

Effects of interfacial charges on semiconductor films

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The electron-phonon coupling and the confined electron binding energy in a semiconductor film with a charge density at both surfaces is investigated. Maxwell equations are solved with appropriate boundary conditions to calculate the dispersion relation of bulk longitudinal-optical (LO) and surface-optical (SO) phonons. The Hamiltonian that describes the electron-phonon interaction is obtained through a quantum treatment, and a perturbation theory up to the second order is used to calculate the ground-state energy of confined polarons. Numerical results are obtained for the dispersion relation, the electron-phonon coupling function, and the ground-state energy of polarons in GaAs films. It is shown that the charged interfaces do not change the volume modes of a GaAs film, but alter significantly its surface modes. The dispersion relation of SO phonons, the electron-phonon coupling function, and the ground-state energy of the polaron depend on the surface charge density, as well as on the film thickness. [S0163-1829(98)03219-6]

I. INTRODUCTION

The interaction between electrons and elementary excitations in the neighborhood of a surface is a matter of relevance to the development of technological applications. There has been great interest in the investigation of the properties of electrons close to a surface or confined in a thin film,¹⁻⁸ where the electron-surface interaction is very important. The coupling electron-interface modes in quantum wells and superlattices have attracted considerable attention recently due to its relevance to the properties of semiconductor heterostructures, which are important for device applications.⁹⁻¹⁴ The interaction between an electron and the optical polarization in homogeneous crystal films have been studied by Lucas, Kartheuser, and Badro¹⁵ and Licari and Evrard.¹⁶ In these works, the interaction between the electron and longitudinal-optical (LO) and surface-optical (SO) phonons was calculated including electronic polarization effects due to ionic motion. Starting from a classical approach and considering a quantum-mechanical treatment, Wendler¹⁷ has calculated the interaction operator for an electron in a dielectric bilayer system. Using these results, the ground and the first excited state of a polaron confined in a film of a polar crystal has been calculated by Liang, Gu, and Lin.² Considering multilayer finite heterostructures, Pokatilov¹⁸ and Shi, Pan, and Liu¹⁹ have studied the interaction of an electron with bulk (LO) and surface (SO) phonons in three- and four-layer heterostructures, respectively. More recently, the binding energy and effective mass of a polaron in a GaAs/Al_xGa_{1-x}As quantum well structure has been studied by Hai, Peeters, and Devreese.²⁰ In all these works, the electron confinement produces significative changes on the scattering rates and on the polaron energy due to the electron-surface optical modes interaction.

The presence of a surface charge density at the interfaces of a thin film causes a considerable effect on the dispersion relation of surface-optical phonons.^{21,22} Consequently, it is expected that it should also change significantly the interaction between an electron and the surface modes, as well as

the binding energy of confined polarons in thin semiconductor films. In the present paper, we study the effect of a two-dimensional (2D) surface charge density on a polaron confined in a thin polar semiconductor film.

The paper is organized as follows. In Sec. II, we calculate the dispersion relation of bulk LO and SO phonons. Using these results we derive in Sec. III the surface electron-phonon coupling and the Hamiltonian that describes the polaron confined in a film with the presence of a charge density at the interfaces. In Sec. IV, we obtain the ground-state energy of the polaron up to the second-order perturbation theory. Numerical results for the dispersion relation of the SO modes, the electron-phonon coupling function, and the ground-state energy in GaAs films with different thickness and surface charge densities are shown in Sec. V. Finally, we present our concluding remarks in Sec. VI.

II. DISPERSION RELATION

The system we consider is a polar semiconductor film, which is infinite in the x - y plane and has plane interfaces placed at $z = \pm a$. The semiconductor film is characterized by a dielectric constant $\epsilon(\omega)$ and it is immersed in vacuum. We assume that the effective-mass approximation is valid for an electron inside the film and that the potential barrier at the interfaces is infinite. We consider the existence of a surface charge at both interfaces with the same density.

