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Optimization of a solar-blind and middle infrared two-colour photodetector using GaN-based bulk material and quantum wells*

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This paper calculates the wavelengths of the interband transitions as a function of the Al mole fraction of $Al_xGa_{1-x}N$ bulk material. It is finds that when the Al mole fraction is between 0.456 and 0.639, the wavelengths correspond to the solar-blind (250 nm to 280 nm). The influence of the structure parameters of $Al_yGa_{1-y}N$/GaN quantum wells on the wavelength and absorption coefficient of intersubband transitions has been investigated by solving the Schrödinger and Poisson equations self-consistently. The Al mole fraction of the $Al_yGa_{1-y}N$ barrier changes from 0.30 to 0.46, meanwhile the width of the well changes from 2.9 nm to 2.2 nm, for maximal intersubband absorption in the window of the air ($3\ \mu m < \lambda < 5\ \mu m$). The absorption coefficient of the intersubband transition between the ground state and the first excited state decreases with the increase of the wavelength. The results are finally used to discuss the prospects of GaN-based bulk material and quantum wells for a solar-blind and middle infrared two-colour photodetector.

Keywords: quantum well, two-colour detector, intersubband transition

PACC: 4280S, 7820J, 7830G

1. Introduction

Ultraviolet (UV) photodetectors are an interesting subject due to a variety of current and potential applications in the military, industrial and scientific areas.[1,2] With a wide, direct band gap ranging from 365 nm to 200 nm, $Al_xGa_{1-x}N$ covers much of the UV wavelength range. For the wavelength range of about 250–280 nm, the atmosphere strongly absorbs solar radiation, making this wavelength regime "solar-blind". It is important in the military for missile threat warning systems and jet engine monitoring.[3,4] Meanwhile, the intersubband transitions (ISBTs) in semiconductor quantum wells have attracted significant interest over the past few years owing to the possible applications in ultrafast optoelectronic devices, such as all-optical switches for optical communication networks, near-infrared photodetectors, and quantum cascade lasers.[5−9] The ISBTs in $Al_yGa_{1-y}N$/GaN quantum wells (QWs) are shown to be advantageous over other III–V semiconductor ones due to the large conduction band offset at $Al_yGa_{1-y}N$/GaN heterointerfaces, the large LO-phonon energy, and the large electron effective mass in GaN. These properties make the ISBTs in $Al_yGa_{1-y}N$/GaN QWs have a shorter wavelength and a shorter carrier relaxation time in comparison with those in other III–V semiconductor QWs.[10−12]

Multispectral cameras operating in entirely different wavelength ranges such as UV and the infrared (IR) wavelength ranges are attracting increasing interest for applications in surveillance, failure analysis, and meteorology.[13] A photoconductive UV interband detector based on an $Al_{0.65}Ga_{0.35}N$ thin film and a photovoltaic near-IR intersubband detector based on an AlN/GaN superlattice has been realized.[13] This is important to realize the two-colour detector in which the wavelength of the UV detector is chosen in the solar-blind range (250 nm to 280 nm) and that of the infrared detector is chosen in the windows of the air ($3\ \mu m < \lambda < 5\ \mu m$). In this paper, the wavelengths of the interband transitions as a function of the Al mole fraction of $Al_xGa_{1-x}N$ bulk material is calculated and the influence of the structure parameters of $Al_yGa_{1-y}N$/GaN QWs on the wavelength and absorption coefficient of ISBTs has been investigated by

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solving the Schrödinger and Poisson equations self-consistently.

2. Theoretical calculation

In the calculation, the band gap is chosen to be 3.4 eV for GaN and 6.2 eV for AlN, respectively.[14] Parameters for $Al_xGa_{1-x}N$ are calculated from Vegard's rule. The energy of the interband transition as a function of the Al mole fraction of $Al_xGa_{1-x}N$ bulk material is calculated by the following formula:[14]

$$E_g(Al_xGa_{1-x}N) = 6.2x + 3.4(1-x) - x(1-x). \quad (1)$$

Meanwhile, the absorption coefficients of the ISBTs in the conduction band of $Al_yGa_{1-y}N$/GaN QWs can be expressed as a function of ω by the following formula:[15]

$$\alpha(\omega) = \frac{\omega}{L}\sqrt{\frac{\mu_0}{\varepsilon_0\varepsilon_r}}\sum_{m>n}\frac{|M_{mn}|^2[N_n - N_m](\hbar/\tau)}{[E_m - E_n - \hbar\omega]^2 + (\hbar/\tau)^2}, \quad (2)$$

