Linewidth enhancement factor and modulation bandwidth of lattice matched 1.5 micron InGaAsN/GaAs quantum well lasers

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ABSTRACT

The linewidth enhancement factors of lattice-matched 1.5 μm wavelength InGaAsN/GaAs and InGaAs/InP single-quantum-well structures have been calculated using microscopic theory including many-body effects and a 10×10 effective-mass Hamiltonian. For applications which require high gain and carrier densities, InGaAsN/GaAs quantum wells have a much lower linewidth enhancement factor over a temperature range 300–400 K than InGaAs. The linewidth enhancement factor of InGaAsN is almost independent of both carrier density and temperature compared with InGaAs. The small-signal modulation characteristics of these 1.5 μm lattice-matched structures and their temperature dependence have also been calculated. It is found that the maximum bandwidth of the InGaAsN/GaAs quantum well lasers is about 2.3 times larger than that of the InGaAs/InP quantum well lasers due to the high differential gain. The slope efficiency for the 3dB bandwidth as a function of optical density is twice as large for InGaAsN/GaAs as for InGaAs/InP quantum well lasers.

Key-words: InGaAsN materials, Semiconductor quantum wells, linewidth enhancement factor, small signal modulation, bandwidth.

INTRODUCTION

InGaAsN/GaAs quantum wells (QWs) have recently been shown to be very promising materials systems as active media for long wavelength lasers at 1.3 μm and possibly 1.5 μm in optical communications systems¹. The large conduction band offset in the InGaAsN system results in a much greater electron confinement compared with the InGaAsP system and should result in much improved high temperature performance in optimized devices^{2,3}. In addition, the large refractive index difference in this AlAs-GaAs based system makes it possible to fabricate monolithic Bragg reflectors with a small number of mirror pairs. For use as practical laser systems, a number of key performance parameters need to be investigated for the InGaAsN system and compared with the standard InGaAsP system in order to be able to best choose the system for its particular application. We have carried out a modeling study of the linewidth enhancement factor (LWEF) and the small signal modulation characteristics as a function of carrier density and temperature. The results show that InGaAsN quantum wells have much superior properties over the InGaAs system which is presently used in communications systems lasers. There remains a problem with the growth of InGaAsN materials and as yet, lattice matched materials at 1.5 microns have not been grown. A preliminary report on our modeling studies has been published.⁴

The LWEF is one of the most important parameters of the semiconductor lasers for many practical applications^{5,6}. It describes the carrier induced coupling of the gain change to the refractive index change in the active region of the semiconductor laser. The laser linewidth, modulation-induced wavelength chirp, gain guiding, and sensitivity to feedback are dependent on the LWEF. To explore the optimization conditions, it is very important to investigate the dependencies of the LWEF on the gain medium and structural properties of the lasers. Many successful operations of ridge waveguides⁷ distributed-feedback⁸, and vertical-cavity surface-emitting lasers,⁹ with InGaAsN as active layers have been reported. For high-speed optical communication, direct modulation of the laser diodes is essential. Therefore it is important to investigate the dynamic properties of the laser diodes and to understand the modulation characteristics, especially in this new material system. Presently, many experimental results are reported for lasers in 1.3 μm wavelength region and now a major challenge is directed towards the achievement of 1.5 μm wavelength lasing.

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THEORETICAL MODEL

The material parameters for the lattice-matched 1.5 micron InGaAsN quantum wells are determined using the band anti-crossing model and simple interpolations using known experimental results. Figure 1 shows the bandgap dependence with nitrogen mole fraction for various In alloy concentrations. The bandgap energy in the quaternary system is given by:

$$E_g(x, y) = xyE_g(\text{InN}) + x(1-y)E_g(\text{InAs}) \\ + (1-x)yE_g(\text{GaN}) + (1-x)(1-y)E_g(\text{GaAs}) \\ - x(1-x)[yC_{\text{InGaN}} + (1-y)C_{\text{InGaAs}}] \\ - y(1-y)[xC_{\text{InNAs}} + (1-x)C_{\text{GaNAs}}]$$

Within the band anti-crossing model, although there is no direct coupling between the nitrogen band and the valence bands, there is an indirect interaction through the coupling with the conduction band¹⁰⁻¹². A 10x10 effective mass Hamiltonian is used for energy band structure calculations of an InGaAsN/GaAs QW including the conduction-valence interaction with the spin degenerate nitrogen band. In the free carrier model with simple phenomenological relaxation time approximation, the LWEF is overestimated and it is underestimated in the model which includes band gap renormalization but ignores the Coulomb enhancement effect.¹³

Figure 1. The bandgap energy dependence of the quantum well material with nitrogen concentration at various In concentrations. The solid lines are the band anti-crossing model and the dashed lines, the interpolation from the experimental data.

