QUASIPARTICLE TUNNELING BETWEEN CONDUCTORS WITH CHARGE DENSITY WAVES

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Abstract

The tunneling current (ac and dc) between two charge density wave (CDW) phase domains in the standard geometry of a point contact is calculated. Temperature Green's function for pure CDW and the transfer Hamiltonian of Artemenko and Volkov are used to compute the current analytically. Extension to the more realistic pseudo-gap structure is achieved by using Sadovskii's method of resumming all diagrams for the one-particle Green's function - including the crossing diagrams which carry a momentum $Q=2k_F$. The method results in averages over effective gap values which are carried out analytically. The corresponding results for $\mathrm{Re}\,\sigma(\omega)$ are displayed. They show absorption also inside the gap region.

Theory

I consider a tunnel junction: two CDW phase domains separated by an insulating layer. I calculate the current in this quasi one-dimensional system by the method of the transfer Hamiltonian used by Artemenko and Volkov [1] for the same problem. Thus, I write the Hamiltonian $\hat{K}$ of the system as $\hat{K}=\hat{K}_L+\hat{K}_R+\hat{H}_T=\hat{K}_0+\hat{H}_T$, where $\hat{K}_L$ and $\hat{K}_R$ are the left and right hand side Hamiltonians for the two pure CDW phase domains. $\hat{H}_T$ is the transfer Hamiltonian. To find the current in the system I calculate the change in the number of particles in the left part of the system. In the present case, $\hat{H}_T$ [2] can be written as

$$\hat{H}_T = \sum_{k,q,\sigma} \underline{\alpha}_\sigma^+(k)\{T_0 + T'_Q\tau_1 + T''_Q\tau_2\}\underline{\beta}_\sigma(q) + \text{c.c.} , \qquad (1)$$

where T_0, $T'_Q=T_Q\cos(\delta)$ and $T''_Q=-T_Q\sin(\delta)$ are constant transfer matrix elements without (T_0) and with "Umklapp" (T_Q) from one of the Fermi planes to the other, involving the wave vector $Q=2k_F$ of the CDW. In (1), δ is the phase difference between these direct and backscattering transfer matrix elements. $\underline{\alpha}_\sigma^+(k)$ is defined as $\underline{\alpha}_\sigma^+(k)=(\hat{c}_\sigma^+(Q/2+k),\hat{c}_\sigma^+(-Q/2+k))$ for the left hand side of the junction, $\underline{\beta}_\sigma(q)$ is defined for the right hand side in an analogous way, and $|k|,|q| \ll Q$. The τ's are Pauli spin matrices and σ denotes the spin state of the electron. Now I introduce the temperature Green's function $G_0(k,\tau)$ for the pure CDW phase domain, e.g. for the left hand side, $G_0(k,\tau)=-\langle T_\tau(\tilde{\underline{\alpha}}_\sigma(k,\tau) \odot \bar{\tilde{\underline{\alpha}}}_\sigma(k,0))\rangle_0$. Here, T_τ implies imaginary time ordering. The symbol $\odot$ denotes the dyadic product. The α's are in the interaction representation with imaginary time and $\langle \ldots \rangle_0$ is the equilibrium average. The Fourier transform $G_0(k,i\nu_m)$ of $G_0(k,\tau)$ is given

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in the mean field approximation by $G_0(k,i\nu_m)=(i\nu_m+\tilde{\varepsilon}(k)\tau_3+\tilde{\Delta}\tau_++\tilde{\Delta}^*\tau_-)/((i\nu_m)^2-\tilde{\varepsilon}^2(k)-|\tilde{\Delta}|^2)$, where $\nu_m=(\pi/\hbar\beta)(2m+1)$ denotes the Fermi frequencies. In $G_0(k,i\nu_m)$, $\tilde{\varepsilon}(k)=\tilde{\varepsilon}(Q/2+k)=-\tilde{\varepsilon}(-Q/2+k)$ is the nesting condition and $2|\Delta|$ is the width of the energy gap in the quasiparticle spectrum. The matrix $\tau_\pm$ is defined by $\tau_\pm=(1/2)(\tau_1\pm i\tau_2)$. In order to calculate the tunneling current I use the linear response theory with respect to $\hat{H}_T$.

DC Response

I consider a tunneling junction where the left hand side is grounded and the right hand side is held at fixed voltage V_{ext}. Consequently, in addition to the Hamiltonian for the pure CDW phase, I have an extra term on the right hand side which is given by $\hat{H}_{ext}=-e_0V_{ext}\hat{N}_R$. The external perturbation $\hat{H}_{ext}$ mereley produces a phase in the interaction representation of $\underline{\beta}_0(q)$: $\underline{\beta}_0(q)\to\underline{\beta}_0(q,t,\dot{\phi})=\exp(i\dot{\phi}t)\underline{\beta}_0(q,t)$, where $\dot{\phi}$ is defined by $\dot{\phi}=(e_0/\hbar)V_{ext}$. In the formula for the linear response I consider only terms which are bilinear in α,α^+ and β,β^+. This is a consequence of the fact that $\hat{K}_{L,R}$ conserves the number of particles. With respect to the tunneling current the phase $\exp(i\dot{\phi}t)$ appears in front of equilibrium averages, which thus are invariant under a time shift. To deal with these averages I introduce the temperature Green's function by going from the real to imaginary time. After some transformations [2], I obtain the time independent tunneling current

