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Pressure influence on the Stark effect of impurity states in a strained wurtzite $GaN/Al_xGa_{1-x}N$ heterojunction*

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A variational method is adopted to investigate the properties of shallow impurity states near the interface in a free strained wurtzite $GaN/Al_xGa_{1-x}N$ heterojunction under hydrostatic pressure and external electric field by using a simplified coherent potential approximation. Considering the biaxial strain due to lattice mismatch or epitaxial growth and the uniaxial strains effects, we investigated the Stark energy shift led by an external electric field for impurity states as functions of pressure as well as the impurity position, Al component and areal electron density. The numerical result shows that the binding energy near linearly increases with pressure from 0 to 10 GPa. It is also found that the binding energy as a function of the electric field perpendicular to the interface shows an un-linear red shift or a blue shift for different impurity positions. The effect of increasing x on blue shift is more significant than that on the red shift for the impurity in the channel near the interface. The pressure influence on the Stark shift is more obvious with increase of electric field and the distance between an impurity and the interface. The increase of pressure decreases the blue shift but increases the red shift.

Keywords: $GaN/Al_xGa_{1-x}N$, strain, pressure, Stark effect, binding energy of impurity state
PACC: 7155F, 7340L, 7320D

1. Introduction

In recent years, the physical properties of quantum heterostructures composed of the group-III hexagonal wurtzite nitrides semiconductors with wide-band-gaps, such as AlN, GaN, and InN, and their ternary compounds, have been widely studied due to their promising potential for short-wavelength electroluminescence devices. Much attention has been paid to the strain effect since the electronic and optical properties of semiconductor heterostructures depend crucially on the strain due to the lattice mismatch of different materials composing these structures. In an early year, Jogai studied the effect of strain on wurtzite GaN by using an tight-binding model.[1] More recently, Shi calculated the interface optical-phonon modes in stained wurtzite GaN/AlN quantum wells.[2] These works furthered the understanding of the strain effect for this kind of heterostructures.

In the last few years, high pressure technology has also become an important tool in determining the band structures and understanding the electronic and optical properties of bulk semiconductors and quantum well (QW) heterostructures. As a result, the optical properties of wurtzite InGaN/GaN and GaN/AlGaN QWs under hydrostatic pressure have been extensively studied.[3−5] Wagner *et al* [6] presented the *ab initio* calculations of the structural, dielectric, and lattice-dynamical properties of zinc-blende and wurtzite GaN and AlN under hydrostatic pressure. In an experiment, Goñi *et al* [7] investigated the pressure behavior of phonon modes on the hexagonal (wurtzite) and cubic (zinc-blende) modifications of GaN and hexagonal AlN, respectively. Ban *et al* [8,9] calculated the pressure effect on donors and exciton binding energies for heterojunctions and QWs respectively and found that both the exciton and donor binding energies nearly linearly increase with pressure. To simplify the calculation, they only considered the zinc-blend $GaN/Al_xGa_{1-x}N$ QWs,[9] for which the strain effect can be reasonably neglected. Within our knowledge, the influence of hydrostatic pressure on the Stark effect in a real heterojunction with free strain has not been reported.

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This paper is focused on the hydrostatic pressure effect on the binding energies of impurity states near the interface of a strained wurtzite GaN/$Al_xGa_{1-x}N$ heterojunction to show the quantum confined Stark effect led by an external electric field. We adopt a variational approach to obtain the binding energies and extend a simplified coherent potential approximation[10] (SCPA) to obtain some physical parameters for a ternary mixed crystal of wurtzite nitrides in III–V group since its properties are more similar to that of a crystal of II–VI group. The numerical results of the relations among the impurity binding energies and pressure, impurity position, electric areal density and the Al components for strained wurtzite heterojunctions with the [0001] orientation are given and discussed. This work is organized as follows. In Section 2, the theoretical method is described. The pressure and strain dependence of physics parameters used in our calculations are presented in Section 3. In Section 4, the results and discussion are performed. Finally, a brief summary is given in Section 5.

