International Journal of Scientific and Technological Research
ISSN 2422-8702 (Online)
Vol 1, No.1, 2015

Optical Properties of $In_xGa_{1-x}N_yAs_{1-y}$/GaAs Heterostructure Quantum Well Lasers for 1.3 µm Laser Emission with Different In/N Concentrations

Sinan Yasar (Corresponding author)
Department of Physics, Mustafa Kemal University
Hatay 31030, Turkey
E-mail: sinan_yasar@msn.com

Ismail Bilican
Science and Technology Application and Research Center, Aksaray University
Aksaray 68100, Turkey
E-mail: bilicanismail@gmail.com

Murat Oduncuoglu
Vocational School of Technical Sciences, Gaziantep University
Gaziantep 27310, Turkey
E-mail: muratodn@hotmail.com

Sedat Agan
Department of Physics, Kirikkale University
Kirikkale 71450, Turkey
E-mail: sedatagan@hotmail.com

Ihsan Uluer
Department of Electrical and Electronics Engineering, Karabuk University
Karabuk 78050, Turkey
E-mail: ihsanuluer@gmail.com

Abstract

We investigate the optical gain of InGaNAs/GaAs heterostructure quantum well lasers (QWL) with an emission wavelength of 1.3 µm and compare the results with that of an equivalent nitrogen-free InGaAs/GaAs structure. The effects of parameters and its influence on the optical gain are identified. It is shown that the gain of InGaNAs quantum wells is reduced by incorporating N into a well layer. Secondly, the temperature dependence of optical gain is also investigated. In this study, we reviewed and compared the theoretical results of optical gain of dilute nitride systems for better understanding of structure for high-temperature and high-speed operation of device characteristics in fiber optic communications.

Keywords: Band Anticrossing Model (BAC), Dilute Nitride, Fabry-Parot structure, Opto-electronics devices, Quantum well lasers, Spontaneous emission, Semiconductor laser

1. Introduction

Semiconductors are used extensively in many areas from electronics industry to scientific studies, energy production and telecommunication. High speed and high capacity optic systems are needed for fiber optic systems which are basic of modern communication system. Need for optic sources which are suitable for performances with optic communication systems improved quickly are increased.

Semiconductor based products are materials which can respond to these needs. In beginning of 1960's, the discovery of the semiconductor is excepted as a big step in optics and photonic technologies (Hall 1963). In 1961 N. Basov et al. introduce the idea that in semiconductor stimulated emission can occur with the recombination of carriers which are injected into p-n junction and the first simple junction laser diode which works successfully in low temperatures was produced in 1962 (Basov *et al.*1962). The first semiconductor laser diodes were GaAs based lasers which are consist of p-n junction a few micron in thickness. In this type of lasers optic feedback are provided with Fabry-Parot resonators which are consist of two parallel refractive surfaces (Born *et al.* 1999). The most suitable semiconductors for production of opto-electronics devices are produced with combination of elements which are III (In,Ga,Al,etc.) and V (N,P,As,etc.) group of periodic tables. III-V Nitride groups are important group in which many works have been done on semiconductors.

Band sequence and band edges are important for device performances which will be produced. To cancel these restrictions, band gaps were reduced with produced Nitride doped systems, effective mass were increased with lattice constant and conductive band gap were increased in band sequence. The nitride doped structures were attracted all the attentions because of these new extraordinary differences (Kondow *et al.* 1999; Royall & Balkan 2009; Sun *et al.* 2007; Gonul *et al.* 2003). The structures which are obtained by dilute Nitride were a good alternative of the structure which are produced so far, with high performance and physical properties and became the most searched materials, today. The InGaNAs/GaAs quantum well laser systems which have long wavelength dilute Nitride have many extraordinary properties compared to III-V quantum well systems which are used extensively. The understanding of physical and electronically properties of these new structures is important for design and production of new generation electronic devices.

Nowadays, III-V semiconductors which are used extensively, present different physical by compared to III-N-V alloy of InGaNAs structures. The band gap of III-V semiconductors increases with decreases of lattice constant but decreases in III-N-V systems. In this alloy, the increase of Nitride concentration reduces the InGaNAs structure band gap which is cubic structure (Wei & Zunger 1996). An interesting implication of the band-structure modification due to N in (InGaAs) is the strong nonparabolicity of the conduction band predicted by theory. The addition of N to the ternary compound produces a quaternary with a splitting conduction band (CB), change in the band gap and lattice constant. This makes it possible to grow material lattice-matched to a GaAs substrate (integrated with GaAs) operating at wavelengths used in long-distance optical communications, device technologies for improved functionality, reliability, lower cost, reduced size, etc.

