Design of GaN-based VCSEL with high performance

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Doping concentration of the distributed Bragg reflectors (DBRs) can strongly affect efficiency of the vertical cavity surface emitting laser (VCSEL) by increasing radiative recombination of carriers. In this paper, Integrating System Engineering Technology Computer Aided Design (ISETCAD) software was used to enhance the performance of GaN-based VCSEL by changing doping concentrations of the DBRs. the effect DBRs doping concentration on the threshold current and differential quantum efficiency in GaN VCSELs has been investigated.

1. Introduction

Nitride-based wide-bandgap ternary alloys are ideal for fabrication of light- emitting devices such as light emitting diodes (LEDs), laser diodes (LD) and vertical cavity surface emitting lasers (VCSELs). A semiconductor laser based on wide-bandgap of GaN, AlN and InN materials and their alloys are very attractive due to their potential applications in full-color displays and high density optical storage [1]. The bandgap of III- nitride materials are direct, and they cover a very large energy scale at room temperature. Therefore, they are essential materials for semiconductor devices because of their excellent mechanical strength [2]. In VCSELs, a micro cavity is only a few λ optical thicknesses. These devices have a small optical mode volume and can emit a single mode with circular symmetry beam and a small beam divergence; because of these characteristics these devices are superior more than the edge emitting lasers and desirable for many practical applications in high density optical storage and laser printing [3]. In general a VCSEL consists of an active region sandwiched between two DBRs. The thickness of each layer in DBRs is equal to one quarter of the operating wavelength of light. There are several quantum wells (QWs) in the center of device and two spacer layers form a separate confinement for efficient carrier trapping and optical confinement [4]. The short active cavities in these devices are in a direction orthogonal to that of the conventional semiconductor laser. The thickness of the active region is only ten or hundreds of angstrom and the resonator length is only in wavelength order. obtaining enough gain in such thin active region in VCSELs is difficult, therefore in order to reduce the loss of the resonant cavity and achieve stimulated emission, mirrors with high reflectivity are necessary [5, 6]. For increasing the performance of VCSELs, the optimization of the DBRs is important, but an anomalously high series resistant in top DBRs is one of the serious problems in VCSELs. To solve this problem many attempts have been made, for example use of graded heterointerfaces and modulation doping [7-9]. One method for reducing the resistance is doping the entire p-DBRs heavily. This reduction of the series resistance helps to reduce the operating voltage. In this paper, the effect of doping concentration of DBRs on the threshold current and external quantum efficiency in GaN VCSELs has been investigated using ISETCAD software.

2. VCSEL design in numerical simulation

GaN top surface emitting VCSEL is shown in Fig. 1. In this design, the device has been constructed with n-GaN substrate followed by n-DBR. In order to get a good performance of device, GaN material at high refractive index ~ 2.5067 and $Al_{0.38}Ga_{0.62}N$ material at low refractive index ~ 2.3433 were used for p and n- type DBRs, respectively. The lower section of the device contains sixty three pairs of n-DBRs, while the upper section of p-DBR pairs was forty two pairs with λ/4 thicknesses [10]. The active medium consists of $In_{0.01}Ga_{0.99}N$ as a barrier and $In_{0.13}Ga_{0.87}N$ as a quantum well. Lowest threshold current and highest in output power and both of slope efficiency, and differential quantum efficiency were observed when the quantum well numbers are double (DQWs) VCSEL with λ-cavity [11, 12]. The well and barriers are sandwiched between two cladding layers of $Al_{0.15}Ga_{0.85}N$. The emission wavelength of the VCSELs is about 415 nm and the radius of the device is 1 μm. Since holes have difficulty to move from left to right quantum well due to the relatively large effective mass, low mobility and high band offset in valence band, therefore, the doping concentration of p-DBRs and n-DBRs are varied between 4 and 7×10^{18} cm^{-3} and 4 and 7×10^{17} cm^{-3}, respectively.
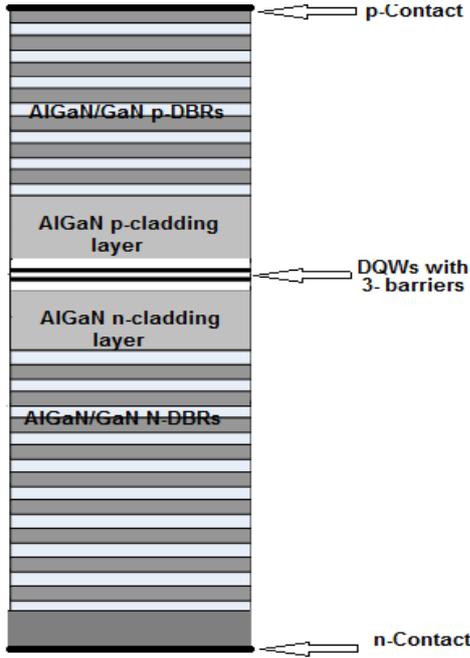
Fig. 1. Schematic configuration of GaN-based MQWs VCSEL.

3. Simulation results and discussion

The Transfer Matrix Method (TMM) with vertical solver is employed to solve the optical and electrical problems inside the GaN- based VCSEL structure.

