RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 42, NUMBER 18 15 DECEMBER 1990-II

Polaron effects in one-dimensional lateral quantum wires and parabolic quantum dots

Marcos H. Degani
Departamento de Física e Ciência dos Materiais, Instituto de Física e Química de São Carlos, Universidade de São Paulo, 13560 São Carlos, São Paulo, Brazil

Gil A. Farias
Universidade Federal do Ceará, Departamento de Física-Campus do Pici, 60000 Fortaleza, Ceará, Brazil
(Received 20 August 1990)

The polaronic effects for electrons confined in one-dimensional lateral quantum wires and parabolic quantum dots are calculated taking into account both the electron–bulk-LO-phonon interaction and the electron–interface-phonon interaction. We find that the effects of the interface phonons are important and cannot be neglected in these systems. Our calculations suggest that the polaron effects on quantum dots are larger than on lateral quantum wires due to the weaker in-plane confinement in the latter.

In the last two decades our ability to control planar epitaxial growth of heterojunctions, quantum wells, and superlattices has revolutionized semiconductor and device physics. Quantum-wire and quantum-dot structures were successfully fabricated by use of lithographic techniques on a high-mobility two-dimensional (2D) electron-gas system, usually a GaAs-based device.[1] As a consequence of the possibility of their application in microelectronic devices, these systems have been the subject of theoretical and experimental research. The interaction of the electrons with longitudinal-optical (LO) phonons in quantum-well wires with different geometrical shapes has been investigated by various authors.[2–6] In these studies the phonons were assumed to be bulklike. However, this approximation is an oversimplification, as suggested by the experimental results of Klein,[7] who has used inelastic light scattering to study the confined phonons and interface modes.

Recently Constantinou and Ridley[8] have used a dispersive hydrodynamic continuum theory to describe the LO phonons and interface phonons in cylindrical quantum wires and in free-standing GaAs quantum wires. They found that the scattering rate is markedly reduced compared with the bulk value.

In this paper we calculate the polaronic effects for confined electrons in a one-dimensional lateral quantum wire and parabolic quantum dots, taking into account the interaction of both (i) the electron with the bulk LO phonons and (ii) the electron with the interface phonons. We show that the contribution of the interface phonons to the self-energy and to the effective mass is large, and that this interaction cannot be neglected. Our results suggest that the polaronic corrections for the parabolic quantum dots are larger than for the lateral quantum wires, since the confinement on the former is more effective.

We will assume that for the lateral quantum wires confinement in the y direction is parabolic. Self-consistent calculations indicated that this approximation is quite reasonable.[9] The electronic motion is also confined to the z direction due to the depletion layer which exist close to the interface of the heterojunction $Al_xGa_{1-x}As/GaAs$, and the motion is almost free in the x direction. For the case of the quantum dots we will consider an additional confinement in the x direction, which will also be parabolic.

Since the electron-phonon interaction is weak in these systems, in the sense that the Fröhlich constant is small ($\alpha \ll 1$), we will use second-order perturbation theory to obtain the polaron corrections on the self-energy and the effective mass using the electron-phonon interaction potentials defined in Ref. 10. Since the electron motion is strongly confined to the z direction we will take the extreme quantum limit by considering only the ground-state subband for this potential well. We will then find the following contributions to the self-energy of the nth energy level for the bulk LO phonons (ΔE^B), and for the interface phonons (Δe^I)

$$\Delta E^B_{n0} = -\frac{2\alpha_B}{\pi}\hbar\omega_L \sum_m \int_0^\infty dq_x \frac{F^B_{mn0}(q_x)}{D^B_{nm}(q_x)}, \tag{1}$$

$$\Delta E^I_{n0} = -\sum_{m,\lambda}\frac{2\alpha_\lambda}{\pi}\hbar\omega_\lambda \int_0^\infty dq_x \frac{F^I_{mn0}(q_x)}{D^I_{nm}(q_x)}, \tag{2}$$

where the bulk form factor $F(q_x)$ for the lateral quantum wire is given by

$$F^B_{nm0}(q) = \int_0^\infty d\tau \frac{|G_{nm}(\tau)|^2}{(\tau^2+q^2)^{1/2}}[H_1(q,\tau)-H_2(q,\tau)], \tag{3}$$

