Eur. Phys. J. B **25**, 417–421 (2002)
DOI: 10.1140/epjb/e20020047

THE EUROPEAN PHYSICAL JOURNAL B

EDP Sciences

Current-voltage characteristics for a Peierls-conducting point contact

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Received 4 July 2001 and Received in final form 13 September 2001

Abstract. Current-voltage (J-V) and differential-conductivity-voltage ($\mathrm{d}J/\mathrm{d}V$-V) characteristics are analytically calculated at zero temperature for a point contact consisting of: two Peierls conductors $\mathrm{P}_\imath$ ($\imath = 1, 2$) separated by an insulator (I). Here P is a conductor with charge density wave (CDW). The J-V and $\mathrm{d}J/\mathrm{d}V$-V characteristics depend on the CDW phases $\varphi_\imath$ ($\imath = 1, 2$) in the mean field approximation. To calculate them analytically we assumed, $\Delta_{\mathrm{P}_1} = \Delta_{\mathrm{P}_2} \equiv \Delta$ where $\Delta_{\mathrm{P}_\imath}$ ($\imath = 1, 2$) are the energy gaps of $\mathrm{P}_\imath$ ($\imath = 1, 2$). The current J has a discontinuous jump at $eV = 2\Delta$ for $\varphi_1 = \varphi_2 \neq 0$. The differential conductivity $\mathrm{d}J/\mathrm{d}V$ has a singularity at $eV = 2\Delta$ for $\varphi_1 = \varphi_2 \neq 0$. The relation $J(V, \varphi_1, \varphi_2) = -J(-V, \varphi_1 + \pi, \varphi_2 + \pi)$ is obtained.

PACS. 71.45.Lr Charge-density-wave systems – 73.40.Gk Tunneling

1 Introduction

Charge density waves (CDW) can be characterized by the complex order parameter. The phase φ is very important and the fluctuation of the phase corresponds to sliding motion, which produces remarkable behavior, like non-Ohmic conductivity [1] and narrow band noise [2]. The fluctuation of the phase in bulk systems has already received much attention in the last few decades [3].

In contrast, the CDW tunnel junctions have been investigated little in the mean field approximation. So far, the dependence of the current on the CDW phase φ has been investigated for P_1-I-P_2 and P-I-N junctions where P, I, and N denote a Peierls conductor, insulator and normal metal, respectively [4–8]. A Peierls conductor is a conductor with CDW. In 1983 and 1984, Artemenko and Volkov [4,5] treated the three-dimensional P_1-I-P_2 and P-I-N junctions using the Keldysh technique. They introduced random potentials in the planes of the junctions and averaged the currents over random potentials, obtaining the results corresponding to those for quasiparticle tunneling across S_1-I-S_2 and S-I-N junctions, respectively where S denotes a superconductor. In 1990, Munz and Wonneberger [6] treated the same junctions with the conventional tunnel Hamiltonian approach. They averaged the currents over the phases of the tunnel matrix elements, and obtained similar results to theirs. In 1996, Tanaka *et al.* [8] treated the one-dimensional P-I-N junction by solving the Bogoliubov-de Gennes equation for CDW. Without averaging the conductance like Artemenko *et al.* and Munz *et al.*, they showed that the conductance is dependent on the CDW phase φ, but Artemenko *et al.* and Munz *et al.* showed that the term dependent on the CDW phase φ vanished in their averaging for the three-dimensional P-I-N junction. Additionally, Artemenko *et al.* and Munz *et al.* showed that the terms dependent on the phases $\varphi_i (i = 1, 2)$ *i.e.*, the terms proportional to $\cos(\varphi_1 + \varphi_2)$ and $\cos\varphi_1 - \cos\varphi_2$ vanished in averaging for the three-dimensional P_1-I-P_2 junction.

In this paper, we reinvestigate the dependence of the current-voltage (J-V) and differential- conductivity-voltage ($\mathrm{d}J/\mathrm{d}V$-V) characteristics on the CDW phases $\varphi_\imath$ ($\imath = 1, 2$) for the one-dimensional P_1-I-P_2 junction (a point contact) in the conventional tunnel Hamiltonian approach where we need not average the current as above. Therefore, we can investigate the current including the terms which vanish due to averaging. Additionally, we show that our results include those Gabovich and Voitenko [9] have obtained for $\varphi_1 = \varphi_2 = 0, \pi$.

