Current-Voltage Characteristics for Point Contact Composed of Two Peierls Conductors at Finite Temperature

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Abstract

Current-voltage (J-V) characteristics are numerically investigated at finite temperature for a point contact consisting of two Peierls conductors (P) separated by an insulator in the conventional tunnel Hamiltonian approach. Here P is a conductor with a charge density wave (CDW). The J-V characteristics depend on the CDW phases in the mean field approximation where the phases (φ) and energy gaps (Δ) in both Peierls conductors are assumed to be equal, respectively. The current J is a periodic function of the phase φ with a period π, and has a discontinuous jump at $eV = 2\Delta$ ($\varphi \neq 0$). The jump increases as the phase φ increases. For $0 < eV < 2\Delta$ the current J decreases as the phase φ increases, but while for $eV > 2\Delta$ the current J increases as the phase φ increases.

Key words: charge density wave; tunnel junction; phase

1. Introduction

Charge density wave (CDW) can be characterized by the complex order parameter. So far, the fluctuation of the CDW phase (φ) in bulk systems has received much attention, while the phases in the tunnel junctions have been investigated little in the mean field approximation [1–4]. Artemenko and Volkov [1] and Munz and Wonneberger [2] have investigated the current J for the junction consisting of two Peierls conductors (P) separated by an insulator in three dimensions, and neglected a part of the current J dependent on the phases by averaging. We reinvestigate the current J at finite temperature ($T > 0$) for a one-dimensional point contact where we need not average the current J like them, and how the neglected term influences on the current.

2. Methods

The current J is calculated at finite temperature T for a one-dimensional point contact in the conventional tunnel Hamiltonian approach [5]. For simplicity, the right- and left-hand sides of the junction include no impurities. We assume that the tunneling occurs at $x = 0$, so that the tunnel Hamiltonian H_{T} can be expressed as $H_{\mathrm{T}} = \sum_{k,p,\sigma} \tilde{T} a^{\dagger}_{k\sigma} a_{p\sigma} + \mathrm{H.c.}$ where $\tilde{T}$ is the tunnel matrix element independent of the wave numbers k and p. The operators $a^{\dagger}_{k\sigma}$ ($a_{p\sigma}$) are the creation (annihilation) operators of an electron with k (p) and spin projection σ ($\hbar = 1$). In §3, the current J is obtained in the second order of the perturbation theory in H_{T} at $T > 0$ where the phases (φ) and energy gaps (Δ) in both Peierls conductors are assumed to be equal, respectively.

3. Results and Discussion

The current J is expressed as

$$J = J_1 + J_2, \tag{1}$$

$$J_1 = \frac{2\sigma}{e} \int_{\Delta}^{\infty} \mathrm{d}E \frac{E}{\sqrt{E^2 - \Delta^2}}$$

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$$
\begin{aligned}
&\times\Big[\frac{E-eV}{\sqrt{(E-eV)^2-\Delta^2}}\Big\{\tanh(\frac{E}{2T})-\tanh(\frac{E-eV}{2T})\Big\}\\
&\times\Big\{\theta(E-eV-\Delta)-\theta(-E+eV-\Delta)\theta(eV-2\Delta)\Big\}\\
&+\frac{E+eV}{\sqrt{(E+eV)^2-\Delta^2}}\Big\{\tanh(\frac{E+eV}{2T})-\tanh(\frac{E}{2T})\Big\}\\
&\times\Big\{\theta(E+eV-\Delta)-\theta(-E-eV-\Delta)\theta(-eV-2\Delta)\Big\}\Big],
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
J_2 = &\frac{2\sigma}{e}\cos^2\varphi\int_{\Delta}^{\infty}\mathrm{d}E\frac{\Delta}{\sqrt{E^2-\Delta^2}}\\
&\times\Big[\frac{\Delta}{\sqrt{(E-eV)^2-\Delta^2}}\Big\{\tanh(\frac{E}{2T})-\tanh(\frac{E-eV}{2T})\Big\}\\
&\times\Big\{\theta(E-eV-\Delta)-\theta(-E+eV-\Delta)\theta(eV-2\Delta)\Big\}\\
&+\frac{\Delta}{\sqrt{(E+eV)^2-\Delta^2}}\Big\{\tanh(\frac{E+eV}{2T})-\tanh(\frac{E}{2T})\Big\}\\
&\times\Big\{\theta(E+eV-\Delta)-\theta(-E-eV-\Delta)\theta(-eV-2\Delta)\Big\}\Big],
\end{aligned} \tag{3}
$$

