Vol 16 No 12, December 2007
1009-1963/2007/16(12)/3766-06

Chinese Physics

© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

Pressure effect on the electron mobility in AlAs/GaAs quantum wells*

Hao Guo-Dong(郝国栋), Ban Shi-Liang(班士良)†, and Jia Xiu-Min(贾秀敏)

Department of Physics, College of Sciences and Technology, Inner Mongolia University, Hohhot 010021, *China*

(Received 27 February 2007; revised manuscript received 13 April 2007)

By taking the influence of optical phonon modes into account, this paper adopts the dielectric continuum phonon model and force balance equation to investigate the electronic mobility parallel to the interfaces for AlAs/GaAs semiconductor quantum wells (QWs) under hydrostatic pressure. The scattering from confined phonon modes, interface phonon modes and half-space phonon modes are analysed and the dominant scattering mechanisms in wide and narrow QWs are presented. The temperature dependence of the electronic mobility is also studied in the temperature range of optical phonon scattering being available. It is shown that the electronic mobility reduces obviously as pressure increases from 0 to 4GPa, the confined longitudinal optical (LO) phonon modes play an important role in wide QWs, whereas the interface optical phonon modes are dominant in narrow QWs, the half-space LO phonon modes hardly influence the electronic mobility expect for very narrow QWs.

Keywords: electronic mobility, pressure effect, quantum well
PACC: 6320K, 7220D, 7320D

1. Introduction

In the past two decades there has been considerable interest in electronic and optical properties of low–dimensional structures, such as quantum wells (QWs) and heterojunctions.[1−7] Since the electron-phonon interaction plays an important role for many properties such as optical absorption or emission and carrier transport etc., several analytical models were developed to describe the Fröhlich interaction between the electrons confined in these structures and different phonon modes.[1−3,8] Furthermore, the electron-phonon interaction in ternary mixed crystals is helpful to understand the corresponding properties in layered materials.[9]

Intensive studies of these kinds of interaction in AlAs/GaAs QWs showed that the bulk phonon approximation is reasonably good for estimating the electronic mobility under infinite barrier approximation,[4] which is adoptable only for wide QWs. However, in narrow QWs or heterojunctions the scattering by interface phonons may become important.[5,6] It is necessary to clarify how the electronic mobility is influenced by the scattering from different phonon modes to understand quantitatively the obvious decrease of the mobility even in a single QW at finite temperature.

Hydrostatic pressure can shift effectively the energy levels of tetrahedral semiconductors without altering the crystal symmetry. The study of the pressure dependence of the electrical and optical properties of semiconductors provides information on the band structure and other parameters. Furthermore, it may help ones to understand the properties of layered materials under strain and stress.[10,11] In an early year, Lefebvre *et al.*[12] presented a theoretical calculation about the pressure coefficients of carrier effective mass in $GaAs/Al_xGa_{1-x}As$ QWs. Their results showed that the effective masses of electrons increase with increasing pressure. Goi *et al.*[13] measured the dispersion of refractive index for Ge and GaAs between 0.6 and 1.4 eV under a hydrostatic pressure up to 8GPa and also obtained the variation of high frequency dielectric constant with pressure. Their results showed that the high frequency dielectric constant decreases monotonically with increasing pressure. Tang *et al.*[14] studied hydrostatic pressure coefficients of the photoluminescence for InAs/GaAs quantum dots based on nonlinear elasticity theory. The results showed that the pressure dependence of energy gap and electronic

*Project supported by the National Natural Science Foundation of China (Grant No 60566002) and the project for excellence subject-directors of Inner Mongolia Autonomous Region of China.
†E-mail: slban@imu.edu.cn

confined energy are the main reasons that lead to the small pressure coefficients of the photoluminescence. The accumulation of these physical data gave the possibility to discuss the pressure effect of electronic mobility in a heterostructure with a macroscopic continuum model.[15]

