Vol 17 No 8, August 2008
1674-1056/2008/17(08)/3067-10

Chinese Physics B

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Dynamical study on charge injection and transport in a metal/polythiophene/metal structure*

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(Received 4 September 2007; revised manuscript received 31 March 2008)

The dynamical process of charge injection from metal electrode to a nondegenerate polymer in a metal/polythiophene (PT)/metal structure has been investigated by using a nonadiabatic dynamic approach. It is found that the injected charges form wave packets due to the strong electron-lattice interaction in PT. We demonstrate that the dynamical formation of the wave packet sensitively depends on the strength of applied voltage, the electric field, and the contact between PT and electrode. At a strength of the electric field more than 3.0×10^4 V/cm, the carriers can be ejected from the PT into the right electrode. At an electric field more than 3.0×10^5 V/cm, the wave packet cannot form while it moves rapidly to the right PT/metal interface. It is shown that the ejected quantity of charge is noninteger.

Keywords: metal/polythiophene/metal structure, electron-phonon interactions, carriers transport, wave packet

PACC: 7280L, 7340, 7138

1. Introduction

Conjugated organic materials have been attracting much theoretical and experimental interest because of their novel physical properties and the technological potential of electronic devices fabrication.[1−3] Polythiophene (PT), which has a nondegenerate ground state structure, is the antitype of conjugated polymer. The effect of the heteroatom sulfur on π-conjugated electrons made thiophene an important material in technological applications, such as efficient organic light-emitting diodes (OLEDs),[4] nonlinear optical device,[5] field-effect transistors (FETs),[6] etc. In 1990, organic light-emitting triodes were fabricated by using oligothiophene as a basic material. In these electronic devices, conjugated polymers were used as the light-emitting and charge-transporting layers, into which electrons and/or holes are injected by an external field from the metal electrode. It is very important to understand the mechanism of the charge injection from metal electrode into organic material in the sense of the performance of these organic-based devices. Owing to the strong electron-lattice interactions, it is well known that the doped electrons or holes form self-trapping states called solitons (only in *trans*-polyacetylene),[7] polarons,[8] or bipolarons,[9] thereby serving as the transport carriers in conjugated polymers. Formation and transport of such charge carriers are believed to be of fundamental importance for these organic electronic devices.

Extensive research on the dynamics of charge injection and transport in a metal/polymer/metal structure has been carried out before. Wu *et al*[10] studied the electron injection and motion process in a metal/polymer/metal structure. They believed that under an adequate bias, an electron could be injected to the polymer chain and exist in the form of a polaron. When the applied bias voltage increased, the injected quantity of the charge could increase up to two electronic charges and these charges would form a bipolaron.[11] H. Méndez *et al*[12] studied experimentally the charge transport mechanism in a hybrid metal/organic/inorganic device. Ren *et al*[13] studied the current spin polarization in a ferro-

*Project supported by the State Key Program of National Natural Science of China (Grant Nos 10474056 and 10574082) and the Natural Science Foundation of Shandong Province (Grant No Z2005A01).

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magnetic/organic semiconductor/ferromagnetic system. Davids *et al*[14] gave a picture of bipolaron lattice formation at a metal/polymer interface by using a nondegenerate continuum model. All these researches seem to show that electrons are injected one by one from the electrode into the polymer. However, in an organic device, an electronic state belongs to the whole system. In one of our recent studies, Fu *et al*[15] investigated the dynamic process of charge injection for an open conjugated polymer chain in contact with a metal electrode, and they indicated that the injected charges formed wave packets, which contained any quantity of charges up to two electronic unit charges. Li *et al*[16] studied the injection and transport of the charge carriers in a metal/impurity polymer/metal structure, and they indicated that the impurity ion acted as a control gate on the charge carriers, while the state of the control gate was determined by the strength of the electric field and the magnitude of the bias voltage. In the previous studies, extensive research focused on the charge injection into polyacetylene (PA), however, we know that PT has more unique optical properties and more extensive applications than PA.[17] In this paper, we present our results from a nonadiabatic dynamical study on the evolution of the electronic states in a metal/ PT/metal system. We will discuss the formation and transport of the wave packet in a metal/PT/metal structure under an external field. Furthermore, on the basis of our previous work, we will consider the process of charge ejection from PT to the right metal.

2. Model and method

We consider a one-dimensional metal/PT/metal structure with a PT chain attached to the ends of two metal electrodes. The model is shown in Fig.1.

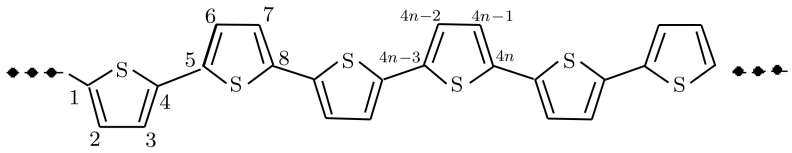


Fig.1. The model of metal/PT/metal.