with

$$G_{nm}(\tau) = \int_{-\infty}^{+\infty} dy\, \Phi^*_n(y) e^{i\tau y}\Phi_m(y), \tag{4}$$

and

$$H_1(q,\tau) = \int_0^\infty dz|\xi(z)|^2 \int_0^\infty dz'|\xi(z')|^2 \times \exp(-\sqrt{\tau^2+q^2}|z-z'|), \tag{5}$$

and

$$H_2(q,\tau) = \left[\int_0^\infty dz|\xi(z)|^2 \exp(-z\sqrt{\tau^2+q^2})\right]^2, \tag{6}$$

 © 1990 The American Physical Society

and the interface form factor is

$$F^I_{nm0}(q)=\int_0^\infty d\tau \frac{|G_{nm}(\tau)|^2}{(\tau^2+q^2)^{1/2}} H_2(q,\tau)\,, \tag{7}$$

where

$$\xi(z)=(\delta^3/2)^{1/2} z\, e^{-\delta z/2}\,,$$

$$\Phi_n(y)=(a_0^2/\pi)^{1/4}\exp(-y^2/2a_0^2)2^{-n/2}/\sqrt{n!}\,\mathcal{H}_n(y/a_0)\,,$$

$\mathcal{H}_n(x)$ is the nth-degree Hermite polynomial, $a_0=(\hbar/m^*\omega_0)^{1/2}$, m^* is the band effective mass, and ω_0 is the frequency corresponding to the parabolic potential. The functions $D_{nm}(q_x)$ which appear in Eqs. (1) and (2) are given by

$$D^B_{nm}(q_x)=(n-m)\frac{\omega_0}{\omega_L}+1+q_x^2 \tag{8}$$

and

$$D^I_{nm}(q_x)=(n-m)\frac{\omega_0}{\omega_\lambda}+1+q_x^2\,. \tag{9}$$

There is an additional potential confinement for quantum dots in the x direction, which we will also consider to be parabolic. The energy shift for these systems can be calculated using Eq. (1), by changing the function G_{nm}, Eq. (4), to

$$G_{nm}(\tau)=\int_{-\infty}^{+\infty} dx\,\Phi^*_{n_x}(x)e^{i\tau x}\Phi_{m_x}(x) \times\int_{-\infty}^{+\infty} dy\,\Phi^*_{n_y}(y)e^{i\tau y}\Phi_{m_y}(y)\,, \tag{10}$$

where n and m must now be read as $n=(n_x,n_y)$ and $m=(m_x,m_y)$, and the functions D_{nm} in Eqs. (1) and (2) have to be taken with argument zero ($q_x=0$). In the expressions above, ω_L is the bulk-LO-phonon frequency of GaAs, ω_λ is the interface-phonon frequency, and α_B and α_λ are the usual Fröhlich coupling constant and the interface-coupling constant, respectively.

The polaronic corrections to the effective mass for the lateral quantum wire have contributions from the electron-bulk-LO-phonon interaction (ΔM^B), and from the electron-interface-phonon interaction (ΔM^I) which are given by

$$\Delta M^B_{n0}=\frac{8\alpha_B}{\pi}\sum_m\int_0^\infty dq_x \frac{q_x^2 F^B_{mn0}(q_x)}{[D^B_{nm}(q_x)]^3}\,, \tag{11}$$

$$\Delta M^I_{n0}=\sum_{m,\lambda}\frac{8\alpha_\lambda}{\pi}\int_0^\infty dq_x \frac{q_x^2 F^I_{mn0}(q_x)}{[D^I_{nm}(q_x)]^3}\,. \tag{12}$$

In order to calculate the interface phonons we have assumed, for simplicity, that the concentration x of Al is equal to one. The numerical values used for the interface, bulk-LO-phonon frequencies and coupling constants for the electron-phonon interaction are given in Table I.

