Reduction of cavity length dependence and improvement of characteristics of 1.55 μm quantum dot based LASER using indium nitride

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Reduction of cavity length dependence and improvement of characteristics of 1.55 μm quantum dot based LASER using Indium Nitride

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This paper presents the improvement of certain important characteristics of 1.55 μm laser by reducing the dependence of cavity length using InN based quantum dot in the active layer of the device structure. The improvement of these characteristics has been investigated in terms of ultra low threshold current density, minimization of internal loss, enhancement of the modal gain, external differential efficiency and the photon lifetime. In this paper these characteristics have been investigated using InN based quantum dot in the active layer of the laser structure and compared with GaN and AlN based quantum dot laser. The comparison results reveal that InN based quantum dot provides lower threshold current density, reduced internal loss compared to GaN and AlN quantum dot based laser. Beside these enhanced modal gain, improved efficiency and higher photon lifetime have also been reported using InN based quantum dot in the active layer of the laser structure. In addition to these improvements obtained from the numerical results it is ascertained that InN based quantum dot in the active layer of the laser structure offers weaker dependence of cavity length on these characteristics. From the results it is revealed that InN can be a promising material to design high performance quantum dot based laser operating at 1.55 μm with reduced cavity length dependence in the very near future.

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Keywords: threshold current density, internal loss, modal gain, photon lifetime, external differential efficiency.

1. Introduction

Self-organized quantum dots (QDs) have become one of the most important subjects for the researchers in the field of optoelectronic device fabrication [1]. The laser characteristics depend on many factors such as: properties of the material, QD parameters and the structural parameters of the device itself. The material properties include: band-gap energy, carrier life time, and the other non uniform characteristics of the material used in the active layer like carrier density [2, 3]. The laser characteristics vary in a complex way on many QD parameters like size, shape, dimensions, strain, and composition. The confinement layers composition, residual strain along with ground quantized energy levels of carriers are also important parameters related to the QD. These parameters also have an impact on the laser characteristics. Among the parameters related to the design of the device structure, the length of the cavity is the most important parameter that affects the device performance significantly [4, 5]. Cavity length has a radical effect on output characteristics such as output power, emission wavelength, quantum efficiency and so on [6, 7]. So, this research is devoted to the reduction of cavity length dependence of revolutionary QD lasers (QDLs) characteristics using InN.

Group-III nitride-based devices are of particular interest due to their wide range of emission frequencies from red to ultraviolet and their potential for high-power electronic applications [8, 9]. Among the three (0.85 μm, 1.3μm & 1.55 μm) windows of optical fiber communication, silica fiber offers the lowest attenuation, greater repeater spacing and higher bit rate for the window of 1.55 μm wavelength. These phenomena made it possible to use coherent optical sources and are compatible with the standard silicon processing procedures. Thus 1.55 μm is the most promising candidate for long distance optical fiber communication. The existing materials used to design 1.55 μm QDLs are ternary $Ga_{0.47}In_{0.53}As$ [10] and quarternary InGaAsN [4]. These materials are difficult to grow with constituent of high nitrogen element to reach the wavelength of 1.55μm. It also creates many non-radiative centers in the active layer leading to the degradation of the quality of the material which in turn reduces the device performance. Therefore, researchers are looking for the better alternative materials. Recently it has been reported that InN is compatible to 1.55μm emission due to its band gap of 0.7 eV [11].

This paper presents the significant improvements in the characteristics of the semiconductor laser using InN based QD in the active layer. These improvements have been demonstrated in terms of higher performances such as ultralow threshold current density, high gain, high efficiency and improved photon lifetime. Therefore, potential device applications range from high power semiconductor lasers to high speed light sources for fiber optic data transmission systems [4].

