Research Article

Optical Investigation of p-GaAs/i-GaN$_{0.38y}$As$_{1-1.38y}$Sb$_y$/n-GaAs Quantum Wells Emitters

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We have studied the 1.55 $\mu$m optical properties of p-GaAs/i-GaN$_{0.38y}$As$_{1-1.38y}$Sb$_y$/n-GaAs quantum wells using a self-consistent calculation combined with the anticrossing model. We have found that the increase of injected carriers’ density induces the increase of optical gain and radiative current density. The rise of doping density causes a blue shift of the fundamental transition energy accompanied with significant increase of optical gain. The quantum-confined Stark effect on radiative current density is also studied. The variation of radiative current as function of well width and Sb composition is also examined. In order to operate the emission wavelength at the optical fiber telecommunication domain, we have adjusted the well parameters of p-GaAs/i-GaN$_{0.38y}$As$_{1-1.38y}$Sb$_y$/n-GaAs.

1. Introduction

Antimony-based III-V semiconductors have a great interest in the field of optoelectronics for the design of long wavelength infrared detection devices [1–3]. In fact, these compounds reveal motivated electrical and optical properties, especially a significant reduction of the gap covering the telecom and the long infrared domains [4, 5]. Technological progress in growth techniques, such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition, offers the opportunity to control the incorporation of small Sb or N amounts into GaAs host matrix. In fact, the incorporated N atom induces a strong band gap reduction around 180 meV/%N [6–10]. As proof of this behavior, Chakir et al. [7] have studied the band structure reconstruction of GaAs$_{1-x}$N$_x$ using the 10 $\times$ 10 band anticrossing (BAC) model. Similarly, the incorporation of Sb leads to a band gap reduction of about 16 meV/%Sb [11, 12]. Alberi et al. [11] have used the 12 $\times$ 12 BAC model to calculate the valence bands in GaAs$_{1-x}$Sb$_x$ material. Consequently, the simultaneous incorporation of N and Sb into GaAs matrix accelerates the ratio of the band gap reduction. Experimental reported works [12–15] indicate that the band gap of GaAs$_{0.89}$N$_{0.03}$Sb$_{0.09}$ material reaches a low value of 0.835 eV. Also, many research groups have succeeded in developing thin film structures based on GaAs$_{1-x-y}$N$_x$Sb$_y$/GaAs quantum wells using a self-consistent calculation combined with the anticrossing model. We have found that the increase of injected carriers’ density induces the increase of optical gain and radiative current density. The rise of doping density causes a blue shift of the fundamental transition energy accompanied with significant increase of optical gain. The quantum-confined Stark effect on radiative current density is also studied. The variation of radiative current as function of well width and Sb composition is also examined. In order to operate the emission wavelength at the optical fiber telecommunication domain, we have adjusted the well parameters of p-GaAs/i-GaN$_{0.38y}$As$_{1-1.38y}$Sb$_y$/n-GaAs.
coefficient of GaNAsSb/GaAs double-QWs emitting at 1.55 μm is equal to 2 × 10⁵ cm⁻¹.

The purpose of this work is to investigate the optical gain and radiative current density of 1.55 μm p-GaAs/i-GaN0.38yAs1-0.62ySb/N-GaAs quantum wells emitters. We examined the dependence of optical gain on the injected carrier density and doping effect. In addition, the applied electric field, well width, and Sb composition effects on the radiative current density are also discussed.