The pressure effect on the electronic mobility in GaAsN and AlGaAs alloys at room temperature was investigated by Skierbiszewski *et al.*[16] and Saxena,[17] respectively. The pressure dependence of electronic mobility in a GaAs/GaAlAs heterostructure at low temperature, concentrating on the deformation potential behaviour, was examined by Gorczyca *et al.*[18,19] It was found that the electronic mobility decreases with increasing pressure. Although there were many experimental and theoretical references on the pressure effect in bulk materials and heterostructures, the pressure effect on electronic mobility in GaAs/AlAs QWs in the temperature range of optical phonon (especially the interface phonon) scattering being available should be investigated in detail since this structures have an active application in quantum cascade lasers and high electron mobility transistors[20,21]even under hydrostatic pressure.[22]

Lei and Ting[23] developed a balance equation approach to deal with the problem of carrier transport for electron-phonon-impurity systems. The formulation has been proved to be effective in study of the linear and nonlinear carrier transport.[4,24]

In this paper, we adopt the force balance equation[23]to calculate the electronic mobility in QWs with finite barriers under hydrostatic pressure. The pressure effects of the electron effective mass, the dielectric constants and the band offsets between the well and barrier materials are considered in our calculation. Meanwhile, the effect of the electronic wave functions penetrating into the barrier regions is also taken into account. Our results show that the electronic mobility decreases in pressure range from 0 to 4GPa.

In an early year of the last decade, Zhu *et al* studied the electronic mobility in single and multiple QWs at zero pressure.[25] It was shown that the electronic mobility experiences a strong decrease with increasing temperature in a single QW. Unfortunately, after comparing with their results, we find that even though the scattering mechanism of electrons and confined longitudinal optical (LO) phonons naturally lead to a mobility decrease versus temperature, but it is not sufficient to explain the whole set of experimental data by using this mechanism. We also find that the confined LO phonons play an important role in wide QWs, whereas the interface optical (IO) phonon modes are dominant in narrow ones. This may be considered both in theory and design of devices. In comparison, it indicates that our result is in better agreement with the experimental data[25] at temperatures above 120K under zero pressure since we have not found suitable experimental data under pressure.

2. Electronic mobility and its pressure effect

We consider an electron confined in a single QW consisting of two different polar semiconductors as shown in Fig.1. The z axis is chosen to be perpendicular to the interfaces. The well material is in the region of $|z| \leq d$ denoted as material 1, the barrier materials are in the regions of $|z| > d$ denoted as material 2.

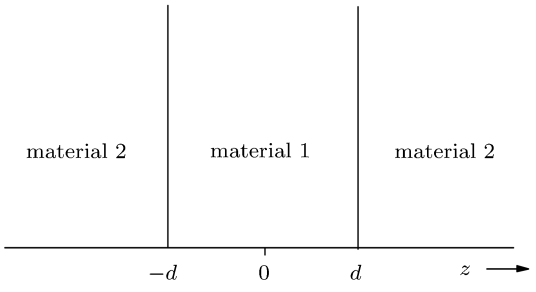


Fig.1. Schematic drawing of a single quantum well composed of two different polar semiconductors.

In a semiconductor heterostructure, the phonon modes are modified due to the presence of interfaces. For a single AlAs/GaAs quantum well with finite barriers, there are three types of optical-phonon modes which couple to electrons: (1) the four branches of IO modes with frequency $\omega_{S\pm}$ and $\omega_{A\pm}$; (2) the confined slab LO modes in the well with frequency ω_{LO1}; (3) the half-space LO modes in the barrier layers with frequency ω_{LO2}.

The frequencies of the symmetric IO modes $\omega_{S\pm}$ are given by the solution of

$$\varepsilon_1(\omega)\tanh(q_{//}\,d) + \varepsilon_2(\omega) = 0. \tag{1}$$

The frequencies of the antisymmetric IO modes $\omega_{A\pm}$ are given by the solution of

$$\varepsilon_1(\omega)\coth(q_{//}\,d) + \varepsilon_2(\omega) = 0. \tag{2}$$

The dielectric function $\varepsilon_i(\omega)$ is given by

$$\varepsilon_i(\omega) = \varepsilon_{\infty i}\frac{\omega^2 - \omega_{\mathrm{LO}i}^2}{\omega^2 - \omega_{\mathrm{TO}i}^2}, \tag{3}$$

where $\omega_{\mathrm{LO}i}$ and $\omega_{\mathrm{TO}i}$ are the frequencies of LO phonon and transverse-optical (TO) phonon in material i, respectively. $\varepsilon_{\infty i}$ is the corresponding high-frequency dielectric constant, $q_{//}$ is the two-dimensional wave vector of the phonon modes in the x-y plane.

