Localized (cục bộ, định xứ) phonon-assisted cyclotron resonance in GaAs/AlAs quantum wells 4 h 30	Cộng hưởng cyclotron định xứ có sự tham gia của phonon trong các giếng lượng tử GaAs/AlAs
The theory of phonon-assisted cyclotron resonance in quantum wells is given; we consider cases where electrons are scattered by confined LO phonons described by the Huang and Zhu model, Fuchs-Kliewer slab modes, and Ridley's guided mode model. The effect of interface phonon	Trong bài báo này, chúng tôi trình bày lý thuyết cộng hưởng cyclotron có sự tham gia của phonon trong các giếng lượng tử; chúng tôi xét trường hợp các electron bị tán xạ bởi các phonon LO giam cầm, một hiện tượng đã được mô tả bằng mô hình Huang và Zhu, mô hình slab (phiến, tấm, mô hình phân lớp) Fuchs-Kliewer, và mô hình guided mode

modes on cyclotron resonance is also studied. Extra peaks due to transitions between Landau levels accompanied by emission of confined and interface phonons in the absorption spectrum are predicted. Numerical results for frequency, field, and well-width dependence are given for parameters characteristic of GaAs/AlAs quantum wells.	(mode dẫn, mode định hướng) Ridley. Chúng tôi cũng nghiên cứu ảnh hưởng của các mode phonon ở bề mặt phân cách đến cộng hưởng cyclotron. Theo dự đoán của chúng tôi, sẽ có sự xuất hiện thêm các peak trong phổ hấp thụ do dịch chuyển giữa các mức Landau dẫn đến sự phát các phonon giam cầm và các phonon bề mặt phân cách. Các kết quả tính toán số về sự phụ thuộc tần số, trường và độ rộng giếng cũng được đưa ra ứng với các tham số đặc trưng của các giếng lượng tử GaAs/AlAs.
I. INTRODUCTION In recent years there has been much interest in the study of the effects of the electron-phonon interaction on the optical properties of two-dimensional electron systems formed in semiconductor heterojunctions and quantum wells (QW's) in the presence of a quantizing magnetic field.1,2 In QW structures such as those formed from weakly polar III-V compound semiconducting materials, electron-polar-optical-phonon interaction plays a dominant role in determining various electronic properties. An important effect relevant to any discussion of electron-phonon interaction in the presence of a magnetic field is the phonon-assisted cyclotron resonance (PACR), in which electron transition between the Landau levels due to absorption of a photon is accompanied by absorption or emission of a phonon. There exist in the litera-ture exhaustive theoretical3-6 and experimental7,8 inves-tigations of PACR in bulk semiconductors. Calculations of PACR in two-dimensional QW structures9-11 are based on a bulk description of the phonons. In widely studied QW	[redacted] [redacted]

structures such as GaAs/AlAs the optical- phonon branches of the two materials do not overlap, and hence an optical phonon in one material is heavily damped in the other. The optical phonons can therefore be considered to be confined to the individual layers. Also, the presence of heterointerfaces gives rise to interface modes which are localized in the vicinity of the interfaces. Raman spectroscopy measurements made upon superlattice (SL) structures,12-14 and investigations15-17 of I-V characteristics of phonon-assisted tunneling in Ga As/Ga j _ x Alx As double-barrier resonant-tunneling structures, have confirmed the confinement of optical vi-brations to the respective layers as well as the existence of interface modes.

Various models have been proposed to describe the confined and interface phonon modes. Of the two macro-scopic dielectric continuum models, one corresponds to the “slab modes” of a free ionic slab18,19 and the other to the “guided modes” of a model layered structure.20 Recently, Huang and Zhu21 (HZ) have proposed a simple lattice-dynamical model for describing phonon modes in SL’s. These models differ in the way the boundary conditions are imposed on the electrostatic potential or vibrational amplitude of the phonons at the interfaces. Calculations of electron intra- and intersubband scattering rates in GaAs QW’s due to confined LO phonons have been performed using the three models above, and estimates22,23 based on the HZ model were found to be in

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good agreement with the experimental results.[24,25] Also, there have been theoretical investigations of electron scattering rates in QW's due to confined LO phonons, described by the above three models, in the presence of an applied electric field[26] and a quantizing magnetic field,[27] apart from the calculations of infrared absorption[28] and free-carrier absorption[29] based on the HZ model for confined phonons. The HZ model has received wide acceptance and best describes[30,31] the electron-phonon interaction in quasi-two-dimensional (Q2D) systems.

