Tunneling current through a quantum dot with strong electron-phonon interaction

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The tunneling current through a quantum dot(QD) in the presence of local electron-phonon interaction (EPI) and intradot Coulomb repulsion is studied theoretically for arbitrary strength of EPI. It is found that the renormalization of the intradot Coulomb repulsion and QD level position leads to intriguing effects on the tunneling current. The interplay of Coulomb blockade and phonon-assisted tunneling processes gives rise to a rich variety of tunneling current behavior.

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I. INTRODUCTION

Transport properties of quantum dot nanostructures have been extensively studied both experimentally[1–5] and theoretically.[6–8] It was shown that electron-electron interaction in single electron transistors (SET) made of quantum dot tunneling junctions can lead to interesting effects such as the Kondo resonance, Coulomb blockade, and parity effect.[1–5] A SET is composed of two leads (reservoirs) and one or more quantum dots (QD's), which can be a normal metal, superconductor, ferromagnetic material, or semiconductor. The behavior of the tunneling current is sensitive to the properties of the QD's.

Today's advanced nanostructure techniques such as molecular-beam epitaxy and metal-organic chemical-vapor deposition coupled with *e*-beam lithography can provide a good control on the size and shape of semiconductor quantum dots. Quantum dots have potential application in optoelectronic devices, such as infrared detectors,[9,10] and semiconductor lasers.[11] In these optoelectronic devices the materials used are the III-V semiconductors such as GaInAs/GaAs, GaInP/GaP, and GaInN/GaN. The strength of the electron-phonon interaction (EPI) for longitudinal optical (LO) phonons in polar semiconductor QD's by itself is an interesting topic.[12–14] Recently, it was found that the electron-LO phonon interaction (ELOPI) in semiconductor quantum dots can be substantially enhanced due to the quantum confinement effect with an effective coupling strength exceeding 1.[12–14] For InGaN/GaN systems, the ELOPI is strong even in the bulk material (due to the strong polarity);[15,16] thus, we expect that the InGaN/GaN QD system to display very significant ELOPI effect on the tunneling current.

In this paper, we study the effect of ELOPI on the tunneling current of semiconductor QD's. In the heterostructures consisting of quantum wells the EPI on the tunneling current have been extensively studied by many authors.[17–21] Because of the small strength of EPI in quantum wells, the effect of EPI on the tunneling current was studied with a perturbative method. Only a few literatures discussed the tunneling current through QD's including the electron-phonon interaction.[22,23] In Ref. 22, Konig *et al.* have discussed the effect of EPI on the Kondo resonance in the limit of infinite intradot Coulomb repulsion. In the infinite U limit considered in Ref. 22, the effect from the renormalization of Coulomb potential on the tunneling current is missing. In Ref. 23 Li *et al.* have studied the differential conductance of QD with weak EPI and finite U by a perturbative method. Consequently their results show only one-phonon sideband and no significant effect from the Coulomb potential.

Here we study the tunneling current in the regime of finite intradot Coulomb potential and strong ELOPI. We find that the strong ELOPI not only significantly renormalizes the Coulomb repulsion (can make it negative), but also produces pronounced features in the tunneling current due to multiphonon-assisted tunneling. Our theoretical analysis provides a guide to future experimental studies on the tunneling current of QD systems with strong ELOPI, which can be used as an alternative means to evaluate the strength of ELOPI in QD's.

We start with the following Hamiltonian $H=H_0+H_1$. H_0 is the Hamiltonian of an electron in a SET system

$$H_0=\sum_{\mathbf{k},\sigma}\epsilon_{\mathbf{k}}C^{\dagger}_{\mathbf{k},\sigma}C_{\mathbf{k},\sigma}+\sum_{\mathbf{p},\sigma}\epsilon_{\mathbf{p}}C^{\dagger}_{\mathbf{p},\sigma}C_{\mathbf{p},\sigma}+\sum_{\mathbf{k},\sigma}V_{\mathbf{k}}C^{\dagger}_{\mathbf{k},\sigma}d_{\sigma}+\sum_{\mathbf{p},\sigma}V_{\mathbf{p}}C^{\dagger}_{\mathbf{p},\sigma}d_{\sigma}+\mathrm{H.c.}+\sum_{\sigma}E_0 d^{\dagger}_{\sigma}d_{\sigma}+Ud^{\dagger}_{\downarrow}d_{\downarrow}d^{\dagger}_{\uparrow}d_{\uparrow}, \tag{1}$$