In order to calculate the dispersion relation of SO phonons, we use the boundary conditions at the interfaces $z = \pm a$ and consider the existence of an equal charge density at both interfaces, which is represented by a 2D current density given by²²

$$\sigma = i \frac{n_s e^2}{m_s \omega^2}, \quad (1)$$

where $n_s(m_s)$ is the charge density (mass) of the 2D carriers at the interfaces. Thus, imposing the continuity of the component $E_{\parallel}^{\nu}(q_{\parallel}, z)$ and considering the discontinuity of the

component $E_z^s(q_{\parallel}, z)$ at $z = \pm a$, where \mathbf{q}_{\parallel} is a wave vector in the x - y plane, we obtain the dispersion relation of the SO phonons:

$$(\epsilon + F)\mp(\epsilon - F)e^{-2q_{\parallel}a} = 0, \quad (2)$$

with

$$F = \left(1 - \frac{q_{\parallel}n_s e^2}{m_s w^2 \epsilon_o}\right). \quad (3)$$

The term F in Eq. (3) contains the correction in the surface modes dispersion relation due to the presence of the charge density at the interfaces. Now, using in Eq. (2) the dielectric constant in the Lyddane-Saches-Teller format,^{23,24} we obtain the two frequency modes (a lower mode $w_{\text{SO}-}$ and an upper mode $w_{\text{SO}+}$) for the SO phonons:

$$w_{\text{SO}\pm}^2 = \frac{(w_{\sigma=0\pm}^2 + C_{\pm}) + \sqrt{(w_{\sigma=0\pm}^2 + C_{\pm})^2 - 4w_{\text{TO}}^2 C_{\pm}}}{2}, \quad (4)$$

where

$$C_{\pm} = \frac{q_{\parallel}n_s e^2}{\epsilon_o m_s} \frac{1 \pm e^{-2q_{\parallel}a}}{(\epsilon_{\infty} + \epsilon) \pm (\epsilon_{\infty} - \epsilon)e^{-2q_{\parallel}a}}, \quad (5)$$

and

$$w_{\sigma=0\pm}^2 = w_{\text{TO}}^2 \frac{(\epsilon_s + 1)\mp(\epsilon_s - 1)e^{-2q_{\parallel}a}}{(\epsilon_{\infty} + 1)\mp(\epsilon_{\infty} - 1)e^{-2q_{\parallel}a}}, \quad (6)$$

being w_{TO} the TO-phonon frequency, and $\epsilon_s(\epsilon_{\infty})$ the static (optical) dielectric constant of the semiconductor. Equation (6) is the well-known SO-phonon dispersion relation in a film without the presence of a charge density at the interfaces.¹⁶ The term C_{\pm} in Eq. (4) includes the contribution of the surface charge density to the SO-phonon modes. We observe that when $q_{\parallel} \rightarrow 0$, $C_{\pm} \rightarrow 0$ we have $w_{\text{SO}\pm} \rightarrow w_{\sigma=0\pm}$, showing that for small values of the wave vector the charge density at the interfaces has no influence on the dispersion relation. When $\sigma \rightarrow 0$ Eq. (4) also reproduces the dispersion relation obtained by Licari.¹⁶

III. ELECTRON-PHONON COUPLING AND THE HAMILTONIAN

To obtain the electron-surface-optical-phonon interaction, we have first to calculate the components of the electric field for each mode. Using the boundary conditions of the electric field at the interfaces $z = \pm a$, their components can be written as

$$E_{\parallel\pm}^s(q_{\parallel}, z) = iC^s \begin{cases} e^{-q_{\parallel}(z-a)} & ; \quad z > a, \\ \begin{cases} \cosh(q_{\parallel}z)\cosh(q_{\parallel}a) & \text{branch}(+) \\ \sinh(q_{\parallel}z)/\sinh(q_{\parallel}a) & \text{branch}(-) \end{cases} & ; \quad a > z > -a, \\ \pm e^{q_{\parallel}(z+a)} & ; \quad -a > z, \end{cases} \quad (7)$$

