Gain Characteristics of InGaAsN Quantum Well Heterostructures with GaAs and InP Substrates

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Abstract. The present paper reports the effect of substrate on the optical gain characteristics of InGaAsN material based quantum well (QW) heterostructure. To analyze the substrate effect on the optical gain, two substrate, namely, GaAs and InP have been chosen. Taking in to account both of the substrates, the quantum mechanical approach (k.p method) has been adopted to calculate the confinement of the carriers related with quantum well and the optical gain. In addition, for InGaAsN/InP heterostructure, the cladding effect has also been observed. The simulated results exhibit that the substrate has played a very important role in modifying the optical gain characteristics due to the presence of strain which comes into play due to the lattice discrepancy.

Keywords: optical gain, strain, lattice mismatch, InP, GaAs, InGaAsN

1. Introduction

III-Nitride semiconducting heterostructures have paying attention researchers belonging to electro-optic society due to their probable utilizations in FET (field effect transistors), LEDs (light emitting diodes) [1-4], solar cells, detectors and laser diodes [5, 6]. The reason behind their vast applications is that these semiconductors based heterostructures have been found to contribute exceptional features and exclusive electronic, electrical, mechanical and optical properties which can be exploited for designing of future optoelectronic and photonic devices [7-9]. So far, III-nitrides founded photodetectors running in ultraviolet regime have exhibited promising output. Additionally, III-nitrides established LEDs had been commercialized because of emission of tremendous vibrant blue and inexperienced gentle. Additionally, these substances have some fine bodily residences which make the contraptions ready for applications past the info storage and imaging [10]. These materials are additionally valuable in high temperature electronics and area functions on the grounds that these are bodily and chemically powerful. This feature makes them ultimate for operation in crucial environment.

Keeping in views the interesting properties of III-N QW heterostructures, a thorough study has been carried out on InGaAsN QW heterostructure, in the following sections, by optimizing its valence band mechanism and optical gain characteristics taking into account two different substrates (i.e. GaAs, and InP). In addition, a slight attention has also been paid towards the role of claddings on the gain characteristics of InGaAsN/InP heterostructure.

2. Theory

In any quantum well devices which can absorber produce photonic energies, the confinement of the carriers and radiations is a big issue. The confinement of the carriers and radiations should be larger as much as possible to show a good output. Hence, to estimate the confinement of the carriers allied with
the quantum well, $6 \times 6$ Luttinger-Kohn Hamiltonian has been solved [11-13]. By deliberating the carrier’s confinements and their localities, the optical transitions elements have been calculated followed by gain computations. Since the proposed heterostructures are symmetrical (i.e. heterostructures containing the QW sandwiched by barriers followed by claddings on both the sides) and, consequently, for symmetrical structure, the optical gain can be expressed as [12];

$$G(h\omega) = \frac{2. \pi \sigma^2}{n c \omega L m^2} \sum_{\sigma=\pm} \sum_{n,m} \int \left[ \mathcal{E} M_{n,m}^{\sigma}(k_{\perp}) \right]^2 \times \frac{\left( f_{\sigma}^{\nu}(k_{\perp}) - f_{\sigma m}(k_{\perp}) \right) \left( \frac{2}{\gamma} \right)}{\left( E_{\sigma m}^{\nu}(k_{\perp}) - \omega \pm h k_{\perp} \right)^2 + \gamma^2} \frac{k_{\perp} d k_{\perp}}{2\pi}$$

In the above expression, the detail of all the terms can be seen in ref. [12].

3. Results and Discussion

Generally, any opto-electronic device’s output performance is calculated in terms of optical inverse loss or optical features since it is most significant and primary condition for the understanding the mechanism of a semiconducting materials-based laser. It is due to the stimulated emission that take place by electron and hole pairs (EHPs) recombination. For InGaAsN/GaAs (GaAs is substrate) heterostructure, the simulated optical gain and modal gain is shown in figure 1. In figure 1, it can be seen that the both the gain i.e. peak optical gain and the peak modal gain (which is determined by multiplication of optical gain with confinement factor) is achieved at a single wavelength $\sim 1.30 \mu m$. Moreover, in figure 1, two peaks can be observed. Appearance of these two peaks are due to two transitions which occurs between first electronic state (lying in conduction band) and heavy and light hole states (lying within the valence band).