The Hamiltonian is composed of three parts and expressed as

$$H = H_{\rm e} + H_{\rm latt} + H_{\rm ext}, \tag{1}$$

PT has a molecular and electronic structure related to that of PA. In PT, because of the influence of the heteroatom sulfur on π electrons, the Hamiltonian of the electronic part is

$$\begin{aligned} H_{\rm e} = & -\sum_{n,\sigma} \varepsilon_n C^+_{n,\sigma} C_{n,\sigma} - \sum_{n,\sigma} t_n \left(C^+_{n+1,\sigma} C_{n,\sigma} + {\rm H.c} \right) \\ & - \sum_{n,\sigma} t_2 \left(C^+_{4n-3,\sigma} C_{4n,\sigma} + {\rm H.c.} \right) \\ & - \sum_{n,\sigma} t_3 \left(C^+_{4n,\sigma} C_{4n,\sigma} + C^+_{4n+3,\sigma} C_{4n+3,\sigma} \right), \end{aligned} \tag{2}$$

where ε_n denotes the on-site electronic energy on a lattice site (CH group), t_n is the hopping integral between sites n and n+1. We set $t_n = t_0$ in the two metal electrodes, and $t_n = t_0 - \alpha\left(u_{n+1} - u_n\right) - t_1 \cos\dfrac{n\pi}{2}$ for the PT chain, where t_0 denotes the hopping integral between the nearest neighbouring carbon atoms of the unpolymerized chain, t_1 is introduced to lift the ground-state degeneracy for a nondegenerate polymer, α is the electron-lattice coupling constant between neighbouring sites, u_n is the coordinate displacement of the nth site from its equidistant position. t_2 and t_3 are the contribution from the sulphur atom. $C^+_{n,\sigma}(C_{n,\sigma})$ denotes the electron creation (annihilation) operator at site n with spin $\sigma(\sigma = \uparrow, \downarrow)$. In this paper, we neglect the internal electron-electron interactions. It has been indicated that the electron-lattice interactions will predominate the properties of polymers if the electron-electron interactions are not too strong.

Interfacial coupling between the PT and the metal electrode is described by the hopping integral $t_{M-P} = \beta t_0$, where β is the weighting parameter. It has been indicated that $\beta > 1$ means an interface of a potential well, whereas $\beta < 1$ means an interface of a potential barrier.[18]

The Hamiltonian due to the lattice distortion in PT is

$$H_{\rm latt} = \frac{K}{2} \sum_n \left(u_{n+1} - u_n\right)^2 + \frac{M}{2} \sum_n \dot{u}_n^2, \tag{3}$$

where K denotes the elastic constant and M the mass of a CH group.

The contribution from an external electric field is

$$H_{\text{ext}} = \sum_{n,\sigma} V_n(\tau)\left(C^{+}_{n,\sigma}C_{n,\sigma} - 1\right), \tag{4}$$

where $V_n(\tau)$ is the lift potential energy of the left metal electrode at time τ for the charge injection $V_n(\tau) = V(\tau)$, or the driving field for the moving of the injected charges in PT, $V_n(\tau) = -|e|E(\tau)[(n-n_0)a + u_n]$, where e is the electronic charge, n_0 is the first site of the PT, and a is the lattice constant. At the right metal electrode, a field-free field, $V_n(\tau) = V_{n_1}(\tau)$, with site n_1 being the last site of PT.

The wavefunction of electron is $|\Phi_{\mu,\sigma}(\tau)\rangle = \sum_n \Psi_{\mu,\sigma}(n,\tau)|n\rangle$. The evolution of the electronic state is obtained by solving the time-dependent Schrödinger equation,

$$\begin{aligned} &\mathrm{i}\hbar\dot{\Psi}_{\mu,\sigma}(n,\tau) \\ &= -t_n\Psi_{\mu,\sigma}(n+1,\tau) - t_{n-1}\Psi_{\mu,\sigma}(n-1,\tau) \\ &\quad -t_2\Psi_{\mu,\sigma}(n+3,\tau)\Delta\left(\frac{n+3}{4},\text{int}\right) \\ &\quad -t_2\Psi_{\mu,\sigma}(n-3,\tau)\Delta\left(\frac{n}{4},\text{int}\right) \\ &\quad -t_3\Psi_{\mu,\sigma}(n,\tau)\left(\Delta\left(\frac{n}{4},\text{int}\right) + \Delta\left(\frac{n+3}{4},\text{int}\right)\right) \\ &\quad +V_n(\tau)\Psi_{\mu,\sigma}(n,\tau), \end{aligned} \tag{5}$$

where the site index n runs over the whole chain.