The IO modes appearing in the QWs generate the following potentials:

$$\phi_{S\pm,\boldsymbol{q}}(z) = \begin{cases} V_{S\pm,\boldsymbol{q}}\exp[-q_{//}(|z|-d)], & |z| > d, \\ V_{S\pm,\boldsymbol{q}}\cosh(q_{//}z)/\cosh(q_{//}d), & |z| \le d, \end{cases} \tag{4}$$

for the symmetric interface phonon modes, and

$$\phi_{A\pm,\boldsymbol{q}}(z) = \begin{cases} V_{A\pm,\boldsymbol{q}}\exp[-q_{//}(|z|-d)], & |z| > d, \\ V_{A\pm,\boldsymbol{q}}\sinh(q_{//}z)/\sinh(q_{//}d), & |z| \le d, \end{cases} \tag{5}$$

for the antisymmetric interface phonon modes. Here $V_{S\pm,\boldsymbol{q}}$, $V_{A\pm,\boldsymbol{q}}$ is given by Ref.[8].

The phonon modes confined in quantum well are given by[8]

$$\phi_{\mathrm{LO1},\boldsymbol{q}}(z) = \Big[\frac{2\pi\hbar\omega_{\mathrm{LO1}}e^2}{\varepsilon_0 Sd}\Big(\frac{1}{\varepsilon_{\infty 1}} - \frac{1}{\varepsilon_{01}}\Big)\Big]^{1/2}\begin{cases} 0, & |z| > d, \\ \sin(q_m(z+d)/\sqrt{q_{//}^2 + q_m^2}, & |z| \le d. \end{cases} \tag{6}$$

The half-space phonon modes located in barrier side are given by[8]

$$\phi_{\mathrm{LO2},\boldsymbol{q}}(z) = \Big[\frac{2\pi\hbar\omega_{\mathrm{LO2}}e^2}{\varepsilon_0 Sd}\Big(\frac{1}{\varepsilon_{\infty 2}} - \frac{1}{\varepsilon_{02}}\Big)\Big]^{1/2}\begin{cases} \sin(q_z(|z|-d)/\sqrt{q_{//}^2 + q_z^2}, & |z| > d, \\ 0, & |z| \le d. \end{cases} \tag{7}$$

On the effective mass and finite square-well potential approximation, the electron wavefunction of subband n is $\Psi_{n,\boldsymbol{k}}(\boldsymbol{r}) = (1/\sqrt{S})\psi_n(z)\mathrm{e}^{\mathrm{i}\boldsymbol{k}_{//}\cdot\boldsymbol{\rho}}$ with

$$\psi_n(z) = \begin{cases} N\cos(k_1 d)\exp[-k_2(|z|-d)], & |z| > d, \\ N\cos(k_1 z), & |z| \le d, \end{cases} \tag{8}$$

where the normalization constant N and wave vectors k_1 and k_2 are given by Ref.[26], $\boldsymbol{\rho} = (x, y)$ is the two-dimensional coordinate vector and S is the area of the quasi-two- dimensional electron gas in the x–y plane.

According to Lei and Ting's force-balance equation,[23] the linear mobility μ of the quasi-two-dimensional electron gas is given by

$$\frac{1}{\mu} = \frac{2}{N_s eT}\sum_{n,n',\boldsymbol{q},\lambda} q_x^2|M_{n,n'}(\boldsymbol{q},\lambda)|^2 \times \Pi_2(n,n',\boldsymbol{q}_{//},\omega_\lambda)\times\frac{\mathrm{e}^{\omega_\lambda/T}}{(1-\mathrm{e}^{\omega_\lambda/T})^2}, \tag{9}$$

where the Fröhlich interaction matrix between subband n and n' coupling to the λ'th branch of phonon modes is written as

$$|M_{n,n'}(\boldsymbol{q},\lambda)| = |e\int \mathrm{d}z\psi_n(z)\phi_{\lambda,\boldsymbol{q}}(z)\psi_{n'}(z)|. \tag{10}$$

In Eq.(9), $\Pi_2(n,n',\boldsymbol{q}_{//},\omega_\lambda)$ is the imaginary part of the zero-order two-dimensional density-density correlation function.[27] The areal electronic density $N_s = 2.0\times10^{11}$ cm^{-2} is used in our calculation.