The paper is organized as follows. In Section 2, the general expression for the tunnel current J is presented for P_1-I-P_2 junction in the conventional tunnel Hamiltonian approach. The current J is expressed using the Green's functions of P. Firstly, the Hamiltonian of P is given in the mean field approximation, then, the Green's functions are written down. Finally, the general expression for the tunnel current J is presented for the junction. In Section 3, the dependence of the J-V and $\mathrm{d}J/\mathrm{d}V$-V characteristics on the CDW phases $\varphi_\imath$ ($\imath = 1, 2$) is analytically calculated at zero temperature for the junction. The results are discussed in Section 4. In Section 5, the conclusions are presented.

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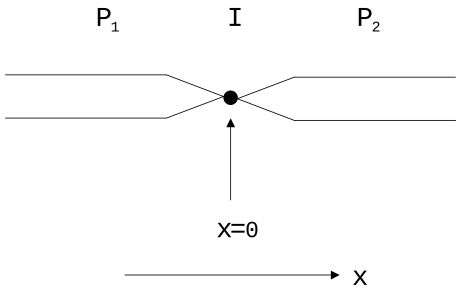

Fig. 1. The geometry for a P_1-I-P_2 junction (a point contact) where P and I denote a Peierls conductor and insulator, respectivly. Charge density wave (CDW) appears along the x axis, and the insulator I exists at $x = 0$.

2 General expression for tunnel current

The general expression for the tunnel current J is presented for a P_1-I-P_2 junction (see Fig. 1) in the mean field approximation. The junction is a one-dimensional point contact. For simplicity, the right- and left-hand electrodes of the junction include no impurities. The current J is expressed using the Green's functions of P. In this paper, the conventional tunnel Hamiltonian approach [10,11] is used.

Here, the Hamiltonian of P is presented in the mean field approximation. The Hamiltonian of P ($H_{\rm P}$) is presented in the form [9]

$$H_{\rm P} = \sum_{k\sigma} \xi_k a^\dagger_{k\sigma} a_{k\sigma} - \sum_{k\sigma} (a^\dagger_{k\sigma} a_{k+2k_{\rm F}\sigma} \Delta \mathrm{e}^{\imath\varphi} + \text{h.c.}), \quad (1)$$

where Δ and φ are the amplitude and phase of the order parameter of P, respectively, and $k_{\rm F}$ is the Fermi wave number. The first term is the free-electron Hamiltonian. The operators $a^\dagger_{k\sigma}$ ($a_{k\sigma}$) are the creation (annihilation) operators of an electron with wave number k ($\hbar = 1$) and spin projection σ.

From the above Hamiltonian, the Green's functions of P are presented at finite temperature ($T \neq 0$). The Green's functions of P are presented in the form [12]

$$G_{++}(k, \imath p_n) = \frac{\imath p_n + \xi_{k+k_{\rm F}}}{(\imath p_n)^2 - (\xi^2_{k+k_{\rm F}} + \Delta^2)}, \quad (2)$$

$$G_{+-}(k, \imath p_n) = \frac{\Delta \mathrm{e}^{\imath\varphi}}{(\imath p_n)^2 - (\xi^2_{k+k_{\rm F}} + \Delta^2)} \quad (3)$$

where $p_n = (2n + 1)\pi T$ ($k_{\rm B} = 1$), $n = 0, \pm 1, \pm 2, ...$ The Green's functions $G_{++}(k, \imath p_n)$ and $G_{+-}(k, \imath p_n)$ are Fourier transforms of $G_{++}(k, \tau) = -\langle T_\tau a_{k+k_{\rm F}}(\tau) a^\dagger_{k+k_{\rm F}} \rangle_{\rm P}$ and $G_{+-}(k, \tau) = -\langle T_\tau a_{k+k_{\rm F}}(\tau) a^\dagger_{k-k_{\rm F}} \rangle_{\rm P}$, respectively where $a_{k+k_{\rm F}}(\tau) = \exp(\tau H_{\rm P}) a_{k+k_{\rm F}} \exp(-\tau H_{\rm P})$, and the operator T_τ denotes the Wick time-ordering operator. Here we have abbreviated spin projection σ, and defined the average

$$\langle \cdots \rangle_{\rm P} = \frac{\mathrm{Tr}\{\mathrm{e}^{-H_{\rm P}/T} \cdots\}}{\mathrm{Tr}\{\mathrm{e}^{-H_{\rm P}/T}\}} \cdot \quad (4)$$