Classically, the lattice displacement $\{u_n\}$ of the system is determined by the following Newtonian equations of motion in a nonadiabatic approach:

$$\begin{aligned} M\ddot{u}_n(\tau) = &-K(2u_n(\tau) - u_{n+1}(\tau) - u_{n-1}(\tau)) \\ &+2\alpha[(\rho_{n,n+1}(\tau) - \rho_{n-1,n}(\tau))] \\ &+|e|E(\tau)[\rho_{n,n}(\tau) - 1], \end{aligned} \tag{6}$$

where site index n runs only in the PT chain. $\rho_{n,n'}$, the element of the density matrix, is defined as

$$\rho^{\sigma}_{n.n'}(\tau) = \sum_{\mu} \Psi^{*}_{\mu,\sigma}(n,\tau) f_{\mu,\sigma}\Psi_{\mu,\sigma}(n',\tau), \tag{7}$$

where $f_{\mu,\sigma}$ is the time-independent distribution function determined by the initial occupation (being 0, 1 or 2). The coupled differential equations (5) and (6) can be solved numerically by using Runge–Kutta method of order 8 with step control.[19]

Dynamical evolution starts from a system with a static structure, which is given by a static lattice configuration obtained by minimizing total energy of the system,

$$u_n = \frac{1}{2}\left\{u_{n+1} + u_{n-1} + \frac{2\alpha}{K}{\sum_{\mu}}'[\Psi_{\mu,\sigma}(n+1,\tau=0)\Psi_{\mu,\sigma}(n,\tau=0) - \Psi_{\mu,\sigma}(n,\tau=0)\Psi_{\mu,\sigma}(n-1,\tau=0)]\right\}. \tag{8}$$

We consider a finite one-dimensional metal/PT/metal system with a 200-monomer PT chain and two 70-site metal electrodes, which is long enough for the present investigation. The following parameters of the model for the PT are cited from experiments[20] and numerical studies in a static state:[21] $t_0 = 2.5\,\text{eV}$, $t_1 = 0.675\,\text{eV}$, $\alpha = 4.5\,\text{eV/Å}$, $K = 21.0\,\text{eV/Å}^2$, $t_2 = t_3 = 0.125\,\text{eV}$, $a = 1.22\,\text{Å}$, and $M = 1349.14\,\text{eV}\cdot\text{fs}^2/\text{Å}^2$. The on-site energies of two metal layers are supposed to be zero, which means that the Fermi level of the metal is almost at the middle of the band gap of PT. Therefore the highest occupied electronic state is confined in the metal electrodes before an external field is applied. In calculation, in order to avoid the boundary effect and pursue a long time simulation, we adopt the end-fixed boundary condition.[22]

In calculation, we assume that the external bias is turned on smoothly, that is, we let $V(\tau) = V_0\exp\left[-(\tau-\tau_c)^2/\tau_{\text{w}}^2\right]$ for $0 < \tau < \tau_c$ and $V(\tau) = V_0$ for $\tau \geq \tau_c$, with τ_c being a smooth turn-on period and τ_{w} the width, which means that the interval ranges from zero to a stable value. The applied electric field $E(\tau)$ is also turned on smoothly with the same mode, i.e. $E(\tau) = E_0\exp\left[-(\tau-\tau_c)^2/\tau_{\text{w}}^2\right]$ for $0 < \tau < \tau_c$ and $E(\tau) = E_0$ for $\tau \geq \tau_c$, with the same τ_c and τ_{w}. In calculation, we take $\tau_c = 30\,\text{fs}$ and $\tau_w = 25\,\text{fs}$, and various values of voltage bias V_0 and E_0.

3. Results and discussion

For an isolated pristine PT chain, the energy gap is about 2.3 eV and the lowest unoccupied molecular orbital (LUMO) level is 1.15 eV in the present parameters. The structure of the metal/PT/metal system at $\tau = 0$ fs is obtained by solving the static Schrödinger equation and the equilibrium condition by iteration. The Fermi level of the metal is supposed to be in the middle of the gap of PT by setting $\varepsilon_n = 0$ as stated above.

Firstly, we present our results about the charge injection by increasing the voltage bias in the absence of external fields. At the initial state ($V_0 = 0$), the Fermi level of the metal electrode lies naturally in the middle of PT gap. In this case, no charge can be injected into the PT chain due to the large energy barrier. Then we increase the voltage bias V_0 applied to the left metal electrode smoothly, which lifts the Fermi level of the electrode, while the energy levels in the other parts remain unchanged. It is found that when the bias is about 0.97 eV the electronic charges are apparently injected into the PT chain through the metal/PT interface. Although this bias is lower than energy level of the LUMO of PT, due to the existence of virtual polaron level in the metal/PT/metal system,[23] the charge could be injected into the PT layer when the Fermi level of the metal is just above the virtual polaron level. However, in a real system, this virtual polaron level does not exist before electron injection. Compared with the case in which the middle polymer chain is replaced by *trans*-PA in the same condition, it is found that the charge with a quantity of about $1e$ is injected into the polymer chain when the voltage bias is 0.59 eV. It is due to the fact that the gap of *trans*-PA is about 1.36 eV, less than that of PT.

To clarify the property of the injected charge, we recall a polaron in an isolated polymer chain. When one extra electron is added to the chain, it will occupy the LUMO level. Due to the strong electron-lattice interactions, this level will fall into the gap and its eigenstate becomes localized. Here in the dynamic process of PT chain in contact with two metal electrodes, an electronic state extends through to the whole metal/PT/metal system. The electron should have probabilities in the electrode and in the PT layer. Although the electronic states in the PT and the metal electrodes are mixed due to the coupling between the PT and the metal electrodes, we can distinguish the part in PT from the part in the metal electrodes by calculating the electronic distribution $\eta_{\nu,\sigma}^{(\kappa)} \left(\equiv \sum_{(n\in\kappa)} |\Psi_{\nu,\sigma}(n)|^2 \right)$ for each state ν, where $\Psi_{\nu,\sigma}(n)$ is the wavefunction at site n and κ is a set of sites (the left metal electrode, PT chain, or the right metal electrode).