where the first two terms describe the electron kinetic energies in the left lead (emitter) and right lead (collector), respectively, the third and fourth term describe the coupling between the QD and the two leads. Electrons in the two leads form a Fermi liquid and they are described by a free-electrons model. The last two terms describe the on-site energy and Coulomb repulsion for electrons in the QD. We only consider the ground state of the QD, because the energy difference between the ground state and the first excited state is much larger than the Coulomb charging energy U for small QD's

$$H_1=\omega_0 b^{\dagger}b+\lambda\sum_{\alpha}d^{\dagger}_{\alpha}d_{\alpha}(b^{\dagger}+b),$$

in which the first term describes a nondispersive longitudinal optical phonon with frequency ω_0 and the second term describes the interaction between the LO phonon and the electrons of the QD with coupling strength λ.

II. TUNNELING CURRENT

Using Keldysh's Green function,[24] Meir, Wingreen, and Lee[7] have proved that the tunneling current density is

$$J=\frac{2e}{h}\sum_{\alpha}\int d\omega[f_L(\omega-\mu_L)-f_R(\omega-\mu_R)]\times\frac{\Gamma_L(\omega)\Gamma_R(\omega)}{\Gamma_L(\omega)+\Gamma_R(\omega)}\mathrm{Im}G_{d\alpha}(\omega), \quad (2)$$

where $f_L(\omega-\mu_L)$ and $f_R(\omega-\mu_R)$ are the Fermi distribution function for the left lead and right lead, respectively. The chemical potential difference between these two leads is related to the applied bias (V) between leads and QD by $\mu_L-\mu_R=2V$. Throughout the paper, the bias is measured in units of eV instead of volts. Γ_L and Γ_R denote the tunneling rate from QD to the left lead and right lead, respectively. $G_{d\alpha}(\omega)$ denotes the retarded Green function for an electron in the QD with spin α. Because it is very difficult to fully include the tunneling rate as a function of energy and bias, we assume that these tunneling rates are energy and bias independent, even though $\Gamma_{L(R)}$ can be determined with a numerical method.[9]

Because we are interested in the case with strong strength of ELOPI ($g=\lambda/\omega_0$), a perturbative method will not work well. We introduce a unitary transformation[25]

$$S=\exp\left[-\frac{\lambda}{\omega_0}\sum_{\alpha} d^{\dagger}_{\alpha}d_{\alpha}(b^{\dagger}-b)\right] \quad (3)$$

and the transformed Hamiltonian can be written as

$$H'_0=\sum_{\mathbf{k},\sigma}\epsilon_{\mathbf{k}}C^{\dagger}_{\mathbf{k},\sigma}C_{\mathbf{k},\sigma}+\sum_{\mathbf{p},\sigma}\epsilon_{\mathbf{p}}C^{\dagger}_{p,\sigma}C_{\mathbf{p},\sigma}+U'd'^{\dagger}_{\downarrow}d'_{\downarrow}d'^{\dagger}_{\uparrow}d'_{\uparrow}+\sum_{\mathbf{k},\sigma}V_{\mathbf{k}}S_bC^{\dagger}_{\mathbf{k},\sigma}d'_{\sigma}+\sum_{\mathbf{p},\sigma}V_{\mathbf{p}}S_bC^{\dagger}_{\mathbf{p},\sigma}d'_{\sigma} \quad (4)$$

and $H'_1=\omega_0 b'^{\dagger}b'$, where the new operators are $d'_{\alpha}=d_{\alpha}e^{-(\lambda/\omega_0)(b^{\dagger}-b)}$, $b'=b-(\lambda/\omega_0)\Sigma_{\alpha}d^{\dagger}_{\alpha}d_{\alpha}$, and $S_b=e^{-(\lambda/\omega_0)(b^{\dagger}-b)}$.