2. Theory

In this part, we detail a theoretical model used to calculate the electronic and optical properties of p-GaAs/i-

\[
\left( -\frac{\hbar^2}{2m_{\text{th}}^*} \nabla^2 + \Delta U(z) + U_H(z) + U_{xc}(z) + eFz \right) \phi_k(z) = E_k \phi_k(z),
\]

where \( m_{\text{th}}^* \) is the effective masses of electrons or holes, \( E_k \) and \( \phi_k \) are, respectively, the \( k \)-th energy level and the envelope wavefunction, \( \phi_k(z) \) satisfies the boundary condition at the interface \( z_0 = 0 \) and \( z_0 = L_w \), \( N_d(z) \) and \( N_a(z) \) are, respectively, the ionized donor and acceptor doping concentrations, and \( n(z) \) and \( p(z) \) are the carrier densities of electrons and holes, respectively.

\[
G(E, E_p) = \frac{1}{L_w} e^2 \hbar \int_{0}^{\infty} dE_p \int_{E}^{E_p} |M_{ij}(E_p)|^2 \left( f_{\text{c}}^{in}(E_p) - f_{\text{c}}^{in}(E_p) \right) L^j_i(E, E_p) dE_p,
\]

where \( C \) and \( \varepsilon_0 \) are, respectively, the velocity of light and permitivity of free space, \( n \) and \( L_w \) are the refractive index and well width, respectively, \( L^j_i \) is the wave function envelope, \( \rho_{ij}^{2D} \) is the two-dimensional density state, \( |M_{ij}^2(E_p)|^2 \) is the optical transition matrix element between heavy hole subband \( h_i \) and electron subband \( e_j \) for TE polarization, \( L^j_i(E, E_p) \) is the Lorentzian line shape function, and \( f_{\text{c}}^{in}(E_p) \) and \( f_{\text{c}}^{in}(E_p) \) are, respectively, Fermi functions for the \( n \)-th subband in the conduction band and \( m \)-th subband in the valence band [28].

For an ideal laser without any nonradiative recombination processes, the radiative current density is given by the following formula [29]:

\[
J_{\text{rad}} = eL_wBN_f^2,
\]

where \( B \) and \( N_f \) are, respectively, the spontaneous radiative recombination coefficient and the injected carrier density [30].

\[
B = \frac{e^2 L_w nE_g |M_{avr}|^2}{m_0^* \varepsilon_0 c^3 k_B T m_{\text{th}}^* (1 + r)}
\]

The optical performances for p-GaAs/i-GaN0.38yAs1-0.62ySb/N-GaAs QW laser structures are estimated in terms of optical gain and radiative current density. The optical gain calculated at photon energy \( E \) is obtained with the contribution of the fundamental transitions \( T_{\text{fund}} \) for \( k_p = 0 \). It was described by the following expression [26, 27]:

\[
\text{J}_{\text{rad}}(E, E_p) = \frac{e^2}{\varepsilon_0 \varepsilon_r} \left( p(z) - N_d(z) + N_a(z) \right)
\]

The electronic band structure of p-GaAs/i-GaN0.38yAs1-0.62ySb/N-GaAs QW without and under an applied electric field \( F = 40 \text{kV/cm} \) is shown in Figure 1. The donor and acceptor doping concentrations are equal to \( 2 \times 10^{18} \text{cm}^{-3} \) and \( 3 \times 10^{18} \text{cm}^{-3} \), respectively. All calculations were performed with temperature 300 K as the input parameter. The Sb composition and well thickness are equal to \( y_{\text{Sb}} = 18.6% \) and \( L_w = 4 \text{ nm} \), respectively.