and

$$E_{z\pm}^s(q_{\parallel}, z) = C^s \begin{cases} -e^{-q_{\parallel}(z-a)} & ; \quad z > a, \\ \begin{cases} \sinh(q_{\parallel}z)/\cosh(q_{\parallel}a) & \text{branch}(+) \\ \cosh(q_{\parallel}z)/\sinh(q_{\parallel}a) & \text{branch}(-) \end{cases} & ; \quad a > z > -a, \\ \pm e^{q_{\parallel}(z+a)} & ; \quad -a > z, \end{cases} \quad (8)$$

where C^s represents the normalization constant that can be obtained through the following normalization condition for the polarization field:¹⁷

$$\sum_{\beta} \int_{-a}^a dz \frac{\Theta^{1/2}(w_i)\Theta^{1/2}(w_j)}{w_{pn}^2} P_{\beta}^{i*}(q_{\parallel}z)P_{\beta}^j(q_{\parallel}z) = \delta_{ij}, \quad (9)$$

where

$$\Theta^{1/2}(w) = \frac{3\epsilon_{\infty}}{\epsilon_{\infty} + 2} \left(\frac{w_{\text{LO}}^2 - w_{\text{TO}}^2}{\epsilon_{\infty}(w_{\text{LO}}^2 - w^2) - (w_{\text{TO}}^2 - w^2)} \right), \quad (10)$$

with

$$P(q_{\parallel}, z) = \epsilon_o \chi(w) E(q_{\parallel}, z), \quad (11)$$

and $\chi(w) = \epsilon(w) - 1$. The normalization constant for both modes is calculated using Eq. (9) in Eqs. (7) and (8), and is given by

$$|C^s|^{\pm} = \frac{1}{\epsilon_o |\chi_{\pm}|} [w_{\text{TO}}(\epsilon_s - \epsilon_{\infty})]^{1/2} w_{\text{TO}}^{1/2} \Xi_{\pm} \times \frac{1}{f_{\mp}(q_{\parallel}a)} \sqrt{q_{\parallel} f_{-}(2q_{\parallel}a)}, \quad (12)$$

where

$$\chi_{\pm} = \frac{\epsilon_s - 1 - (\epsilon_{\infty} - 1)w_{\text{SO}\pm}^2/w_{\text{TO}}^2}{1 - w_{\text{SO}\pm}^2/w_{\text{TO}}^2} \quad (13)$$

and

$$\Xi_{\pm} = \frac{1}{2\epsilon_{\infty}} \left(\frac{\epsilon_{\infty}(w_{\text{LO}}^2 - w_{\text{SO}\pm}^2) - (w_{\text{TO}}^2 - w_{\text{SO}\pm}^2)}{w_{\text{LO}}^2 - w_{\text{TO}}^2} \right), \quad (14)$$

with $f_+(x) = \cosh(x)$ and $f_-(x) = \sinh(x)$.

With the electric field calculated we can now obtain, for the system under consideration, the term in the Hamiltonian that describes the electron-phonon interaction. To do this, we use the fact that the second quantized electron-phonon interaction Hamiltonian can be written as

$$H_{e\text{-ph}} = \sum_{\mathbf{q}_{\parallel}} \sum_i e^{i\mathbf{q}_{\parallel} \cdot \mathbf{x}_e} \Gamma_i(\mathbf{q}_{\parallel}, z) [\hat{a}_i(\mathbf{q}_{\parallel}) + \hat{a}_i^{\dagger}(-\mathbf{q}_{\parallel})], \quad (15)$$

where $\hat{a}_i(\mathbf{q}_{\parallel})[\hat{a}_i^{\dagger}(-\mathbf{q}_{\parallel})]$ is the annihilation (creation) operator associated with the i th mode, and Γ_i is the electron-phonon coupling function,¹⁷

$$\Gamma_i(\mathbf{q}_{\parallel}, z) = - \left(\frac{\hbar \epsilon_o e^2}{2A w_i(q_{\parallel})} \right)^{1/2} \frac{i}{q_{\parallel}} E_{\parallel}^i(\mathbf{q}_{\parallel}, z), \quad (16)$$

with E_{\parallel} given by Eq. (7).