2. Theoretical method

We consider a free strained wurtzite GaN/$Al_xGa_{1-x}N$ heterojunction whose channel side GaN, denoted by material 1, is located at $z > 0$ and barrier side $Al_xGa_{1-x}N$, denoted by material 2, is located at $z < 0$, respectively. The interface of the heterojunction is defined as the x–y plane, which is assumed infinite without losing generality. By considering the biaxial effect due to the lattice mismatch or thermal strain during the epitaxial growth and the uniaxial strain effect influenced by an hydrostatic pressure under an electric field in the z-direction, the Hamiltonian of the electron-impurity system can be written as

$$H = H_{x-y} + H_z + H_c, \tag{1}$$

where

$$H_{x-y} = \frac{p_x^2 + p_y^2}{2m_{\|1}}\theta(z) + \frac{p_x^2 + p_y^2}{2m_{\|2}}\theta(-z), \tag{2}$$

$$H_z = \frac{p_z^2}{2m_{\perp 1}}\theta(z) + \frac{p_z^2}{2m_{\perp 2}}\theta(-z) + V(z) + eFz, \tag{3}$$

$$H_c = -\frac{e^2}{\kappa(z, z_0)[x^2 + y^2 + (z - z_0)^2]^{1/2}}. \tag{4}$$

In Eq.(4), the dielectric constants $\kappa(z, z_0)$ can be determined by impurity position z_0 and electronic position z as follows:

$$\kappa(z, z_0) = \begin{cases} \kappa_{01} & z_0 > 0, z > 0, \\ \dfrac{\kappa_{01} + \kappa_{02}}{2} & z_0 < 0, z > 0, \\ & \text{or} \quad z_0 > 0, z < 0, \\ \kappa_{02} & z_0 < 0, z < 0. \end{cases} \tag{5}$$

All of the parameters used in the above equations have been defined in a previous work[11] except for the electric field term eFz for an electron with a charge $-e$ in Eq.(3). Here, F is defined as the difference of electric potentials per unit length.

The trial wave function for the system can be chosen as

$$\psi(x, y, z) = \varphi(x, y)\xi(z) = \varphi(\rho)\xi(z) \tag{6}$$

with

$$\varphi(\rho) = \left[\frac{1}{2\pi}\right]^{1/2} \gamma\, \mathrm{e}^{\mathrm{i}\,\boldsymbol{k}\cdot\boldsymbol{\rho}} \mathrm{e}^{-\gamma\rho/2}, \tag{7}$$

and

$$\xi(z) = \begin{cases} \xi_1(z) = Bb^{1/2}(bz + \beta)\,\mathrm{e}^{-bz/2} & z > 0, \\ \xi_2(z) = Dd^{1/2}\mathrm{e}^{dz/2} & z < 0, \end{cases} \tag{8}$$

where b, d are the variational parameters, and the normalization constants in the above equation satisfy $B = [\beta^2(1 + b/d) + 2\beta + 2]^{-1/2}$ and $D = B\beta(b/d)^{1/2}$ with $\beta = 2b/(b + d)$.

The variational energy of the impurity state at ground state can be obtained as

$$\begin{aligned} E(b, d) &= \langle\psi|\, H_e + H_z + H_c\,|\psi\rangle \\ &= E_e + \langle T\rangle + \langle V_0\rangle + \langle V_d\rangle + \langle V_s\rangle + E_{\text{ext}} + E_c, \end{aligned} \tag{9}$$

where E_e, $\langle T\rangle$, $\langle V_0\rangle$, $\langle V_d\rangle$, $\langle V_s\rangle$ and E_c were also given in Ref.[11]. In Eq.(9),

$$E_{\text{ext}} = eF\left[-\frac{D^2}{d} + \frac{1}{b}(6B^2 + 4B^2\beta + B^2\beta^2)\right]. \tag{10}$$

Minimizing $E(b, d) - \langle V_s\rangle/2$ with respect to the variational parameters, one can obtain the ground state energy E_g of an impurity state.