In this work, we employ a microscopic theory based on the semiconductor Bloch equations with Coulomb interaction and band gap renormalization. This model is used for the calculation of optical gain and refractive index changes.¹⁴ Carrier-carrier scattering is treated at the level of the quantum kinetic regime instead of using simple phenomenological parameters for the line broadening.¹⁵ According to the band anti-crossing model, the electron-nitrogen coupling of $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ is described by the matrix:

$$\begin{pmatrix} E_0(x, y, T) + \frac{\hbar^2 k^2}{2m^*(x)} & V_{NM}(y) \\ V_{NM}(y) & E_N(x, y) \end{pmatrix}$$

where $m^*(x)$ is the bulk electron effective mass of $\text{In}_x\text{Ga}_{1-x}\text{As}$. The conduction band energy $E_0(x, y, T)$ is given by $E_0(x, y, T) = E^0(x, T=0) - 1.55y - \frac{\alpha T^2}{\beta + T}$ (eV). Considering the indium concentration effect, the nitrogen energy level is taken as¹² $E_N(x, y) = 1.65 - 2.52y - 0.4x(1-x)$ (eV) and the coupling term is $V_{NM}(y) = -3.0\sqrt{y}$ (eV). Following the fitting of the experimental results with various indium and nitrogen mole fractions, the Varshni coefficients α and β are determined which can be used for the temperature dependent bandgap determination. For our modeling study, we choose a 7 nm $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ and $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}_{0.036}\text{As}_{0.964}/\text{GaAs}$ QWs with 1.5 μm emission. The lattice matched condition is obtained by the application of the band anti-crossing model and Vegard's law for the known experimental results.^{12,16,17} The calculated gain spectra in the two quantum well systems are shown in fig. 2.

Figure 2. A comparison of gain in the InGaAs (a) and InGaAsN (b) systems. The gain spectra are calculated for carrier densities of $0.1, 1, 2, 3, 4 \times 10^{18} \text{ cm}^{-3}$.

It is clear that there is much higher gain in the InGaAsN system for a particular carrier density. The better match of the carrier effective masses and therefore the better match of the densities of states in the two bands is responsible for the higher gain in the nitride system. The peak gain of the two systems are presented in Fig. 3 as a function of carrier density.

Figure 3. Peak gains as a function of carrier density for the two quantum well systems, solid line InGaAsN, dashed line InGaAs. Data are presented over the temperature range of 300 to 360 K.

For temperatures below 400 K, the InGaAs system has the lower transparency carrier density. The differential gain of InGaAs is higher than that of InGaAsN and almost insensitive to varying temperatures (see Fig. 7 later). As for the gain, the lower transparency and larger differential gain of InGaAs are due to the large electron effective mass which is $0.104 m_0$ and about 2.4 times larger than that of InGaAs. The better density of states match between conduction band and valence band leads to low values of transparency and high differential gain. The large electron effective mass compared with InGaAs materials comes from the strong interaction between the conduction band and a narrow resonant band formed by the nitrogen states.¹⁰ Using lattice mismatching in the system, the electron and hole effective mass can be changed which leads to changes in threshold conditions and differential gain. Also the increase of nitrogen mole fraction enhances the electron effective mass. Therefore, by adjusting the indium and nitrogen mole fractions in the quaternary material, the matching between the two density of states can be improved resulting in better optical properties.

LINEWIDTH ENHANCEMENT FACTOR

For high-speed modulation of lasers in fiber-optic communication system, a low LWEF with low temperature and carrier density dependencies are required. A low LWEF reduces pulse chirp when compared with the InGaAs system allowing higher speed modulation and therefore higher speed communications. The carrier density dependence of the LWEF and the temperature dependence of LWEF at certain carrier densities are shown in Fig. 4. All LWEFs are obtained at the peak gain positions.