Using Eqs. (7) and (12), the coupling function $\Gamma_i(\mathbf{q}_{\parallel}, z)$ between the electron and the SO-phonon modes is straightforwardly obtained,¹⁷ and is given by

$$\Gamma_{\pm}(\mathbf{q}_{\parallel}, z) = \left[\frac{e^2 \hbar w_{\text{TO}} (\epsilon_s - \epsilon_{\infty})}{2A \epsilon_o} \right]^{1/2} \left(\frac{f_{\pm}(2q_{\parallel}a)}{q_{\parallel}} \right)^{1/2} G_{\pm}, \quad (17)$$

with

$$G_{\pm} = \left(\frac{\Xi_{\pm}}{\chi_{\pm} f_{\mp}(q_{\parallel}a)} \right) \left(\frac{w_{\text{TO}}}{w_{\text{SO}\pm}} \right)^{1/2} \frac{f_{\pm}(q_{\parallel}z)}{f_{\pm}(q_{\parallel}a)}. \quad (18)$$

Considering $\sigma=0$ in Eq. (1), i.e., no charge at the interfaces, the coupling function [Eq. (16)] is reduced to the one obtained by Licari and Evrard.¹⁶

The Hamiltonian of the system under consideration contains four terms:

$$H = H_e + H_{\text{ph}} + H_{e\text{-LO}} + H_{e\text{-SO}}. \quad (19)$$

The first and the second terms correspond to the electron in the rigid lattice of the film and phonons, respectively. The one associated with the electron in the film is given by

$$H_e = - \frac{\hbar^2}{2m^*} \nabla^2 + V_b; \quad |z| < a, \quad (20)$$

where m^* is the electron effective mass and V_b is parameter related to the height of the barrier at the interfaces, which will be considered infinite. The phonon Hamiltonian H_p is constituted of two terms, \hat{H}_{LO} and \hat{H}_{SO} :

$$\hat{H}_{\text{LO}} = \sum_i \sum_{q_{\text{LO}}} \hbar w_{\text{LO}} [\hat{a}_{pi}^{\dagger}(q_{\text{LO}}) \hat{a}_{pi}(q_{\text{LO}}) + \frac{1}{2}], \quad (21)$$

for the bulk LO phonons and

$$\hat{H}_{\text{SO}} = \sum_i \sum_{q_{\parallel}} \hbar w_{\text{SO}i}(\mathbf{q}_{\parallel}) [\hat{b}_{pi}^{\dagger}(\mathbf{q}_{\parallel}) \hat{b}_{pi}(\mathbf{q}_{\parallel}) + \frac{1}{2}], \quad (22)$$