Due to the electron-phonon interaction, the energy of the ground state in the QD and the Coulomb charging energy are renormalized to $E'_0=E_0-\lambda^2/\omega_0$ and $U'=U-2\lambda^2/\omega_0$. The hopping terms between the QD and the leads [the last two terms in Eq. (4)] are also renormalized by a factor S_b, which describes the fact that the electron hopping will be accompanied by a phonon cloud. Note that although the electron-phonon coupling term (H_1) is only included for the localized electron in the quantum dot, it leads to an effective phonon-mediated coupling between the localized electron and the lead electrons. Therefore, even though the electron-phonon scattering rate can be small or vanishing in QD's due to the phonon bottleneck effect (inability to satisfy the energy conservation between discrete QD levels),[26] it can still give rise to significant contribution to the phonon-assisted tunneling, since the energy conservation can be met by electron jumping between the QD and the leads.

In order to decouple the electrons from the phonon system, we replace S_b by its expectation value in the ground state at zero temperature, $\langle S_b\rangle=e^{-(1/2)(\lambda/\omega_0)^2}$. This procedure is valid when one is dealing with a localized polaron[27] as is our case here. In order to make the above approximation more transparent, we compare our derivation with the result of Ref. 28, which corresponds to our case with $U=0$. In Ref. 28 the exact Green function of a localized polaron coupled to a band is obtained, and it is shown that replacing S_b by $\langle S_b\rangle$ is a very good approximation when ω_0 is larger than the width of filled band in the leads.

We now calculate the Green function at zero temperature, $G_{d\alpha}(\omega)=\langle d_{\alpha};d^{\dagger}_{\alpha}\rangle_{\omega}$. Relating it to the correlation function of the new operators

$$\langle d_{\alpha};d^{\dagger}_{\alpha}\rangle_{\omega}=(\langle d'_{\alpha};d'^{\dagger}_{\alpha}\rangle\langle e^{-(\lambda/\omega_0)(b^{\dagger}-b)};e^{(\lambda/\omega_0)(b^{\dagger}-b)}\rangle)_{\omega}, \quad (5)$$

we obtain

$$G_{d\alpha}(\omega)=e^{-(\lambda/\omega_0)^2}\sum_n\left(\frac{\lambda}{\omega_0}\right)^{2n}\frac{1}{n!}[(1-\langle n_{d,\alpha}\rangle)\times G'_{d\alpha}(\omega-n\omega_0)+\langle n_{d,\alpha}\rangle G'_{d\alpha}(\omega+n\omega_0)], \quad (6)$$

where $G'_{d\alpha}(\omega)$ is the retarded Green function of a dressed electron (with a given spin α) described by the new Hamiltonian of Eq. (4), and the index n corresponds to the number of phonons involved. The Green function for the dressed electrons is

$$G'_{d\alpha}(\omega)=\left[\frac{1-\langle n_{d,-\alpha}\rangle}{\omega-\epsilon'_0+i\Gamma'}+\frac{\langle n_{d,-\alpha}\rangle}{\omega-\epsilon'_0-U'+i\Gamma'}\right], \quad (7)$$

where $\Gamma'(\omega)=e^{-(\lambda/\omega_0)^2}[\Gamma_L(\omega)+\Gamma_R(\omega)]$ and $\epsilon'_0=E'_0-\Lambda'(\omega)$. $\Lambda'(\omega)$ and $\Gamma'(\omega)$ are, respectively, the real and imaginary parts of the self-energy $(\langle S_b\rangle^2[\Sigma_k|V_k|^2/(\omega-\varepsilon_k)+\Sigma_p|V_p|^2/(\omega-\varepsilon_p)])$. For simplicity, we have ignored the frequency dependence of Λ' and Γ'. For the Kondo problem the self energy as a function of ω is important. However, we are only interested in the Coulomb blockade regime here, and this effect does not have qualitative change in the tunneling behavior. The derivation of Eq. (7) is based on the scheme described in Ref. 29.