2. Device structure

Laser structure composed of InN based QD in the active layer has been considered for investigating the improvement of the cavity length dependence on the laser characteristics operating at the wavelength of 1.55μm. The laser structure with InN based QDs is shown in Fig.1 Considering the domain of InN emission wavelength raises the possibility to tune the wavelength by controlling the dots size [18]. Hence InN QD posses greater interest for the possible applications in the wide range of optoelectronic devices. For the optimization of the band gap energy of InN QD to operate exactly at 1.55μm the mean height of the QD is reported as 2.7nm [12, 13]. Hence the active layer thickness has been considered as 2.7 nm, which is equal to the QD heights.

p GaN Contact layer (77 nm)
p$Al_{0.13}Ga_{0.87}N$ Upper cladding layer (1000 nm)
p $In_{0.82}Ga_{0.18}N$ Guiding layer (117 nm)
InN undopped QDs Active layer (2.7 nm)
n $In_{0.82}Ga_{0.18}N$ Guiding layer (117 nm)
n $Al_{0.13}Ga_{0.87}N$ Lower cladding layer (1000 nm)
n- GaN Contact layer (77 nm)
C sapphire(0001) substrate

Fig. 1. Schematic layer structure of InN based QDL

Schematic structure of InN based QDL consists of InN-plane sapphire (oriented along 0001 direction) wafer as the substrate along with 77 nm-thick n+ GaN contact layer, a 1000 nm thick n $Al_{0.13}Ga_{0.87}N$ lower cladding layer, a 117nm-thick n- $In_{0.82}Ga_{0.18}N$ guiding layer, a 2.7 nm–thick InN active region with single layer undoped QDs, a 117 nm-thick p $In_{0.82}Ga_{0.18}N$ guiding layer, a 1000 nm thick p $Al_{0.13}Ga_{0.87}N$ upper cladding layer; 77 nm-thick p+ GaN contact layer. The optical confinement layer thickness is 236.7 nm. To form Fabry-Perot cavity mirrors by etching facets FIB etching technique is proposed which provides high quality etched facets. Fabry-Perot resonator is composed of two highly reflective mirrors which allow small portions of light to pass through, while reflecting the most of the light back through the active region, where it can be further replicated through stimulated emission. A pair of parallel planes (or facets) is etched. Under appropriate biasing condition laser light will be emitted from these planes. The two remaining sides are roughened to eliminate lasing in any direction other than main one.

3. Numerical analysis

Cavity length is one of the most important parameter that affects the device characteristics significantly. The cavity length dependence of different characteristics of laser has been investigated extensively in this research work. For any particular device the cavity length is fixed. Therefore an effective way has been proposed to improve the laser performance by changing the active layer material of the QDL structure. The following sub-sections present the numerical analysis of cavity length dependence of losses, modal gain, efficiency and frequency response of the QDL.

3.1. Loss, gain and efficiency

The most important characteristic investigated in this research is the external quantum differential efficiency, which is related to the major two loss components namely mirror loss and the internal loss of the laser cavity. The external differential efficiency η_d is usually approximated by the following equation [14]:

$$\eta_d = \eta_i \frac{\alpha_m}{\alpha_m + \alpha_i} \tag{1}$$

where η_i is the internal quantum efficiency of the stimulated emission;α_m is the mirror loss and α_i is the internal loss of the laser cavity.

Therefore, the mirror loss and the internal loss have been demonstrated as a function of cavity length to investigate the cavity length dependence of the external differential efficiency. The mirror loss is directly related to the cavity length of the laser structure as given by the following equation:

$$\alpha_m = \frac{1}{2L} \ln(\frac{1}{R_1 R_2}) \tag{2}$$

where L is the cavity length of the laser structure; R_1 and R_2 are the reflectivity of the mirrors respectively. The values of R_1 and R_2 are 0.32 and 0.99 respectively [12, 13, 15]

Now in order to calculate efficiency as a function of cavity length the internal loss has also been calculated as a function of cavity length. But the internal loss of a laser is not a direct function of cavity length. Internal loss is a function of threshold current density. The relationship between the internal loss and the threshold current density is given by the following equation.

$$\alpha_i = \alpha_i^o + k_a J_{th} \tag{3}$$

where, k_a is the factor related to the geometry of the laser waveguide. The value of k_a considered in our study is 0.006 cmA^{-1} [14].