A high-speed transmission of data, voice and video over optical fibers, taking advantage of their wide bandwidth, low power attenuation and compact size. Optical wavelengths in the neighborhood of 1300 and 1550 nm offer the lowest attenuation in silica. The optical gain plays an important role in the operation characteristics of any quantum well laser. The optical gain of InGaNAs/GaAs quantum well lasers studied for different In/N concentrations for 1.3 µm wavelength laser emission.

2. Theoretical Analysis

The InGaNAs quantum well laser analysis is performed using physics-based self-consistent laser diode simulation software (Rsoft 2005). This laser device was designed as Fabry–Parot type laser structure in the production process.

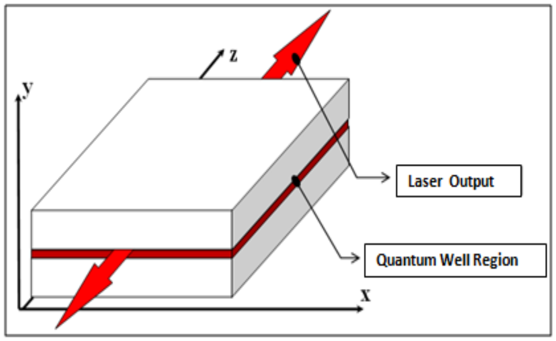

Figure 1. Simulation Plan of Fabry–Parot Structure.

Thickness of substrate is 100 nm and it was enlarged with a $4x10^{18}$ cm^{-3} p–type doping. The next region is quantum well laser region, quantum well is composed 6 nm thick $In_xGa_{1-x}N_yAs_{1-y}$ materials. Quantum well has 6 nm GaAs barrier couples and 2.37% compressive strain between 10 nm confinements. The following region as contact cladding of GaAs with n-type doping of $4x10^{18}$ cm^{-3} with 100 nm thick. InGaNAs/GaAs quantum well laser structure has been completed.

Table 1. Laser region structure and parameters.

	Region	Width (nm)/Doping ($x10^{18}cm^{-3}$)
1.	p- GaAs Cladding	100/4
2.	(QWL) $In_xGa_{1-x}N_yAs_{1-y}$ (BAR) GaAs 1 qwl – 2 qwl	10-6 / Undoped
3.	n-GaAs Cladding	100/4

The band gap of dilute nitride quaternary alloys obtained by using Band Anticrossing Model (BAC) (Shan *et al.* 1999). The other necessary material parameters used in calculations were found by using Vegards law (Denton & Ashcroft 1991). The BAC model explains the CB modification due to the presence of nitrogen in InGaNAs alloys. In this model, an anticrossing interaction of localized N states with the extended state of GaAs or InGaAs leads to a characteristic splitting of the CB into two non-parabolic subbands (Shan *et al.* 1999; Yu 2002). The model has been successfully used to quantitatively describe the dependencies of the upper and lower subband energies on N concentration and hydrostatic pressure of group III-N-V alloys (Shan *et al.* 1999; Shan *et al.* 2000; Yu *et al.* 2001).

The downward shift of the lower subband is responsible for the reduction of the fundamental band gap, and optical transitions from the valence band to the upper subband account for the high-energy edge. The low-energy edges of the subbands are given by the expression;

$$E_{\pm} = \frac{E_N + E_M \pm \sqrt{(E_N - E_M)^2 + 4V_{MN}^{\ 2}}}{2} \quad (1)$$

where E_M and E_N are the energies of the extended state and of the N level relative to the top of the valence band, respectively, and V_{MN} ($V_{MN}=2.7y^{0.5}$ eV (Suemune 2000), where y is the N concentration) is the matrix element of the term describing the interaction between localized N states and the extended states. The nitrogen level dependence on the nitrogen concentration is E_N=1.52-3.9y (Hader *et al.* 2000). The CB energy E_M of the matrix semiconductor is taken to vary in the presence of nitrogen as E_M= E_0-1.55y, where E_0 is the energy in the absence of nitrogen (Walukiewicz *et al.* 2000). E_- transitions shifts towards lower energies with increasing N concentration, on the contrary, E_+ transition shifts towards higher energies with increasing nitrogen concentration, and its intensity increases relative to the E_- intensity (Shan *et al.* 1999; Walukiewicz *et al.* 2000; Perkins *et al.* 1999).

