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Ac response of a coupled double quantum dot

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The effect of phase-breaking process on the ac response of a coupled double quantum dot is studied in this paper based on the nonequilibrium Green function formalism. A general expression is derived for the ac current in the presence of electron–phonon interaction. The ac conductance is numerically computed and the results are compared with those in [Anatram M P and Datta S 1995 *Phys. Rev.* B **51** 7632]. Our results reveal that the inter-dot electron tunnelling interplays with that between dots and electron reservoirs, and contributes prominently to the ac current when inter-dot tunnelling coupling is much larger than the tunnelling coupling between dots and electron reservoirs. In addition, the phase-breaking process is found to have a significant effect on the ac transport through the coupled double dot.

Keywords: electronic transport, electron-phonon interaction, differential conductance, Keldysh Green's function

PACC: 7210, 7210D, 7320D, 7335

In recent years, the time-dependent tunnelling phenomena in systems of coupled quantum dots have received much attention.[1−7] For example, electron pumping has been studied in a coupled double quantum dot with inter-dot capacitance,[1] and the linear response admittance of a double quantum dot in an external time-dependent field has been calculated.[2] Compared to the single quantum dot, the double quantum dot has richer physics. Two important factors in mesoscopic systems, the Coulomb repulsion energy and the quantum coherence, can be displayed in this system. It has been shown theoretically that under a time-dependent potential the conduction electrons will develop an ac sideband weighted by a Bessel function of the ac voltage and the frequency of the external ac field.[8,10] As a result, in the time-dependent process the phase coherent transport of electrons will be affected by the ac-driven forces differently in different parts of the system. In fact, the electrons may absorb external energy to modify their phases, and some nonlinear effects, such as electron pumps[1,11] and photon-assisted tunnelling,[14,15] will exhibit.

Another factor that affects the coherence of electronic transport is the electron-phonon interaction. However, the time-dependent electronic transport involving electron-phonon interaction has received relatively less attention. Recently, Anatram and Datta[8] studied the effect of phase breaking on ac response of a single quantum dot, but their results showed hardly any difference in the ac conductances with or without electron-phonon interaction, particularly at high temperatures. Li reported that phase-breaking process has no significant effect on the ac conductance of a resonant-tunnelling diode in the high-temperature limit but it does have an influence at low temperatures.[9] Although there are many papers on ac transport through coupled double quantum dot,[2−5] to our knowledge, there has not yet been a work involving electron-phonon interaction, which may confirm the results in Refs.[8, 9].

In this paper, the effect of phase-breaking on ac transport through coupled double-dot is considered based on the nonequilibrium Green's function (NGF) technique, which is a convenient approach for exploring the nonlinear and inelastic problems in ac transport, both coherent and incoherent, with or without electron-phonon interaction. The Coulomb interaction is ignored, which is valid in case that the dot size is relatively large. Combined with Keldysh contour integration and equation of motion (EOM) method, a general formalism is derived to calculate the ac current for the coupled double quantum dot system. Follow-

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ing the work on single quantum dot in Ref.[8], the general current formula is expressed for the coupled double-dot in terms of various Keldysh's Green functions, and then the ac current for small ac bias is linearized. The complicated calculation of the first-order change in various Green's functions due to the small ac bias and of the linear ac current is simplified on the assumption that the ac voltage is only restricted to the left contact. The ac conductance in various inter-dot tunnelling couplings is numerically computed. Our results reveal that the inter-dot electron tunnelling interplays with that between dots and electron reservoirs, and makes a significant contribution to the ac current when inter-dot tunnelling coupling is much larger than the tunnelling coupling between dots and electron reservoirs. The electron-phonon interaction is found to have a considerable effect on the ac conductance for double-dot.

The system we consider is a coupled double quantum dot connected to two electron reservoirs by tunnelling coupling, which is introduced as a perturbation. The ac field is applied to the left electron reservoir in addition to a dc voltage, while the right one is connected to the ground. It can be described by the Hamiltonian

$$\begin{aligned} H = & \sum_{k,\alpha\in L,R} \varepsilon_{k\alpha}(t)\, c^{+}_{k\alpha} c_{k\alpha} + \sum_{i,n} \varepsilon^{0}_{i}(t)\, d^{+}_{in} d_{in} \\ & + \sum_{n,m} V_{12}\left(d^{+}_{1n} d_{2m} + \text{h.c.}\right) \\ & + \sum_{k,n} [V_{\text{L}}\left(c^{+}_{k\text{L}} d_{1n} + \text{h.c.}\right) \\ & + V_{\text{R}}\left(c^{+}_{k\text{R}} d_{2n} + \text{h.c.}\right)] + H_{el-ph}, \end{aligned} \tag{1}$$