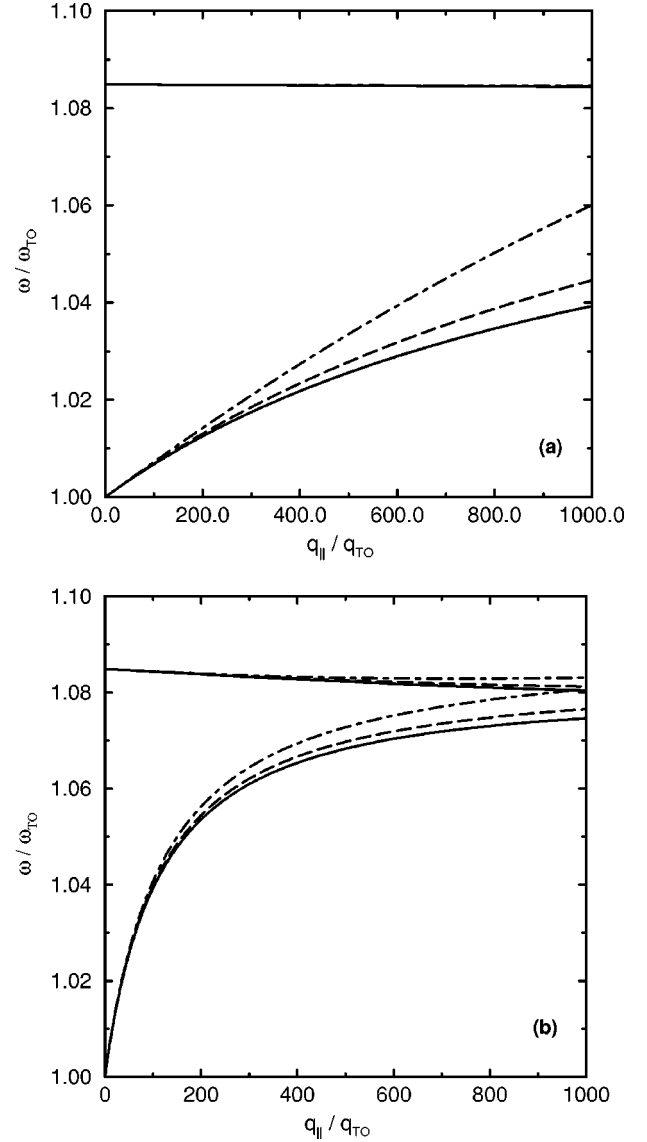


FIG. 1. Dispersion relation of SO phonons in a GaAs film as a function of the wave vector q_{\parallel} , for film thickness of (a) 10 and (b) 100 GaAs ML. The frequencies and wave vectors are normalized by the frequencies and wave vectors of the TO phonons, respectively. The solid curve is the dispersion relation calculated in the absence of a charge density, while the dashed and dotted-dashed curves correspond to a density $n_s = 1.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^9 \text{ cm}^{-2}$, respectively.

for the SO phonons, where w_{LO} is the bulk longitudinal optical frequency, $w_{\text{SO}\pm}(\mathbf{q}_{\parallel})$ is the surface optical frequency given by Eq. (4), $\hat{a}_i(\mathbf{q}_{\parallel})$, $\hat{b}_{pi}(\mathbf{q}_{\parallel})$ and $\hat{a}_i^{\dagger}(-\mathbf{q}_{\parallel})$, $\hat{b}_{pi}^{\dagger}(\mathbf{q}_{\parallel})$ are annihilation and creation phonon operator for bulk and surface states, respectively, with i referring to the sum in different modes.

The third term in Eq. (19), $H_{e\text{-LO}}$, is associated with the Hamiltonian of the electron-bulk longitudinal-optical (LO) phonon. Since a surface charge density does not change the bulk modes, it is well known as is given by Licari and Evrard¹⁶

Finally, using Eqs. (7), (15), (16), (17), and (18), the Hamiltonian that describes the electron-SO-phonon interaction can be written formally as

$$H_{e\text{-SO}} = \left[\frac{e^2 \hbar w_{\text{TO}} (\epsilon_s - \epsilon_\infty)}{2 \epsilon_0 A} \right]^{1/2} \sum_{q_{\parallel}} e^{i \mathbf{q}_{\parallel} \cdot \mathbf{x}_c} \left(\frac{f_{\pm}(2q_{\parallel} a)}{q_{\parallel}} \right)^{1/2} \\ \times \{ G_+(\hat{b}_i(\mathbf{q}_{\parallel}) + \hat{b}_i^\dagger(-\mathbf{q}_{\parallel})) + G_-(\hat{b}_i(\mathbf{q}_{\parallel}) + \hat{b}_i^\dagger(-\mathbf{q}_{\parallel})) \}. \quad (23)$$

Considering $\sigma = 0$ (no charge at the interfaces), it is easy to show that the Hamiltonian associated with the electron SO phonons, Eq. (23) is reduced to that one obtained by Licari and Evrard.¹⁶

IV. GROUND-STATE ENERGY

Since the film on which the electron is confined is a semiconductor with a weak electron-phonon interaction, we can use perturbation theory to obtain the ground-state energy of

the polaron, which is given by

$$\Delta E = - \sum_{n', q_i} \frac{|\langle n, 0 | H_{\text{int}} | n', q_i \rangle|^2}{E_{n' q_i} - E_{n 0}}, \quad (24)$$

where H_{int} represents the perturbation term in the Hamiltonian given by Eq. (19) ($H_{e\text{-LO}}$ or $H_{e\text{-SO}}$), and q_i is the momentum of the LO and SO phonons, respectively.