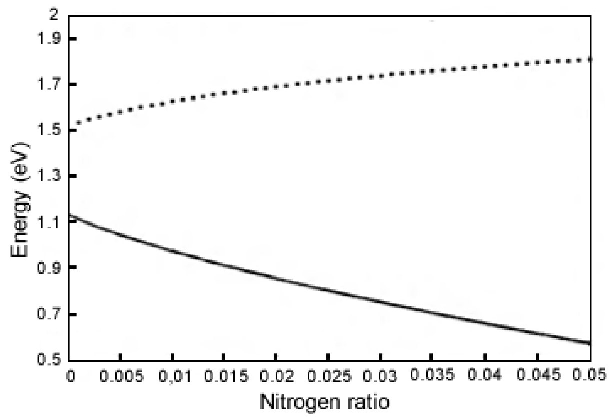

Figure 2. Band gap energy of InGaNAs/GaAs with increasing N content calculated by using BAC model.

The most interesting properties of InGaNAs in III-N-V systems are a serious decrease in basic forbidden band gap energies and excessive increase in electron masses. Unusual changes I calculated material parameters were able to understand with opposite transition model. In figure 2, the decrease in forbidden band gap of InGaNAs which depends on nitride concentration, were shown and seen in good agreement with the results in literature (Chen *et al.* 2008; Yen *et al.* 2007).

We have calculated the change in electron effective mass due to the nitrogen modified CB using the following dispersion relation of:

$$m^* = \frac{\hbar^{\cdot}}{\left.\frac{\partial^2 E_-}{\partial k^2}\right|_{k=0}} = m_M\left[1+\left(\frac{V_{MN}}{(E_N - E_-)}\right)^2\right] \tag{2}$$

Where $\mathbf{m_M}$ is the electron effective mass in the parabolic conduction of the ternary InGaAs. Equation 2 is obtained by Skierbiszewski et al. (2000) to model their experimental results. In a work previously done, it was shown that effective mass decreases with fixed In ratio (Oduncuoglu & Babaoglu 2009). In our work, it is seen in Figure 3, effective mass increases with fixed **In** ratio (0.35) and with increase of **N** concentration. This property is opposite of extensively used semiconductors. The increase of electron effective mass means closing to hole effective mass. In this way, the interference of wave functions of conductive and valance band increases optics restrictions factor and this result leads to high gain values.

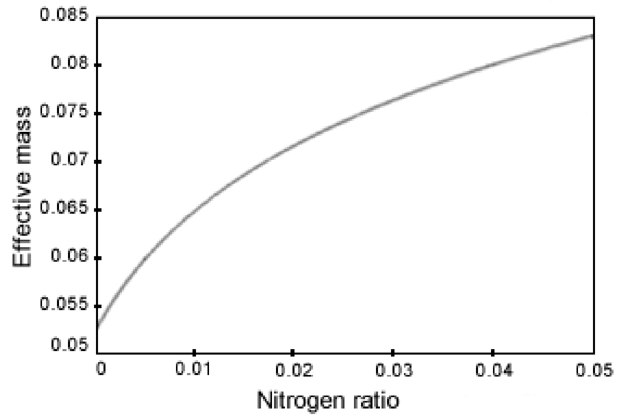

Figure 3. The variation of the calculated electron effective mass of the total nitrogen InGaNAs/GaAs (In=0.35).

Our calculated results show an increased value of the electron effective mass in 1.3µm $In_xGa_{1-x}N_yAs_{1-y}$ with increasing nitrogen concentration, as has been predicted by theories. Such an increase may be beneficial for device designing due to its effect on subband carrier populations. The band offset ratios, temperature dependence of band gap and optical gain of InGaNAs/GaAs for 1.3µm wavelength laser emission for these ratios are calculated theoretically.