For convenience, we smoothly deal with the staggered lattice configuration y_n and charge distribution ρ_n as follows: $\rho'_n = (\rho_{n-1} + \rho_n + \rho_{n+1} + \rho_{n+2})/4$ and $y_n = (-1)^n(u_{n+1} - u_n)$, $y'_n = (y_{n-1} + y_n + y_{n+1} + y_{n+2})/4$. The ρ'_n and y'_n of PT chain at a few typical times are shown in Fig.2 with an interfacial coupling parameter (β) of 0.4 at a voltage bias (V_0) of 0.98 eV, which is just above the minimal value for the charge injection in the absence of the electric field.

From Fig.2, it is found that a localized wave packet forms in the PT layer, which means that the injected charges will accumulate due to strong electron-lattice interactions. The wave packet behaves like a quasiparticle and serves as a transporting carrier in the PT layer. The evolution of the distribution of total injected charges is shown in the inset of Fig.2. Owing to the interaction with the left interface, the charge will move very slowly towards the centre of PT chain. It is easily found that the whole injection process lasts about 500 fs, and then the left electrode and the PT layer reach a dynamical balance. At the present bias, we find that about one electron charge is injected into the PT chain, of which about $0.06e$ are confined at the interface. Particularly, it is also found that the time it takes for the injection process in the metal/PA/metal structure is about 400 fs and the wave packet in the PA moves faster than in the PT in the same condition. This can be attributed to the difference in electronic structure and strength of electron-lattice interaction between the PA and the PT.

Moreover, when the voltage bias is further increased, more charges will be injected and the wave packet may contain two electronic charges with opposite spin orientations. In this case, it is found that a complete spatial electronic state transfers into the PT layer and the wave packet is a double charged bipolaron. Increasing the bias further, another electronic state will begin to transfer toward the PT and another wave packet will form. Each wave packet contains no more than two electronic charges. Figure 3 shows the charge distribution ρ'_n and the lattice configuration y'_n at a few typical times for the case in which a voltage

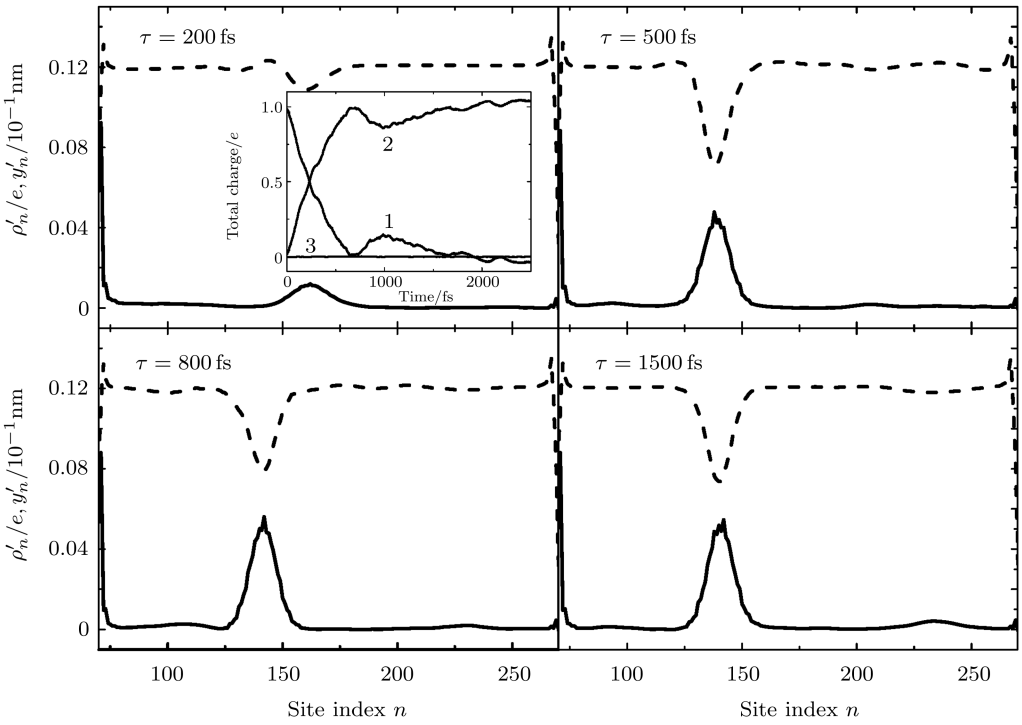


Fig.2. The charge distribution ρ'_n (solid line) and the staggered lattice configuration y'_n (dashed line) of PT chain at a few typical times in the absence of electric field, with $\beta = 0.4$ and $V_0 = 0.98\,\mathrm{eV}$. The inset shows the total charge evolution with 1, 2 and 3 denoting metal (L), polymer, and metal (R), respectively.