Figure 2 shows the variation of maximum gain \( G_{\text{max}} \) and radiative current density \( J_{\text{rad}} \) as function of the injected carrier density \( N_f \) for p-GaAs/i-GaN0.38yAs1-0.62ySb/N-GaAs quantum well structures. The optimized well parameters give rise to \( \lambda_{\text{c}} = 1.55 \mu \text{m} \). By increasing the injected carrier
compressive strains. Chen et al. [35] studied the dependence of gain maximum of W structure with 3 nm compressively strained GaAs$_{0.35}$Sb$_{0.65}$ layers for three different carriers' concentrations. For 3 nm InGaAsSb/3 nm GaAsSbBi quantum well laser is shown in Figure 3. It was significantly enhanced from $4 \times 10^{-10}$ to $6 \times 10^{-4} \text{ cm}^{-3}$ with increasing doping density from $5 \times 10^{-16}$ to $1.5 \times 10^{-17} \text{ cm}^{-3}$. Similarly, Kim et al. [21] reported the increase of optical gain as the function of doping densities of the GaSb$_{0.24}$As$_{0.76}$/In$_{0.06}$Ga$_{0.94}$As$_{0.06}$As$_{0.06}$/GaAs quantum well structure. They claim that this behavior can be explained by the fact that the optical matrix element increases with increasing doping density. Jiang et al. [37] examined the gain spectra for TE-polarized light, the n-doped Ge/GeSi quantum well under various n-type doping concentrations. They indicated that at low strain level, the optical gain could be enhanced when n-type doping concentration increases from $5 \times 10^{-10}$ to $5 \times 10^{-8} \text{ cm}^{-3}$. On the other hand, Huang et al. [38] studied the variation of maximum gain of Ge$_{0.9375-\alpha}$Sn$_{\alpha}$/In$_{0.25}$Ga$_{0.75}$As$_{0.06}$P$_{0.94}$, Ge$_{0.9375-\alpha}$Sn$_{\alpha}$/In$_{0.25}$Ga$_{0.75}$As$_{0.06}$Sb$_{0.94}$, Ge$_{0.9375-\alpha}$Sn$_{\alpha}$/In$_{0.25}$Ga$_{0.75}$Sb$_{0.94}$, and Ge$_{0.9375-\alpha}$Sn$_{\alpha}$/In$_{0.25}$Bi$_{0.94}$ as a function of doping concentration for an injected carrier density of $1 \times 10^{19} \text{ cm}^{-3}$. They illustrated that the gain increase as function of the optical gain and the effects of the doping elements on the optical gain of GeSn can be ranked as Bi > Sb > As > P.

We investigated the effect of the applied electric field on the radiative current density for p-GaAsSb/i-GaAsSb$_{0.38}$As$_{1-0.38}$Sb$_{0.38}$/n-GaAs quantum well structure operating at 1.55 µm telecommunication wavelength, as shown in Figure 4. The antimony composition and well thickness are $y_{Sb} = 18.6\%$ and $L_w = 4 \text{ nm}$, respectively. The radiative current density increases from 67.07 to 102.64 A/cm$^2$ when $F$ changes from 0 up to 40 kV/cm. This behavior was stated in our previous work [39] for p-GaAsSb/i-GaAsBi/n-GaAs QWs. We mentioned that the radiative current density varies from 101.3 to 515.3 A/cm$^2$, with increasing the electric field from 0 up to 40 kV/cm. The rise of the current density is also indicated by Mensfroort et al. [40] for blue polymer-based light-emitting diodes. They interpret this increase by the improvement of the net space charge density caused by the reduced recombination rate for small voltages.

The radiative current density $J_{rad}$ as well as the fundamental transition energy as function of well width $L_w$ is shown in Figure 5(a). $J_{rad}$ increases from 37.81 to 151.04 A/cm$^2$. The increase of $L_w$ from 4 to 4.5 nm induces a significant red-shift of fundamental transition energy from 802 to 774 meV. In another study, Bilel et al. [41] stated that the shift of the fundamental transition energy $E_{1s-h1}$ to lower energies can be explained by the modification of the electron and hole subbands under the effect of the applied electric field. To correct this shift, we adjusted the Sb composition $y_{Sb}$ for each used value of well width $L_w$. The optimized values of $y_{Sb}$ are, respectively, equal to 17.8 and 18.8% for 4 and 4.5 nm, as shown in Figure 5(b). The radiative current density varies from 47 to from 144.7 A/cm$^2$ at 1.55 µm telecommunication wavelength.
Figure 3: Optical gain as function of energy for different doping densities for p-GaAs/i-GaNAsSb/n-GaAs QW laser structure with $N_D$ equal to $5 \times 10^{16}$, $1 \times 10^{17}$, and $1.5 \times 10^{17}$ cm$^{-3}$. The Sb composition and well width are $y_{Sb} = 18.6\%$ and $L_w = 4$ nm, respectively.