The number of the electrons in the QD is solved in a self-consistent way

$$\langle n_{d,-\alpha}\rangle=\langle n_{d,\alpha}\rangle=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\Gamma'_L(\omega)f_L(\omega-\mu_L)+\Gamma'_R(\omega)f_R(\omega-\mu_R)}{\Gamma'_L(\omega)+\Gamma'_R(\omega)}\times\mathrm{Im}G'_{d\alpha}(\omega)d\omega. \quad (8)$$

In the absence of ELOPI, $G_{d\alpha}$ reduces to $G'_{d\alpha}$. When the Coulomb interaction is zero, $G_{d\alpha}$ in Eq. (6) becomes

$$G_{d\alpha}(\omega)=e^{-(\lambda/\omega_0)^2}\sum_n \left(\frac{\lambda}{\omega_0}\right)^{2n}\frac{1}{n!}\left[\frac{1-\langle n_{d,\alpha}\rangle}{\omega-\epsilon_0'-n\omega_0+i\Gamma'}+\frac{\langle n_{d,\alpha}\rangle}{\omega-\epsilon_0'+n\omega_0+i\Gamma'}\right]. \tag{9}$$

There are two types of poles in Eq. (9): $\omega=\epsilon_0'+n\omega_0$ and $\omega=\epsilon_0'-n\omega_0$. If $\langle n_{d,\alpha}\rangle=0$ (an empty QD), only the first type of poles contributes. This implies that electrons in the left lead with energies higher than ϵ_0' can enter the QD via the phonon-emission process. On the other hand, when $\langle n_{d,\alpha}\rangle=1$ (a singly occupied QD), only the second type of poles exist. This implies that an electron in the QD with energy ϵ_0' can leave the QD via the phonon-emission process. It is also easy to check that $\mathrm{Im}G_{d\alpha}(\omega)$ satisfies the following sum rule:

$$1=\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\mathrm{Im}G_{d\alpha}(\omega). \tag{10}$$

III. RESULTS

Substituting Eq. (6) into Eq. (2), we obtain the tunneling current $J=J^++J^-$ with

$$J^{\pm}=J_0e^{-(\lambda/\omega_0)^2}\sum_n\left(\frac{\lambda}{\omega_0}\right)^{2n}\frac{(\mathcal{N})^{\pm}}{n!}\{(1-\langle n_{d,-\alpha}\rangle)\times[F(V\pm n\omega_0)-F(-V\pm n\omega_0)]+\langle n_{d,-\alpha}\rangle\times[F(V\pm n\omega_0-U')-F(-V\pm n\omega_0-U')]\}, \tag{11}$$

where $J_0=(4e/h)(\Gamma_L\Gamma_R)/(\Gamma_L+\Gamma_R)$, $\mathcal{N}^+=\langle n_{d,\alpha}\rangle$, $\mathcal{N}^-=1-\langle n_{d,\alpha}\rangle$, $F(x)=\tan^{-1}(x+E_F-\epsilon_0'/\Gamma')-\tan^{-1}(x-\epsilon_0'/\Gamma')$, and

$$\langle n_{d,\alpha}\rangle=\frac{\Gamma_LF(V)+\Gamma_RF(-V)}{\pi\Gamma+\Gamma_L[F(V)-F(V-U')]+\Gamma_R[F(-V)-F(-V-U')]}.$$

Using Eq. (11), we show the tunneling current and differential conductance ($G_0=dJ/dV$) as a function of bias for various ELOPI strengths ($g=\lambda/\omega_0=0,0.3,0.5,0.6$) in Figs. 1 and 2 for a low filling (narrow band) case ($E_F\leqslant U$) and a high filling (wideband) case ($E_F>U$), respectively. The common parameters used in both Figs. 1 and 2 are (in units of ω_0) $E_0=2$, $\Gamma_L=\Gamma_R=0.02$, and $U=0.5$. In a typical QD, $U\sim e^2/\epsilon(0)D$, where $\epsilon(0)$ is the static dielectric constant