In GaAs/AlAs QWs, the lowest subband is usually populated and the transition to upper subbands is unimportant if $k_{\mathrm{B}}T_{\mathrm{e}}$ is less than the subband separation, which is about 20 meV[28] for $N_s = 2.0\times10^{11}$ cm^{-2}. In this case the balance equation can be simplified so that we can confine ourselves only to $n' = n = 0$ terms. Thus the expression for the

mobility is reduced to

$$\frac{1}{\mu} = \frac{2}{N_s eT} \sum_{\boldsymbol{q},\lambda} q_x^2 |M(\boldsymbol{q},\lambda)|^2 \times \Pi_2(\boldsymbol{q}_{//},\omega_\lambda) \times \frac{\mathrm{e}^{\omega_\lambda/T}}{(1-\mathrm{e}^{\omega_\lambda/T})^2}. \quad (11)$$

In order to obtain the pressure effect on the electronic mobility in the QWs, we first discuss the dependence of the electronic effective mass, dielectric constants for the bulk materials and band offset between GaAs and AlAs on the hydrostatic pressure. The pressure dependence of the electronic effective mass is given by[29]

$$\frac{m_0}{m(p)} = 1 + \frac{C}{E_\mathrm{g}(p)}, \quad (12)$$

where m_0 is the mass of free electron, $E_\mathrm{g}(p) = E_\mathrm{g} + \alpha p$ is the band gap and C is constants for different materials given in Table 1.

For the pressure dependence of high frequency dielectric constant, we use the equation given by[16]

$$\frac{\partial \ln \varepsilon_{\infty i}}{\partial \ln V} \approx \frac{5(\varepsilon_{\infty i}-1)}{3\varepsilon_{\infty i}}(0.9 - f_\mathrm{I}), \quad (13)$$

where f_I is the ionicity of the material under pressure. The volume $V$of the material can be determined by the Murnaghan state equation. It satisfies approximately the following linear relation[30] in low pressure range:

$$B(P) = -V\frac{\partial P}{\partial V} = B_0 + B_0' P. \quad (14)$$

Here B is the bulk modulus and is assumed being linear with the pressure for not very high pressures. B_0 and B_0' are the bulk modulus and its first order pressure deviation at zero pressure, respectively. Thus we can write the pressure coefficient for the high frequency dielectric constant as

$$\frac{\partial \varepsilon_{\infty i}}{\partial P} = -\frac{5(\varepsilon_{\infty i}-1)}{3B}(0.9 - f_\mathrm{I}). \quad (15)$$

The static dielectric constant is then determined by the famous Lyddane–Sachs–Teller relation:

$$\varepsilon_{0i} = \varepsilon_{\infty i}(\hbar\omega_{\mathrm{LO}i}/\hbar\omega_{\mathrm{TO}i})^2. \quad (16)$$

According to the mode-Grüneisen parameter

$$\gamma_\lambda = B_0 \frac{1}{\omega_\lambda}\frac{\partial \omega_\lambda'}{\partial P}, \quad (17)$$

we can obtain the optical phonon energy dependence on pressure. In the above equation,B_0 is the bulk modulus, ω_λ and ω_λ' are the optical phonon frequencies under hydrostatic pressure $P = 0$ and $P \neq 0$ respectively. The values γ_λ for the λ'th branch of phonon modes are given in Table 1.

Table 1. Parameters used in the computation.

	ε_∞	$\hbar\omega_\mathrm{LO}$/meV	$\hbar\omega_\mathrm{TO}$/meV	m^*/m_0	f_I	B_0/GPa
GaAs[a]	10.89	36.25	33.29	0.067	0.310	77[b]
AlAs[a]	8.16	50.09	44.88	0.15	0.274	74.8[b]
	C/meV	B_0'	E_g/eV	α/(meV/GPa)	γ_LO	γ_TO
GaAs[a]	19829	4.6[b]	1.511[d]	115	1.01[c]	1.12[c]
AlAs[a]	12285	4.6[b]	3.050[d]	102	0.85[c]	1.08[c]

[a]Ref.[31], [b]Ref.[32]. [c]Ref.[33] , [d]Ref.[34].

