13D2-5

Differential gain in InGaAsN quantum well structures

(Regular Paper)

M.S. Wartak
Senior Member IEEE
Department of Physics and Computer Science
Wilfrid Laurier University
Waterloo, Ontario N2L3C5, Canada
Email: mwartak@wlu.ca
Telephone: (519) 884-1970, ext.2436
Fax: (519) 746-0677

P. Weetman
Department of Physics and Computer Science
Wilfrid Laurier University
Waterloo, Ontario N2L3C5, Canada
Email: pweetman@eml.cc
Telephone: (519) 884-1970, ext.2685
Fax: (519) 746-0677

***Abstract*— Numerical studies of differential gain in InGaAsN quantum well systems are reported. Our approach is based on 10×10 Hamiltonian solved self-consistently with the Poisson's equation. It was found that the properties of that system can be effectively modified.**

The differential gain is one of basic parameters which characterize operation of quantum well (QW) based semiconductor lasers [1]. It is defined as the derivative of the optical material gain with respect to the injected carrier density. It is linked with the modulation bandwidth of these devices. The differential gain is often determined from measurements of the relaxation oscillation frequency as a function of the emitted optical power under the approximation of small signal modulation [2], [3]. The differential gain is an intrinsic property of the material in the active layer and is independent of the laser structure.

In recent years we have witnessed tremendous progress in the research on a new class of materials based on nitride semiconductors [4], [5]. Dilute Nitride lasers based on GaAs are considered as replacements for InP based lasers in metropolitan and local area networks. It has been found that replacing a small amount of the group V element by nitrogen in a III-V material systems reduces the energy gap. This reduction significantly changes band structure and offers new possibilities of improving optoelectronic properties of devices based on those materials. For example, impressive improvements of in-plane lasers [6] and [7] as well a VCSELs [8] based on those materials have been reported.

Differential gain of quantum well nitride structures have been studied recently [9]. It was found that differential gain with respect to either current or carrier concentration is reduced in dilute-nitride devices. Differential gain among other factors was recently analyzed theoretically by Alexandropoulos and Adams [10] in the BAC model. It was found that an increase of Nitrogen content reduces the peak differential gain. We have extended their analysis to 10×10 Hamiltonian and also included electrostatic effects on the heterostructure potentials of electrons and holes.

Our approach is based on a 10×10 k·p Hamiltonian [11] which is a generalization of the 8×8 Lüttinger-Kohn Hamiltonian [12] that accounts for coupling between the conduction and hole bands. Substitution of nitrogen splits the conduction band to create the additional 'nitrogen band'. This new system necessitates the introduction of an additional band in the description of the electron-hole bandstructure. For this purpose, a 10×10 Hamiltonian which accounts for nitrogen, conduction, light- and heavy-holes and spin bands is used here.

We have recently applied 10×10 Hamiltonian [13] to numerically analyze the effective masses in InGaAsN quantum-well structures with self-consistent effects. In that paper we were able to obtain detailed band structures for various well parameters such as nitrogen compositions. We use this information in the material gain computations.

The structure simulated is similar to that used previously [13] and consists of undoped $In_{0.36}Ga_{0.64}As_{1-y}N_y$ system. The Nitrogen composition (y) changes in the range $0.00 < y < 0.05$. We have considered several values of well widths.

We performed the following steps of our computations:
1. produce gain spectrum at a given temperature
2. determine differential gain at peak value
3. increase temperature and repeat process
4. plot differential gain such determined vs temperature.

Below, we report on some representative results.

In Fig.1 we plotted differential gain vs energy for two values of barrier composition and three values of well widths. One can observe that the effect of Nitrogen content in the barrier is relatively small for all well widths considered. One can also observe that by varying well width, we can significantly change maximum value of differential gain. Its peek value stays roughly the same at a particular energy. There is however optimum value of well width for which differential gain reaches maximum. In Fig.2 we plotted differential gain as a function of Nitrogen composition for four values of well width. As was noticed with data shown in Fig.1, for a given Nitrogen composition, that the value of differential gain is the largest for 6 nm well width. For all values of

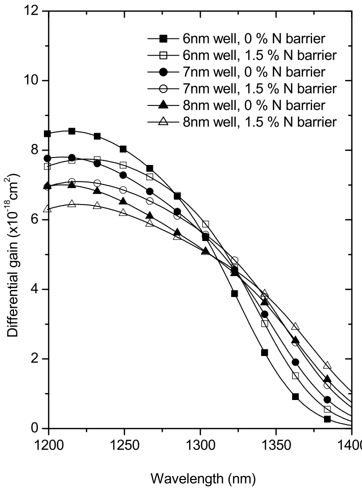

Fig. 1. Differential gain versus photon wavelength for three wells and two values of barrier composition.