If one chooses Eq.(4) as zero and replaces Eq.(7) by $\varphi(\rho) = \mathrm{e}^{\mathrm{i}\,\boldsymbol{k}\cdot\boldsymbol{\rho}}/\sqrt{2\pi\hbar}$, the ground state energy E_f for a free electron can be also derived by using the same process. Then, the binding energy of the impurity state can be written as

$$E_B(F) = E_f(F) - E_g(F). \tag{11}$$

The Stark energy shift of the impurity state is

$$\Delta E = E_g(F) - E_g(0). \tag{12}$$

3. Pressure and strain dependence of physical parameters

Under hydrostatic pressure P, the components of biaxial stress tensors are equal to $\varepsilon_{xx,\,i} = \varepsilon_{yy,\,i} = \varepsilon_{zz,\,i}$, and the Hooke's law gives a relationship between the components of uniaxial and biaxial strain tensor[12] $\varepsilon_{zz,\,i} = R^H \varepsilon_{xx,\,i}$ with coefficient

$$R^H = \frac{C_{11,\,i}(P) + C_{12,\,i}(P) - 2C_{13,\,i}(P)}{C_{33,\,i}(P) - C_{13,\,i}(P)} \quad (i = 1, 2), \tag{13}$$

where $C_{\alpha\beta,\,i}(P)$ is the pressure-dependent elastic constants for wurtzite nitrides and satisfies

$$C_{\alpha\beta,\,i}(P) = C_{\alpha\beta,\,i}(0) + \gamma_{\alpha\beta,\,i} P + \delta_{\alpha\beta,\,i} P^2. \tag{14}$$

In Eq.(14), coefficients $\gamma_{\alpha\beta,\,i}$ and $\delta_{\alpha\beta,\,i}$ were given in Ref.[13].

In a GaN/$Al_xGa_{1-x}N$ real heterojunction, the biaxial lattice-mismatch-induced strain is given as

$$\varepsilon_{xx,\,1} = \varepsilon_{yy,\,1} = \frac{a_2(P) - a_1(P)}{a_1(P)},$$
$$\varepsilon_{xx,2} = \varepsilon_{yy,2} = \frac{a_1(P) - a_2(P)}{a_2(P)}, \tag{15}$$

where the lattice constant dependence of hydrostatic pressure[14] satisfies

$$a_i(P) = a_i(0)\left(1 - \frac{P}{3B_{0,\,i}(P)}\right) \quad (i = 1, 2). \tag{16}$$

The bulk modulus $B_{0,i}(P)$ in a wurtzite structure is related to the elastic constants by

$$B_{0,i}(P) = \frac{[C_{11,\,i}(P) + C_{12,\,i}(P)]C_{33,\,i}(P) - 2C_{13,\,i}^2(P)}{C_{11,\,i}(P) + C_{12,\,i}(P) + 2C_{33,\,i}(P) - 4C_{13,\,i}(P)} \quad (i = 1, 2). \tag{17}$$

For wurtzites GaN and AlN, the lowest conduction band and the top of the valence band are situated at Γ point. Considering the effect of strain, hydrostatic pressure and the negative crystal field splitting without spin–orbit interaction, the energy gaps of GaN and AlN materials are[15]

$$E_{g,\,\mathrm{GaN}}(P, \vec{\varepsilon}) = E_{g,\,\mathrm{GaN}}(P) + 2(a_{1,\,\mathrm{GaN}} + b_{1,\,\mathrm{GaN}})\varepsilon_{xx,\,\mathrm{GaN}} + (a_{2,\,\mathrm{GaN}} + b_{2,\,\mathrm{GaN}})\varepsilon_{zz,\,\mathrm{GaN}}, \tag{18}$$

and

$$E_{g,\,\mathrm{AlN}}(P, \vec{\varepsilon}) = E_{g,\,\mathrm{AlN}}(P) + 2a_{1,\,\mathrm{AlN}}\varepsilon_{xx,\,\mathrm{AlN}} + a_{2,\,\mathrm{AlN}}\varepsilon_{zz,\,\mathrm{AlN}}, \tag{19}$$

where the pressure-dependent energy gaps is considered by the following expression[16]

$$E_{g,\,i}(p) = E_{g,\,i}(0) + \alpha_i P + \beta_i P^2. \tag{20}$$

In Eqs.(18) and (19), $a_{1,i}$ and $a_{2,i}$ are the deformation potentials of the interband transition, $b_{1,i}$ and $b_{2,i}$ are the same potentials with crystal field splitting. The energy gap of $Al_xGa_{1-x}N$ can be calculated with the SCPA[10]