where μ_0 is the permeability in vacuum, ε_0 the dielectric constant in vacuum, ε_r the relative dielectric constant, L the total QW width, $\hbar$ the reduced Planck constant, τ the dephasing time, and M_{mn} the dipole matrix. τ is assumed to be 20 fs in the calculation.[11] M_{mn} is given by

$$M_{mn} = \int_{-L/2}^{L/2}\psi_m^*(z)ez\psi_n(z)\,\mathrm{d}z, \quad (3)$$

where e is the electronic charge, N_i the total electrons residing in the i-th subband level, E_i and ψ_i $(i = m, n)$ the energy level and the wave function of the i-th subband, respectively. They are obtained by solving the Schrödinger and Poisson equations self-consistently,

$$-\frac{\hbar^2}{2}\frac{\mathrm{d}}{\mathrm{d}z}\left[\frac{1}{m^*(z)}\frac{\mathrm{d}}{\mathrm{d}z}\psi_i(z)\right] + \left[\frac{\Delta E_c}{e} + V_{xc}(z) - e\phi_H(z)\right]\psi_i(z) = E_i\psi_i(z), \quad (4)$$

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[\varepsilon_0\varepsilon_r\frac{\mathrm{d}}{\mathrm{d}z}\phi_H(z)\right] = -e\left[N_D^+(z) - n_{2D}(z) + \delta(z)\Delta P\right], \quad (5)$$

$$V_{xc}(z) = -0.985\frac{e^2}{4\pi\varepsilon_0\varepsilon_r}n_{2D}^{1/3}(z)\left\{1 + \frac{0.034}{\alpha_H^* n_{2D}^{1/3}(z)}\ln\left[1 + 18.376a_H^* n_{2D}^{1/3}(z)\right]\right\}, \quad (6)$$

where z is the space coordinate along the growth direction, $m^*(z)$ the position-dependent effective mass, ΔE_c the conduction band offset, $\phi_H(z)$ the Hartree potential due to the electrostatic interaction, $V_{xc}(z)$ the exchange correlation potential, $a_H^* = 4\pi\varepsilon_0\varepsilon_r\hbar^2/m^*(z)e^2$, $\delta(z)$ the Delta function, ΔP the polarization field discontinuity at the heterointerface, $N_D^+(z)$ the ionized donor density, $n_{2D}(z)$ the two-dimensional (2D) electron density in all subbands. Under the equilibrium condition, $n_{2D}(z)$, and N_i are given by the formulas as follows, respectively[15]

$$\begin{aligned} n_{2D}(z) &= \sum_i n_{2D_i}(z) \\ &= \sum_i \frac{m_i^* KT}{\pi\hbar^2}|\psi_i(z)|^2\ln\left[1 + \exp\left(\frac{E_f - E_i}{KT}\right)\right], \end{aligned} \quad (7)$$

$$N_i = \int n_{2D_i}(z)\,\mathrm{d}z, \quad (8)$$

where K is the Boltzmann constant, T the absolute temperature, m_i^* the effective mass of electrons residing in the i-th subband level, for simplicity, the same effective mass is used in the well, E_f the Fermi level, $N_C(z)$ the 3D density of states and $F_{1/2}$ the Fermi–Dirac integral. In the calculation, the initial potential profile is assumed to be a rectangular potential profile. In order to ensure constringency of solving the Schrödinger and Poisson equations self-consistently, the potential profile of the next iteration is recalculated from a linear combination of new and old values of the potential profiles. The detailed self-consistent procedure can be found elsewhere.[16]

3. Results and discussion

The minimum of the conduction band profile (Dot L_1 in Fig.2) of $Al_yGa_{1-y}N$/GaN QWs is defined as the zero reference energy. Under the assumption of the periodic potential model, the charge neutrality condition is adopted, which means that the sum of the charges in a periodic $Al_yGa_{1-y}N$/GaN QWs is zero. The struc-

ture of $Al_yGa_{1-y}N$/GaN QWs used in the calculation is 10 nm $Al_xGa_{1-x}N/L_w$ nm GaN. The total polarization field discontinuities (ΔP) are chosen to be:[15] $\Delta P = 0.0168$ C/m^2. The doping concentration in the left barrier is assumed to be 5×10^{18} cm^{-3}.