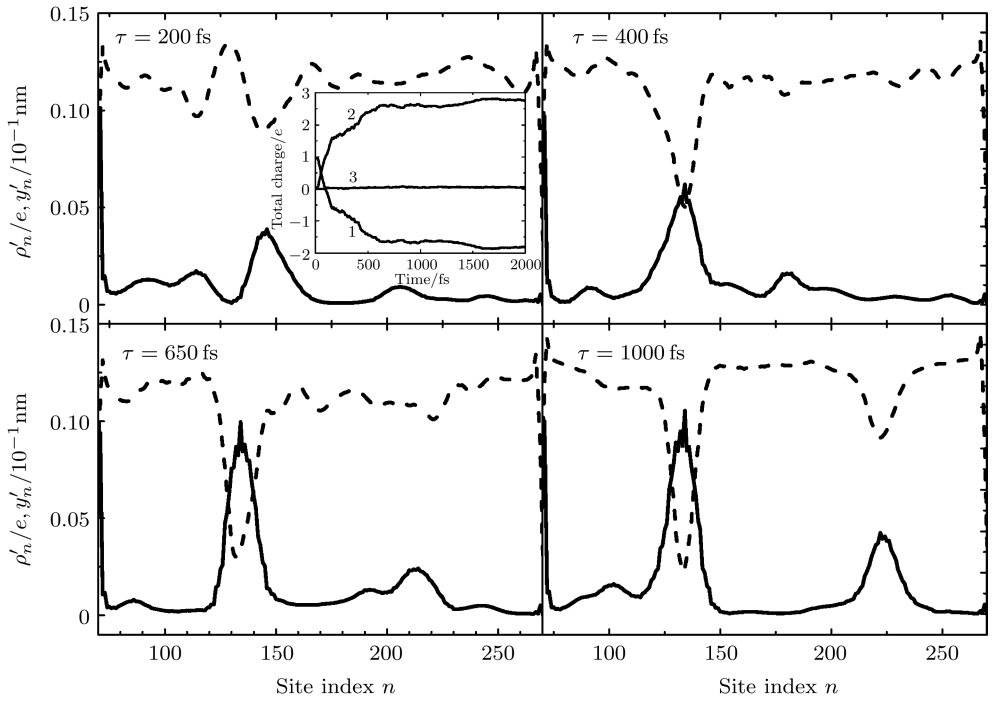


Fig.3. The same caption as that for Fig.2 but with $\beta = 0.4$ and $V_0 = 1.2\,\mathrm{eV}$. The inset shows the total charge evolution with 1, 2 and 3 denoting metal (L), polymer, and metal (R), respectively.

bias (V_0) of 1.2 eV is applied. It is found that about 2.83e are injected into the PT layer, of which about 0.05e are confined at the interface. Two wave packets are formed in the PT layer, one with two electronic charges and the other with about 0.78e. From the evolution at $\tau = 650$ fs, it is also found that the formation of a stable wave packet is not instantaneously completed, but along with the process of the charge accumulation. The wave packet with fewer charges moves faster than that with more charges, which implies that the charge accumulations will slow down the carriers' transportation or lower the conductance in polymers.

Here the metal and the polymer are considered as forming a composite system and the noninteger charge injection is a consequence of the wave characteristic of the electron.

We have also investigated the relation between the injected charges and the coupling constant β with larger values. A large value of β means a strong contact between the electrode and the PT. Figure 4 shows the charge distribution ρ'_n and the lattice configuration y'_n at a few typical times in the absence of the electric field and at a voltage bias (V_0) of 0.98 eV for $\beta = 0.8$. It is found that a wave packet is formed within nearly 100 fs. From the inset, we can see that more than two electronic charges, about 2.1e, are injected into the PT chain very fast (within 100 fs). Compared with the weak coupling case (Fig.2), it is shown that a strong contact is in favour of the charge injection.