The current J can be presented by using these Green's functions. Here the conventional tunnel Hamiltonian approach is used. The total Hamiltonian H is expressed as

$$H = H_{\rm R} + H_{\rm L} + H_{\rm T}. \quad (5)$$

The terms $H_{\rm R}$ and $H_{\rm L}$ describe the right- and left-hand electrodes of the junction. We assume that the tunneling occurs at $x = 0$, so that the tunnel Hamiltonian $H_{\rm T}$ can be presented as follows:

$$H_{\rm T} = \sum_{k,p,\sigma} \tilde{T} a^\dagger_{k\sigma} a_{p\sigma} + \text{h.c.}, \quad (6)$$

where $\tilde{T}$ are the tunnel matrix element independent of k and p. Hereafter k and p denote the wave numbers in the right- and left-hand sides, respectively.

The general expression for the current J obtained in the second order of the perturbation theory in $H_{\rm T}$ becomes

$$J = 2e\,\mathrm{Im}\{X(\imath\omega_n \to -eV + \imath\delta)\}, \quad (7)$$

where δ is positive and infinitesimally small and $\omega_n = 2n\pi T, n = 0, \pm 1, \pm 2, ...$ The voltage V is expressed as the difference between chemical potentials $\mu_{\rm R}$ and $\mu_{\rm L}$, *i.e.*, $eV = \mu_{\rm L} - \mu_{\rm R}$ where $\mu_{\rm R}$ and $\mu_{\rm L}$ correspond to the right- and left-hand sides of the junction, respectively. The correlation function $X(\imath\omega_n)$ is presented in the form

$$X(\imath\omega_n) = \sum_{k,p,\sigma} \sum_{k',p'} |\tilde{T}|^2 \times \int_0^{1/T} \mathrm{d}\tau \mathrm{e}^{\imath\omega_n\tau} \langle T_\tau a_{k'\sigma} a^\dagger_{k\sigma}(\tau) \rangle_{\rm R} \langle T_\tau a_{p\sigma}(\tau) a^\dagger_{p'\sigma} \rangle_{\rm L}, \quad (8)$$

where $a^\dagger_{k\sigma}(\tau) = \exp(\tau H_{\rm R}) a^\dagger_{k\sigma} \exp(-\tau H_{\rm R})$ and $a_{p\sigma}(\tau) = \exp(\tau H_{\rm L}) a_{p\sigma} \exp(-\tau H_{\rm L})$. Here we have defined the averages

$$\langle \cdots \rangle_{\rm R} = \frac{\mathrm{Tr}\{\mathrm{e}^{-H_{\rm R}/T} \cdots\}}{\mathrm{Tr}\{\mathrm{e}^{-H_{\rm R}/T}\}}, \ \langle \cdots \rangle_{\rm L} = \frac{\mathrm{Tr}\{\mathrm{e}^{-H_{\rm L}/T} \cdots\}}{\mathrm{Tr}\{\mathrm{e}^{-H_{\rm L}/T}\}} \cdot \quad (9)$$

For a P_1-I-P_2 junction ($H_{\rm L} = H_{\rm P_1}$ and $H_{\rm R} = H_{\rm P_2}$), the correlation function can be presented by using the Green's functions of P