In order to calculate the ground-state energy of the polaron, we follow the procedure used by Liang, Gu, and Lin.² Through a straightforward calculation, the second-order correction to the polaron energy is obtained as

$$\Delta E = \Delta E_{q\text{LO}+} + \Delta E_{q\text{LO}-} + \Delta E_{q\text{SO}+} + \Delta E_{q\text{SO}-}, \quad (25)$$

with

$$\Delta E_{q\text{LO}\pm} = - \alpha \hbar w_{\text{LO}} \frac{8 N a \kappa_L n^2}{\pi^4} \sum_{m, n'} \frac{\{ [(n' + m)^2 - n^2]^{-1} - [(n' - m)^2 - n^2]^{-1} \}^2}{[m^2 + n^2 - n'^2 - \kappa_L^2 (N a / \pi)^2]} \ln \left[\frac{m^2}{n'^2 - n^2 + (\kappa_L N a / \pi)^2} \right], \quad (26)$$

where κ_L is the wave vector defined as $\hbar^2 \kappa_L^2 / 2m^* = \hbar w_{\text{LO}}$, $m = 1, 3, 5, \dots$, $(n' - n) = \pm 0, \pm 2, \pm 4, \dots$ for $E_{q\text{LO}+}$, and $m = 2, 4, 6, \dots$, $(n' - n) = \pm 1, \pm 3, \pm 5, \dots$ for $E_{q\text{LO}-}$, and

$$\Delta E_{q\text{SO}\pm} = - \alpha \hbar w_{\text{LO}} 8 N a \kappa_L (\epsilon_s \epsilon_\infty^3)^{1/2} \sum_{n'} \int_0^\infty dx \sinh(x) \\ \times \left[\left(\frac{\Xi_\pm}{\chi_\pm \sinh(x/2)} \right) \left(\frac{w_{\text{TO}}}{w_\pm} \right)^{1/2} \tanh(x/2) \right]^2 \\ \times \left\{ \left[\frac{x}{x^2 + [(n - n') \pi]^2} \right] - \left[\frac{x}{x^2 + [(n + n') \pi]^2} \right] \right\}^2 \\ \times [x^2 + (\kappa_{S\pm} N a)^2 + \pi^2 (n'^2 - n^2)]^{-1}, \quad (27)$$

with $(n - n') = 0, \pm 2, \pm 4, \dots$ for $E_{q\text{SO}+}$ and $(n - n') = \pm 1, \pm 3, \pm 5, \dots$ for $E_{q\text{SO}-}$, N is the number of monolayers of the film, and $\kappa_{S\pm}$ are the wave vectors defined as $\hbar^2 \kappa_{S\pm}^2 / 2m^* = \hbar w_{\text{SO}\pm}$, and in these equations we have defined the coupling constant,

$$\alpha = \frac{m^* e^2}{\hbar^2 \kappa_L} \left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_0} \right). \quad (28)$$

V. NUMERICAL RESULTS

The analytical results displayed in the previous section can be used in any system provided it presents a weak electron-phonon coupling. In order to obtain numerical results, we have chosen a GaAs film² to illustrate the effects on the polaronic corrections due to the presence of a (2D) surface charge. To present the results, initially we plot in Fig. 1 the dispersion relation of SO phonons as a function of the wave vector q_{\parallel} , for a film of $N = 10$ and 100 GaAs ML. The

solid curve is the dispersion calculated in the absence of a charge density, while the dotted and dashed curves correspond to charge densities $n_s = 1.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^9 \text{ cm}^{-2}$, respectively. We observe that when $q_{\parallel} \rightarrow 0$, $C_{\pm} \rightarrow 0$, implying that $w_{\text{SO}\pm} \rightarrow w_{\sigma=0\pm}$, i.e., the positive and negative modes of the dispersion relation tends to the phonon frequencies in a film without surface charge densities. When $\sigma \rightarrow 0$, we do not have the presence of a charge density and our result [Eq. (4)] reproduces the one obtained by Licari and Evrard.¹⁶ As can be seen in Fig. 1(a) for the lower mode $w_{\text{SO}+}$, there is a considerable change of the dispersion relation with the doping, but this change is not observed in the case of the upper mode $w_{\text{SO}-}$. As can be seen in Fig. 1(b), the effects of the surface charge in a thicker film are significant only for large values of q_{\parallel} .