$$\langle\hat{I}_{OP}\rangle(\dot{\phi}) = \frac{8\pi e_0}{\hbar^2}(T_0^2+T_Q^2)\int_{-\infty}^{\infty}d\omega(f(\omega)-f(\omega+\dot{\phi}))N_L^{CDW}(\omega)N_R^{CDW}(\omega+\dot{\phi})\{1+\alpha\frac{|\tilde{\Delta}_L||\tilde{\Delta}_R|}{\omega(\omega+\dot{\phi})}\}, \quad (2)$$

where $f(\omega)$, $N^{CDW}(\omega)$ and Φ are the Fermi distribution function, the density of states in the pure CDW phase domain and the phase of the order parameter Δ, respectively. In (2), α is defined by $\alpha=(T_0^2/(T_0^2+T_Q^2))\cos(\Phi_L-\Phi_R)$. The formula (2) coincides with the result in [1] and shows in addition to the usual term in the current a term proportional to $\cos(\Phi_L-\Phi_R)$.

Photon - Assisted Tunneling

In the previous section I made the restriction that the voltage across the junction should be constant. Now I assume a sinusoidal voltage $V_{ext}(t)=V_{ext}+u\cdot\cos(\omega_{ext}t)$ across the junction, which leads to a time dependent tunneling current. For small ac excitation, i.e. $e_0u \ll \hbar\omega_{ext}$, and in the absence of dc bias $\dot{\phi}=0$, I obtain [2]

$$\langle\hat{I}_{OP}\rangle(t) = \frac{e_0u}{\hbar\omega_{ext}}I_1(\omega_{ext})\cos(\omega_{ext}t) + \frac{e_0u}{\hbar\omega_{ext}}I_2(\omega_{ext})\sin(\omega_{ext}t) . \quad (3)$$

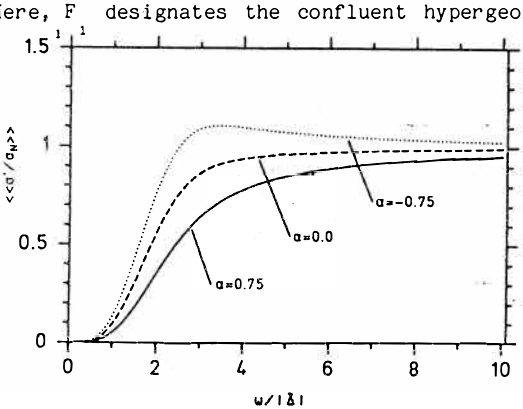
$I_1(\omega)$ and $I_2(\omega)$ are related by the Kramers-Kronig relations. It is well known that there is a scaling relation between $I_1(\omega)$ and the dc current (2) $\langle\hat{I}_{OP}\rangle(\dot{\phi})$: $I_1(\omega)=\langle\hat{I}_{OP}\rangle(\dot{\phi}=\omega)$. The real part of the conductivity is given by $\mathrm{Re}\sigma(\omega)=(e_0D/\hbar A)(I_1(\omega)/\omega)$, where D and A are the the thickness and contact area of the junction, respectively. Note that again there is a scaling relation between $\mathrm{Re}\sigma(\omega)$ and the dc conductivity $\sigma_{dc}(\dot{\phi})$: $\mathrm{Re}\sigma(\omega)=\sigma_{dc}(\dot{\phi}=\omega)$. As usual, $\mathrm{Re}\sigma(\omega)$ and $\mathrm{Im}\sigma(\omega)$ are related by the Kramers-Kronig relations.

Extension to Pseudo-Gap Structure

Extension to the more realistic pseudo-gap structure is achieved by using Sadovskii's [3] method of resumming a class of diagrams - including the crossing diagrams - for the one-particle Green's function. The diagrams have an alternating sequence of free Green's functions $\{i\nu_m-\tilde{\varepsilon}(p)\}^{-1}$ and $\{i\nu_m+\tilde{\varepsilon}(p)\}^{-1}$, where $p\approx k_F$, and an alternating sequence of vertices with incoming or outgoing interaction lines carrying a momentum Q or -Q. The method results in averages over effective gap values $\Delta \rightarrow \xi^{1/2}\Delta$ with Sadovskii's distribution function $P_S(\xi)=\exp(-\xi)$. These averages are carried out analytically in [2] for identical CDW systems and T=0. The real part of the conductivity is

$$\mathrm{Re}\sigma(\omega) = 4\sigma_N|\tilde{\Delta}|\frac{\mathrm{sgn}(\omega)}{\omega}\int_0^{|\omega/\tilde{\Delta}|} dx\,x^2(x-|\omega|/|\tilde{\Delta}|)^2\{{}_1F_1(1,3/2,-x^2)\cdot{}_1F_1(1,3/2,-(x-|\omega|/|\tilde{\Delta}|)^2) - \frac{\pi^2}{16}\alpha\,{}_1F_1(3/2,2,-x^2)\cdot{}_1F_1(3/2,2,-(x-|\omega|/|\tilde{\Delta}|)^2)\}. \quad (4)$$

Here, ${}_1F_1$ designates the confluent hypergeometric function. In (4), σ_N denotes the conductivity above the critical temperature. The real part of the the averaged conductivity is displayed vs. scaled frequency. The real part of conductivity shows absorption also inside the gap region.



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