Various methods have been proposed to obtain interface modes in single or double heterostructures.[18,32-36] From an analysis of vibrational modes in an ionic slab, Fuchs and Kliewer[18] have found sinusoidal bulk LO modes with nodes at the interface and symmetrical and antisymmetrical interface modes which decay exponentially away from the interfaces. A Frohlich-type Hamiltonian describing electron-optical-phonon interaction in a double heterostructure of a polar semiconductor was derived by Lassnig[32] using the electron energy loss method. Calculations of electron scattering rate[22] and infrared absorption[28] due to interface modes in GaAs/AlAs QW's, following the method of Lassnig, indicate that interface modes are as important as confined modes. Re-cent investigations of electron scattering rates due to interface optical phonons in GaAs/AlAs QW's (Ref. 37) and SL's (Ref. 38) in the presence of an electric field have indicated the strong

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coupling between electrons and interface modes.

To better understand electron-phonon interaction in QW's it is of interest to study PACR when electrons are scattered by confined and interface optical phonons. Re¬cently, Hai, Peeters, and Devreese39 have studied the effects of interface and confined slab LO-phonon modes, described by a model due to Wendler and co-workers,33,34 on polaron cyclotron resonance frequency for a GaAs/AlAs QW structure using memory-function for¬malism, and found that interface optical-phonon modes influence the magnetopolaron resonance considerably near the optical-phonon frequencies for narrow QW's. In this paper, following Bass and Levinson,3 we present a theory of PACR in QW's employing a perturbation tech¬nique. This technique has been used successfully in analyzing PACR in bulk semiconductors and free-carrier absorption in low-dimensional structures.40,41 One ad¬vantage of this method is its simplicity compared with the calculations based on linear response theory.9,10,39 Our emphasis is on the HZ model. Calculations predict extra peaks in the magneto-optical spectrum due to tran¬sitions between Landau levels accompanied by absorption and emission of confined and interface optical phonons, besides the usual cyclotron resonance. Though the HZ model is well accepted30,31 for describing the electron- phonon interaction in QW structures, for comparison, we present numerical results for confined modes described by the Fuchs-Kliewer slab modes,

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and Ridley’s guided mode model. Also, we perform calculations to show the effect of electron interaction with interface optical-phonon modes on the PACR spectrum. In this we employ the model due to Lassnig.32

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The paper is organized as follows. In Sec. II we outline the theory of electron-phonon interaction. In Sec. Ill we calculate absorption coefficients. We give the numerical results and discussion in Sec. IV.

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II. ELECTRON-PHONON INTERACTION

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A. Electron-confined-LO-phonon interaction

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The electron-confined-LO-phonon interaction Hamil¬tonian as derived from the Frohlich interaction is given by19,21

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where a,a^ are the phonon annihilation and creation operators, e/ = (e“1 — e^1)_l with e0 and £«* denoting, respectively, the static and high-frequency dielectric constants, and V is the volume, q = (qx,qy) and r = (;*:,.)>) are, respectively, the two-dimensional phonon wave vector and the position vector in the plane of the layer and a are the even (—) and odd (+) confined phonon modes. una(z) is the parallel component of the displacement vector in the direction of spatial confinement. For the HZ model21 una is given by

(14)

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where ap^a^ are, respectively, the phonon annihilation and creation operators and A is the normalization area. The subscript p represents the symmetric (s) or antisymmetric (a) forms of the interface phonon modes and/* = ± distinguishes the two interface phonon modes corresponding to the well (—) and the barrier (+) materials. In Eq. (14) the other quantities are

(CO2

(19)

where wLOi and coLQ2 denote the bulk LO-phonon frequencies.

III. ABSORPTION COEFFICIENTS

The absorption coefficient can be related to the transition probabilities for the absorption and emission of photons. It can be expressed as43

where iV=0,1,2,. . . , / = 1,2,3,..., and E0 = (n2fi2/ 2m*L2). <f>N represents the harmonic-oscillator wave function centered at x0=—X2ky with X = (Hc/eB)1/2 being the cyclotron radius, and coc = \e\B /m*c the cyclotron frequency. N denotes the Landau level index and I the electric subband quantum number. The envelope function is

with u=kq /2, nx =ma.x(N,N')9 and n2==mm(N9Nr). Ln 1 2 are the associated Laguerre polynomials. Gft?, is

This overlap integral can easily be evaluated for intrasubband (1->1) and intersubband (1—*2) transitions for all three models. In the HZ model only even modes and in slab modes only odd modes contribute for intrasubband transitions. For intersubband transitions, odd modes contribute in the HZ model and even modes in the slab model. In the case of guided modes, only the n = 2 mode contributes for intrasubband transitions and the n = 1 and 3 modes contribute for intersubband transitions.