where $c^{+}_{k\alpha}\,(c_{k\alpha})$ creates (annihilates) an electron in α reservoir, while $d^{+}_{in}\,(d_{in})$ creates (annihilates) an electron including spin in the ith $(i=1,2)$ quantum dot at nth site in the uncoupled two dots region, $V_{\text{L}}\,(V_{\text{R}})$ is the tunnelling coupling between dot 1 (2) and the left (right) reservoir, and V_{12} is the tunnelling coupling between the two dots. The Hamiltonian for the electron–phonon interaction is of the form

$$\begin{aligned} H_{el-ph} = & \sum_{m,n,q} M^{(1)}_{m,n,q} d^{+}_{1m} d_{1n}\left(b_{1q} + b^{+}_{1q}\right) \\ & + \sum_{m,n,q} M^{(2)}_{m,n,q} d^{+}_{2m} d_{2n}\left(b_{2q} + b^{+}_{2q}\right). \end{aligned} \tag{2}$$

In Eq.(1) we have neglected the time dependence of tunnelling coupling amplitude between dots and reservoirs and that between the two dots. At small ac bias voltage this is a valid approximation.[8,16]

Applying a sinusoidal potential $v_{\text{ac}}\cos(\omega_0 t)$ to contact α causes the electron energy in the contact to vary as $\varepsilon_{k\alpha}(t) = \varepsilon_{k\alpha} + v_{\text{ac}}\cos(\omega_0 t)$, and this ac potential results in a time-dependent energy in the two dots: $\varepsilon^{0}_{i}(t) = \varepsilon^{0}_{i} + \Delta_i \cos(\omega_0 t)\,(i=1,2)$. The ac conduction current can be calculated based on the change rate of the electron density in the two dots[8,10]

$$\begin{aligned} J(t) = & 2e\text{Re}\Big\{ \sum_{n} \int \text{d}t_1 \Big[G^{r}_{1n,1n}(t,t_1) \sum\nolimits^{<}_{L}(t_1,t) \\ & + G^{<}_{1n,1n}(t,t_1) \sum\nolimits^{a}_{L}(t_1,t) \\ & + G^{r}_{2n,2n}(t,t_1) \sum\nolimits^{<}_{R}(t_1,t) \\ & + G^{<}_{2n,2n}(t,t_1) \sum\nolimits^{a}_{R}(t_1,t) \Big] \Big\}, \end{aligned} \tag{3}$$

where the "lesser" and retarded Green's functions are defined in the tunnelling-coupled dot region

$$G^{<}_{in,in}(t) = \text{i}\langle d^{+}_{in}(0) d_{in}(t)\rangle, \tag{4}$$

$$G^{r}_{in,in}(t) = -\text{i}\theta(t)\langle\{d_{in}(t), d^{+}_{in}(0)\}\rangle \quad (i=1,2), \tag{5}$$

and the self-energies are related to the free-particle Green's function in the electron reservoirs and the tunnelling coupling between the contacts and dots

$$\sum\nolimits^{r,a,<}_{\alpha}(t,t') = V^{2}_{\alpha} \sum\nolimits_{k} g^{r,a,<}_{k\alpha}(t,t') \quad (\alpha = L,R). \tag{6}$$

Equation (3) is valid in general, even in the presence of strong electron-electron and electron-phonon interactions, and it is applicable to quantum dot systems with multiple energy levels. As a solvable example, the case that each dot contains only one energy level is considered in this paper.