The sample structure in the calculation is as follows. First, a 300-nm thick Si-doped $Al_xGa_{1-x}N$ bulk material layer was grown on an AlN-on-sapphire template. Then, regular 50 period $Al_yGa_{1-y}N$/GaN QWs with 10 nm Si-doped $Al_yGa_{1-y}N$ barriers ([Si] $= 5 \times 10^{18}$ cm^{-3}) are calculated. By using reactive ion etching, the wafer was then mesa-structured. The UV detectors were fabricated in those areas where the QWs had been etched down to the $Al_xGa_{1-x}N$ bulk material layer. The IR detectors were fabricated by using the $Al_yGa_{1-y}N$/GaN QWs. Figure 1 shows the wavelengths of the interband transitions as a function of the Al mole fraction of $Al_xGa_{1-x}N$ bulk material. It is found that when the Al mole fraction is between 0.456 and 0.639, the wavelengths correspond to the solar-blind (250 nm to 280 nm).

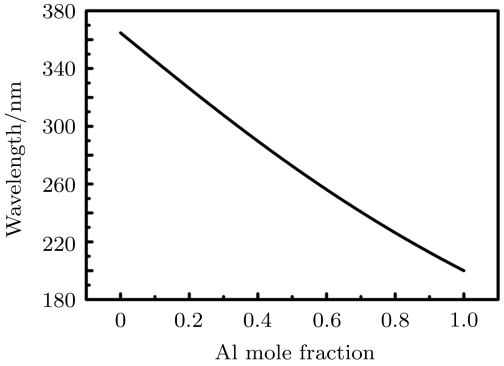


Fig.1. The wavelengths of the interband transitions as a function of the Al mole fraction of $Al_xGa_{1-x}N$ bulk material.

Figure 2 shows the schematic conduction band profile of $Al_{0.37}Ga_{0.63}N$/GaN QWs and the moduli square of the wave functions. $Al_yGa_{1-y}N$/GaN QWs are lattice-mismatched systems (~2.5% for AlN/GaN) and have a strong piezoelectric effect and spontaneous polarization. The polarization-induced electric fields result in the asymmetry of the conduction band profile of the $Al_{0.37}Ga_{0.63}N$/GaN QWs. The wave functions are localized in one side of the well, meanwhile the energy difference between the ground state and the first excited state blue shifts, due to the quantum confined Stark effect (QCSE).[17]

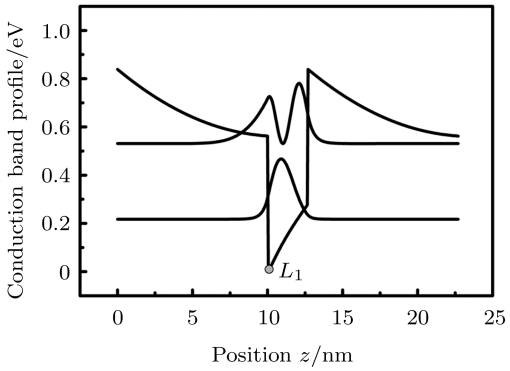


Fig.2. Schematic conduction band profile of $Al_{0.37}Ga_{0.63}N$/GaN QWs and the moduli square of the wave functions.

Figure 3 shows contour plot of both the ISBT wavelengths (dashed line, unit: nm) and the absorption coefficient between the ground state and the first excited state (solid line, unit: m^{-1}) in a single QW structure as functions of the relevant structural parameters (the well width L_w and the Al mole fraction y in the barrier layer). A fixed value of the barrier width is chosen to be 10 nm since it does not influence the results much. In order to give specific examples, the cases of 3 μm $\sim$ 5 μm are considered, which are important in applications. The structural parameters which deliver the 3-μm intersubband absorption can be read from the dashed line labelled 3000 (in units of nm). Any choice along this line gives the same wavelength, but the absorption coefficients vary. Usually one aims at having the largest possible absorption coefficient, and the optimal structural parameters occur where a solid line just touches the 3000 dashed line. In this case, it is obtained with $L_w = 2.9$ nm and

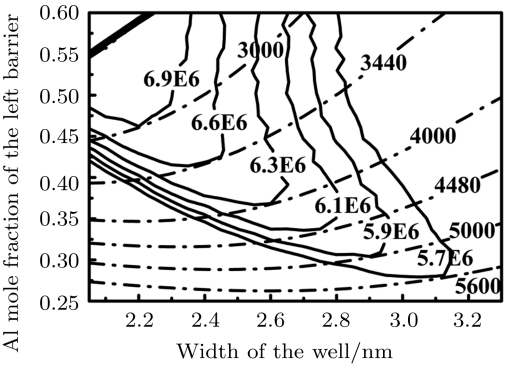


Fig.3. The contour plots of the transition wavelengths (dashed line, unit: nm) and the absorption coefficients between the ground state and the first excited state (solid line, unit: m^{-1}).