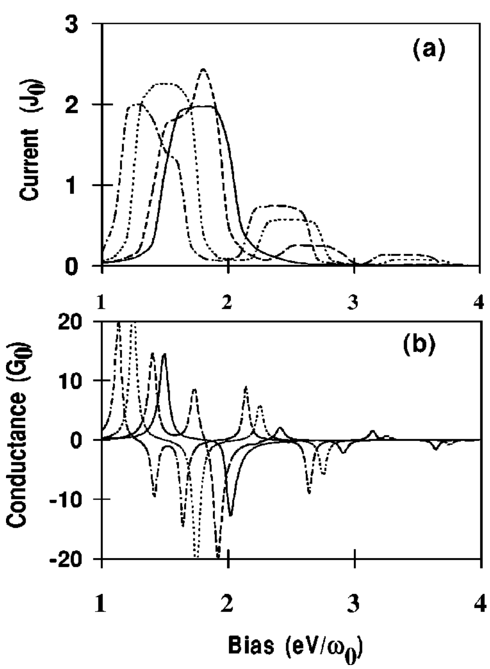

FIG. 1. Current density and differential conductance as a function of bias for different electron longitudinal optical phonon interactions shown by (a) and (b), respectively; $g=0$ (solid line), $g=0.3$ (dashed line), $g=0.5$ (dotted line), and $g=0.6$ (dash-dotted line), where $J_0=(4e/h)(\Gamma_L\Gamma_R)/(\Gamma_L+\Gamma_R)$ and $E_{FL}=E_{FR}=0.5$.

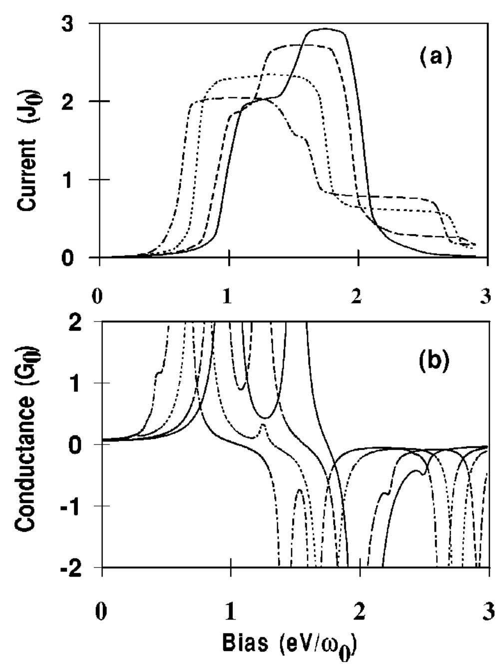

FIG. 2. Current density and differential conductance as a function of bias for different electron longitudinal optical phonon interactions shown by (a) and (b), respectively; $g=0.0$ (solid line), $g=0.3$ (dashed line), $g=0.5$ (dotted line), and $g=0.6$ (dash-dotted line), where $E_{FL}=E_{FR}=1$.

and D is the diameter of the QD. For InAs, $\epsilon(0)\sim 13$ and $\omega_0\sim 29$ meV, so $U=0.5\omega_0$ corresponds to a QD with diameter around 80 Å. Here we are in the regime of strong intradot Coulomb repulsion, since U is much larger than the tunneling strength Γ and the Coulomb blockade effect in the tunneling current will be prominent.