The retarded and "lesser" Green functions defined for the two dots in Eq.(3) can be calculated by the method of EOM[17] and Keldysh's contour integration[18]

$$G^{r}_{ii} = G^{r0}_{ii} + G^{r0}_{ii} V_{12} G^{r0}_{\bar{i}\bar{i}} V_{12} G^{r}_{ii}, \tag{7}$$

$$G^{<}_{ii} = G^{r}_{ii} \sum\nolimits^{<}_{i} G^{a}_{ii} + G^{r}_{ii} V_{12} G^{r0}_{\bar{i}\bar{i}} \sum\nolimits^{<}_{\bar{i}} G^{a0}_{\bar{i}\bar{i}} V_{12} G^{a}_{ii}, \tag{8}$$

where $i=1,2$ and $\bar{i} = 3-i$ (this prescription is used afterwards in this paper), and G^{r0}_{ii} is defined by

$$G^{r0}_{ii} = g^{r}_{ii} + g^{r}_{ii} \sum\nolimits^{r}_{i} G^{r0}_{ii}. \tag{9}$$

In Eq.(9), g^{r}_{ii} are the free particle Green functions in the absence of tunnelling and electron-phonon interaction, and $\sum^{r}_{i} = \sum^{r}_{\alpha} + \sum^{r}_{i\phi}(i=1(2)$ corresponds to α=L(R), this prescription is followed afterwards),

where $\sum_{\alpha}^{r}$, the retarded self-energy due to the tunnelling, is given by Eq.(6), while $\sum_{i\phi}^{r}$, the retarded self-energy due to the electron-phonon interaction in the ith dot, is given by

$$\begin{aligned}\sum\nolimits_{i\phi}^{r}(t,t') = &-\sum\nolimits_{q}(M_q^{(i)})^2[G_{ii}^{<}(t,t')D_{iq}^{r}(t,t') \\ &+ G_{ii}^{r}(t,t')D_{iq}^{<}(t,t') \\ &+ G_{ii}^{r}(t,t')D_{iq}^{r}(t,t']. \end{aligned} \tag{10}$$

Here $\sum_{i\phi}^{r,<}(t,t')$ is the phonon Green function in the dot i and $M_q^{(i)}$ is the phonon coupling.

Unlike the case of dc bias where the Green functions $G_{ii}^{r,a,<}$ have simple expressions in energy representation, in the presence of ac bias and electron–phonon interaction they are much more complicated but in principle can be calculated by iteration from Eqs.(7) and (8). However, for small ac voltage, the Green's functions and then the current about the steady-state can be linearized, i.e., they are expanded in the order of the ac voltage $v_{\rm ac}$, Δ_1 and Δ_2, and then the quadratic and higher order terms are omitted. First, linearizing the conduction current leads to

$$\begin{aligned}\delta J_{\alpha}(\omega) =& e\int\frac{{\rm d}\omega_1}{2\pi}\Big\{\delta\sum\nolimits_{\alpha}^{<}(-\omega_1-\omega,-\omega_1) \\ &\times[G_{ii}^{r}(\omega_1+\omega)-G_{ii}^{a}(\omega_1)] \\ &+\delta G_{ii}^{r}(-\omega_1-\omega,-\omega_1)\sum\nolimits_{\alpha}^{<}(\omega_1) \\ &-\delta G_{ii}^{a}(-\omega_1-\omega,-\omega_1)\sum\nolimits_{\alpha}^{<}(\omega_1+\omega) \\ &+{\rm i}\Gamma^{\alpha}\delta G_{ii}^{<}(\omega_1-\omega,\omega_1)\Big\}\quad(\alpha={\rm L,R}), \end{aligned} \tag{11}$$

where the subscript α=L(R) corresponds to $i=1(2)$, and the Fourier transform from the double-time coordinates to double-energy coordinates follows the prescription

$$F(\omega_1,\omega_2)=\iint{\rm d}t_1{\rm d}t_2 f(t_1,t_2){\rm e}^{-{\rm i}(\hbar\omega_1 t_1-\hbar\omega_2 t_2)}.$$

In Eq.(11) we have denoted Σ, G and Γ with single energy argument as the steady-state quantities corresponding to dc bias and used the notation δ to denote the variation of all important quantities due to the small ac potential $v_{\rm ac}$. This prescription is followed afterwards. In the wide-band limit the steady-state retarded self-energy $\sum_{\alpha}^{r}(\omega)$ takes the form $-\frac{\rm i}{2}\Gamma^{\alpha}$ (where $\Gamma^{\alpha}$is a constant). Similarly we have $\sum_{i\phi}^{r}(\omega)=-\frac{\rm i}{2}\Gamma_{i\phi}$, but $G_{ii}^{r,a}$ are of stair-case form.[19] Terms on the right-hand side of Eq.(11) are grouped into three categories as they have different physical significance. The effect of oscillating an electron reservoir at frequency ω leads to sidebands $E+n\hbar\omega$ for each energy E in the contact. The first term here represents the correlated injection into the device due to electrons at energies E and $E+n\hbar\omega$. The second and the third terms represent injection from the contact at one energy to a changing density of states in the device. Finally, the fourth term represents the injection into the contact due to the changing charge in the device. It is assumed that the phonon Green's function are dispersionless so that from Eq.(10) we obtain