As shown analytically in Sec. III, a modification in the dispersion relation due to the presence of the surface charge induces a change in the interaction of the electron with the surface modes. To analyze this, we present in Fig. 2 the electron-phonon coupling function Γ_{\pm} of the electron-surface optical phonons [see Eq. (17)] as a function of the z coordinate for a GaAs film of 10 GaAs ML. The solid curve is the coupling function calculated in the absence of a surface charge density, while the dotted curve corresponds to a density $n_s = 3.0 \times 10^9 \text{ cm}^{-2}$. We observe a very small change in the coupling function corresponding to the antisymmetric mode Γ_- (left branch in Fig. 2). This is consistent with the behavior of $w_{\text{SO}-}$. However, for the symmetric mode Γ_+ (right branch in Fig. 2), the increase on the coupling constant is very significant, which is expected since it is related to the lower mode $w_{\text{SO}+}$. As can be seen, the effect of the symmetric surface charge on the coupling function is to enhance its strength and consequently increase the confinement of the electron in the film. Although it is not presented here, we have observed that the effect of a surface

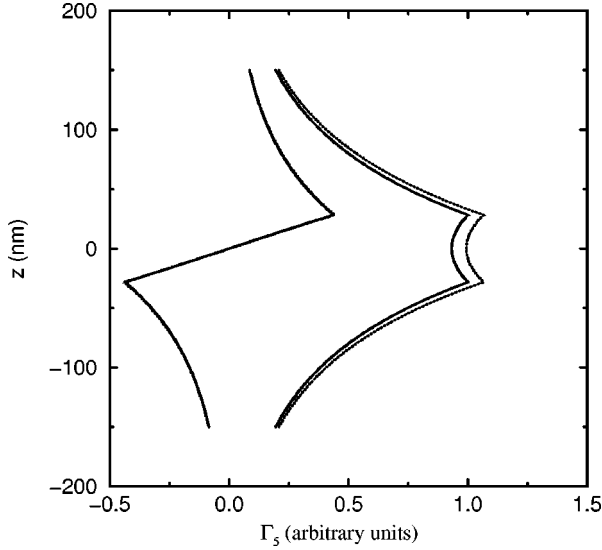


FIG. 2. The electron-phonon coupling function of the electron-surface optical phonons as a function of z coordinate in a GaAs film of 10 GaAs ML. The solid curve is the coupling function calculated in the absence of a surface charge density, while the dotted curve corresponds to a density $n_s = 3.0 \times 10^9 \text{ cm}^{-2}$.

charge density in the coupling constant decreases when the film thickness increases.

In Fig. 3, we plot for a GaAs film the second-order correction in the polaron energy due to the SO modes [see Eq. (27)] as a function of the monolayers N of the film given in terms of the GaAs lattice parameter. The solid curve is the the second-order correction in the absence of a charge density, which reproduces the one obtained by Liang, Gu, and Lin,² while the dashed and dotted-dashed curves correspond to a density $n_s = 1.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^9 \text{ cm}^{-2}$, respectively. The increases of the polaron energy is directly related with the enhancement of the coupling constant shown