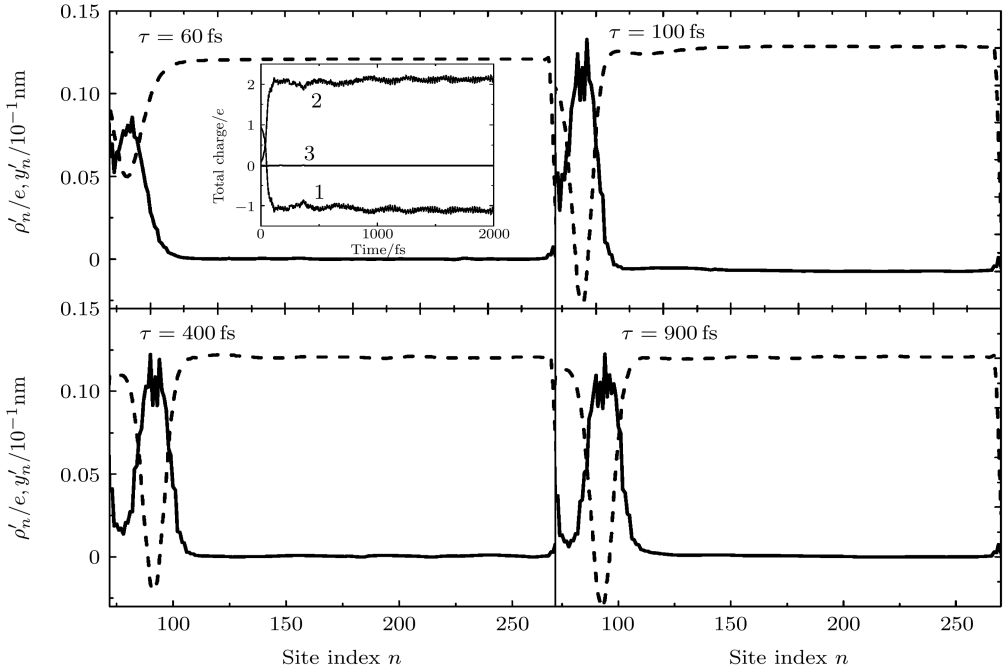


Fig.4. The same caption as that for Fig.2 but with $\beta = 0.8$ and $V_0 = 0.98$ eV. The inset shows the total charge evolution with 1, 2 and 3 denoting metal (L), polymer, and metal (R), respectively.

The behaviour of charge injection through the metal/PT interface under an applied electric field is further investigated. The evolutions of the charge distribution ρ'_n and the lattice configuration y'_n at a few typical times are shown in Fig.5 with an interfacial coupling parameter (β) being 0.4 at a voltage bias (V_0) of 0.98 eV and weak electric field (E_0) of 5×10^3V/cm. The evolution of the total injected charges is shown in the inset of Fig.5. It is observed that a small wave packet forms within about 200 fs, and it contains one electronic charge at about 500 fs and accumulates around the 140th site, and then the wave packet is a polaron. Thereafter it moves towards the right interface driven by the electric field. Comparing with the results in the absence of external field, we can find that the applied field reduces effectively the potential barrier, thereby favouring the charge injection. From the inset of Fig.5, one can find that the charge does not enter the right metal electrode, which means that the electric field is too weak to overcome the barrier at the right PT/metal interface.

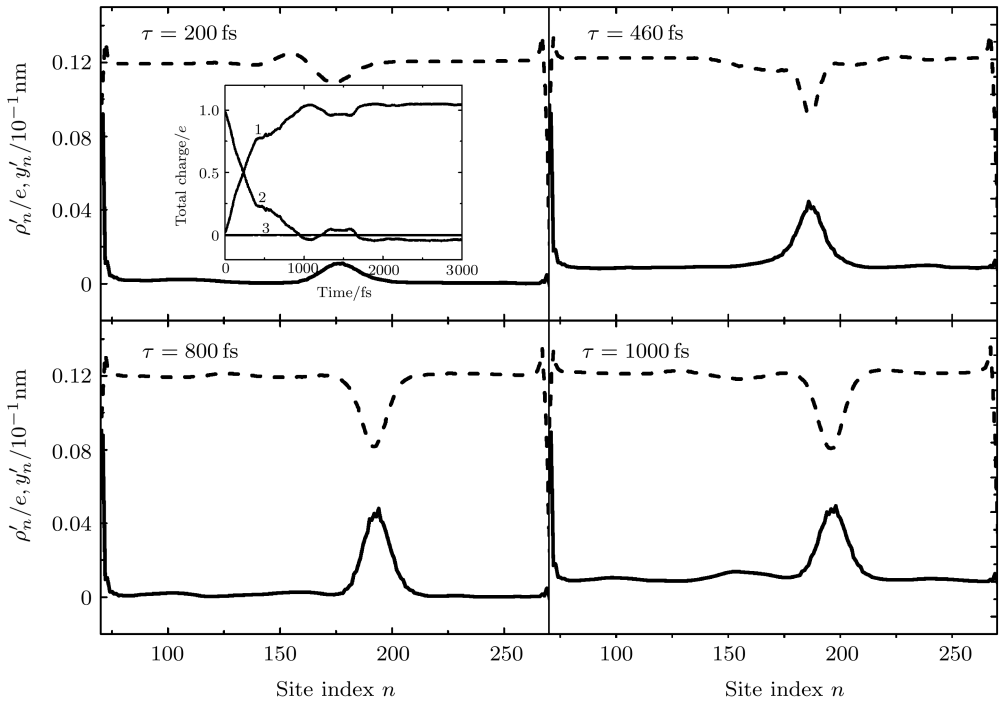


Fig.5. The same caption as that for Fig.2 but with an electric field (E_0) of 5×10^3 V/cm and $\beta = 0.4$, $V_0 = 0.98$ eV. The inset shows the evolution of total charge with 1, 2 and 3 denoting metal (L), polymer, and metal (R), respectively.

The charge injection process under a higher electric field, $E_0 = 4\times10^4$ V/cm, is shown in Fig.6. Unlike the case in which $E_0 = 5\times10^3$ V/cm, it is found that the charge gradually accumulates to form a wave packet at the right interface within 500 fs. From the inset of Fig.6, we observe that at 950 fs, the total charge in the PT chain reaches its maximum value, less than an electronic unit charge. The reason is that a small quantity of charge, about $0.1e$, has been transferred into the right metal electrode. At about 700 fs, the charge in the polymer chain begins to move into the right metal electrode. This can be explained as being due to the electric field reducing the barrier of the charge jumping through the interface. It is interesting to note that the charge held by the wave packet is continually transferred into the right metal electrode, which indicates that the quantity of charge transferred from the polymer into the electrode is a noninteger, similar to the case of the charge injection into PT chain. Eventually, a small quantity of charge kept in the wave packet enters into the right electrode, and a small quantity of charge is left in the PT chain and performs some irregular oscillations.