Figure 4: The radiative current density as function of applied electric field $F$ varying from 0 up to 40 kV/cm for p-GaAs/i-GaNAsSb/n-GaAs QW structure operating at 1.55 µm telecommunication wavelength. The Sb composition and the well width are $y_{Sb} = 18.6\%$ and $L_w = 4.1$ nm, respectively.

Figure 5: (a) Variation of radiative current density and fundamental energy transition as function of well width. (b) The adjusted value of Sb composition and radiative current density at 1.55 µm.
4. Conclusion

The optoelectronic properties of 1.55 μm p-GaAs/i-GaN_{0.38}As_{1-0.38}Sb/n-GaAs quantum wells were theoretically investigated using a self-consistent calculation combined with an anticrossing model. The maximum of gain is enhanced with increasing the injected carrier density. The optical gain reaches the value 9.6 × 10^3 cm^{-1} for doping density equal to 1.5 × 10^{17} cm^{-3}. Moreover, the applied electric field significantly affects the radiative current density of the studied structure. The radiative current density is about 151.04 A/cm^2 for 4.5 nm well width. The fundamental transition energy \( E_{2\rightarrow 1} \) shifts from 28 meV to lower energies when the well width varies from 4 to 4.5 nm. We can conclude that the obtained results are advantageous to the design of p-i-n based GaNAsSb quantum well laser structures operating at 1.55 μm telecommunication wavelength.

Data Availability

The datasets used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] Y. Wei, A. Gin, and M. Razeghi, “Advanced InAs/GaSb superlattice photovoltaic detectors for very long wavelength infrared applications,” Applied Physics Letters, vol. 80, p. 3262, 2002.

[2] C. Jin, J. Chen, Q. Xu, C. Yu, and L. He, “Electrical and optical performances of InGaAs/GaSb superlattice short-wavelength infrared detectors,” Optical Engineering, vol. 56, no. 5, Article ID 057102, 2017.

[3] P. Deshmukh, J. Li, S. Nalamati, M. Sharma, and S. Iyer, “Molecular beam epitaxial growth of GaAsSb/GaAsSbN/GaAlAs core-multishell nanowires for near-infrared applications,” Nanotechnology, vol. 30, p. 275203, 2019.

[4] L. Ma, X. Zhang, H. Li et al., “Bandgap-engineered GaAsSb alloy nanowires for near-infrared photodetection at 1.31 μm,” Semiconductor Science Technology, vol. 30, Article ID 105033, 2015.

[5] E. Ahmad, M. Karim, S. Bin Hafiz, C. L. Reynolds, Y. Liu, and S. Iyer, “A two-step growth pathway for high Sb incorporation in GaAsSb nanowires in the telecommunication r-wavelength range,” Scientific Reports, vol. 7, Article ID 10111, 2017.

[6] J. Wu, W. Shan, and W. Walukiewicz, “Band anticrossing in highly mismatched III-V semiconductors alloys,” Semiconductor Science Technology, vol. 17, p. 860, 2002.

[7] K. Chakir, C. Bilel, M. M. Habchi, A. Rebey, and B. El Jari, “Theoretical study of the carrier effective mass in diluted III-V semiconductor alloys using 10-band k.p model,” Thin Solid Films, vol. 630, no. 25, 2017.

[8] I. Vurgaftman and J. R. Meyer, “Band parameters for nitrogen-containing semiconductors,” Journal of Applied Physics, vol. 94, no. 6, pp. 3675–3696, 2003.

[9] K. Uesugi, N. Morooka, and I. Suemune, “Reexamination of N composition dependence of coherently grown GaNAs band gap energy with high-resolution x-ray diffraction mapping measurements,” Applied Physics Letters, vol. 74, p. 1254, 1999.

[10] W. Shan, W. Walukiewicz, K. M. Yu et al., “Band anticrossing in III–N–V alloys,” Physical Status Solidi B, vol. 223, p. 75, 2001.