$$E_{\mathrm{TMC}} = \frac{E_A E_B}{xE_A + (1-x)E_B}. \tag{21}$$

Since the ratio of the conduction band to valence band offset is given to be 65:20 in the strained wurtizite nitride QW,[17] the barrier height V_0 can be determined by

$$V_0 = 0.765(E_{g2} - E_{g1}), \tag{22}$$

where E_{g2} and E_{g1} are the energy gaps of $Al_xGa_{1-x}N$ and GaN, respectively.

The biaxial, uniaxial and hydrostatic pressure dependences of the effective masses[18] in the z direction and x–y plane of electron can be calculated by

$$\frac{m_{i,\alpha\alpha}^0}{m_{i,\alpha\alpha}(P)} = 1 + \frac{C_i}{E_{g,\,i}(P)} \quad (i = 1, 2; \quad \alpha = x, z), \tag{23}$$

where C_i is a fixed value for a given material with $P = 0$. The effective mass of $Al_xGa_{1-x}N$ can be obtained by the linear interpolation method.

In Eq.(5), under consideration of the biaxial, uniaxial and strain in a wurtzite structure modified by hydrostatic pressure, the dielectric constants and the phonon eigenfrequencies will also change.

The tensor components of the static dielectric constant κ_0 in a wurtzite structure are derived from a

generalized Lyddane–Sachs–Teller relation

$$\kappa_{0,\alpha\alpha} = \kappa_{\infty,\alpha\alpha}\left(\frac{\omega_{\mathrm{LO},\alpha\alpha}}{\omega_{\mathrm{TO},\alpha\alpha}}\right)^2 \quad (\alpha = x, z), \tag{24}$$

where the certain tensor component ($\alpha = x$ or z denotes the displacement direction) is related to the frequencies of zone-center LO- and TO- phonons.

The frequencies of LO- and TO- phonons affected by strain can be written as[12]

$$\omega_{j,\alpha\alpha} = \omega_{j,\alpha\alpha}(0) + 2K_{j,\parallel}\varepsilon_{\parallel} + K_{j,\perp}\varepsilon_{\perp} \parallel (j = A_1, E_1), \tag{25}$$

where $K_{j,\parallel}$ and $K_{j,\perp}$ are the strain coefficients related to the deformation potential of phonon modes.

Furthermore, the hydrostatic pressure dependence of $\omega_{j,\alpha\alpha}$ can be determined by the given mode-Grüneisen parameters

$$\gamma_{j,\alpha\alpha} = B_0\frac{1}{\omega_{j,\alpha\alpha}}\frac{\partial\omega_{j,\alpha\alpha}(P)}{\partial P}. \tag{26}$$

The influence of hydrostatic pressure on the high frequency dielectric constants in Eq.(23), following the relation given in Ref.[19], can be rewritten as

$$\frac{\partial\kappa_{\infty,\alpha\alpha}(p)}{\partial p} = -\frac{5(\kappa_{\infty,\alpha\alpha}-1)}{3B_0}(0.9 - f_i), \tag{27}$$

where f_i is the ionicity of the material under pressure. Then the hydrostatic-pressure-modified biaxial and uniaxial strain dependence of the static dielectric constants is fully considered, whereas the dielectric constant of $Al_xGa_{1-x}N$ can be calculated by the SCPA[10]

$$\kappa_{\mathrm{TMC}} = [((1-x)m_B\kappa_A^2 + xm_A\kappa_B^2) \times (x/m_A + (1-x)/m_B)]^{1/2}. \tag{28}$$

4. Numerical results and discussion

We have computed the binding energies of impurity states in a hexagonal $GaN/Al_xGa_{1-x}N$ heterojunction with biaxial and uniaxial free strain by considering hydrostatic pressure effect with an external electric field.

The parameters used in our computation are listed in Tables 1 and 2.