$$\begin{aligned}&\delta\sum\nolimits_{i\phi}^{r}(-\omega_1-\omega,\omega_1) \\ =&(B+D)\int\frac{{\rm d}\bar{\omega}}{2\pi}\delta G_{ii}^{r}(\bar{\omega}-\omega,\bar{\omega}) \\ &+B\int\frac{{\rm d}\bar{\omega}}{2\pi}\delta G_{ii}^{<}(\bar{\omega}-\omega,\bar{\omega}), \end{aligned} \tag{12}$$

where

$$B=-\sum\nolimits_{q}(M_q^{(i)})^2 D_{iq}^{r}$$

and

$$D=-\sum\nolimits_{q}(M_q^{(i)})^2 D_{iq}^{<}\equiv\Gamma_{i\phi}.$$

As we consider in this paper the effect of phase breaking on ac conductance of the system, following Anatram and Datta[8] and Büttiker *et al*,[16] it is also assumed that due to small ac voltage in the left contact the ac voltage is vanishingly small in the dot and hence $\Delta_1=\Delta_2=0$. In addition, in the wide-band limit $\delta\sum_{\rm L}^{r}$ and B vanish. These conditions result in $\delta G_{ii}^{r}=0$ in Eq.(11), which can be shown alternatively by directly linearizing G_{ii}^{r} about Δ_1 and Δ_2 using Eq.(7) and then Eq.(9), where the variation of g_{ii}^{r} is given by

$$\delta g^r_{ii}(-\omega_1-\omega,-\omega_1) = 2\pi\delta(\omega-\omega_0)\frac{1}{2}\frac{\Delta_i}{\hbar\omega_0}[-g^r_{ii}(\omega_1+\omega_0)+g^r_{ii}(\omega_1)] + 2\pi\delta(\omega+\omega_0)\frac{1}{2}\frac{\Delta_i}{\hbar\omega_0}[-g^r_{ii}(\omega_1)+g^r_{ii}(\omega_1-\omega_0)]. \tag{13}$$

Substituting variations of Green' functions and self-energies into Eq.(11), the linear ac conduction currents flowing through the two quantum dots are obtained

$$\delta J_{\rm L}(\omega) = -\pi {\rm i}e^2 v_{\rm ac}\Gamma^{\rm L}\int\frac{{\rm d}\omega_1}{2\pi}\left\{\left[\delta(\omega-\omega_0)\frac{f_{\rm L}(\hbar\omega_1+\hbar\omega_0)-f_{\rm L}(\hbar\omega_1)}{\hbar\omega_0} + \delta(\omega+\omega_0)\frac{f_{\rm L}(\hbar\omega_1)-f_{\rm L}(\hbar\omega_1-\hbar\omega_0)}{\hbar\omega_0}\right]\times[G^r_{11}(\omega_1+\omega)-G^a_{11}(\omega_1)]\right\} - \frac{e}{\hbar}\Gamma^{\rm L}Q_1(\omega), \tag{14a}$$

$$\delta J_{\rm R}(\omega) = -\frac{e}{\hbar}\Gamma^{\rm L}Q_2(\omega), \tag{14b}$$

where the ac charge density caused by the time-dependent field in the dots is defined by

$$Q_i(\omega) = -{\rm i}\hbar\int\frac{{\rm d}\bar{\omega}}{2\pi}\delta G^<_{ii}(\bar{\omega}-\omega,\bar{\omega}) \quad (i=1,2). \tag{15}$$

Equation (15) is solved from a coupled equation obtained by linearizing Eq.(8) and then substituting into Eq.(15),