where $\sigma = 4\pi e^2|\tilde{T}|^2 N_{\mathrm{R}}N_{\mathrm{L}}$. Here N_{R} and N_{L} are the densities of states at the Fermi levels in the right- and left-hand sides, respectively. The function $\theta(x)$ is the Heaviside step function. Additionally, the voltage V is expressed as the difference between chemical potentials μ_{R} and μ_{L}, i.e., $eV = \mu_{\mathrm{L}} - \mu_{\mathrm{R}}$ where μ_{R} and μ_{L} correspond to the right- and left-hand sides of the junction, respectively. From the result, the current J is a periodic function of the phase φ with a period π.

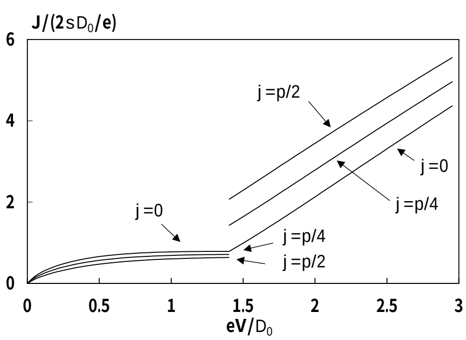

Fig. 1. The dependence of the J-V characteristics on the phase φ for $\varphi = 0, \pi/4$, and $\pi/2$ at $T/T_{\mathrm{P}} = 0.8$ where T_{P} is the Peierls transition temperature and Δ_0 is the energy gap at $T = 0$.

The dependence of the J-V characteristics on the phase φ is numerically calculated (See Fig. 1) for $eV > 0$ at $T/T_{\mathrm{P}} = 0.8$ where T_{P} is the Peierls transition temperature. The current J has a discontinuous jump at $eV = 2\Delta$ ($\varphi \neq 0$). The jump increases as the phase φ increases because for $0 < eV < 2\Delta$ the current J decreases as the phase φ increases, but while for $eV > 2\Delta$ the current J increases as the phase φ increases.

Next, we discuss the results. The first term J_1 is generated by the terms $\mathrm{Re}\{G_{++}G_{++} - G_{++}G^*_{++}\}$, while the second term J_2 is generated by the terms $\mathrm{Re}\{G_{+-}G^*_{+-} + G_{+-}G_{+-}\}$ where G_{++} and G_{+-} are the diagonal and off diagonal elements of the Green's function, respectively [6] and the asterisk denotes the complex conjugation. The contribution from the term $\mathrm{Re}\{G_{+-}G_{+-}\}$ makes the current phase-dependent when both phases are equal. Artemenko et al. [1] and Munz et al. [2] have neglected the contribution by averaging. For $\varphi = 0, \pi$, Gabovich and Voitenko [7] have also investigated the J-V characteristics, and their results are the same as our ones.

The first term J_1 corresponds to the quasiparticle current in Josephson junction, so that J_1 has a discontinuous jump at $eV = 2\Delta$. The existence of the second term J_2 makes the current J deviate from the current J_1, and the deviation makes our results different from those in Josephson junction.

4. Conclusions

We have numerically investigated the J-V characteristics at finite temperature for the junction consisting of two Peierls conductors (P) separated by an insulator (the one-dimensional point contact) in the second order of the perturbation theory by using the conventional tunnel Hamiltonian approach. The J-V characteristics depend on the CDW phases in the mean field approximation where the phases (φ) and energy gaps (Δ) in both Peierls conductors are assumed to be equal, respectively. The current J is a periodic function of the phase φ with a period π, and has a discontinuous jump at $eV = 2\Delta$ ($\varphi \neq 0$). The jump increases as the phase φ increases. For $0 < eV < 2\Delta$ the current J decreases as the phase φ increases, but while for $eV > 2\Delta$ the current J increases as the phase φ increases.

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