However, the expression of threshold current density as a function of cavity length is required to relate the internal loss with the cavity length. The threshold current density is related to the cavity length by the following equation [16]:

$$J_{th} = \frac{J_0 d}{\eta_i}\{1 + \frac{1}{g_0 \Gamma}[\alpha_i^0 + \frac{1}{2L}\ln(\frac{1}{R_1 R_2})]\} \qquad (4)$$

The internal loss is a function of threshold current density as given by equation (3). Moreover, the dependence of the threshold current density on the cavity length is given by equation (4). So to demonstrate the cavity length dependence of internal loss we correlated equation (3) and (4).

Now in order to overcome these losses and to amplify light to a sufficient level to have more amplified light the modal gain characteristics of the laser has been investigated. At threshold, modal gain compensates the total losses [17]. The dependence of modal gain on threshold current density is given by the imperial relationship:

$$J_{th} = J_0 \ln(\frac{g_0}{g_0 - g_{\text{mod}}}) \qquad (5)$$

By solving equations (4) and (5) the effect of cavity length on the modal gain has been demonstrated.

3.2. Frequency response

Output frequency response is an additional major characteristic of a laser which is affected by the cavity length directly. The output frequency response is governed by the photon lifetime. The photon lifetime τ_{ph} as a function of the cavity is given by [15]:

$$\frac{1}{\tau_{ph}} = \frac{c}{n_r}(\alpha_i + \frac{1}{2L}\ln(\frac{1}{R_1 R_2})) \qquad (6)$$

where c is the speed of light in vacuum, n_r is the refractive index, L is the cavity length, R_1 and R_2 are the cavity mirror reflectivities, and α_i is the internal loss.

4. Results and discussion

The cavity length dependence of different characteristics of laser has been analyzed extensively in this research work using GaN, AlN and InN based QD material in the active layer of the QDL structure. From the results it is revealed that InN based QD reduces the dependence of the cavity length of the laser structure with superior performance of the laser characteristics.

First of all the cavity length dependence of the threshold current density is fitted directly by equation (4) as shown in Fig. 2. After that the effect of cavity length on the internal loss and modal gain characteristics has been analyzed by using equation (3) and (5) via the correlation of equation (4). These correlations were necessary because the modal gain and the external differential efficiency are not directly related to cavity length but to the threshold current density. On the other hand, the equation (4) represents direct relationship between the cavity length and the threshold current density. Similarly using the correlation among equations (1)-(4) the external differential efficiency is determined with respect to cavity length. The internal loss, modal gain and the external differential efficiency are graphically shown in Fig. 3, Fig. 4 and Fig. 5 respectively. Finally, the effect of cavity length on the photon lifetime has been demonstrated using equation (6). The photon lifetime with respect to cavity length is illustrated in Fig. 6. The line curve, dashed curve and the dotted curve represent the QDL characteristics using InN, GaN and AlN based QD correspondingly in Fig. 2 to Fig. 6.

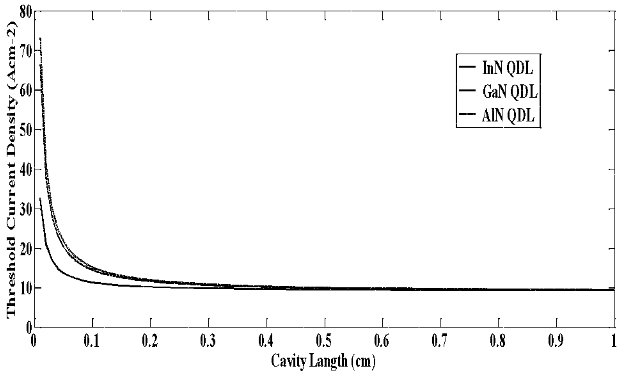

Fig. 2. Cavity length dependence of threshold current density of QDL using InN, GaN and AlN based QDs as the active layer material