We show in Fig. 1 a plot of the energy shift due to the polaronic effects on the ground state ($n=0$) of an electron inside a lateral quantum wire as a function of the confinement in the y direction (a_0), for three values of the confinement in the z direction ($z_0=3/\delta$). As can be seen in this figure, the polaron effects increase when the lateral length in the y or z directions of the system decreases. We also observe that the total interface contribution to the ground state is of the same order of magnitude as the bulk contribution, and consequently the electron-interface-phonon interaction cannot be neglected.

TABLE I. The parameters used in the calculations: frequencies of the bulk LO phonons and interface phonons (in meV), and the coupling constants for the electron-phonon interaction.

ω_L	ω_{I+}	ω_{I-}	α_B	α_{I+}	α_{I-}
36.25	47.54	34.75	0.069	0.050	0.032

The energy shift due to the polaron correction of the ground state ($n_x=n_y=0$) of an electron confined in a parabolic quantum dot as a function of the in-plane confinement (a_0) for three values of the confinement in the z direction is plotted in Fig. 2. We found that the energy shift in quantum dots is larger than in lateral quantum wires since the confinement is enhanced. For quantum dots as for lateral quantum wires, if the in-plane effective confinement length is smaller than the effective confinement length in the z direction ($a_0<z_0$), we find that the bulk contribution (ΔE^B) is larger than the two contributions (ΔE^{I+} and ΔE^{I-}) from the interface.

For an electron in the lowest energy level ($n=0$) of a

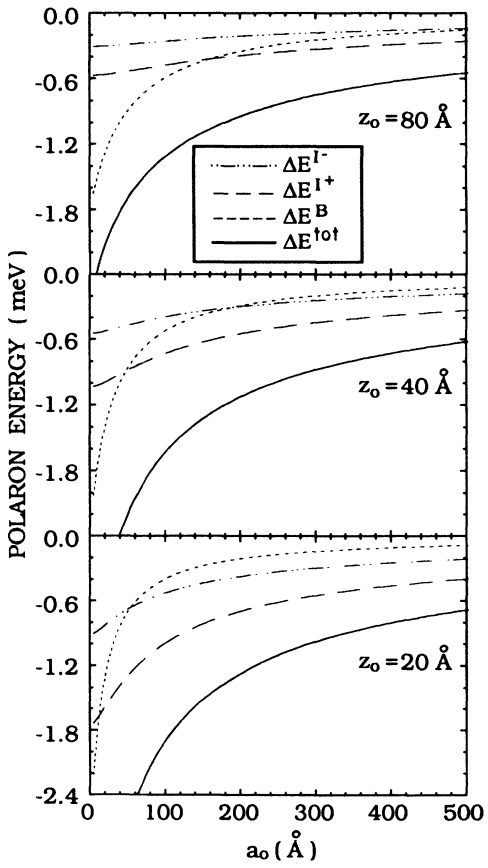

FIG. 1. Polaron energy shift on the ground state of a lateral quantum wire as a function of the confinement length $a_0=(\hbar/m^*\omega_0)^{1/2}$ for three different values of $z_0(=3/\delta)$.

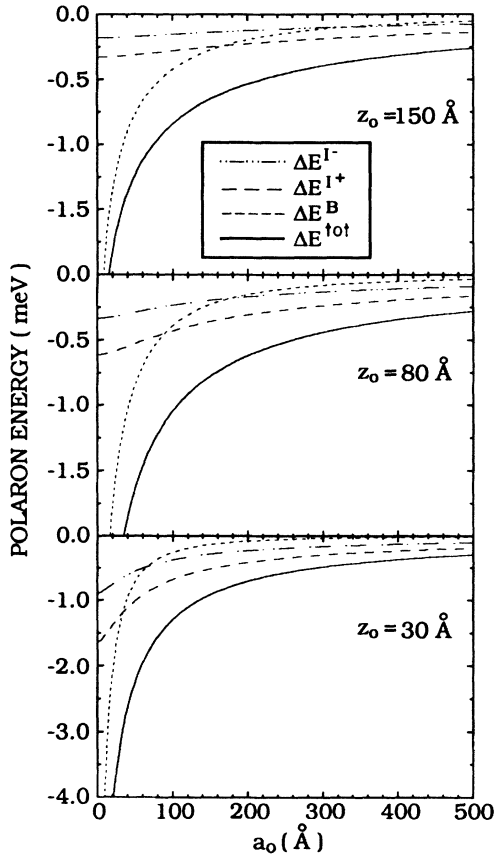

FIG. 2. Polaron energy shift on the ground state of a parabolic quantum dot as a function of the confinement length $a_0=(\hbar/m^*\omega_0)^{1/2}$ for three different values of $z_0(=3/\delta)$.