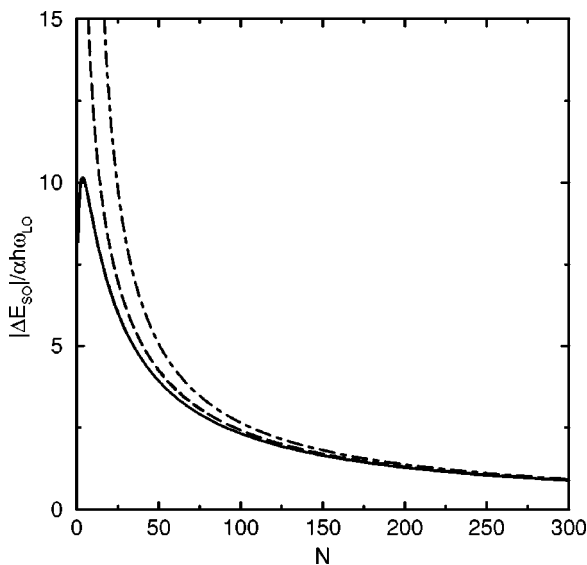


FIG. 3. The second-order correction to the polaron energy in a GaAs film due to the SO modes as a function of the number of monolayers. The solid line is the second-order correction in the absence of a charge density, while the dashed line and dotted-dashed curve correspond to a density $n_s = 1.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^9 \text{ cm}^{-2}$, respectively.

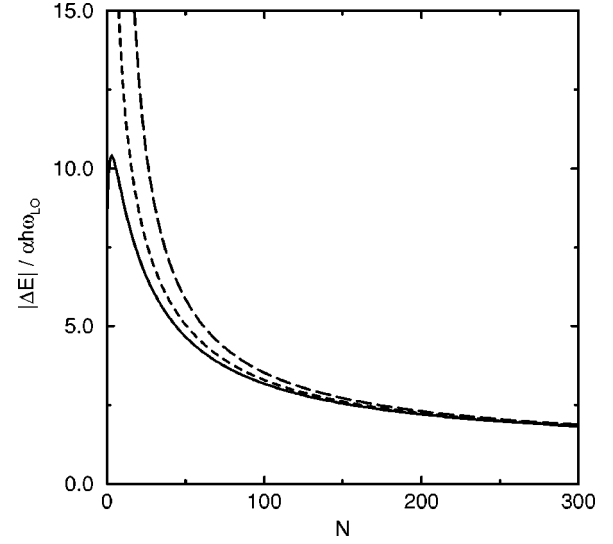


FIG. 4. The second-order correction to the polaron energy ΔE [Eq. (25)] in a GaAs film as a function of the number of monolayers. The solid curve is the second-order correction in the absence of a charge density, while the dashed and long-dashed curve correspond to a density $n_s = 1.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^9 \text{ cm}^{-2}$, respectively.

in Fig. 2. As can be seen, the influence of the surface charge density is very significant, mainly on thin films.

Finally, we plot in Fig. 4 the second-order correction ΔE to the polaron energy [Eq. (25)] as a function of the monolayers N of the film, given in terms of the GaAs lattice parameter. It was calculated in the absence of a charge density, and for the densities $n_s = 1.0 \times 10^9 \text{ cm}^{-2}$ and $3.0 \times 10^9 \text{ cm}^{-2}$. Since the surface charge density does not change the bulk modes, the difference on the energies is due only to changes on the surface modes. In fact, the contribution of the volume modes tends to zero in very thin films and contributes with less than 10% of the total polaronic correction for films with $N \approx 200$.

From the results we have obtained, we can not expect that a perturbation theory up to the second-order correction can be used for very thin films ($a \leq 5$ GaAs lattice parameters).

VI. CONCLUSIONS

In conclusion, the dispersion relation of SO phonons, the electron-phonon interaction, and the second-order correction to the polaron energy have been obtained for films with an equal surface charge density. The numerical results we have presented are restricted to the weak-coupling limit, but the analytical results for the dispersion relation and the electron-phonon coupling are general. It is also important to notice that, although a symmetric surface charge density does not produce a macroscopic electric field inside the film, it modifies the surface modes. Therefore, the change in the electron-phonon interaction induces a confinement on the electron that is responsible for a remarkable correction on the energy of a polaron confined in thin films. It is expected that these changes are also important for the polaron effective mass, and consequently in all transport properties of electrons confined in films with a surface charge density. These calculations are now under consideration.

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