(a)

(b)

Figure 4. (a) The linewidth enhancement factor versus carrier density (b) The linewidth enhancement factor versus temperature at a fixed carrier density of $3.5 \times 10^{18} \text{ cm}^{-3}$.

For the whole carrier density range of the figure in Fig. 4(a), the LWEF of InGaAs is lower than that of InGaAs and is almost constant with carrier density. This independence of the LWEF on carrier density is particularly valuable as it results in low pulse chirp at high modulation frequencies. This is a direct result of high differential gain as shown in Fig. 3. Figure 4(b) shows the temperature dependence of LWEF at a carrier density of $3.5 \times 10^{18} \text{ cm}^{-3}$. At a fixed carrier density, the temperature dependence of InGaAs is larger than that of InGaAs due to the larger differential-gain decrease with increasing temperature. The temperature dependence of the LWEF for InGaAs increases at the elevated carrier densities compared with that for InGaAs which is almost temperature insensitive.

To compare the thermal characteristics of the LWEF for InGaAs and InGaAs in real operating environments, the temperature dependence of LWEF at a gain of 2500 cm^{-1} is shown in Fig. 5. The LWEF for InGaAs is much lower

Figure 5. The LWEF as a function of temperature at a peak gain of 2500 cm^{-1} .

than that for InGaAs and for the temperatures between 300 and 360 K, the relative change of LWEF for InGaAs is smaller than that for InGaAs by a factor of 2. To obtain a gain of 2500 cm^{-1} , a higher carrier density is needed for the InGaAs system which results in a reduction of the differential gain as shown in Fig. 3. Due to the larger difference of the conduction band and valence band effective masses for InGaAs, it requires more carriers to achieve the same gain compared with InGaAs. In high temperature and high electric field environments for device applications, the large conduction band offset and electron effective mass of InGaAs make this material a strong candidate for high-speed devices.

MODULATION CHARACTERISTICS

Using rate equations and nonlinear gain saturation, the small signal frequency response function is given by:

$$R_{\text{mod}}(\omega) = \left(\frac{\Gamma \tau_p}{qd} \right) \frac{\omega_r^2}{\sqrt{(\omega^2 - \omega_r^2)^2 + \omega^2 \gamma^2}}$$

where the damping factor is defined as

$$\gamma = K f_r^2 + \frac{1}{\tau} \quad \text{and the } K \text{ factor is given by: } K = 4\pi^2 \left(\tau_p + \frac{\epsilon}{vg'} \right)$$

where τ_p , τ , f_r , g' , Γ , and ϵ are the photon lifetime, carrier lifetime, resonant frequency, differential gain, optical confinement factor, gain suppression coefficient, and the frequency $\omega_r = 2\pi f_r$, respectively¹⁸.

In the numerical calculations, τ_p , τ , Γ , and ϵ are set equal to 1.5 ps, 1.0 ns, 0.1, and $3.0 \times 10^{-23} \text{ m}^3$, respectively for both material systems. For the first three parameters, this is a very good approximation and we will discuss the ϵ parameter further below. Fig.6 shows the small-signal frequency response of InGaAs/GaAs and InGaAs/InP QW lasers with different optical densities at a temperature of 300 K. At the same optical density, the bandwidth of InGaAs/GaAs QW

Figure 6. Frequency responses of InGaAs/GaAs QW (solid lines) and InGaAs/InP QW (dotted lines) at a temperature of 300 K for various optical densities.

lasers is larger than that of InGaAs/InP QW lasers and also the amount of increase with the optical density increase is enhanced in the former system. The differential gains of the two systems are presented in fig.7 as a function of temperature at a peak gain of 2500 cm^{-1} . Once again, it is clear that the InGaAsN system has a much greater differential gain, although it decreases more with temperature than InGaAs. In fig. 8(a) the temperature dependence of K-factors for