Fig. 2 presents the characteristics of the threshold current density of QDL with respect to cavity length. The threshold current density reduces nonlinearly with the uniform increase of cavity length as shown in Fig. 2. It is revealed from the line curve of this figure that the threshold current density has decreased notably using InN QD as the active layer material of the laser structure. Moreover, slope of the curve indicates the rate of change of threshold current density with the change in cavity length. As shown in Fig. 2 the slope of the line curve is the minimum and after the cavity length of 0.1 cm it is almost flat. The higher flatness of the curve indicates the weaker cavity length dependence. So, InN based QD in the active layer provides the lowest threshold current density as well as the weakest dependence of cavity length on threshold current density.

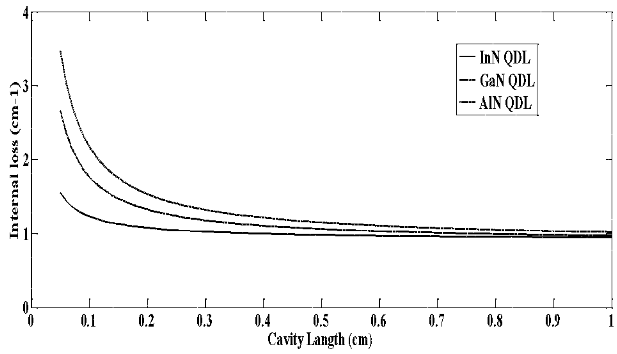

Fig. 3. Cavity length dependence of internal loss of QDL using InN, GaN and AlN based QDs as the active layer material

Fig. 3 describes the effect of cavity length on the internal loss of QDL. The internal loss drops down with the rise of cavity length. Fig. 3 represents the comparison of the internal loss characteristics with respect to cavity length using InN, GaN and AlN based QD in the active layer of the laser structure. From Fig. 3 it is ascertained that although the internal loss is decreasing as the cavity length increases for any material. However, InN QD in the active layer of the laser structure offers lower internal loss than that of GaN and AlN based QD for any cavity length. From the gradient of the curve it is found that for any cavity length beyond 0.15 cm the internal loss is almost uniform. This uniformity of the line curve signifies the reduction of the cavity length dependence of internal loss.

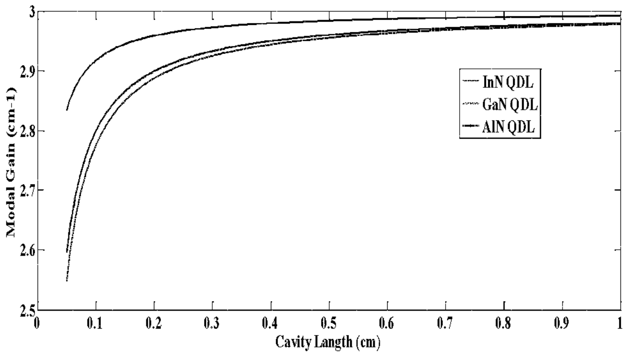

Fig. 4. Cavity length dependence of modal gain of QDL using InN, GaN and AlN based QD as the active layer material

As illustrated in Fig. 4 the modal gain has a non-linier dependence on the cavity length of QDL. The modal gain rises very sharply up to the cavity length of 0.1 cm. After that until the cavity length of 0.15 cm the gain increases slowly and reaches at the saturation soon afterwards. As long as the modal gain remains negative it is not sufficient to compensate the overall losses. When the gain reaches at the saturation after crossing the zero value then it can compensate the total loss and aids in the amplification of light in the gain medium. From Fig. 4 it is revealed that although the modal gain is increasing as the cavity length increases for any material, InN QD in the active layer offers the maximum modal gain for any cavity length of the QDL. It also reaches to the saturation at lower cavity length. From the overall discussion it is revealed that InN QD offers lesser dependence of cavity length along with the higher gain.