Table 1. Parameters used in the computation.

materials	a	E_g	α	β	C_{11}	C_{12}	C_{13}	C_{33}
GaN	3.189[a]	3.507[a]	39[b]	–0.32[b]	366[c]	139[c]	98[c]	403[c]
AlN	3.122[a]	6.23[a]	40[b]	–0.32[b]	397[c]	143[c]	112[c]	372[c]

[a]Ref.[20], [b]Ref.[16], [c]Ref.[13]

Table 2. Parameters used in the computation.

materials	$\kappa_{\infty,xx}$	$\kappa_{\infty,zz}$	$\omega_{\mathrm{LO},xx}$	$\omega_{\mathrm{LO},zz}$	$\omega_{\mathrm{TO},xx}$	$\omega_{\mathrm{TO},zz}$	$\gamma_{\mathrm{LO},xx}$	$\gamma_{\mathrm{LO},zz}$	$\gamma_{\mathrm{TO},xx}$	$\gamma_{\mathrm{LO},zz}$
GaN	5.20[d]	5.39[d]	757[e]	748[e]	568[e]	540[e]	0.91[e]	0.82[e]	1.18[e]	1.02[e]
AlN	4.30[d]	4.52[d]	924[e]	898[e]	677[e]	618[e]	0.99[e]	0.98[e]	1.19[e]	1.21[e]

[d]Ref.[12], [e]Ref.[6]

The results for the binding energies of donor-impurity states in a free strained wurtzite $GaN/Al_xGa_{1-x}N$ heterojunction with the [0001] orientation as functions of impurity position z_0 are illustrated in Fig.1. From Fig.1(a), it can be seen that there always is a maximum for the binding energy E_B with respect to z_0 under different electric fields. The detailed explanation of the maximum with zero field was given in Ref.[11]. The electric field F has an opposite effect on the electron bound to a donor. On the one hand, when the impurity is located near the interface and the electronic average position $\overline{z}$ is larger than the impurity position z_0, E_B may increase with F since it enforces the electron moving towards the donor then to increase the Coulomb interaction. On the other hand, E_B decreases when $\overline{z}$ is less than z_0 since F enforces the electron moving far away from the donor to decrease the Coulomb interaction. Both of the tendencies surely become obvious with an increase of F. As a result, when z_0 is less than a certain value, a blue Stark shift appears, whereas a red Stark shift appears when z_0 exceeds a certain value and both of the shifts are remarkable with increase of F.

This indicates that the electric field increases the two-dimensional (2D) character for the impurity state and is similar to that in a QW and is in contrast to the common result of decreasing E_B in an electric field for a bulk material. Furthermore, the maximum also moves towards a less z_0 as increasing F since it together with the band bending counteracts the repulsion from the interface potential. In Fig.1(b), the Stark energy shift of binding energy for a donor impurity state as a function of z_0 under different electric fields is given to show the shift increases with F. This result agrees with the result shown in Fig.1(a).

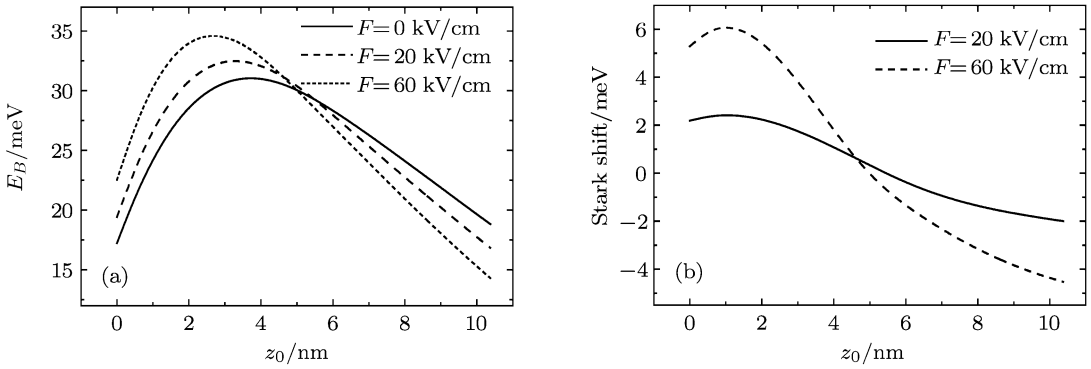


Fig.1. (a) Binding energies and (b) Stark shift of the impurity states in a free strained wurtzite $GaN/Al_xGa_{1-x}N$ heterojunction with the [0001] orientation as functions of impurity position z_0 under different electric fields.