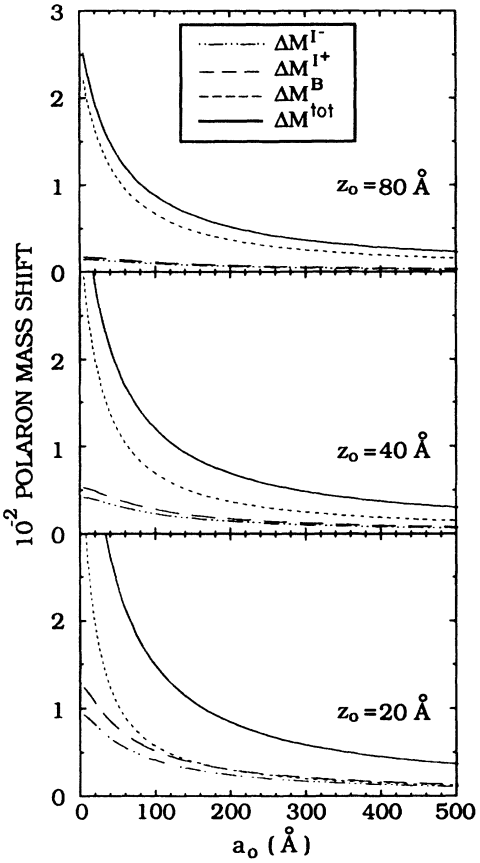

FIG. 3. Polaron mass correction for a lateral quantum wire as a function of the confinement length $a_0=(\hbar/m^*\omega_0)^{1/2}$ for three different values of $z_0(=3/\delta)$.

lateral quantum wire, the change in the effective mass due to the polaron effects as a function of the effective confinement length a_0 for three different values of z_0 is presented in Fig. 3. The interface contribution to the effective mass is more pronounced for large effective confinement in both directions.

In conclusion, we have calculated the polaron energy shift and the effective-mass correction in lateral quantum wires and parabolic quantum dots taking into account both the electron-interface-phonon interaction and the electron-bulk-LO-phonon interaction. We find that both energy and polaron mass increase with the enhancement of the effective confinement. It is important to stress that the effect of the electron-interface-phonon interaction plays an important role in these systems and cannot be neglected.

M.H.D. would like to acknowledge support by Fundação de Amparo à Pesquisa do Estado de São Paulo and G.A.F. would like to acknowledge support by Coordenação de Aperfeiçoamento de Pessoal do Ensino Superior, Fulbright and Financiadora de Estudos e Projetos, Brazil.

[1]K. Kash, J. Lumin. **46**, 69 (1990).

[2]J. P. Leburton, J. Appl. Phys. **56**, 2850 (1984).

[3]M. H. Degani and O. Hipólito, Solid State Commun. **65**, 1185 (1988).

[4]M. H. Degani and O. Hipólito, Superlattices Microstruct. **5**, 137 (1989).

[5]N. C. Constantinou and B. K. Ridley, J. Phys. Condens. Matter. **1**, 2283 (1989).

[6]M. H. Degani, Phys. Rev. B **40**, 11937 (1989).

[7]M. V. Klein, IEEE J. Quantum Electron. **QE-22**, 1760 (1986).

[8]N. C. Constantinou and B. K. Ridley, Phys. Rev. B **41**, 10622 (1990); **41**, 10627 (1990).

[9]S. E. Laux, D. J. Frank, and F. Stern, Surf. Sci. **196**, 101 (1988).

[10]M. H. Degani and G. A. Farias, Phys. Rev. B **41**, 3572 (1990).