3. Numerical results and discussion

We have calculated the electronic mobility in GaAs/AlAs QWs influenced by the three kinds of optical phonon modes. The original data of material parameters are listed in Table 1.

In Fig.2, the total mobility in an AlAs/GaAs QW is plotted as a function of well width $L = 2d$, at temperature $T = 300$ K. The contribution from the IO, confined LO and half-space LO phonons are also shown with separated lines. It is found that the confined modes play an important role in wide QWs, but the IO modes are dominant in narrow ones. The LO phonon in the barrier material hardly influence the electronic mobility expectation for very narrow QWs and it is dominant only for the well width of $d < 0.6$ nm. It can be easily understood since the electron is confined in the well and far away from the interfaces in wide QWs, for which the confined phonon scattering is dominant. However, as the well width decreases, the average distance between the electron and the interfaces decreases and the scattering from the IO

phonons becomes stronger and that from confined LO phonons becomes weaker. The former contribution is dominant for narrower wells. For much narrower wells, the penetrating effect of the electrons into barrier sides is obvious so that the scattering both from IO and half-space LO becomes important. The latter is dominant for very narrow wells since the electron penetrates the barriers deeply. At this moment, our model is not suitable because a quasi-2D approximation is adopted here. As a result, the total mobility first increases and reaches a peak (around 1.5 nm), then decreases towards a valley (around 7.4 nm) and finally increases. It should be noticed that the appearance of peak and valley is caused by the existence of IO phonons.

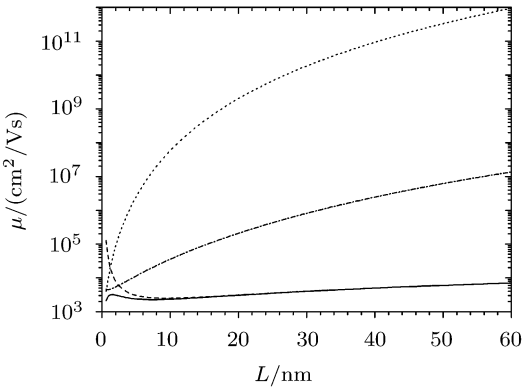


Fig.2. Electric mobility as a function of well width L due to the scattering from the half-space LO (μ_{HLO}, dot line), IO (μ_{IO}, dash-dot line), confined LO phonons (μ_{CLO}, dashed line) for the given temperature $T = 300$ K. The total mobility is denoted by the solid line and satisfies $\mu_{\mathrm{T}}^{-1} = \mu_{\mathrm{CLO}}^{-1} + \mu_{\mathrm{HLO}}^{-1} + \mu_{\mathrm{IO}}^{-1}$.

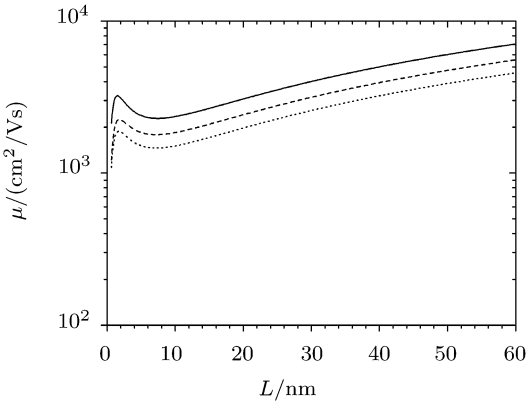


Fig.3. Electric mobility as a function of well width L, for the given temperature $T = 300$ K and pressure $P = 0$, 2 and 4 GPa, corresponding to the solid, dashed and dot lines, respectively.

The electronic mobility as a function of well width L, at temperature $T = 300$ K corresponding to different pressures is shown in Fig.3. Comparing the results at $P = 2$ GPa and $P = 4$ GPa with that at $P = 0$ GPa, we can find the net decreases of mobility are 21% and 36%, respectively. On the one hand, the electron effective mass and energies of phonons increase with increasing pressure. On the other hand, the barrier potential and high dielectric constants decrease with increasing pressure. The large pressure-induced reduction of mobility can be attributed to the complex effects of the pressure on the electron effective mass, energies of phonons, high dielectric constants and the barrier potentials, and the magnitude of pressure effect of electron effective mass is significant. The properties of mobility at different pressures are similar to that at zero pressure.