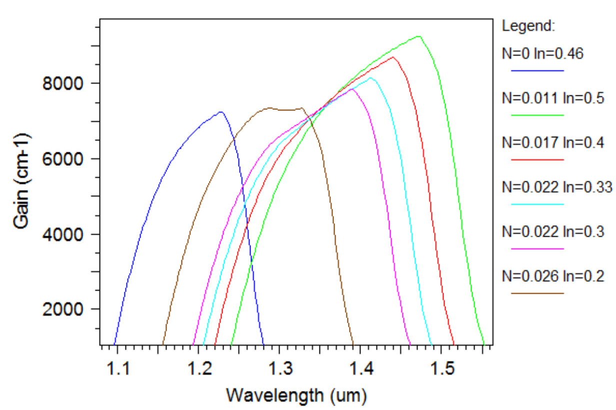

Figure 4. The gain spectra of InGaNAs/GaAs with different **In / N** content (300 K).

In Figure 4 the laser gain values are shown that different **In** and **N** concentrations depending and at 300 K temperature.

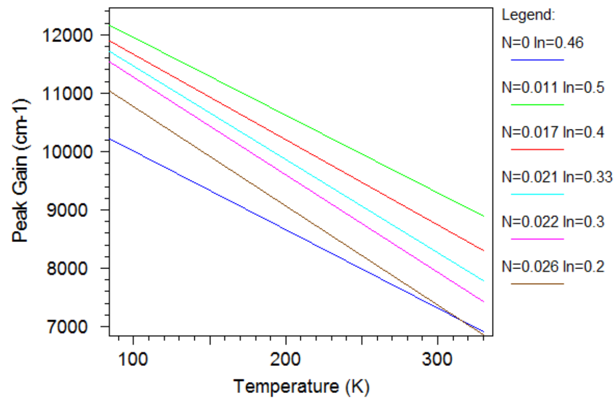

Figure 5. The peak gain of InGaNAs/GaAs with different **In / N** content (300 K).

As seen in Figure 5, when the temperature of environment is increased gradually from 100 K to 300 K, material gain decreases for the carrier density is at $3x10^{12}$ cm^{-2} value of that structure.

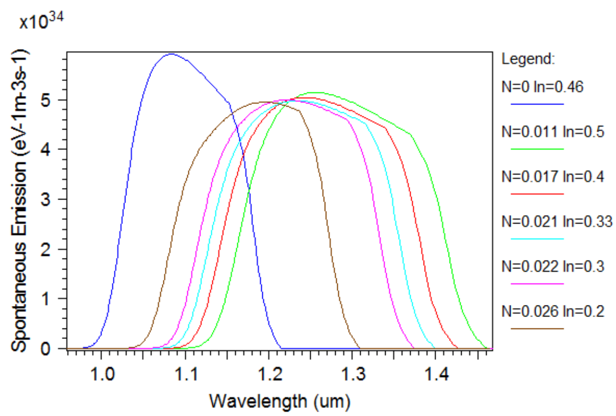

Figure 6a. InGaNAs/GaAs Quantum Well Laser spontaneous emission (77 K).

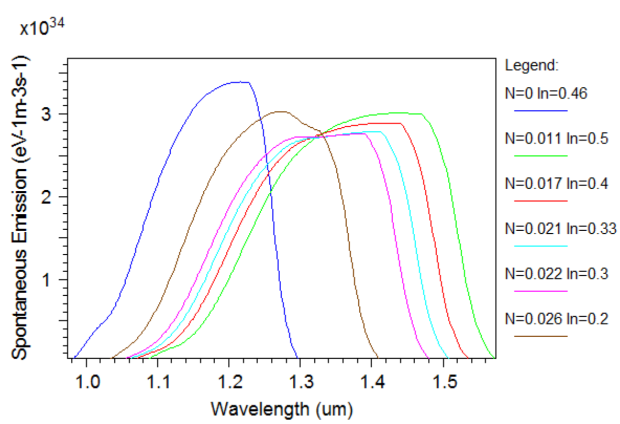

Figure 6b. InGaNAs/GaAs Quantum Well Laser spontaneous emission (300 K).

In figure 6.a and 6.b, it is seen that spontaneous emission graphics of InGaNAs/GaAs depend on wavelength and different In/N concentrations at the temperature of 77 K and 300 K. It was shown that spontaneous emission factor increases with increase of nitride concentrations (Oduncuoglu and Gonul 2005).