We first discuss Fig. 1, the narrow-band case (with $E_F=0.5$). For $g=0$ (solid line) the tunneling current has a simple one-bump structure. Its corresponding conductance curve shows a peak at a bias $V\sim 1.5\omega_0$ when the Fermi level is aligned with the QD level (E_0) and a negative peak at $V\sim 2.1\omega_0$ when the bottom of the band in the left lead is aligned with QD level. In this case, the *I-V* characteristic is similar to a double-barrier tunneling junction, and it does not display any ''Coulomb blockade'' behavior. This is because the width of the filled band in the lead is not large enough to have occupied band states aligned simultaneously with both the one-electron QD level (at E_0) and the two-electron QD level (at E_0+U). For $g=0.3$ (dashed line), we have $E_0'=1.91$ and $U'=0.32$. Note that U' is reduced (due to phonon renormalization) to a value less than the width of the filled band. This allows the ''Coulomb blockade'' effect to become apparent. As a result, the tunneling current displays a main structure of two bumps with the second bump occurred when the Fermi level passes the two-electron QD level (at $E_0'+U'$). The corresponding conductance curve shows two peaks at $V=E_0'-E_F$ and $V=E_0'+U'-E_F$ followed by a dip at $V=E_0'$. In addition, there is a secondary structure, which is caused by one-phonon-assisted tunneling process. For $g=0.5$ (dotted line), U' happens to be zero (due to the exact cancellation of U with the phonon renormalization term $2\lambda^2/\omega_0$). In this case the Coulomb blockade effect is eliminated. Thus, the tunneling current only displays a single bump with enhanced strength and a line shape similar to the $g=0$ case. Two secondary structures appear in the tunneling current curve at the high bias side. They are caused by the one-phonon- and two-phonon-assisted tunneling process, respectively. For $g=0.6$ (dash-dotted line), the phonon renormalization effect surpasses the Coulomb repulsion, and we have a negative U' situation (here $U'=-0.22$). The negative-U' effect leads to a two-bump structure in the tunneling current with an ''inverted'' line shape (as compared to the positive-U' case). This line shape is caused by a reduction in tunneling current when the one-electron QD level is nearly half filled (for a given spin component) and the two-electron QD level ($E_0'+U'$) is below the bottom of the band in the left lead [see Eq. (11)]. This occurs at $V=E_0'+U'\sim 1.42$, where the corresponding conductance curve shows a dip. The conductance curve for the negative-U' case is characterized by a peak at $V=E_0'-E_F$ followed by two dips at $V=E_0'+U'$ and $V=E_0'$. Again, the one-phonon- and two-phonon-assisted tunneling processes lead to additional secondary structures at the high bias side. Note that the band widths of the main bump and the secondary bumps are equal to the width of the filled band in the left lead. As expected, the strength of the secondary bumps increases with increasing strength of EPI.

The conductance curves shown in Fig. 1(b) display sharp positive and negative peaks, which mark precisely the onset (when the Fermi level is aligned with an allowed discrete level in QD) and ending (when the bottom of the band in the left lead is aligned with an allowed discrete level in QD) of each tunneling process. The tunneling process can be either a direct tunneling or phonon-assisted tunneling and the allowed discrete level can be either E_0' (one-electron level) or $E_0'+U'$ (two-electron level). Here for the narrow-band case, the phonon-assisted tunneling process is always of the first type (an electron in the left lead tunnel through a QD level while emitting phonons), and their peak positions are marked by $V=E_0'-E_F+n\omega_0$ or $V=E_0'+U'-E_F+n\omega_0$.

We now discuss Fig. 2, the wideband case with $E_F=1$. For $g=0$ (solid line), the tunneling current displays a typical ''Coulomb blockade'' behavior with a second plateau appearing at a bias greater than $(E_0-E_F)+U$. For $g=0.3$ (dashed curve), the main structure is similar in shape, but shifted to lower bias side due to the phonon renormalization term. For $g=0.5$ (dotted curve) (the $U'=0$ case), the tunneling current displays a single plateau in the main band (due to the absence of Coulomb blockade) followed by a sideband at higher bias side (due to the phonon-assisted tunneling). For $g=0.6$ (dash-dotted curve) (the negative-U' case), the tunneling current displays a two-plateau structure with ''inverted'' line shape (with a reduction in current when the bottom of the band in the left lead moves above the two-electron QD level) followed by the phonon side bands.