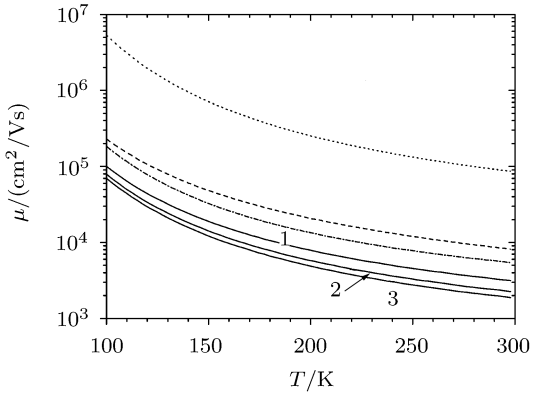


Fig.4. The total mobility of electrons as a function of temperature T, for the given well width $L = 2$ nm and pressure $P = 0$, 2 and 4 GPa, corresponding to curves 1, 2, 3, respectively. The dot, dashed, and dash-dot lines indicate the contribution from the half-space, confined, and interface modes, respectively.

In Fig.4, the calculated mobility versus temperature T, corresponding to different pressures, is presented for given well width $L = 2$ nm. It can be seen that the IO modes are obviously dominant to influence the mobility in comparison with the confined LO modes for narrow QWs and the former effect is more important at high temperature. The scattering from the half-space LO modes can be neglected. Furthermore, comparing the results of mobility under different pressures, we can also find that pressure leads to a large reduction of the electronic mobility, whereas the mobility at different pressures decreases as the temperature increases.

Figure 5 presents the results of mobility μ as a function of temperature T for given well width $L = 12.4$ nm corresponding to different pressures. The experimental result under zero pressure from Ref.[25] is also shown in Fig.5 for comparison. It can be found that the calculated electron mobility under pressure

has the same tendency with that of the experimental result at zero pressure.

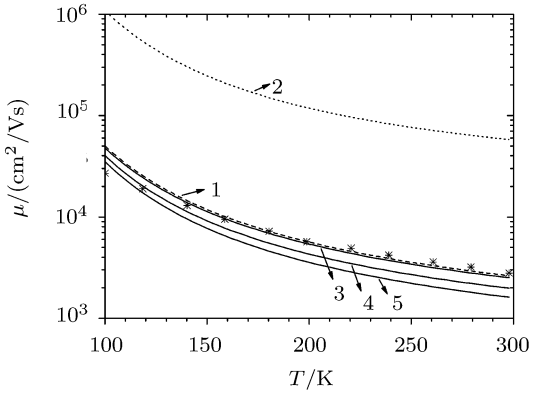


Fig.5. The total mobility of electrons as a function of temperature T, for the given well width $L = 12.4$ nm and pressure $P = 0$, 2 and 4 GPa, corresponding to curves 3, 4, 5, respectively. The contributions to the mobility scattering from confined LO and IO phonons are denoted by curves 1, 2 and the experimental result from Ref.[24] denoted by asterisks.

It is also shown that out result below 120K is obviously higher than that given by experiment, whereas our result is slightly lower than the experimental result above 210K, and the discrepancy between the former and the latter is small at higher temperatures to show that our result is in better agreement with the experimental result at a temperature above 120 K.[25] This may indicate that the optical phonons are less important to influence the mobility and the other scattering mechanism such as acoustic phonons *et al* should be considered below 120K. Furthermore, it can be seen that the confined LO modes play an important role in wide QWs and pressure causes a large reduction on the electronic mobility.

4. Conclusions

We studied the pressure effect on electronic mobility in QWs with finite barriers at temperature range of optical phonons being available. It was found that the mobility decreases with the increase of pressure from 0 to 4GPa. The Fröhlich interaction matrix of electrons with confined modes, interface modes and half-space modes is obtained by using the phonon dielectric continuum model. The results show that the confined LO phonon modes play an important role in wide QWs, whereas the IO phonon modes are dominant in narrow QWs, and the half-space LO phonon modes hardly influence the electronic mobility expectation for very narrow QWs. Our result is in better agreement with the experimental data above 120K at zero pressure.