$$\begin{aligned} X_{\rm P_1-I-P_2}(\imath\omega_n) = 4T \sum_{kp} \sum_{\imath p_m} |\tilde{T}|^2 \\ \times[&\mathrm{Re}\{G_{++}(p, \imath p_m) G_{++}(k, \imath p_m - \imath\omega_n)\} \\ &+\mathrm{Re}\{G_{+-}(p, \imath p_m) G^*_{+-}(k, \imath p_m - \imath\omega_n)\} \\ &+\mathrm{Re}\{G_{+-}(p, \imath p_m) G_{+-}(k, \imath p_m - \imath\omega_n)\} \\ &-\mathrm{Re}\{G_{++}(p, \imath p_m) G^*_{++}(k, \imath p_m - \imath\omega_n)\} \\ &+2\imath\mathrm{Im}\{G_{++}(p, \imath p_m)\}\mathrm{Re}\{G_{+-}(k, \imath p_m - \imath\omega_n)\} \\ &+2\imath\mathrm{Re}\{G_{+-}(p, \imath p_m)\}\mathrm{Im}\{G_{++}(k, \imath p_m - \imath\omega_n)\}], \end{aligned} \quad (10)$$

where the asterisk denotes the complex conjugation.

In Section 3, the current J is analytically calculated at zero temperature for the junction, using the above expression.

3 Results

The current J is analytically presented at zero temperature by calculating the correlation function for a P_1-I-P_2 junction. In the analytical calculation, $\Delta_{P_1} = \Delta_{P_2} \equiv \Delta$ is assumed. From the analytical expression, the dependence of the J-V and $\mathrm{d}J/\mathrm{d}V$-V characteristics on the CDW phases $\varphi_\imath$ $(\imath = 1, 2)$ is investigated.

For $eV > 0$, the current J is given by

$$J = J_1 + J_2 + J_3 + J_4, \tag{11}$$

$$J_1 = \frac{4\sigma_0}{e}\theta(eV - 2\Delta)\left[\frac{(eV)^2}{eV + 2\Delta}\mathrm{K}(\alpha) - (eV + 2\Delta)\{\mathrm{K}(\alpha) - \mathrm{E}(\alpha)\}\right], \tag{12}$$

$$J_2 = -\frac{8\sigma_0}{e}\theta(eV - 2\Delta)\frac{\Delta^2}{eV + 2\Delta}\mathrm{K}(\alpha)\cos(\varphi_1 - \varphi_2), \tag{13}$$

$$J_3 = -\frac{8\sigma_0}{e}\theta(eV - 2\Delta)\frac{\Delta^2}{eV + 2\Delta}\mathrm{K}(\alpha)\cos(\varphi_1 + \varphi_2), \tag{14}$$

$$J_4 = -\frac{8\sigma_0}{e}\theta(eV - 2\Delta)\frac{\Delta eV}{eV + 2\Delta}\mathrm{K}(\alpha)\{\cos\varphi_1 - \cos\varphi_2\}, \tag{15}$$

$$\sigma_0 = 4\pi e^2|\tilde{T}|^2 N_\mathrm{R} N_\mathrm{L},\ \alpha = \frac{eV - 2\Delta}{eV + 2\Delta}, \tag{16}$$

where $\mathrm{K}(\alpha)$ and $\mathrm{E}(\alpha)$ are the complete elliptic integrals of the first and second kind, respectively. The function $\theta(x)$ is the Heaviside step function. Here N_R and N_L are the densities of states at the Fermi levels in the right- and left-hand sides, respectively.

From the result, we note four points. Firstly, $J_i \neq 0$ $(i = 1, \cdots, 4)$ for $eV > 2\Delta$. Secondly, the first term J_1 corresponds to a quasiparticle current in S_1-I- S_2 junction. Thirdly, the second term J_2 is proportional to $\cos(\varphi_1 - \varphi_2)$, but the third term J_3 is proportional to $\cos(\varphi_1 + \varphi_2)$. Finally, the fourth term J_4 is proportional to $\cos\varphi_1 - \cos\varphi_2$.