For a nondegenerate Q2D electron gas in a quantizing magnetic field, the distribution function fNl can be

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shown to be .
with
and ne denoting the carrier concentration.
Using Eq. (20) and a straightforward calculation of transition probabilities, and replacing Dirac 8 functions by a Lorentzian of width T, we obtain the following expression for the absorption coefficient for PACR in a nondegenerate Q2D electron system in a QW structure due to confined modes described by the HZ model:
is the Bose distribution function for the interface mode, the function JNN,(u) *s as defined in Eq. (27), and are now given by
with
and
The subscript IP refers to interface phonons. Equations (31) and (34) can be compared with the following expression for the PACR absorption coefficient which we have obtained for the bulk description of phonons in a QW structure:
where F (t) = (1 — e t)/t. The subscript BP refers to bulk phonons.

IV. RESULTS AND DISCUSSION

We have evaluated numerically the above expressions for absorption coefficients obtained for electron interaction with confined, interface, and bulk phonons in the GaAs/AlAs QW system. The material parameters used are45 #g>lo1 = 36.2 meV, ficoL02 = 50.09 meV, fe>T01 = 33.29 meV, ficoT02 =44.28 meV, £1^ = 10.89, e2oo = 8.16, and m * =0.067m0. Figure 1 shows the variation of absorption coefficient with Cl/o)cf for bulk phonons (full curve), confined phonons described by the HZ

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FIG. 1. Dependence of the absorption coefficient on £l/coc calculated for L = 100 A at T—ll K and 5 = 10 T. The full curve is for bulk phonons, the dashed curve is for confined modes described by the HZ model, the dot-dashed curve is for interface cos + modes, and the dotted curve is for interface cos _ modes.

model (dashed curve), symmetric interface AlAs-like (g>j+) modes (dot-dashed curve), and symmetric interface GaAs-like (cos-) modes (dotted curve), calculated for a QW of width L = 100 A at T = ll K, B = 10 T. The surface concentration of electrons ns (= neL) is taken to be 1.0X 1011 cm-2. The Landau level width T is assumed to be 1 meV. This value of the broadening parameter is reasonable, according to the results of our recent self- consistent calculations of electron scattering rates in GaAs/AlAs QW’s due to confined27 and interface44 phonons in the presence of a quantizing magnetic field. The main cyclotron resonance occurs at £l = coc. The singularity at fl==coc in the figure is associated with the factor A(fl,coc) in Eqs. (31), (34), and (35). The other peaks in the curves correspond to the phonon-assisted resonance transitions between the Landau levels. These transitions can be of different types depending upon the Landau level separation and photon and phonon energies. Possible processes are shown in Figs. 2-4. Figure 2 is for the case a>c> (Dp, where cop represents the phonon frequency. In this case absorption of a photon is possible only by a transition to a higher

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Landau level. Further, different possibilities like Ci>cop and O < cop are also shown. In the figures, /, /, and j denote the initial, final, and intermediate levels, respectively. The resonance frequencies are given by n = (oc+(op. The upper sign (—) and the lower sign (+) correspond, respectively, to phonon absorption and emission. The transitions for coc < cop can be of four different types as shown in Fig. 3. In this case only transitions with phonon emission are possible. Figure 3(a) shows the case in which £l>cop and the transitions cause resonance at il = cop+cQc. Figure 3(b) shows the case in which H < cop and the transitions cause resonance at H = (op — coc. The transitions which lead to resonance absorption when electrons remain in the same Landau level are shown in Fig. 4. The intermediate level can be an upper or lower level and £l = (op. These phonon- assisted transitions are not restricted only to the neighboring Landau levels. Electrons can undergo resonant transitions between Landau levels with energy separation mfi(oc, with m being an integer. Thus conditions for resonant transitions, in general, can be written as ilz=(op-irm(oc for the cases shown in Fig. 3. Resonant transitions are also possible when fl = (op=zmo)c.

For a magnetic field of strength B = 10 T, the energy separation of the Landau levels is smaller than the phonon energy, and peaks other than that at £l = (oc in Fig. 1 are due to the transitions shown in Figs. 3 and 4. It may be noted that peaks due to confined phonon modes coincide with those of bulk phonons. This is due to

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equivalence in the energies of bulk and confined phonons. However, the magnitude of the absorption coefficient due to confined phonons is lower than that due to bulk phonons. The peak value of KCF corresponding to ra = 1 is 40.7% of that due to bulk phonons. In the HZ model only even modes contribute and the maximum contribu-

FIG. 4. PACR transitions leading to resonant absorption when electrons remain in the initial Landau level.

tion is from n = 2, whereas in the case of bulk phonons all modes contribute. The resonance peaks due to confined modes described by the slab and guided mode models occur at the same positions as those for the bulk phonons. The peaks due to confined and bulk phonons occurring at fl/oc= 2.09 are due to transitions of the type shown in Fig. 4, and the value of m is taken as zero as the electron remains in the initial Landau level at the end of the process. The peaks at £l/a)c = 3.1 are due to transitions of the type shown in Fig. 3(a) and the value of m is 1. The numbers on the top of the peaks in Fig. 1 indicate the value of m.