[11] K. Alberi, J. Wu, W. Walukiewicz et al., “Valence-band anticrossing in mismatched III-V semiconductor alloys,” Physical Review B, vol. 75, Article ID 045203, 2007.

[12] R. Teissier, D. Sicault, J. C. Harmand, G. Ungaro, G. Le Roux, and L. Largeau, “Temperature-dependent valence band offset and band-gap energies of pseudomorphic GaAsSb on GaAs,” Journal of Applied Physics, vol. 89, p. 5473, 2001.

[13] K. I. Lin, K. L. Lin, B. W. Wang, H. H. Lin, and J. S. Hwang, “Double-band anticrossing in GaAsSb induced by nitrogen and antimony incorporation,” Applied Physical Express, vol. 6, Article ID 121203, 2012.

[14] N. Ben Sedrine, C. Bouhafs, J. C. Harmand, R. Chitourou, and V. Darakchieva, “Effect of nitrogen on the GaAs_{0.9–x}N_{x}Sb_{0.1} dielectric function from the near-infrared to the ultraviolet,” Applied Physical Letter, vol. 97, Article ID 201903, 2010.

[15] C. Z. Zhao, H. F. Guo, T. Wei, S. S. Wang, and K. Q. Lu, “Composition dependence of the band gap energy for the dilute nitride and as-rich GaN_{x}Sb_{y}As_{1–x–y} (0 ≤ x ≤ 0.05, 0 ≤ y ≤ 0.3),” Physica B: Physics Conductor Matter, vol. 485, no. 35, 2016.

[16] J. C. Harmand, G. Ungaro, J. Ramos et al., “Investigations on GaAsSbN/GaAs quantum wells for 1.3–1.55 μm emission,” Journal of Crystal Growth, vol. 227, p. 553, 2001.

[17] J. C. Harmand, A. Caliman, E. V. K. Rao et al., “GaNAsSb: how does it compare with other dilute III-V-nitride alloys,” Semiconductor Science Technology, vol. 17, Article ID 778, 2002.

[18] Y. T. Lin, T. C. Ma, T. Y. Chen, and H. H. Lin, “Energy gap reduction in dilute nitride GaAsSb,” Applied Physics Letter, vol. 93, Article ID 171914, 2008.

[19] S. A. Lourenço, I. F. L. Dias, L. C. Poças, J. L. Duarte, J. B. de Oliveira, and J. C. Harmand, “Effect of temperature on the optical properties of GaAsSbN/GaAs single quantum wells grown by molecular-beam epitaxy,” Journal of Applied Physics, vol. 93, Article ID 4475, 2003.

[20] K. Ohtani, N. Matsumoto, H. Sakuma, and H. Ohno, “Intersubband absorption in n-doped InAs/AlSb multiple-quantum-well structures,” Applied Physics Letter, vol. 82, no. 37, 2003.

[21] J. J. Kim and S. H. Park, “Effects of modulation doping on the optical properties of a type-II 1.55-μm GaAsSbInGaNAs/GaAs trilayer quantum-well structure,” Journal of the Korean Physical Society, vol. 57, no. 826, 2010.

[22] K. H. Tan, S. F. Yoon, W. K. Loke et al., “High responsivity GaNAsSb p-i-n photodetectors at 1.3 μm grown by radio-frequency nitrogen plasma-assisted molecular beam epitaxy,” Optics Express, vol. 16, pp. 7720–7725, 2008.

[23] H. Luo, J. A. Gupta, and H. C. Liu, “1.55 μm GaAsSb photodetector on GaAs,” Applied Physics Letter, vol. 86, Article ID 211121, 2005.

[24] I. Guizani, C. Bilel, M. M. Habchi, and A. Rebey, “Optical gain spectra of 1.55 mm GaSb/GaSb_{1−0.5}Sb_{0.5} by GaAs single quantum well,” Superlattice and Microstructure, vol. 102, p. 141, 2017.
[25] I. Guizani, K. Chakir, M. M. Habchi, and A. Rebey, "Investigation of optical gain in 1.55 µm p-i-n GaNAsBi-based DQWs," Physical Status Solidi C, vol. 14, Article ID 1700163, 2017.