To investigate the dependence of the J-V characteristics on the CDW phases, we consider a simpler case: $\varphi_1 = \varphi_2 \equiv \varphi$. The current J is presented in the form

$$J = \frac{4\sigma_0}{e}\theta(eV - 2\Delta)\left[\frac{(eV)^2}{eV + 2\Delta}\mathrm{K}(\alpha) - (eV + 2\Delta) \times \{\mathrm{K}(\alpha) - \mathrm{E}(\alpha)\} - \frac{2\Delta^2}{eV + 2\Delta}\{1 + \cos 2\varphi\}\mathrm{K}(\alpha)\right]. \tag{17}$$

The current J is a periodic function of φ with a period π. The CDW-phase dependence is shown in Figure 2. From Figure 2, we note two points. The current J has a discontinuous jump at $eV = 2\Delta$ for $\varphi \neq 0$ $(0 \leq \varphi \leq \pi/2)$. This jump depends on the CDW phase φ

$$J(2\Delta^+) = \frac{\pi\sigma_0}{e}\Delta\{1 - \cos 2\varphi\}, \tag{18}$$

where $2\Delta^+ \equiv 2\Delta + \delta$. Secondly, the current J increases as the CDW phase φ $(0 \leq \varphi \leq \pi/2)$ increases.

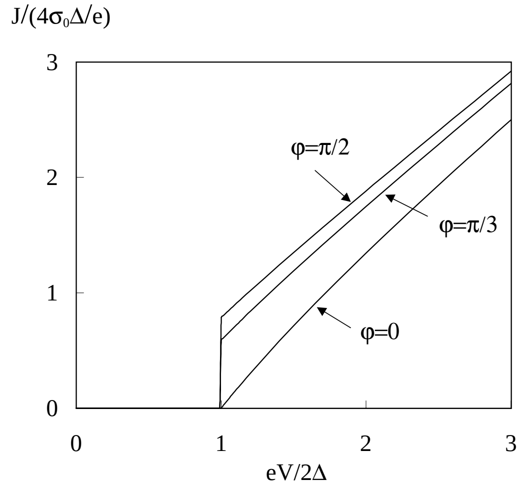

Fig. 2. The dependence of the J-V characteristics on the CDW phase φ for a P_1-I-P_2 junction. The current J has a discontinuous jump at $eV = 2\Delta$ for $\varphi \neq 0$ $(0 \leq \varphi \leq \pi/2)$ which increases as the CDW phase φ $(0 \leq \varphi \leq \pi/2)$ increases.

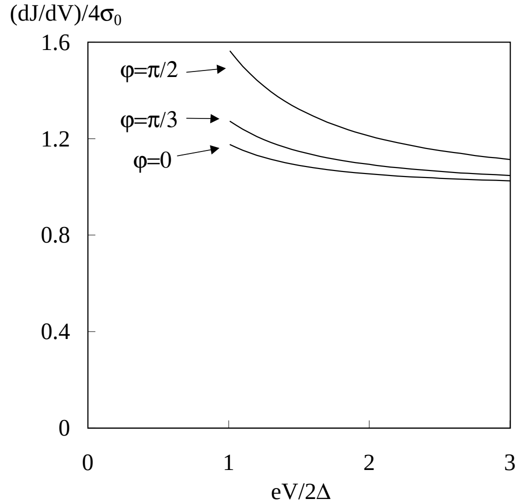

Fig. 3. The dependence of the $\mathrm{d}J/\mathrm{d}V$-V characteristics on the CDW phase φ for a P_1-I-P_2 junction. The differential conductivity $\mathrm{d}J/\mathrm{d}V$ has a singularity at $eV = 2\Delta$ for $\varphi \neq 0$ $(0 \leq \varphi \leq \pi/2)$ which increases as the CDW phase φ $(0 \leq \varphi \leq \pi/2)$ increases.

Next, we investigate the dependence of the $\mathrm{d}J/\mathrm{d}V$-V characteristics on the CDW phase φ in the conditions: $eV > 0$ and $\varphi_1 = \varphi_2 \equiv \varphi$. The differential conductivity $\mathrm{d}J/\mathrm{d}V$ is given by

$$\frac{\mathrm{d}J}{\mathrm{d}V} = 4\sigma_0\theta(eV - 2\Delta)\left[\frac{1}{(eV + 2\Delta)(eV - 2\Delta)}\mathrm{K}(\alpha) \times\{(6\Delta^2 - 4\Delta eV) + 2\Delta^2\cos 2\varphi\} + \frac{1}{eV(eV - 2\Delta)}\mathrm{E}(\alpha)\{(eV)^2 - 3\Delta^2 - \Delta^2\cos 2\varphi\}\right]. \tag{19}$$

The CDW-phase dependence is shown in Figure 3. We note, the differential conductivity $\mathrm{d}J/\mathrm{d}V$ has a singularity at $eV = 2\Delta$ for $\varphi \neq 0$ $(0 \leq \varphi \leq \pi/2)$. For $eV = 2\Delta^+$ and

$\varphi = 0$, this becomes

$$\frac{\mathrm{d}J}{\mathrm{d}V} = 2\pi\sigma_0 < +\infty. \quad (20)$$

Also, the differential conductivity $\mathrm{d}J/\mathrm{d}V$ increases as the CDW phase φ $(0 \le \varphi \le \pi/2)$ increases.