$y = 0.30$. Similarly, one can see from the figure that the absorption at 4 μm and 5 μm can be achieved for

$L_w = 2.6$ nm, 2.2 nm and $y = 0.37$, 0.46, respectively. Along with the optimal parameters, the figure shows the range of parameters which can provide any (suboptimal) structure for a given wavelength, and also indicates where it is sensitive to a parameter. The absorption coefficient of the ISBT between the ground state and the first excited state decreases from 6.9×10^6 m^{-1} to 5.9×10^6 m^{-1} with the increase of the wavelength from 3 μm to 5 μm.

4. Conclusions

In conclusion, the wavelengths of the interband transitions as a function of the Al mole fraction of $Al_xGa_{1-x}N$ bulk material are calculated. It is found that when the Al mole fraction is between 0.456 and 0.639, the wavelengths correspond to the solar-blind (250 nm to 280 nm). The influence of structure parameters of $Al_yGa_{1-y}N$/GaN QWs on the wavelength and absorption coefficient of the ISBTs has been investigated by solving the Schrödinger and Poisson equations self-consistently. The Al mole fraction of the $Al_yGa_{1-y}N$ barrier changes from 0.30 to 0.46, meanwhile the width of the well changes from 2.9 nm to 2.2 nm, for maximal intersubband absorption in the window of the air (3 μm $< \lambda <$ 5 μm). The absorption coefficient of the ISBT between the ground state and the first excited state decreases with the increase of the wavelength. The results are finally used to discuss the prospects of GaN-based bulk material and QWs for a solar-blind and middle IR two-colour photodetector.

References

[1] Khan M A, Kuznia J N, Olson D T, Blasingame M and Bhattarai A R 1993 *Appl. Phys. Lett.* **63** 2455

[2] Razeghi M and Rogalski A 1996 *J. Appl. Phys.* **79** 7433

[3] Sandvik P, Mi K, Shahedipour F, McClintock R, Yasan A, Kung P and Razeghi M 2001 *J. Crystal Growth* **231** 366

[4] Razeghi M 2002 *Proceedings of the IEEE* **90** 1006

[5] Gmachl C, Ng H M and Cho A Y 2001 *Appl. Phys. Lett.* **79** 1590

[6] Tchernycheva M, Nevou L, Doyennette L, Julien F H, Guillot F, Monroy E, Remmele T and Albrecht M 2006 *Appl. Phys. Lett.* **88** 153113

[7] He Z, Kang Y, Tang Y W, Li X and Fang J X 2006 *Chin. Phys.* **15** 1325

[8] Liu Z, Wang X L, Wang J X, Hu G X, Guo L C and Li J M 2007 *Chin. Phys.* **16** 1467

[9] Zhou J J, Jiang R L, Sha J, Liu J, Shen B, Zhang R and Zheng Y D 2003 *Chin. Phys.* **12** 785

[10] Suzuki N and Iizuka N 1997 *Jpn. J. Appl. Phys.* Part 2 **36** L1006

[11] Tchernycheva M, Nevou L, Doyennette L, Julien F H, Warde E, Guillot F, Monroy E, Bellet-Amalric E, Remmele T and Albrecht M 2006 *Phys. Rev.* B **73** 125347

[12] Lei S Y, Shen B and Zhang G Y 2008 *Acta Phys. Sin.* **57** 2386 (in Chinese)

[13] Hofstetter D, Theron R, Baumann E, Giorgetta F R, Golka S, Strasser G, Guillot F and Monroy E 2008 *Electron. Lett.* **44** 986

[14] Ambacher O, Smart J, Shealy J R, Weimann N G, Chu K, Murphy M, Schaff W J, Eastman L F, Dimitrov R, Wittmer L, Stutzmann M, Rieger W and Hilsenbeck J 1999 *J. Appl. Phys.* **85** 3222

[15] Lei S Y, Shen B, Cao L, Xu F J, Yang Z J, Xu K and Zhang G Y 2006 *J. Appl. Phys.* **99** 074501

[16] Ali A E and Klaus S 1993 *J. Appl. Phys.* **74** 3273

[17] Takeuchi T, Wetzel C, Yamaguchi S, Sakai H, Amano H and Akasaki I 1998 *Appl. Phys. Lett.* **73** 1691