[26] A. M. Khan, "Tuning of gain spectra in GaAsSb/InGaAsHeterostructure," AIP Conference Proceedings, vol. 2220, Article ID 020008, 2020.

[27] S. H. Park, H. M. Kim, and J. J. Kim, "Threshold current density of 1.3-µm GaAsSb/GaInAs/GaAs Type-II trilayer quantum well lasers on GaAs substrates," Journal of the Korean Physical Society, vol. 50, Article ID 1018, 2007.

[28] C. Lok, L. YanVoon, and M. Willatzen, The k.P Method, Springer, New York, NY, USA, 2009.

[29] E. S. Kzal Mohammed Qader, "Threshold courant density of Al0.1Ga0.9N/GaN triple quantum well laser," Energy Procedia, vol. 157, no. 75, 2019.

[30] L. Ömer, "Revealing the effects of nitrogen on threshold current density in GaNxAsyP1-x-y/GaP/AlzGa1-zP type I QW laser structures by hydrostatic pressure," Physica E: Low-Dimensional Systems and Nanostructures, vol. 81, p. 760, 2016.

[31] H. Zhao, G. Liu, J. Zhang, R. A. Arif, and N. Tansu, "Current injection efficiency induced efficiency droop in InGaN quantum well light emitting diodes," Solid State Electron, vol. 54, Article ID 1119, 2010.

[32] S. Liu, S. L. Chuang, and S. Park, "Optical gain of strained GaAsSb/GaAs quantum-well lasers: a self-consistent approach," Journal of Applied Physics, vol. 88, Article ID 5554, 2000.

[33] S. H. Park, "Optical gain of 1.3 mm GaAsSb/NiAs quantum well lasers," IET Optoelectronics, vol. 1, no. 42, 2007.

[34] S. H. Park, "Optical gain characteristics in 1.55-µm GaAsSb/NiAs quantum well structures," Journal of the Korean Physical Society, vol. 50, p. 1152, 2007.

[35] B. Chen and A. L. Holmes Jr., "Optical gain modeling of InP based InGaAs(N)/GaAsSb type-II quantum wells laser for mid-infrared emission," Optical Quantum Electronics, vol. 45, p. 127, 2013.

[36] B. Chen, "Optical gain analysis of GaAs-based InGaAs/ GaAsSbBi type-II quantum wells lasers," Optics Express, vol. 25, Article ID 25183, 2017.

[37] J. Jiang and J. Sun, "Calculation of enhanced direct-gap optical gain in uniaxial tensile strained and n+-doped Ge/GeSi quantum well," Advanced Photonics, vol. paper ITu4A.1, 2016.

[38] W. Huang, H. Yang, B. Cheng, and C. Xue, "Theoretical study of the effect of different n-doping elements on band structure and optical gain of GeSn alloys," Physical Chemistry Chemical Physics, vol. 19, no. 39, pp. 27031–27037, 2017.

[39] I. H. Guizani and A. A. Rebey, "Spontaneous emission rate and radiative current density in p-GaAs/I-GaNAsBi/n-GaAs quantum well lasers," Journal of Computational and Theoretical Nanoscience, vol. 16, no. 11, pp. 4474–4478, 2019.

[40] S. L. M. van Mensfoort, J. Billen, M. Carvelli, S. I. E. Vulto, R. A. J. Janssen, and R. Coehoorn, "Predictive modeling of the current density and radiative recombination in blue polymer-based light-emitting diodes," Journal of Applied Physics, vol. 109, no. 6, Article ID 064502, 2011.

[41] C. Bilel and A. Rebey, "Optical absorption of new n-doped GaN0.38As1-0.38ySby/GaAs QWs suitable for the design of 0.8 - 1 eV solar cells," International Journal of Control, Energy and Electrical Engineering (CEEE), vol. 9, p. 20, 2019.