac{\Delta_0^d}{2\Delta_0}$ ($\gamma = 1.7810\ldots$ is the Euler constant, and the Boltzmann constant $k_B = 1$). When the Cooper pairing is absent, only a parent partially gapped CDW-metal (CDWM) phase would have developed with the DOP $\Sigma_0^d = \Sigma_0^d e^{\mu}x$ and the CDW transition temperature $T_d^d = \frac{2\Delta_0^d}{\mu}$. The interplay between SOP and DOP gives rise to their “renormalization”. As a result [10], two BCS-like gaps appear on the FS: $\Delta(T) = \Delta_0 \text{M"uh}(T/T_c)$ on the $n$ FS section and in the interval $0 < T < T_c$, where $\Delta_0 = (\Delta_0^d \Sigma_0^d)^{1/2}$, $T_c = \frac{\Delta_0^d}{2\Delta_0}$, and $\text{M"uh}(x)$ is the M"uhlschlegel dependence with $\text{M"uh}(0) = 1$, and $D(T) = \Sigma_0^d \text{M"uh}(T/T_d)$ on the $d$ FS section and in the interval $0 < T < T_d$.

3. Quasiparticle currents

Quasiparticle tunnel CVCs $J(V)$ were calculated for CDWS-I-N and CDWS-I-CDWS junctions, where N means a normal metal and I stands for an insulator. Previously developed Green’s function-based approach [11,13] was used.

Equations for CVCs must be supplemented with an account of a non-homogeneous background existing in many cuprates, including BSCCO. In this connection, our theory assumes the combination CDW + inhomogeneity to be responsible for the appearance of the so-called dip-lump structures (DHSs) [14] and is expounded in Ref. [4]. Its main conclusion is that it is the dispersion of the parameter $\Sigma_0^d$ – and, as a result, the $D$-peak smearing (the $\Delta$-peak is smeared to a much lesser extent) – that gives the dominant contribution to the effect. For our purpose, it was sufficient to average only over $\Sigma_0^d$.

4. Experimental support of our viewpoint

Superconducting and PG electron states in hole-doped cuprates are especially well probed by tunnel, photoemission and optical spectroscopies. The peculiar energy-gap features of the electron spectrum for those materials can be summarized as follows. There is a gap with a larger amplitude, widely spatially varying [5] and manifesting itself without its PG counterpart in the nodal
Figure 1. $G(V)$-dependences of the tunnel junction between an inhomogeneous CDWS and a normal metal for various temperatures $T$. See explanations in the text.

region [12,15], although it is observed also in the anti-nodal region, the area dependent on the doping parameter $p$ [12]. We identify this gap with our superconducting gap $\Delta$, unique for the whole FS. Its symmetry is mostly claimed to be $d_{x^2-y^2}$-like, but is actually blurred by its interplay with $\Sigma$ [12,15], not to talk about more sophisticated objections against such a canonical form [7, 8].

5. Results of calculations
Below are demonstrated some typical theoretical tunnel spectra obtained for electronically inhomogeneous high-$T_c$ oxides. Our experimental results qualitatively agree with the theoretical ones and were partially published earlier [17]. One of our main results presented here shows that the same approach can explain the DHS and PG phenomena at high $T$, when the DHS is smoothed out.

An example of the transformation of the DHS-decorated tunnel spectra into the typical PG-like ones is shown in Fig. 1 for CDWS-I-N junctions with $\phi = \pi$ (panel a) and $\pi/2$ (panel b). Hereafter, $R$ is the resistance of the junction in normal state (at $T > T_d$). The CDWS parameters are $\Delta_0^* = 20$ meV, $\Sigma_0^* = 50$ meV, $\mu = 0.1$, and $\delta \Sigma_0^* = 20$ meV; the temperature $T = 4.2$ K. For this parameter set, the “actual” superconducting critical temperatures $T_c$ of CDWS domains lie within the interval $114 - 126$ K, and the temperatures of the CDW phase transition $T_d$ is in the range $197 - 461$ K. The asymmetric curves displayed in panel a are similar to the measured STM $G_{ns}(V)$ dependences for overdoped and underdoped BSCCO compositions [18]. An interesting feature of our results is the modification of the $\Delta$-peak and the shift of its position. Although $\Delta$ diminishes as $T$ grows, the $\Delta$-peak moves towards higher $V$; such a behavior of the $\Delta$-peak is undoubtedly associated with its closeness to the $\Sigma$-governed DHS. In experiments, a confusion of identifying this $\Delta$-driven singularity with a PG feature may arise, since the observed transformation of $\Delta$-features into PG- ($D$-) ones looks very smooth [14].