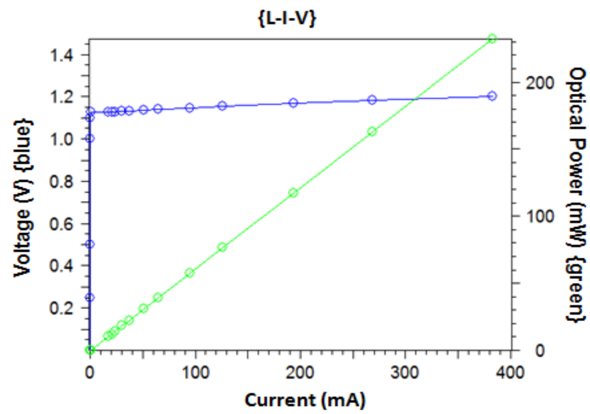

Figure 7a. $In_{0.35}Ga_{0.65}N_yAs_{1-y}$/GaAs quantum well laser depending **N** concentration (% 1.1) L-I-V graph.

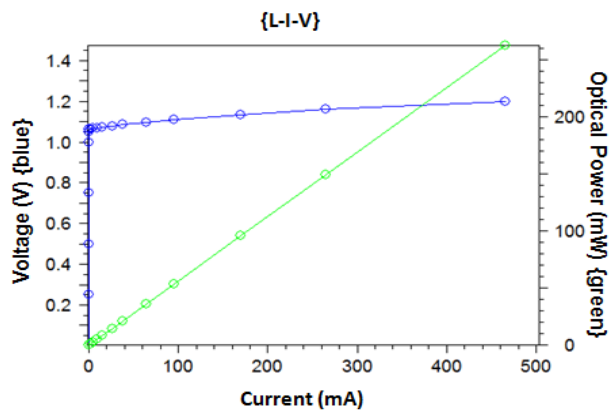

Figure 7b. $In_{0.35}Ga_{0.65}N_yAs_{1-y}$/GaAs quantum well laser depending **N** concentration (%1.7) L-I-V graph.

As seen in Figure 7a and 7b, when N concentration of environment is increased gradually, output power increases. These results are in agreement with the literature (Kuo *et al.* 2007; Yang *et al.* 2010; Kuo *et al.* 2007).

3. Conclusion

In this study, the optical properties and physical parameters of InGaNAs/GaAs quantum well systems for long wavelength emission were investigated. The leasing operation at 1.3 µm should be achieved by changing In and N concentrations of the GaInNAs active layer. In this emission wavelength, the frequency dispersion and insertion loss in fiber optics are minimum. The band gap and effective mass of dilute nitride quaternary alloys were found by using band anticrossing method (BAC). By using the calculated parameters, optical gain of dilute nitride quantum well systems of different In and N concentrations at different temperatures were obtained.

A lasers structure with higher conduction band offsets and an addition of small amount of nitride into InGaAs semiconductors gives good results. The charge carriers can be confined in this deep conduction band and secondly, the leakages of carriers are decreased at high temperatures. This property allows designing of novel optical and optoelectronic devices working in room temperature

In theoretical calculations, it was seen that effective mass increases with increase of nitride concentrations. This is an opposite characteristics of extensively used semiconductors. The increase in electron effective mass means that it closes to hole effective mass. The addition of In and N changes band energy, effective mass and conductive and valance bands positively. These effects lead to high gain values for dilute nitrides. The theoretical results presented that the choice of high amount of In or low amount of N is most suitable for 1.3 µm $In_xGa_{1-x}N_yAs_{1-y}$/GaAs laser systems. The high peak gains, lower spontaneous emission factors and appropriate band alignment are found in this range. The optical gain at different In and N concentrations of InGaNAs/GaAs quantum well laser systems are investigated for better understanding of this structure in fiber optic communications at different temperatures.

Acknowledgment

We thank to Light Tec. and Synopsys / RSoft Company for their permission using the LaserMOD devices.

References

Basov, N.G., Krokhin, O.N. & Popov, Y.M. (1962), "Production of negative temperature states in p-n junctions of degenerate semiconductors", *Sov. Phys. JETP* **13,** 1320-1321.

Born, M. et al. (1999), "Principles of optics: electromagnetic theory of propagation, interference and diffraction of light", *Cambridge University Press*.

Chen, C.-Y. et al. (2008), "Optical properties of InGaNAs/GaAs quantum well structures with GaNAs strain relief buffer layers", *Journal of Physics and Chemistry of Solids* **69,** 493-496.

Denton, A.R. & Ashcroft N.W. (1991), "Vegards law", *Physical Review A.* **43,** 3161.