$$\begin{aligned} Q_1(\omega) =& -\hbar\pi e^2 v_{\rm ac}\Gamma^{\rm L}\int\frac{{\rm d}\omega_1}{2\pi}\left\{\left[\delta(\omega-\omega_0)\frac{f_{\rm L}(\hbar\omega_1+\hbar\omega_0)-f_{\rm L}(\hbar\omega_1)}{\hbar\omega_0} + \delta(\omega+\omega_0)\frac{f_{\rm L}(\hbar\omega_1)-f_{\rm L}(\hbar\omega_1-\hbar\omega_0)}{\hbar\omega_0}\right]G^r_{11}(\omega_1+\omega)G^a_{11}(\omega_1)\right\} \\ &+\hbar DQ_1(\omega)\int\frac{{\rm d}\omega_1}{2\pi}G^r_{11}(\omega_1+\omega)G^a_{11}(\omega_1) \\ &+\hbar DQ_2(\omega)V^2_{12}\int\frac{{\rm d}\omega_1}{2\pi}G^r_{11}(\omega_1+\omega)G^{r0}_{22}(\omega_1+\omega)G^{a0}_{11}(\omega_1)G^a_{22}(\omega_1), \end{aligned} \tag{16a}$$

$$\begin{aligned} Q_2(\omega) =& \hbar DQ_2(\omega)\int\frac{{\rm d}\omega_1}{2\pi}G^r_{22}(\omega_1+\omega)G^a_{22}(\omega_1) \\ &-\pi e^2 v_{\rm ac}\Gamma^{\rm L}\int\frac{{\rm d}\omega_1}{2\pi}\left\{\left[\delta(\omega-\omega_0)\frac{f_{\rm L}(\hbar\omega_1+\hbar\omega_0)-f_{\rm L}(\hbar\omega_1)}{\hbar\omega_0} + \delta(\omega+\omega_0)\frac{f_{\rm L}(\hbar\omega_1)-f_{\rm L}(\hbar\omega_1-\hbar\omega_0)}{\hbar\omega_0}\right]G^r_{11}(\omega_1+\omega)G^a_{11}(\omega_1)\right\} \\ &+\hbar DQ_1(\omega)V^2_{12}\int\frac{{\rm d}\omega_1}{2\pi}G^r_{22}(\omega_1+\omega)G^{r0}_{11}(\omega_1+\omega)G^{a0}_{2211}(\omega_1)G^a_{11}(\omega_1). \end{aligned} \tag{16b}$$

Equations (14) and (16) provide a simple approach to investigate the ac response of the coupled double quantum dot. In the following some numerical results of the linear ac conductance at equilibrium $\mu_{\rm L} = \mu_{\rm R}$ based on these equations are presented. In the wide-band limit, the linewidth functions $\Gamma^\alpha(\varepsilon)(\alpha \in {\rm L},\ {\rm R})$ are energy-independent constants, and it is assumed that $\Gamma^{\rm L}(\varepsilon) = \Gamma^{\rm R}(\varepsilon) = \Gamma$ for the two quantum dots in the numerical calculations, and the energy level of the two dots are assumed to be equal. Figure 1 shows the low-temperature ($kT = 0.2\Gamma$) ac conductance of the double dot against the frequency ω_0 of the applied ac field for three different inter-dot tunnelling coupling amplitudes: $V_{12} = 0.1\Gamma$, 2.0Γ and 10Γ. The energy level of the two dots ε_0 is set to be 95Γ (all energies are measured in units of Γ) while the identical left and right Fermi level $\mu_{\rm L} = \mu_{\rm R} = \mu$ is taken to be 100Γ. Also, the phonon Green's function D, which is assumed to be dispersionless, is set to be 6Γ. The choice of the values of ε_0, $\mu_{\rm L}$ and $\mu_{\rm R}$ are such that the peaks of the conductance without electron-phonon interaction can be

displayed properly, as the distance between them are in the range of $2V_{12}$, which will be seen below, while the effect of phase-breaking effect remains pronounced when it is included.