The phonon-assisted tunneling process for the wideband case can be either of type I or type II. This leads to some fine structures that can only be distinguished in the conductance plot as shown in Fig. 2(b). For example, with $g=0.5$ (dotted curve) there are small peaks at bias $V=0.25$ and $V=1.25$ due to the one-phonon- and two-phonon-emission processes of the second type (an electron tunnels from the QD to the right lead while emitting phonons) via the one-electron QD level (E_0'). Here the peak strength at $V=0.25$ (due to one-phonon emission) is smaller than that at $V=1.25$ (due to two-phonon emission). This is because the strength for the type-II phonon-assisted tunneling is proportional to $\langle n_{d,\alpha}\rangle$, which is very small at low bias ($V=0.25$). The small peak of dash-dotted line (for $g=0.6$) at $V=0.49$ is due to a type-II one-phonon-emission process via a two-electron QD level ($V=\omega_0+E_0'+U'-E_F$). The type-II phonon-emission processes become pronounced as the width of filled band in the leads increases, and it should be detectable for the heavy doping case.

Recently, the strength of ELOPI in QD's has been reported to be in the range 0.5–1.25,[12–14] which is strong enough to give rise to observable effect in the tunneling current. Here we consider the ELOPI to be ''strong'' when the phonon-induced renormalization in the Coulomb charging energy, $2\lambda^2/\omega_0$ is comparable to the bare intradot Coulomb repulsion U, i.e., $g\sim\sqrt{U/2\omega_0}$. These experimental results can be illuminated by the theory of Ipatova, Maslov, and Proshina.[30] In QD's ELOPI is given approximately by

$$g=\frac{\lambda}{\omega_0}=\alpha\frac{a_0}{R}=\frac{e^2}{2\hbar\omega_0}\left(\frac{2m^*\omega_0}{\hbar}\right)^{1/2}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_0}\right)\frac{a_0}{R},$$

where α is the Fröhlich parameter, a_0 is the radius of the polaron, and R is the radius of QD. The polaron effect becomes more pronounced as the dot size decreases. If $a_0/R \gg 1$, the enhancement of ELOPI is very large. If the strong-coupling criterion $g>0.5$ (for $U=0.5\omega_0$) is met, the probability of multiphonon assisted tunneling is large. Therefore, we expect that multiphonon sidebands can be observed experimentally, and their strength can be used to estimate the enhancement of ELOPI in QD's.

IV. CONCLUSION

In this paper we have theoretically studied the tunneling current through quantum dots in which the EPI and intradot Coulomb repulsion (U) are strong. Using a unitary transformation allows us to obtain the tunneling current for the arbitrary strength of EPI. The closed-form expression [Eq. (11)] provides a convenient tool to analyze the tunneling current including both Coulomb blockade and phonon-assisted effects. For small QD's the electron-phonon interaction can be enhanced substantially and our study shows that it will lead to pronounced sidebands in tunneling current caused by multiphonon emissions. Two types of phonon emission processes are identified. One corresponds to electrons from the left lead tunneling to the QD while emitting phonons; the other corresponds to electrons in the QD tunneling to the right lead while emitting phonons.

We have shown that the effective Coulomb repulsion U' can be reduced substantially due to EPI and it can even become negative for a strong EPI. We have also shown that for the narrow-band case the Coulomb blockade effect is not apparent without EPI, but the reduction of U' due to EPI can make the Coulomb blockade effect apparent. Furthermore, a negative U' due to strong EPI effect can lead to "inverted" line shape in the tunneling current. The renormalization of the Coulomb interaction due to electron-phonon interaction has been noted in Refs. 22 and 25, while Anderson was the first to point out the importance of negative U in amorphous semiconductors.[31] We note that the negative effective Coulomb interaction for electrons in QD's could lead to interesting collective phenomena such as the superconducting state or spontaneous magnetic ordering in two-dimensional quantum dot arrays,[32] where a narrow band is formed due to the weak interdot coupling.

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