Figure 2 shows the Stark shift of E_B as a function of the electric field for different impurity positions. From Fig.2(a), it can be clearly seen a non-monotonous blue (red) shift of the Stark effect as increasing F when the impurity is located at the channel side with some typical values when $\overline{z}$ is larger (less) than z_0. It is evident that E_B is determined not only by the confinement from the interface potential and band bending, but also by the effect of the electric field which makes the Coulomb interaction stronger or weaker decided by the relative position between $\overline{z}$ and z_0.

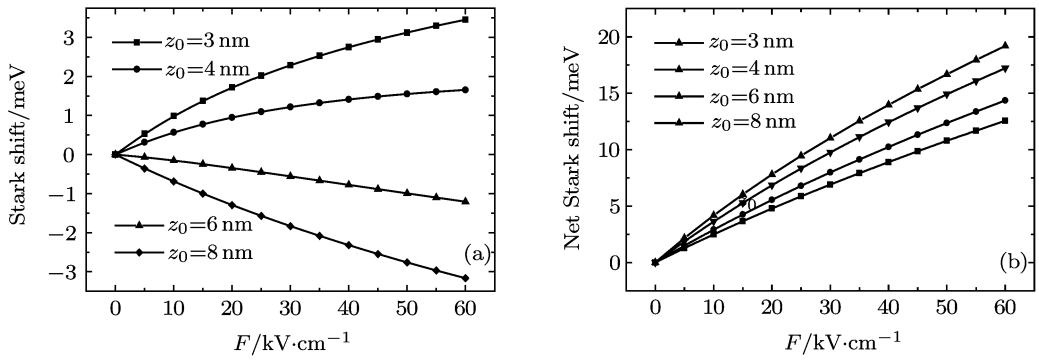


Fig.2. The Stark energy shift of a donor impurity located at different positions as a function of the electric field.

In Fig.2(b), the results of the net Stark shift compared with Fig.2(a) are shown. The net Stark shift[21] is defined as $\Delta E_{\rm net} = E(F) - E(0) = \Delta E_f - \Delta E_B$, where $\Delta E_f = E_f(F) - E_f(0)$ and $\Delta E_B = E_B(F) - E_B(0)$. Though both the binding energy and the energy induced by the electric field for an impurity at different positions have the same tendency with increasing F, the change of the former is much larger than that of the latter. As a result, the net shift increases with F. On the other hand, the net shift also increases when the impurity is located farther from the interface. Furthermore, by our calculation it was also found that the binding energy presents a non-monotonously blue shift as the impurity position located in the barrier side. The result has not been given here for the sake of reducing page length.

The relation between E_B and hydrostatic pressure P was also calculated and is shown by Fig.3. It can be seen clearly that P nearly linearly increases E_B due to the comprehensive effect from P on physical parameters such as dielectric constants, phonon frequencies, electronic effective masses, barrier height, and conduction energy band bending. When P ranges from 0 to 10 GPa, the net increments of E_B are 3.441, 4.136, 3.187 meV, and 1.79 meV with percentages of 14.56%, 13.31%, 10.63% and 7.43% for $z_0 = 1$, 3, 5 nm and 8 nm, respectively. A decrease appears as the distance between the impurity and interface increases due to the comprehensive effect of P on the physical parameters to influence E_B.

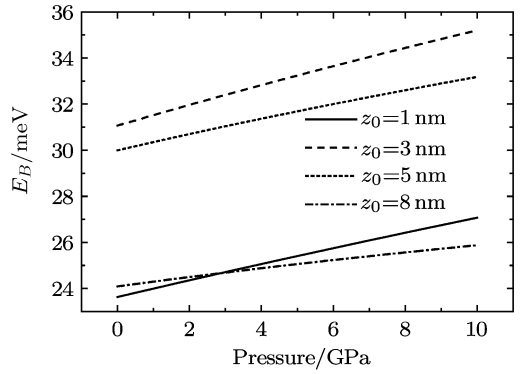


Fig.3. The binding energy as a function of hydrostatic pressure for different impurity positions.