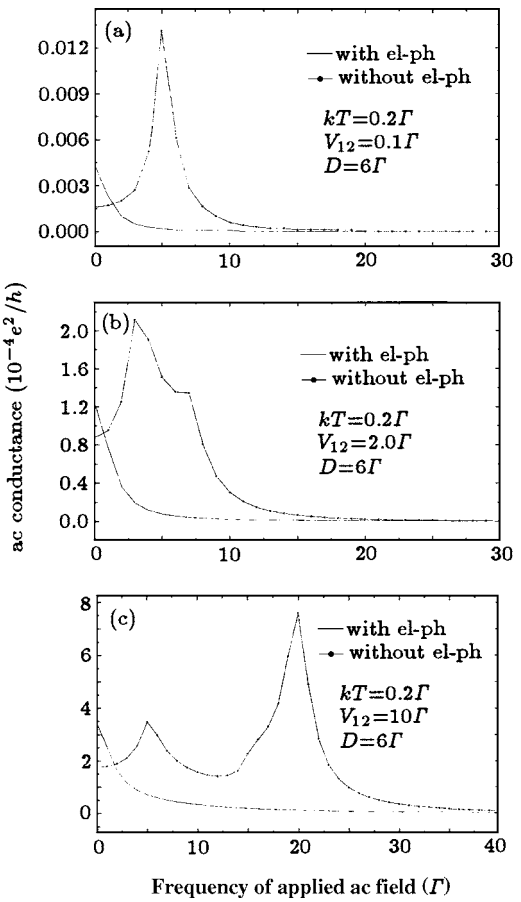


Fig.1. Plot of the ac conductance of a double dot against the frequency of applied ac field. $\varepsilon_0 = 95\Gamma$, $\mu_{\rm L} = \mu_{\rm R} = \mu = 100$, kT=0.2 and V_{12}= 0.1 (a), 2 (b), 10 (c). The solid line is for D=6 while the dot line is for D=0. All energies are expressed in units of $\Gamma = \Gamma_L = \Gamma_{\rm R}$. Inset: the same plot for D=6 in small scale.

It can be seen from Fig.1 that for all three inter-dot tunnelling couplings (V_{12}) the ac conductance without electron-phonon interaction increases as ω_0 increases from zero. It reaches the peak values and then steadily drops as ω_0 increases further from the second peak position (see Figs.1(b) and (c)). In Fig.1(a) the two peak positions are very close to each other so they merge into one. The ac conductance peak is expected as the Fermi level is taken to lie above the dot energy level, the density of states below the chemical potential increases as ω_0 increases from very small values. In the presence of inter-dot tunnelling the dot energy level ε_0 splits into $\varepsilon_0 \pm V_{12}$, so the peak position of the low-temperature conductance is given by $\hbar\omega_0 = \mu - (\varepsilon_0 \pm V_{12})$ for small V_{12}. Physically, this can be understood as the electron absorbs from the ac field a photon with energy equal to the difference between the Fermi and the dot energy levels, so that it can tunnel between the electron reservoirs and the dots. This is known as photon-aided tunnelling (PAT).[1,14,15] It can be seen from Fig.1 that for the small and medium tunnelling, the positions of the ac conductance peaks are exactly given by the formula $\hbar\omega_0 = \mu - (\varepsilon_0 \pm V_{12})$. However, for large V_{12} (Fig.1(c)), the conductance has two peaks pinned at $\omega_0 = 5\Gamma$ and $\omega_0 = 20\Gamma$. While the first peak position satisfies the formula, the second one deviates from 15Γ. In this case, the dot energy level splits into 105Γ and 85Γ, which yields a difference of 20Γ. Our result reveals that the inter-dot electron tunnelling plays an important role and hence contributes significantly to the ac current when the inter-dot tunnelling is much larger than the coupling between dots and electron reservoirs. This phenomenon arises from the interplay of the coupling between the two dots and that between the two dots with electron reservoirs, and cannot be observed in the single quantum dot system. A similar effect was discussed in Ref.[1] where the inter-dot tunnelling is called Rabi oscillation and the authors suggested electron pumping via the coupled quantum dot from the an electron reservoir with lower chemical potential to the one with higher chemical potential by Rabi oscillation between the dots.

Unlike the behaviour of that without electron-phonon interaction, the ac conductance with phase-breaking effect decreases monotonously with increasing frequency of the applied ac field, and it approaches zero at sufficiently large ω_0, overlapping with that without phase-breaking. This implies that the electron-phonon interaction reduces the density of states in the double dot, and the phase-breaking processes destroy the coherent transport in the double dot. The asymptotic behaviour is expected because at large ω_0 the charge carriers find that it is difficult for them to run after the fast oscillating electric field in the double dot, and the fact that the scattering probabilities $\delta\sum_{i\phi}^{<}(E+\hbar\omega_0, E)$ and $\delta\sum_{i\phi}^{>}(E+\hbar\omega_0, E)$ are reduced to a very small value when the frequency ω_0 of the applied ac field becomes large.