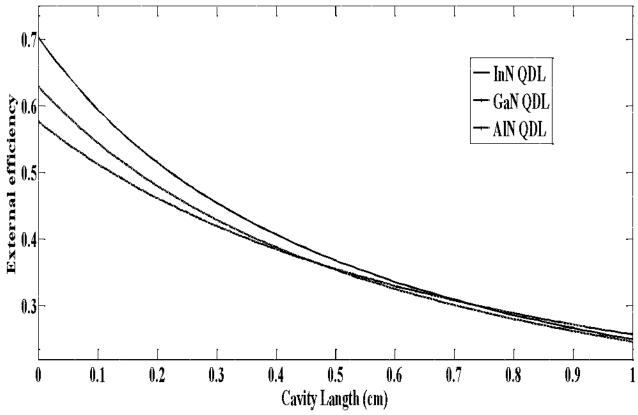

Fig. 5. Cavity length dependence of external efficiency of QDL using InN, GaN and AlN based QD as the active layer material

Fig. 5 demonstrates the cavity length dependence on the external differential efficiency of QDL. The external differential efficiency decreases with the increase in cavity length as shown in Fig. 5, which represents the assessment of the threshold current characteristics with respect to cavity length using InN, GaN and AlN based QD in the active layer of the laser structure. From Fig 5 it is revealed that although the external differential efficiency is decreasing as the cavity length increases for any material, InN QD in the active layer offers the boosted external differential efficiency than that of other group III nitrides.

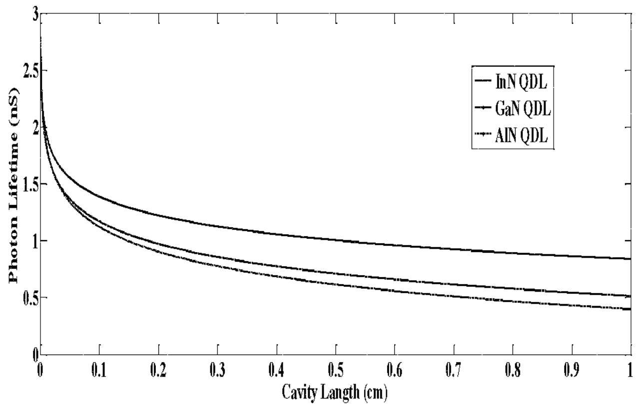

Fig. 6. Cavity length dependence of photon lifetime of QDL using InN, GaN and AlN based QD as the active layer material

Fig. 6 shows the dependence of cavity length on the photon lifetime of QD. The photon lifetime decreases with the increase of cavity length. This figure represents the comparison of the photon lifetime characteristics with respect to cavity length using InN, GaN and AlN based

QD in the active layer of the laser structure. From Fig. 6 it is revealed that although the photon lifetime is decreasing as the cavity length increases for any material but InN in the active layer offers the maximum photon lifetime for any cavity length among the three materials used in this research work.

Finally it can be concluded that InN provides enhanced device performance with lower dependence on the cavity length, which is one of the major parameters related to the device structure.

5. Conclusion

InN based QD in the active layer of the laser structure shows the weakest cavity length dependence among the three materials used in this study. From the results it is ascertained that the internal loss along with the threshold current density have decreased significantly while the modal gain increased dramatically by applying InN based QD for any cavity length of the QDL. As a result of minimization of internal loss and enhancement of gain, the efficiency of the QDL has also been improved. In this present research work it has also been proved that InN based QD not only provides the improvements in internal characteristics like threshold current density, loss, gain and efficiency but also improves the photon life time of the carrier. So from the above discussion it can be concluded that InN can be a promising material to design QDL in the upcoming decades.

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