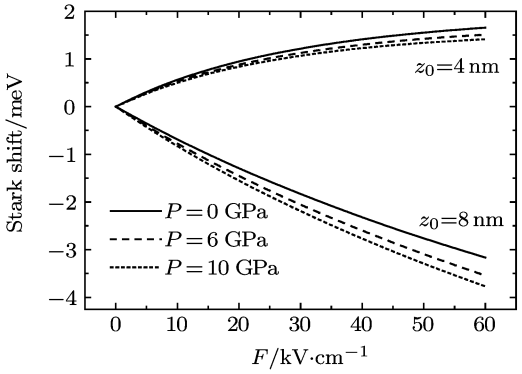


Fig.4. The Stark energy shift of a donor impurity as a function of the electric field for different hydrostatic pressures.

We present the pressure influence on the Stark effect as a function of the electric field by Fig.4. It can be seen that P decreases the blue shift as $z_0 = 4$ nm, whereas increases the red shift as $z_0 = 8$ nm. Pressure has an opposite effect with F to influence E_B as increasing z_0 since one of the effect of P is to increase the interface potential (heightens the barrier height). On the one hand, when the impurity is located near the interface and $\overline{z}$ is larger than z_0, E_B decreases since the potential enforces the electron moving far away from the donor then to decrease the Coulomb interaction. On the other hand, E_B increases when $\overline{z}$ is less than z_0 since the potential enforces the electron moving near the donor to increase the Coulomb interaction. This effect may be weakened as z_0 increases, whereas the other effect from P may increase E_B for a fixed z_0 due to the influence from P on the effective mass of an electron and dielectric constant. As a result, the influence from P on the shift is more obvious with increase of F and z_0.

For the given areal electronic density $n_s = 4.0 \times 10^{12}/\mathrm{cm}^2$ and $z_0 = 3$ nm and 10 nm, respectively, the curves in Fig.5 show that the Al component x influences on the Stark effect as a function of the electric field for $P = 0$ GPa. One can see that the influence of x on the Stark effect becomes more significant as x increases since it heightens the interface potential and it has an opposite effect with F on E_B as discussed above. The dependence of E_B on x is more sensitive as decrease of z_0. When $z_0 = 3$ nm and F ranges from 0 to 60 kV/cm, the Stark effect changes from 0 meV to 3.136, 3.823 and 4.163 meV for $x = 0.2$, 0.5 and 0.8, respectively. As $z_0 = 10$ nm, the red shift changes from 0 meV to –4.194, –4.589 and –4.710 meV for $x = 0.2$, 0.5 and 0.8, respectively. It indicates that the effect of increasing x on the blue shift is more significant than that on the red shift when an impurity is near the interface.

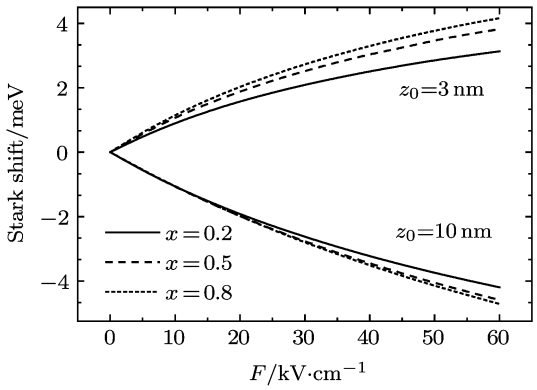


Fig.5. The Stark energy shift of a donor impurity as a function of the electric field for different Al components under zero pressure.

In Fig.6, we display that E_B as a function of areal electronic density n_s varies with electric field F for $z_0 = 4$ nm. As discussed above, F is helpful for the binding of the electron to the impurity since $\overline{z} > z_0$. For a given interface potential, n_s strengthens

the band bending and the 2D character of the impurity state then increases E_B. The superposition of the two effects result in that E_B increases obviously and nonlinearly with n_s and its influence on E_B becomes less and less with increasing F because the interface potential has a strong repulsion to restrict the increase of E_B for larger F and n_s.