Ref to figure 2, the optical gain for InGaAsN/InP (InP is substrate) heterostructure taking into account claddings is simulated and shown. In figure 2, it can be observed that the peak optical inverse loss with claddings is achieved at energy 1.11 eV (at wavelength $\sim 1.11 \mu m$); while the optical gain without claddings are achieved at wavelength $\sim 1.14 \mu m$ (see inset figure). Further, form figure 2, it can be seen that the presence of claddings not only affects the magnitude of optical gain, it also affects the wavelength and photonic energy. Positively, the inclusion of claddings in the heterostructure enhances the strength of the optical inverse loss by confining the much light wave in the quantum well. The
numerically outcome data of the simulation of InGaAsN QW heterostructure with substrates GaAs and InP is shown and compared in table 1.

Table 1: Comparative Study of InGaAsN QW heterostructure with GaAs and InP substrate

| Quantum well Heterostructure | Substrate | Optical Gain (\(\text{/cm}\)) | Wavelength (\(\mu\text{m}\)) |
|------------------------------|-----------|-------------------------------|-----------------------------|
| InGaAsN (with claddings)     | GaAs      | 2100                          | 1.30                        |
| InGaAsN (without claddings)  | InP       | 1675                          | 1.14                        |
| InGaAsN (with claddings)     | InP       | 2353                          | 1.11                        |

**Conclusion**

For InGaAsN quantum well heterostructure with the substrates GaAs and InP, the quantum mechanical approach (k.p method) has been adopted to calculate the confinement of the carriers associated with quantum well and the optical gain. In addition, for InGaAsN/InP heterostructure, the cladding effect has also been observed. The simulated results exhibit that the substrate has played a very significant role in modifying the optical gain features due to the presence of strain which comes into play due to the lattice difference.

**References**

[1]. A. Kuramata, K. Domen, R. Soejima, K. Horino, S. Kubota and T. Tanahashi, “InGaN Laser Diode Grown on 6H–SiC Substrate Using Low-Pressure Metal Organic Vapor Phase Epitaxy”, *Japan. J. Appl. Phys.* 36 L1130 (1997).

[2]. S. Nakamura, S. Pearton and G. Fasol, *The Blue Laser Diode* (Berlin: Springer) 2000.

[3]. J. K. Sheu, F. W. Huang, C. H. Lee, M. L. Lee, Y. H. Yeh, P. C. Chen and W. C. Lai, “Improved conversion efficiency of GaN-based solar cells with Mn-doped absorption layer”, *Appl. Phys. Lett.* 103 063906 (2013).
[4]. F. Y. Wu, P. B. Keller, D. Kapolnek, P. S. Denbaars and U. K. Mishra, “Measured microwave power performance of AlGaN/GaN MODFET”, IEEE Electron. Dev. Lett. 17 455–7 (1995).
[5]. F. Y. Wu, P. B. Keller, P. Parikh, D. Kapolnek, S. P. Denbaars, and U. K. Mishra, “Bias dependent microwave performance of AlGaN/GaN MODFET’s up to 100 V”, IEEE Electron Dev. Lett. 18 290–2 (1997).
[6]. Z. I. Alferov, “The history and future of semiconductor heterostructures”, Semiconductors 32, 1 (1998).
[7]. P. A. Alvi, Sapna Gupta, Meha Sharma, Swati Jha, F. Rahman, “Computational modeling of novel InN/Al0.30In0.70N multilayer nano-heterostructures”, Physica E: Low-Dimensional Syst. Nanostruct., 44, pp. 49-55 (2011).
[8]. P. A. Alvi, "Strain Compensated InN based Superlattice", Adv. Sci. Lett., Vol. 5, No.17, pp. 101-107(2012).
[9]. Sapna Gupta, F. Rahman, M. J. Siddiqui, P. A. Alvi, “Strain Profile in III-Nitride based Multilayer Nano-heterostructures”, Physica B: Condensed Matter, Vol. 411, pp. 40-47 (2013).
[10]. Y. S. Park, “Wide bandgap III-nitride semiconductors: opportunities for future optoelectronics”, Optoelectronics Review 9(2), 117-124 (2001).
[11]. S. L. Chuang, Physics of optoelectronic devices (Wiley, New York, 1995).
[12]. H. K. Nirmal, Nisha Yadav, F. Rahman, P. A. Alvi, “Optimization of High Optical Gain in Type-IIIn0.70Ga0.30As/GaAs0.40Sb0.60Lasing Nano-heterostructure for SWIR Applications” Superlattices Microstruct., 88, 154-160 (2015).
[13]. P. A. Alvi, “Transformation of type-II InAs/AlSb nanoscale heterostructure into type-I structure and improving interband optical gain”, Phys. Status Solidi B, 254, No. 5, 1600572 (2017).