Figure 2 gives the high-temperature ($kT = 300\Gamma$) ac conductance under similar conditions for V_{12}, μ and ε_0. The Fermi function becomes gradually smoothing as the temperature increases, as a result, in principle the high-temperature ac conductance decreases slowly

and monotonically as ω_0 increases and no peak is expected. However, it is noticed that the conductance decreases as ω_0 increases from 0 in all cases except at large inter-dot tunnelling and without electron-phonon interaction, in which there is a peak pinned at $\omega_0 = 20\Gamma$. Again this peak is due to the electron tunnelling between the two dots, or Rabi oscillation between the coupled double dot. The ac conductances with or without electron-phonon interaction approach to zero at sufficiently large ω_0.

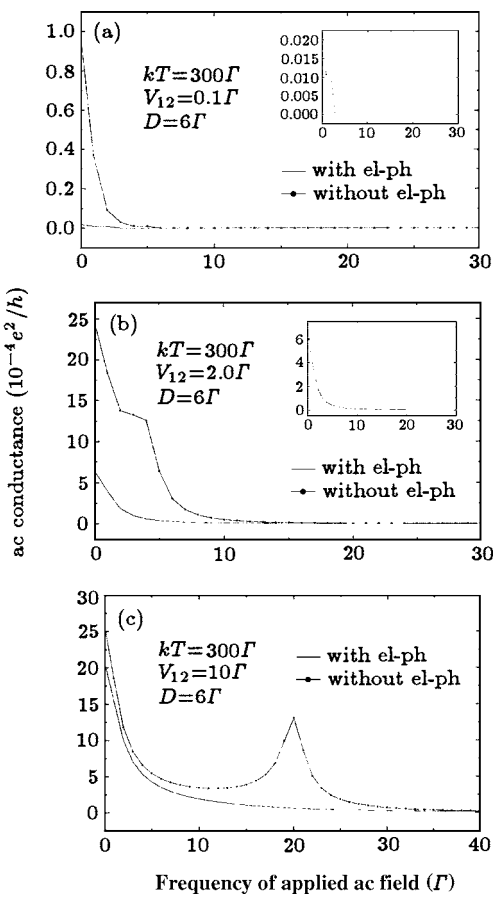


Fig.2. Plot of the ac conductance of a double dot against the frequency of applied ac field. $\varepsilon_0 = 95\Gamma$, $\mu_{\rm L} = \mu_{\rm R} = \mu = 100$, kT=300 and V_{12}= 0.1 (a), 2 (b), 10 (c). The solid line is for D=6 while the dotted line is for D=0. All energies are expressed in units of $\Gamma = \Gamma_L = \Gamma_{\rm R}$.

Compared with the results in Ref.[8], our results are quite different from them. At low temperatures, the ac conductance without phonons in Ref.[8] does have a peak pinned at ω=0.1meV, which is equal to 6Γ in our units. However, the ac conductance in Ref.[8] begins to rise as the frequency increases further, whereas in our case it steadily decreases to zero. The high-temperature ac conductances with and without phase-breaking process are of no difference in Ref.[8], while in our results the one without electron-phonon interaction is always larger than the one with electron-phonon.

It is important to emphasize that the assumption of the ac voltage in the dot region being zero will lead to nonconservation of the total current, even when the left and the right Fermi levels are equal. However, if the displacement current and the ac voltage in the dot region are restored, the total current will satisfy the current conservation and gauge invariance. In principle, for the time-dependent transport the displacement current should be taken into account. To include the displacement current, one has to consider the effects of the long-range Coulomb interaction. As a consequence, the ac conductance will be related to the parasitic capacitances of the dots to the contacts and is thus complex. The leading coefficient proportional to the ac field frequency which describes the displacement currents is called the emittance.[20] However, as Li has addressed, the displacement current does not contribute to the change of the electron number in the dot region but simply contributes a term such as $i\omega C$ to the ac conductance, where C is the effective capacitance of the device. Actually, the ac voltage in the dot region has to be determined self-consistently. This has been studied in detail by Büttiker *et al.*[12]

In summary, by including the electron–phonon interaction, the effect of phase-breaking process on ac transport of a coupled two-dot has been studied, and the results are compared with those in single quantum dot and resonant tunnelling device. Following Refs.[8], [9] and [16], the internal potential due to accumulation of ac charges in the two dots have been ignored for simplicity. The phase-breaking process is found to have a significant influence on the low-temperature ac conductance of the coupled double dot. At high temperatures, however, it has less effect and is only restricted to low frequency. We conclude that the electron tunnelling between the coupled double quantum dot plays an important role and contributes considerably to the ac current when the inter-dot coupling is much larger than the tunnelling coupling of the double dot with the electron reservoirs.

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