Figure 7. Temperature dependence of differential gains for InGaAsN/GaAs QW (solid line with solid squares) and InGaAs/InP QW (dotted line with open circles) at a peak gain of 2500 cm^{-1}

both InGaAsN/GaAs and InGaAs/InP QW lasers are presented. The K-factor of InGaAsN lasers is 0.225 ns and about 2.5 times smaller than that of InGaAs lasers at a temperature of 300 K which gives a maximum resonance frequency of 39.4 GHz (16.7 GHz for InGaAs/InP QW lasers.) using the 3dB cutoff condition, $f_{r,\max} = \frac{2\pi\sqrt{2}}{K}$. This is also due to the enhanced differential gain in the InGaAsN system. For the temperature range of $300 - 360 \text{ K}$, the temperature dependence of the 3dB modulation bandwidth of InGaAs/InP QW lasers is smaller than that of InGaAsN/GaAs QW lasers, but the values are much larger for the InGaAsN system as shown in fig. 8(b). Also, the increasing rate of the 3dB modulation bandwidth for InGaAsN with the injection current (that is, optical density) is twice as large as that for InGaAs resulting in a higher modulation current efficiency factor (the slope of modulation bandwidth as a function of injection current). The large conduction band offset (deep quantum well) in the InGaAsN/GaAs QW increases the electron escape time which leads to the decrease in damping rate¹⁹ and gives better high-temperature performance in high-speed modulation. In this paper, the same gain suppression coefficient ϵ is used for both systems and its temperature-independence is assumed as it was shown by the experiments for $1.3\mu\text{m}$ InGaAsP/InP lasers²⁰. There are no available experimental results to determine the gain suppression coefficient of InGaAsN material, but the stronger confinement of electrons due to the enhanced conduction band offset should result in a lower gain suppression coefficient as shown by the experiments for InGaAs/InAlGaAs QW lasers in comparison with InGaAs/InGaAsP QW lasers²¹. This would further increase the difference of the modulation bandwidth between the InGaAsN/GaAs and InGaAs/InP QW lasers. It is therefore a reasonable assumption that the ϵ coefficient of InGaAsN lasers will be much less than for InGaAsP lasers. Our use of the same value is therefore a cautious approach and the modulation characteristics that will be observed in future devices will likely be even better than those given in this paper.

Figure 8. (a) K-factors as a function of temperature for InGaNaS/GaAs QW (solid line with solid squares) and InGaAs/InP QW (dotted line with open circles.) (b) Temperature dependence of 3dB bandwidth for InGaNaS/GaAs and InGaAs/InP QWs at the optical density of $0.5 \times 10^{21} \text{ m}^{-3}$ (solid line with solid squares) and of $5.0 \times 10^{21} \text{ m}^{-3}$ (dotted line with open circles).

CONCLUSIONS

In conclusion, to allow for a comparison with conventional InGaAs material, the lattice-matched conditions for InGaNaS quantum well materials are determined from experimental results published in the literature. The optical gain, LWEF and their temperature dependence for InGaNaS QWs are calculated with microscopic theory and a 10×10 effective-mass Hamiltonian and a comparison is made with those of InGaAs QWs. It is shown that an InGaNaS/GaAs QW has better characteristics in optical gain and LWEF than InGaAs QWs. The enhanced differential gain and the smaller LWEF of InGaNaS show its potential for application in optical communications. The temperature insensitivity of the LWEF and its clamping with increasing carrier injection in InGaNaS/GaAs QW promise more stable semiconductor lasers which have spectrally and spatially more stable modal properties under high-speed modulation conditions with narrow laser linewidth, reduced filamentation, and low frequency chirp. Also, the larger electron effective mass and conduction band offset of InGaNaS/GaAs QWs, the greater refractive index contrast achievable in GaAs-based systems than conventional InP-based materials make the application of the material for long-wavelength VCSELs possible.

Lattice-matched InGaNaS/GaAs QW lasers have enhanced high-speed modulation characteristics when compared with conventional InGaAs/InP QW lasers for a wavelength of $1.5 \mu\text{m}$. This is mainly due to the larger differential gain in the InGaNaS system resulting again from the larger conduction band effective mass. The maximum 3dB modulation bandwidth of 39.4 GHz (2.3 times larger than that of the InGaAs/InP system) is achieved by assuming that a gain suppression coefficient of $3.0 \times 10^{-23} \text{ m}^3$ at a temperature of 300 K for both systems. Using multiple quantum wells and the introduction of the lattice-mismatch in the InGaNaS material system can further improve the modulation characteristics.

ACKNOWLEDGMENTS

The authors are grateful to James O'Gorman for valuable discussions and suggestions. This work was supported in Korea by the National Research and Development Project for Nano Science and Technology (contract No. N11-0212-04-0003) of NOST. The work was supported by the Phase II projects of Enterprise Ireland under the Programmes in Advanced Technologies in Ireland.

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