All the discussions above are under the condition of a weak driving electric field. In fact, the formation of a wave packet should depend on the strength of the driving field. It is found that there is an upper critical value of the electric field for the forming of a stable wave packet, beyond which the injected charges cannot get together. Figure 7 describes the evolution of the injected charge at a stronger electric field, $E_0 = 2\times10^5$ V/cm. In this case, we find that a small wave packet with some oscillations is formed in the PT chain and quickly come to the right PT/metal interface. From the inset, it can be found that electronic charges are injected into the PT chain continually, and the quantity of charge in the PT chain reaches its maximum value, about $0.8e$, at 830 fs, then decreases accompanied by some oscillations. Meanwhile, we observe that the quantity of charge increases in the right electrode. If we increase the field to a higher value ($\geq 3.0\times10^5$ V/cm), it is found that stable wave packet cannot form and all the injected charges become extended. This result indicates that the electric field applied to the PT chain reduces the potential barriers in the PT/metal interface. The charges injected into the PT chain from the left metal electrode is rapidly transferred to the right metal electrode, and the localized lattice deformation cannot form.

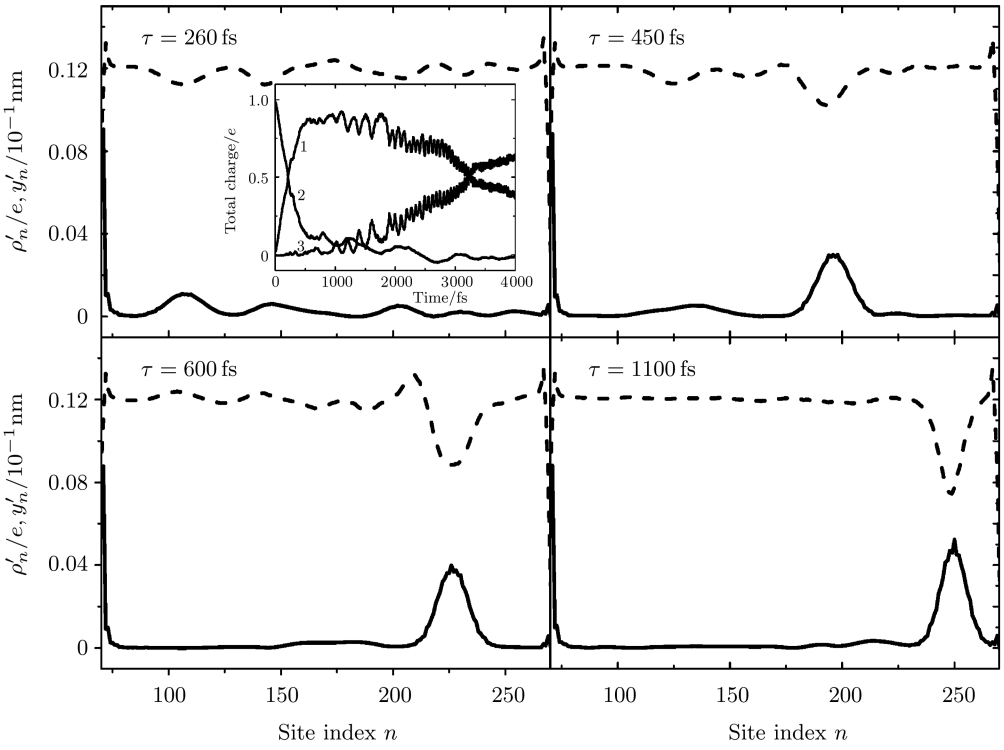


Fig.6. The same caption as that for Fig.2 but with an electric field (E_0) of 4×10^4 V/cm, $\beta = 0.4$, and $V_0 = 0.98$ eV. The inset shows the evolution of total charge with 1, 2 and 3 denoting metal (L), polymer, and metal (R), respectively.