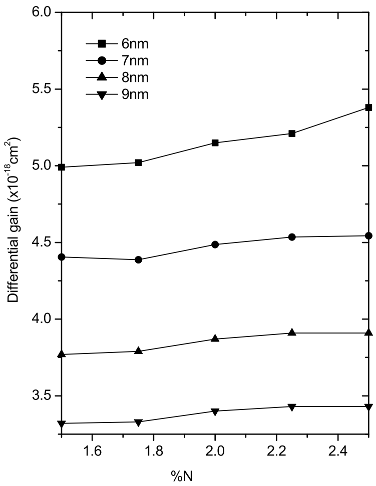

Fig. 2. Differential gain determined at optical gain peak vs nitrogen composition for four values of well widths. Temperature = 300K. Carrier density in the well is equal to $4 \times 10^{18} cm^{-3}$.

well widths, the differential gain shows little dependence on Nitrogen content although its dependence for narrower wells is stronger (and resemblances linear for the values considered). The temperature dependence of differential gain is shown in Fig.3 for several values of well widths ranging from 6 nm to 9 nm. Nitrogen composition is 1.5% and carrier density is equal to $4 \times 10^{18} cm^{-3}$. It is roughly independent of temperature, although some degradation is observed at larger temperatures.

In conclusion, we have analyzed differential gain for some range of parameters important in the design of semiconductor lasers based on single quantum well using InGaAsN material system. The effects of self-consistency were considered for all our computations since it is known that they can significantly affect properties of quantum well systems. This is due to an

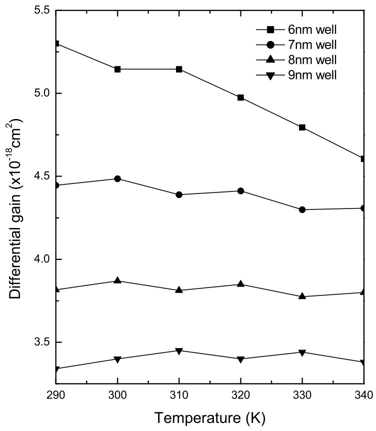

Fig. 3. Temperature dependence of differential gain determined at optical gain peak for several values of well widths. Nitrogen composition 1.5%. Carrier density in the well is equal to $4 \times 10^{18} cm^{-3}$.

increase of the density of conduction electrons and simultaneously the reduction of the hole densities in the active region [14] which modifies the amplitude of the differential gain and the change in relative transition strengths which modifies the spectral dependence. These effects have a large practical importance in the design of an efficient laser as they can reduce the differential gain by significant amounts.

We would like to acknowledge the support from the Natural Science and Engineering Research Council of Canada (NSERC). This work was made possible by the facilities of the Shared Hierarchical Academic Research Computing Network (SHARCNET: www.sharcnet.ca).

REFERENCES

[1] Coldren L.A.and Corzine S.W. ”Diode Lasers and Photonic Integrated Circuits”, John Wiley and Sons, New York (1995).
[2] K. Uomi, T. Tsuchiya, H. Nakano, M. Aoki, M. Suzuki and N. Chinone, IEEE J. Quantum Electron. 27, 1705 (1991).
[3] M. Blez, D. Mathoorasing, C. Kazmierski, M. Quillec, M. Gilleron, J. Landreau and H. Nakajima, IEEE J. Quantum Electron. 29, 1676 (1993).
[4] Morkoc H. 1999 *Nitride Semiconductor and Devices* (Berlin: Springer).
[5] Klar P.J., Prog. Solid State Chem. **31** 301 (2003).
[6] Harris J.S., *International Conference on Indium Phosphite and Related Materials* **15** 333 (2003).
[7] Pessa M., C.S. Peng, T. Jouhti, E.-M. Pavelescu, W. Li, S. Karirinne, H. Liu, and O. Okhotnikov, IEE Proc.: Optoelectron. **150** 12 (2003).
[8] Tawara T., H. Gotoh, T. Akasaka, N. Kobayashi, and T. Daitoh, *The 5th Pacific Rim Conference on Lasers and Electro-Optics* **1** 343 (2003).
[9] Shterengas L., G.L. Belenky, J.-Ya Yeh, L.J. Mawst, and N. Tansu, IEEE J. Selected Topics Quantum Electron. **11** (5), 1063 (2005).
[10] Alexandropoulos D. and M.J. Adams, J. Phys.: Condens. Matter **14** 3523 (2002).
[11] Tomic S., O'Reilly E.P., Fehse R., Sweeney S.J., Adams A.R., Andreev A.D., Choulis S.A., Hosea T.J.C. and Reichert H., IEEE J. Sel. Top. Quantum Electron. **9** 1228 (2003).
[12] Chuang S.L., *Physics of Optoelectronic Devices* (New York: Wiley), 1995.
[13] Wartak M.S. and Weetman P., J. Phys.: Condens. Matter 2005 **17** 6539 (2005).
[14] Weetman P., Kucharczyk M. and Wartak M.S., J. Phys.: Condens. Matter **14** L83 (2002).