For $eV < 0$, the current J can be represented using the relation $J(V, \varphi_1, \varphi_2) = -J(-V, \varphi_1 + \pi, \varphi_2 + \pi)$ which we have already obtained.

4 Discussion

Now we discuss the results obtained in Section 3, *i.e.*, the dependence of the J-V and $\mathrm{d}J/\mathrm{d}V$-V characteristics on the CDW phases $\varphi_\imath$ $(\imath = 1, 2)$ for a P_1-I-P_2 junction in comparing with a S_1-I-S_2 junction. First, we discuss the J-V characteristics. The first term J_1 is generated by the terms $\mathrm{Re}\{G_{++}(p, \imath p_m)G_{++}(k, \imath p_m - \imath\omega_n)\}$ and $\mathrm{Re}\{G^*_{++}(p, \imath p_m)G_{++}(k, \imath p_m - \imath\omega_n)\}$, and corresponds to the quasiparticle current in the S_1-I- S_2 junction [4,5]. The second term J_2 is generated by the term $\mathrm{Re}\{G_{+-}(p, \imath p_m)G^*_{+-}(k, \imath p_m - \imath\omega_n)\}$, and corresponds to the interference current in an S_1-I- S_2 junction. The third term J_3 is generated by the term $\mathrm{Re}\{G_{+-}(p, \imath p_m)G_{+-}(k, \imath p_m - \imath\omega_n)\}$, and does not exist for an S_1-I- S_2 junction because G_{+-} corresponds to F and the current can not be generated by the term FF for the S_1-I- S_2 junction. The fourth term J_4 is generated by the terms $\mathrm{Re}\{G_{+-}(p, \imath p_m)\}\mathrm{Im}\{G_{++}(k, \imath p_m - \imath\omega_n)\}$ and $\mathrm{Im}\{G_{++}(p, \imath p_m)\}\mathrm{Re}\{G_{+-}(k, \imath p_m - \imath\omega_n)\}$, and does not exist for an S_1-I- S_2 junction, either because the current can not be generated by the term GF for an S_1-I- S_2 junction. The terms $J_\imath$ $(\imath = 1, \cdots, 4)$ have discontinuous jumps at $eV = 2\Delta$ because of the mutual action of singular densities of states on both sides of the barrier.

There are three main differences between the P_1-I-P_2 junction and the S_1-I-S_2 junction. Firstly, for the P_1-I-P_2 junction the current J does not include the term proportional to $\sin(\varphi_1 - \varphi_2)$, *i.e.*, the Josephson current because the uncertainty relation $[N, \varphi] = \imath$ (where N is the total particle number) does not exist. Secondly, the current J includes the term proportional to $\cos(\varphi_1 + \varphi_2)$. Finally, the current J includes a term proportional to $(\cos\varphi_1 - \cos\varphi_2)$.

Artemenko and Volkov [4,5] have investigated the same junction using the Keldysh technique. They obtained the same results, but the two terms J_3 and J_4 are absent due to averaging over the random potential.

On the other hand, Munz and Wonneberger [6] have treated the same junction in the same approach, *i.e.*, the conventional tunnel Hamiltonian approach, but the two terms J_3 and J_4 vanish as a result of averaging over the phases of the tunnel matrix elements.

There are two reasons why we have not averaged the current like Artemenko *et al.* and Munz *et al.* (1) We have considered a one-dimensional system, so that we need not necessarily to introduce the random potential in the plane of the junction. (2) We assume that the tunneling occurs at one point $x = 0$, so that the tunnel matrix element $\tilde{T}$ is independent of the wave numbers k and p.