The interface modes (os + and &>s _ are dispersive in na-ture and we have taken this into consideration in our cal-culations. The range of dispersion for the (os+ mode is from 47.42 to 50.09 meV and for the (os_ mode from 33.29 to 34.64 meV. The resonance peaks due to these modes are found to occur at the average values of the respective limits of dispersion. The peak at Ct/(oc = 1.76 is for the (os + mode and is due to a transition of the type shown in Fig.

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3(a) with m = — 1. A kink in the left-hand side of the main cyclotron resonance singularity is due to a similar transition but for m = — 2. The peak at Cl/(oc=2.1% is due to a transition of the type shown in Fig. 4 and the photon energy corresponding to this is 48.16 meV, which is the average of the range of disper-

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FIG. 5. PACR absorption spectrum shown as a function of Cl/coc due to confined modes described by the HZ model (full curve), slab modes (dashed curve), and guided modes (dot- dashed curve), calculated for L = 100 A, 2* = 10 T, and T = ll K. The dotted curve is due to the HZ model for a QW with finite barrier height of 1 eV.

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sion of the cos+ mode. In the measurements of I-V characteristics of phonon-assisted tunneling in GaAs/Ga^^Al^As double-barrier tunneling structures Leadbeater et al.15 have estimated the energy of the in-terface AlAs-like mode to be 48.5 meV. The resonance peaks for a)s_ modes occur at £l/coc = 1.99 and 2.98 and are due to transitions of the type shown in Figs. 4 and 3(a), respectively. The corresponding values of m are 0 and 1. The magnitude of the absorption coefficient due to interface modes is smaller than that due to confined and bulk phonons. This indicates weak coupling between electrons and the interface phonon modes at large well widths.

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Figure 5 shows the absorption spectrum due to confined phonons described by the HZ model (full curve), slab model (dashed curve),

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and guided mode model (dot- dashed curve). Resonant peak positions coincide in all the three models. The magnitudes of the peak value corresponding to m = l due to slab and guided modes are, respectively, 82.5% and 10.9% of that obtained with the HZ model. The large difference in the case of guided modes is due to the involvement of only the n =2 mode in the phonon-assisted transitions. The dotted curve in the figure is for the HZ model calculated with a finite height of 1 eV for the QW barrier. The effect of the finite depth for the QW is to reduce the absorption coefficient.

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The variation of the sum of the absorption coefficients due to confined modes described by the HZ model and the interface and fi>5_) modes with Q/coc is shown in Fig. 6. For the sake of comparison we have drawn the figure to the scale of Fig. 1. The resonance peaks due to interface CDs+ modes appear as satellite peaks to the peaks due to the confined modes and are strong enough to be detected in a PACR experiment.

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The dependence of absorption coefficient on well width is shown in Fig. 7 calculated at T — 11 K, B = 10 T, and m — 1. Curve 1 is for bulk phonons, 2 for confined, 3 for the cos + mode, and 4 for the cos _ mode. It can be noted that for well widths less than 70 A electron interaction with interface modes dominates over that with confined modes. However, the absorption coefficient, in general,

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FIG. 7. Well-width dependence of the peak value of the absorption coefficients for (m = 1) due to bulk phonons (curve 1), confined

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modes described by the HZ model (curve 2), interface CQs+ modes (curve 3), and interface cos- modes (curve 4), calculated at B = 10 T, T= 11 K.

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decreases with increasing well width.

Figure 8 displays the magnetic-field dependence of the peak value of the absorption coefficients calculated for L = 100 A and m = 1. Curve 1 is for bulk phonons, 2 for confined phonons, 3 for cos+ modes, and 4 for cos_ modes. The absorption coefficients due to bulk and confined phonons increase with increasing magnetic field whereas that due to interface modes become saturated at large magnetic fields.

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We have also investigated the dependence of the absorption coefficients due to confined and interface phonon modes on the broadening parameter T for B = 10 T and L = 100 A. The height and the sharpness of the peaks in the absorption spectrum decrease with increase of T. Our results for the overall behavior of the absorption coefficient with well width, magnetic field, and broadening parameter are in agreement with the calculations of

Hai, Peeters, and Devreese.39

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In conclusion, we have presented a theory of PACR in Q2D semiconducting quantum-well structures using a perturbation technique, when electrons are scattered by confined and interface optical phonons. Additional peaks in the absorption spectrum due to interface-phonon- assisted transitions, apart from those due to confined phonons, are predicted. It would be

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interesting to have experimental results to test the predictions of the present	