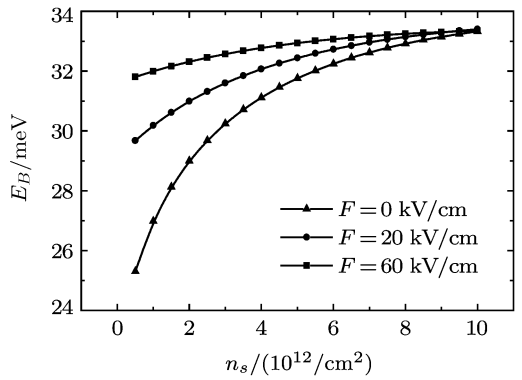


Fig.6. Binding energy as a function of areal electronic density for different electric fields for $z_0 = 4$ nm.

5. Conclusion

In conclusion of this paper, by making use of a variational method, we have investigated the quantum confined Stark effect of an external electric field on the binding energies of the donor impurity states in wurtzite nitride heterojunctions of $GaN/Al_xGa_{1-x}N$ with free strain under hydrostatic pressure from 0 to 10 GPa. A simplified coherent potential approximation is extended to calculate the band-gap and the high frequency dielectric constant for ternary mixed crystals. It is found that the binding energy shows a red shift or a blue shift with different impurity positions. Particularly, the Stark shifts are sensitive to the changes of hydrostatic pressure and the Al component x. The increase of pressure decreases the blue shift but increases the red shift. The effect of increasing x on blue shift is more significant than that on the red shift when the impurity is located near the interface.

References

[1] Jogai B 1998 *Phys. Rev.* B **57** 2382
[2] Shi J J 2003 *Phys. Rev.* B **68** 165335
[3] Perlin P, Gorczyca I, Suski T, Wisniewski P, Lepkowski S, Christensen N E, Svane A, Hansen M, DenBaars S P, Damilano B, Grandjean N and Massies J 2001 *Phys. Rev.* B **64** 115319
[4] Vaschenko G, Patel D, Menoni C S, Gardner N F, Sun J, Götz W, Tomé C N and Clausen B 2001 *Phys. Rev.* B **64** 241308
[5] Łepkowski S P and Majewski J A 2006 *Phys. Rev.* B **74** 035336
[6] Wagner J M and Bechstedt F 2000 *Phys. Rev.* B **62** 4526
[7] Goñi A R, Siegle H, Syassen K, Thomsen C and Wagner J M 2001 *Phys. Rev.* B **64** 035205
[8] Ban S L and Liang X X 2001 *J. Lumines.* **94-95** 417
[9] Zhao G J, Liang X X and Ban S L 2003 *Phys. Lett.* A **319** 191
[10] Ban S L and Hasbun J E 1999 *Eur. Phys. J.* B **8** 453
[11] Ban S L and Hasbun J E 1999 *Phys. Rev.* B **59** 2276
[12] Wagner J M and Bechstedt F 2002 *Phys. Rev.* B **66** 115202
[13] Łepkowski S P 2007 *Phys. Rev.* B **75** 195303
[14] Perlin P, Mattos L, Shapiro N A, Kruger J, Wong W S, Sands T, Cheung N W and Weber E R 1999 *J. Appl. Phys.* **85** 2385
[15] Shan W, Hauenstein R J, Fischer A J, Song J J, Perry W G, Bremser M D, Davis R F and Goldenberg B 1996 *Phys. Rev.* B **54** 13460
[16] Christensen N E and Gorczyca I 1994 *Phys. Rev.* B **50** 4397
[17] Nardelli M B, Rapcewicz K and Bernholc J 1997 *Phys. Rev.* B **55** R7323
[18] Ting D Z-Y and Chang Y C 1987 *Phys. Rev.* B **36** 4359
[19] Goñi A R, Syassen K and Cardona M 1990 *Phys. Rev.* B **41** 10104
[20] Vurgaftman I, Meyer J R, Ram-Mohan L R 2001 *J. Appl. Phys.* **89** 5815
[21] Li K H, Zhang Y T and Li Y C 2004 *Chin. Phys. Lett.* **21** 1616