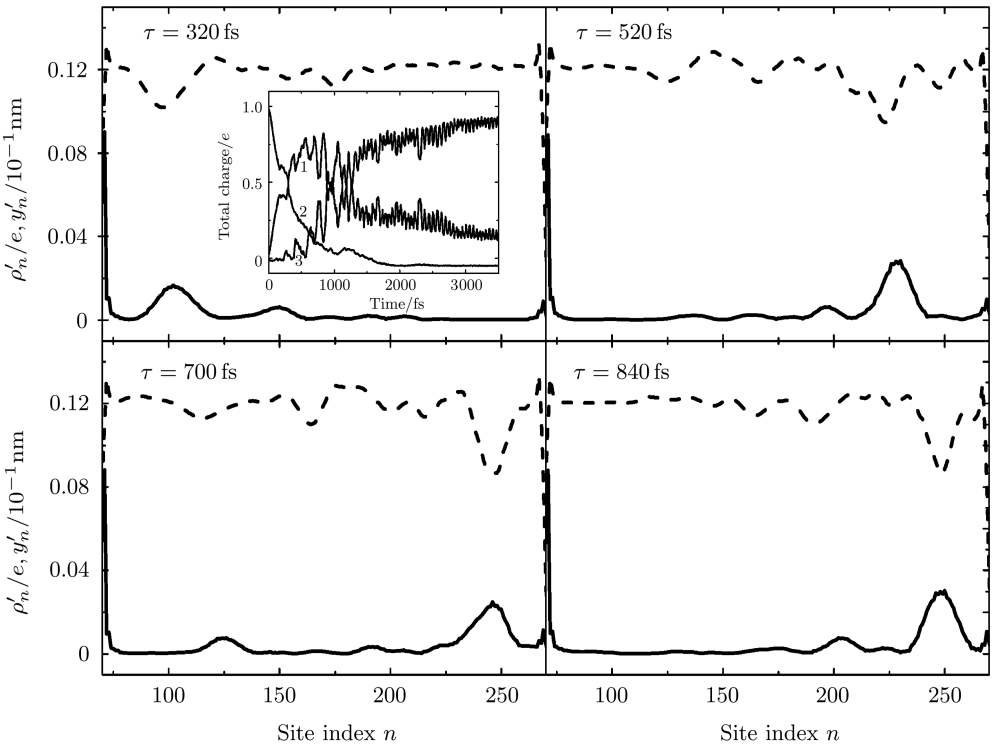


Fig.7. The same caption as that for Fig.2 but with an electric field (E_0) of 2×10^5 V/cm, $\beta = 0.4$, and $V_0 = 0.98$ eV. The inset shows the evolution of total charge with 1, 2 and 3 denoting metal (L), polymer, and metal (R), respectively.

The evolutions of the ejected charges for various electric fields are shown in Fig.8. From the figure, one can find that with the increase of the electric field, a shorter time is needed for the charges to be ejected from the PT into the right metal electrode. As the electric field can effectively reduce the potential barrier in the PT/metal interface, the quantity of the ejected charges increases when the electric field turns stronger. At a field of 5×10^3 V/cm, no electron can be ejected into the right electrode, and when the field increases to 3×10^4 V/cm, only $0.1e$ is ejected after 3000 fs. With the increase of the electric field, more and more charges can be ejected. In the case of 2×10^5 V/cm, nearly all the charges injected into PT chain are ejected from the right electrode. Furthermore, we obtain that the ejected quantity of charge is also a noninteger, which is the same as the injection course described above.

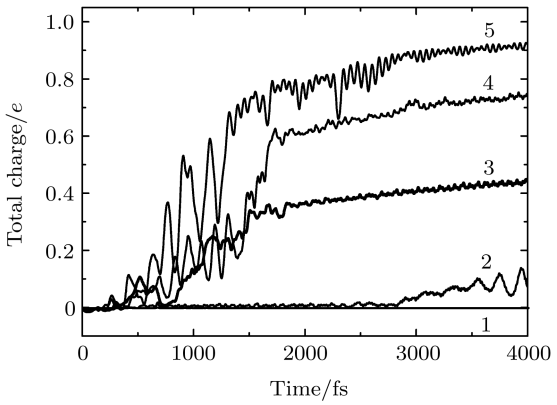


Fig.8. The evolution of total charge in the right metal electrode for various electric fields with 1, 2, 3, 4 and 5 denoting electric fields 5.0×10^3 V/cm, 3.0×10^4 V/cm, 1.0×10^5 V/cm, 1.5×10^5 V/cm and 2.0×10^5 V/cm, respectively.

In the end, it should be stressed that the results obtained here is mode-independent for both $V(\tau)$ and $E(\tau)$. We analyse this effect on the charge injection by adopting different input forms of $V(\tau)$ and $E(\tau)$, i.e. by changing the value of τ_c and τ_w, or by using a linear input mode. It is found that no qualitative change is obtained but with a difference in time taken for the charge injection. It is reasonable that the charge injection occurs only if $V(\tau)$ is raised up to a particular value, i.e. the energy of the virtual polaron level, in the metal/polymer/metal structure.

4. Summary

In this paper, we have analysed the dynamic process of charge injection, transport and ejection in a metal/PT/metal structure by using a nonadiabatic method. It is shown that electronic charges can be injected from the electrode into the PT layer by adjusting the voltage bias of the electrode, the electric field applied to the PT chain and the interfacial coupling parameter. The injected charges will form wave packets due to the strong electron-lattice interactions in the PT chain. Each wave packet contains a quantity of charge, 0–$2e$, depending on the injection condition. On the other hand, we obtain that the wave packet forms only in the absence of the electric field or under a weak electric field, and the electronic charge cannot be ejected from the PT into the right electrode. For a stronger electric field the wave packet can still form while it moves rapidly to the right PT/metal interface, and the electronic charge can be ejected from the PT into the right metal electrode. Furthermore, we study the effect of the applied electric field on the charge ejection, and we obtain that the large electric field applied to the polymer chain is favourable for the charge ejection, and the ejected quantity of charge is also a noninteger.

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