Similar CDW-related features can be found for the CVCs of symmetric CDWS-I-CDWS junctions. The transformation of the symmetric DHS pattern into the PG-like picture is similar to that for the non-symmetric junction. From our CVCs (Fig. 1), it follows that the “dip” is simply a depression between the hump, which is mainly of the CDW origin, and the superconducting coherent peak. Therefore, the dip has no separate physical meaning. It disappears as the temperature increases, because the coherent peak forming the other shoulder of the dip fades down, so that the former dip, by expanding to the $V = 0$ point, becomes an
integral constituent of the shallow PG minimum.

6. Discussion and conclusions
The scenario adopted here is appropriate not only to high-\(T_c\) cuprates, but, e.g., also for superconducting dichalcogenides [11]. A close resemblance between the electronic properties of dichalcogenides and cuprates was noticed long ago [19]. It seems natural due to their electronic two-dimensionality. Nevertheless, only modern ARPES measurements unequivocally demonstrated that the PG in cuprates and that observed in dichalcogenide layered materials – e.g., 2\(H\)-TaSe\(_2\) with its two successive CDW phase transitions – and, hence, undoubtedly being of the FS-nesting origin, are in close relation to each other [20].

To summarize, we have shown that the CDW manifestations against the non-homogeneous background can explain both subtle DHS structures in the tunnel spectra for high-\(T_c\) oxides and large PG features observed both below and above \(T_c\). The DHS is gradually transformed into the PG-like DOS lowering as the temperature grows. Therefore, one should not try to explain DHSs and PGs separately. The dependences of the calculated CVCs on the CDW phase \(\phi\) fairly well describe the variety of asymmetry manifestations in the measured tunnel spectra for BSCCO and related compounds.

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References
[1] Pawłowski G 2006 Eur. Phys. J. B 53 471
[2] Krivolapov Y, Mann A and Birman J L 2007 Phys. Rev. B 75 092503
[3] Lee P A, Nagaosa N and Wen X-G 2006 Rev. Mod. Phys. 78 17
[4] Gabovich A M and Voitenko A I 2007 Phys. Rev. B 75 064516
[5] Boyer M C, Wise W D, Chatterjee K, Yi M, Kondo T, Takeuchi T, Ikuta H and Hudson E W 2007 Nature Phys. 3 802
[6] Eremin I, Tsoncheva E and Chubukov A V 2008 Phys. Rev. B 77 024508
[7] Klemm R A 2005 Phil. Mag. 85 801
[8] Zhao G-m 2007 Phys. Rev. B 75 140510
[9] Bilbro G and McMillan W L 1976 Phys. Rev. B 14 1887
[10] Gabovich A M, Li Mai Suan, Szymbczak H and Voitenko A I 2003 J. Phys.: Condens. Matter 15 2745
[11] Gabovich A M, Voitenko A I and Ausloos M 2002 Phys. Rep. 367 583
[12] Lee W S, Vishik I M, Tanaka K, Lu D H, Sasagawa T, Nagaosa N, Devereaux T P, Hussain Z and Shen Z-X 2007 Nature 450 81
[13] Gabovich A M and Voitenko A I 1997 J. Phys.: Condens. Matter 9 3991
[14] Fischer O, Kugler M, Maggio-Aprile I and Berthod C 2007 Rev. Mod. Phys. 79 353
[15] Kondo T, Takeuchi T, Kaminski A, Tsuda S and Shin S 2007 Phys. Rev. Lett. 98 267004
[16] Guyard W, Le Tacon M, Cazayous M, Sacuto A, Georges A, Colson D and Forget A 2008 Phys. Rev. B 77 024524
[17] Ekino T, Gabovich A M, Li Mai Suan, Pękala M, Szymbczak H and Voitenko A I 2007 Phys. Rev. B 76 180503
[18] Gomes K K, Pasupathy A N, Pushp A, Ono S, Ando Y and Yazdani A 2007 Nature 447 569
[19] Klemm R A 2000 Physica C 341-348 839
[20] Borisenko S V, Kordyuk A A, Yaresko A, Zabolotnyy V B, Inosov D S, Schuster R, Bühner B, Weber R, Follath R, Patthey L and Berger H 2008 Phys. Rev. Lett. 100 196402