Gonul, B. et al. (2003), "Influence of doping on gain characteristics of GaInNAs/GaAs quatum well lasers", *Semicond. Sci. Technol.* **18,** 163-169.

Hall, R.N. (1963), "Coherent light emission from p-n junctions", *Solid-State Electronics* **6,** 405-408.

Hader, J. et al. (2000), "Gain in 1.3 µm materials: InGaNAs and InGaPAs semiconductor quantum-well lasers", *Appl. Phys. Lett.* 77, 630-632.

Kondow, M. et al. (1999), "1.3-µm GaInNAs Laser Diode with a Lifetime of over 1000 Hours", *Jpn. J. Appl. Phys.* **38**, L1355-L1356.

Kuo, Y-K. et al. (2007), "Numerical study on gain and optical properties of AlGaInAs, InGaNAs and InGaAsP material systems for 1.3-µm semiconductor lasers", *Optics Communications* **275,** 156-164.

Kuo, Y.-K. et al. (2007), "Numerical study on strained InGaAsP/InGaP quantum wells for 850-nm vertical-cavity surface-emitting lasers", *Applied Physics B.* **86,** 623-631.

LaserMOD by Rsoft Design (2005), "Photonic device design software tool".

Oduncuoglu, M. & Gonul, B. (2005), "A theoretical comparison of the 1.3 µm doped $In_xGa_{1-x}N_yAs_{1-y}$/GaAs quantum well lasers for different x/y concentrations", *Physica E* **27,** 253-261.

Oduncuoglu, M. & Babaoglu, M. (2009), "Theoretical study of material parameters of InGaNP/GaP quantum structure", **3**, 166-170.

Perkins, J. et al. (1999), "Nitrogen-Activated Transitions, Level Repulsion, and Band Gap Reduction in $GaAs_{1-x}N_x$ with $x<0.03$", *Physical review letters* **82,** 3312.

Royall, B. & Balkan, N. (2008), "Dilute nitride n-i-p-i solar cells", *Microelectron. J.* **40**, 396-398.

Shan, W. et al. (1999), "Band anticrossing in GaInNAs alloys", *Phys. Rev. Lett.* **82,** 1221-1224.

Shan, W. et al. (1999), "Effect of nitrogen on the band structure of GaInNAs alloys", *Journal of Applied Physics* **86,** 2349.

Shan, W. et al. (2000), "Nature of the fundamental band gap in GaN_xP_{1-x} alloys", *Applied Physics Letters* **76,** 3251.

Skierbiszewski, C. et al. (2000), "Large, Nitrogen-Induced Increase of the Electron Effective Mass in $In_yGa_{1-y}N_xAs_{1-x}$", *Appl. Phys. Lett.* **76,** 2409-2411.

Suemune, I., Uesugi, K. & Walukiewicz, W. (2000), "Role of nitrogen in the reduced temperature dependence of band-gap energy in GaNAs", *Appl. Phys. Lett.* **77,** 3021-3023.

Sun, Y. et al. (2007), "Inhibition of negative differential resistance in modulation doped n-type $Ga_xIn_{1-x}N_yAs_{1-y}$/GaAs quantum wells", *Physical Review B* **75**, 205316.

Walukiewicz, W. et al. (2000), "Interaction of localized electronic states with the conduction band: Band anticrossing in II-VI semiconductor ternaries", *Physical review letters* **85,** 1552.

Wei, S.H. & Zunger, A. (1996), "Giant and anomalously composition-dependent optical bowing coefficient in GaAsN alloys", *Phys. Rev. Lett.* **76,** 664-667.

Yang, H.-P.D. et al. (2010), "High-power broad-area InGaNAs/GaAs quantum-well lasers in the 1200 nm range", *Microelectronics Reliability* **50,** 722-725.

Yen, S.-H. et al. (2007), "Gain and treshold properties of InGaAsN/GaAsN material system for 1.3-µm semiconductor lasers", *Optics & Laser Technology* **39,** 1432-1436.

Yu, K.M. et al. (2001), "Synthesis of InN_xP_{1-x} thin films by N ion implantation", *Applied Physics Letters* **78,** 1077.

Yu, K.M. (2002), "Ion beam synthesis and n-type doping of group III–N_x–V_{1-x} alloys", *Semicond. Sci. Technol.* **17**, 785.