References

[1] Wendler L and Pechstedt R 1986 *Phys. Status Solidi* B **138** 197
[2] Wendler L and Pechstedt R 1987 *Phys. Status Solidi* B **141** 129
[3] Ridley B K 1989 *Phys. Rev.* B **39** 5282
[4] Wang X F and Lei X L 1994 *Phys. Rev.* B **49** 4780
[5] Zianni X, Simserides C D and Triberis G P 1997 *Phys. Rev.* B **55** 16324
[6] Hasbun J E and Ban S L 1998 *Phys. Rev.* B **58** 2102
[7] Shi J J, Sanders B C, Pan S H and Goldys E M 1999 *Phys. Rev.* B **60** 16031
[8] Zheng R S and Matsuura M 1999 *Phys. Rev.* B **60** 4937
[9] Liang X X and Ban S L 2004 *Chin. Phys.* **13** 71
[10] Kong Y C, Zheng Y D, Zhou C H, Deng Y Z, Gu S L, Shen B, Zhang R, Han P, Jiang R L and Shi Y 2004 *Acta Phys. Sin.* **53** 2320(in Chinese)
[11] Wang Q X 2005 *Acta Phys. Sin.* **54** 3757 (in Chinese)
[12] Lefebvre P, Gil B and Mathieu H 1987 *Phys. Rev.* B **35** 5630
[13] Goi A R, Syassen K and Cardona M 1990 *Phys. Rev.* B **41** 10104
[14] Tang N Y, Chen X S and Lu W 2005 *Acta Phys. Sin.* **54** 2277 (in Chinese)
[15] Bai X P and Ban S L 2005 *Chin. J. Semiconductors* **26** 2422 (in Chinese)
[16] Skierbiszewski C, Perlin P, Wisniewski P, Suski T, Walukiewicz W, Shan W, Ager J W, Haller E E, Geisz J F, Friedman D J, Olson J M and Kurtz S R 1999 *Phys. Status Solidi* B **216** 135
[17] Saxena A K 1982 *Phys. Rev.* B **25** 5428
[18] Gorczyca I, Suski T, Litwin-Staszewska E, Dmowski L, Krupski J and Etienne B 1992 *Phys. Rev.* B **46** 4328
[19] Gorczyca I and Krupski J 1995 *Phys. Rev.* B **52** 11248
[20] Xu G Y and Li A Z 2005 *Phys. Rev.* B **71** 235304
[21] Li D L and Zeng Y P 2006 *Chin. Phys.* **15** 2735
[22] Jin S R, Ahmad C N, Sweeney S J, Adams A R, Murdin B N, Page H, Marcadet X, Sirtori C and Tomić S 2006 *Appl. Phys. Lett.* **89** 221105
[23] Lei X L and Ting C S 1984 *Phys. Rev.* B **30** 4809
[24] Weng M Q and Wu H S 1999 *Acta Phys. Sin.* **48** 682 (in Chinese)
[25] Zhu X T, Goronkin H, Maracas G N, Droopad R and Stroscio M A 1992 *Appl. Phys. Lett.* **60** 2141
[26] Hai G Q, Peeters F M and Devreese J T 1993 *Phys. Rev.* B **48** 4666
[27] Zou Z Q and Lee Y P 2001 *Physica* B **305** 155
[28] Ando T, Fowler A B and Stern F 1982 *Rev. Mod. Phys.* **54** 437
[29] Ting D Z Y and Chang Y C 1987 *Phys. Rev.* B **36** 4359
[30] Anderson O L 1966 *J. Phys. Chem. Solids* **27** 547
[31] Adachi S 1985 *J. Appl. Phys.* **58** R1
[32] Lam P K, Cohen M L and Martinez G 1987 *Phys. Rev.* B **35** 9190
[33] Holtz M, Seon M, Brafman O, Manor R and Fekete D 1996 *Phys. Rev.* B **54** 8714
[34] Ban S L and Hasbun J E 1999 *Phys. Rev.* B **59** 2276