For $\varphi_1 = \varphi_2 \equiv \varphi$ $(\varphi = 0, \pi)$, Gabovich and Voitenko [9] investigated the same junction and obtained the relation $J(V, \varphi_1 = \varphi_2) = -J(-V, \varphi_1 = \varphi_2)$. We obtain a more general relation $J(V, \varphi_1, \varphi_2) = -J(-V, \varphi_1 + \pi, \varphi_2 + \pi)$. For $\varphi = 0$, the current J is continuous at $eV = 2\Delta$ because the jump in $J_2 + J_3$ has the opposite sign and totally compensates the jump in J_1. For $\varphi \ne 0$ $(0 \le \varphi \le \pi/2)$, the current J has a discontinuous jump at $eV = 2\Delta$, and the jump is dependent on the CDW phase φ because the current J includes the third term J_3 which is proportional to $\cos 2\varphi$. On the other hand, for an S_1-I-S_2 junction, a jump also exists at $eV = 2\Delta_S$ where Δ_S is the energy gap of S, but the jump is independent of the S phase ϕ $(\phi_1 = \phi_2 \equiv \phi)$ because the current is not a function of the sum $\phi_1 + \phi_2$.

Next, we discuss the $\mathrm{d}J/\mathrm{d}V$-V characteristics. For $\varphi_1 = \varphi_2 \equiv \varphi$ $(\varphi = 0, \pi)$, Gabovich and Voitenko [9] obtained the relationship

$$\frac{\mathrm{d}}{\mathrm{d}V} J(V, \varphi_1 = \varphi_2) = \frac{\mathrm{d}}{\mathrm{d}(-V)} J(-V, \varphi_1 = \varphi_2), \quad (21)$$

but from the expression $J(V, \varphi_1, \varphi_2) = -J(-V, \varphi_1 + \pi, \varphi_2 + \pi)$ we obtain

$$\frac{\mathrm{d}}{\mathrm{d}V} J(V, \varphi_1, \varphi_2) = \frac{\mathrm{d}}{\mathrm{d}(-V)} J(-V, \varphi_1 + \pi, \varphi_2 + \pi). \quad (22)$$

For $\varphi = 0$, the differential conductivity $\mathrm{d}J/\mathrm{d}V$ has a discontinuous jump at $eV = 2\Delta$, while for $\varphi \ne 0$ $(0 \le \varphi \le \pi/2)$, $\mathrm{d}J/\mathrm{d}V$ has a singularity at $eV = 2\Delta$, which is dependent on the CDW phase φ due to the term $\mathrm{d}J_3/\mathrm{d}V$ which is proportional to $\cos 2\varphi$. On the other hand, for an S_1-I-S_2 junction, a singularity also exists at $eV = 2\Delta_S$, but it is independent of the S phase ϕ $(\phi_1 = \phi_2 \equiv \phi)$ because the differential conductivity is not the function of the sum $\phi_1 + \phi_2$.

5 Conclusions

We have investigated the dependence of the J-V and $\mathrm{d}J/\mathrm{d}V$ $-V$ characteristics on the CDW phases $\varphi_\imath$ $(\imath = 1, 2)$ at zero temperature for the one-dimensional P_1-I-P_2 junction (the point contact) in the conventional tunnel Hamiltonian approach. The current J has a discontinuous jump at $eV = 2\Delta$ for $\varphi_1 = \varphi_2 \equiv \varphi \ne 0$, while the differential conductivity $\mathrm{d}J/\mathrm{d}V$ has a singularity at $eV = 2\Delta$ for $\varphi \ne 0$. We have also obtained the relation $J(V, \varphi_1, \varphi_2) = -J(-V, \varphi_1 + \pi, \varphi_2 + \pi)$.

In this paper, we have considered a system in which both electrodes include no impurities. This means that the CDW phases $\varphi_\imath$ $(\imath = 1, 2)$ are independent of the position in the Peierls conductors, *i.e.*, $\varphi_\imath$ $(\imath = 1, 2)$ are constant. Therefore, when there are impurities in P_1 and P_2, the results obtained in this paper are not applicable. In the future, we will consider the effect of the impurities.

The author would like to thank S. Kurihara and S. Ohtuka for useful discussions.

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