Fig. 2 and Fig. 3 show the variation of threshold current and differential quantum efficiency respectively, with respect to the change of n-doping DBRs concentration when the p-doping is fixed. It was found from Fig. 2 and Fig. 3 that VCSEL threshold current and differential quantum efficiency monotonically increases as the doping level in the n-type DBR is increased, while the doping level in the p-type DBR has no create large changes in both threshold current and differential quantum efficiency as in Fig. 4 and Fig. 5.
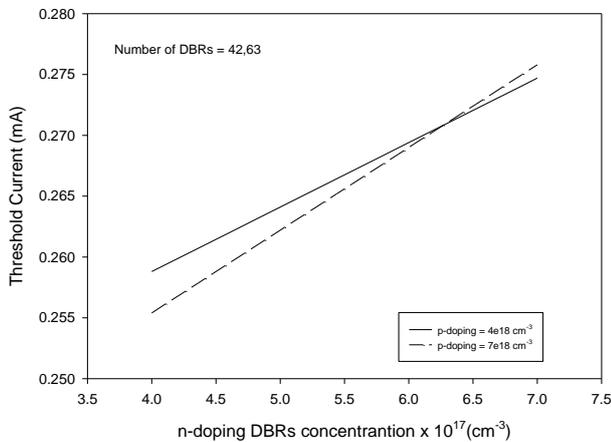
Fig. 2. Threshold current versus n-doping DBRs concentration for GaN VCSEL.
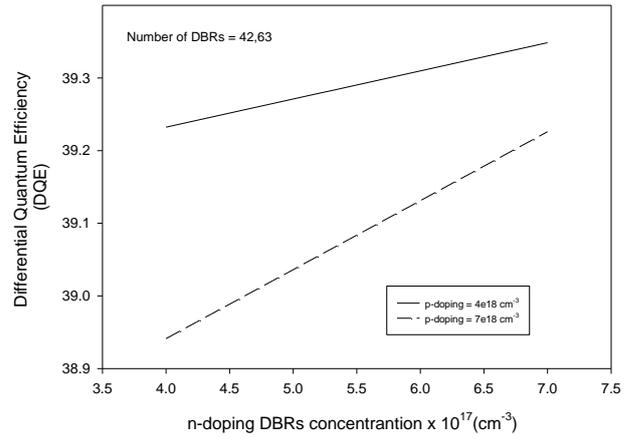
Fig. 3. Differential quantum efficiency versus n-doping DBRs concentration for GaN VCSEL.
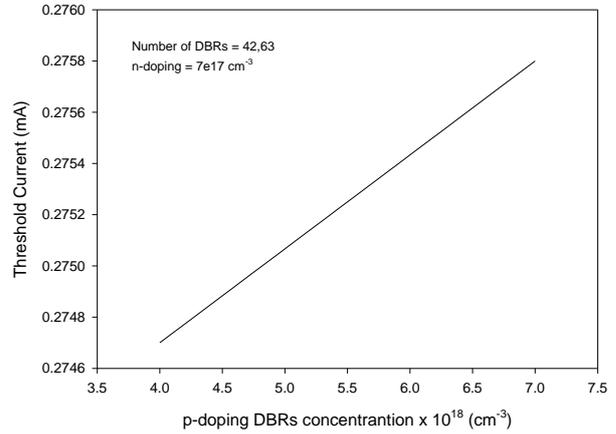
Fig. 4. Threshold current versus p-doping DBRs concentration for GaN VCSEL.

It has been investigated the n-doping changes in concentration are more important. The reduction of n-doping reduces the threshold current and creates better condition for laser performing. It is due to the injected longitudinal modes in mirrors and optical absorption. Because, the emission is from top, the changing of p-doping concentration hasn't created large changes in threshold current. When the doping increases the carrier increases, consequently the threshold current increases and differential quantum efficiency decreases. With increasing in doping concentration, higher number of carriers is injected to the active region consequently radiative recombination increases and threshold current and differential quantum efficiency increase. In p-doping, when the concentration increases, because the emission is from top and p-doping DBRs, consequently field emission from p-DBRs reduces and DQE also decrease. But in n-doping, because the injected field between the farthest parts of DBRs is low, DQE has been increased.
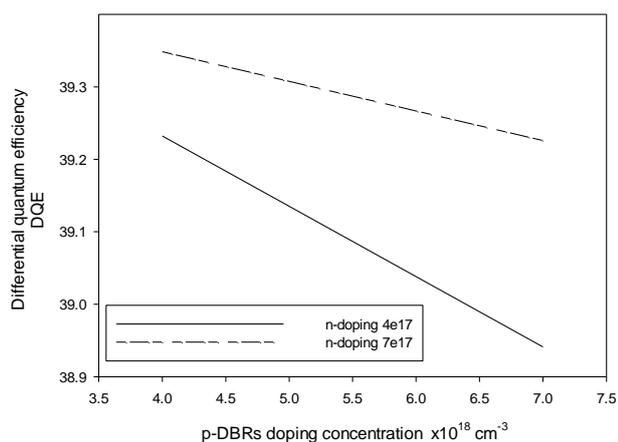
Fig. 5. Differential quantum efficiency versus p-doping DBRs concentration for GaN VCSEL.

4. Conclusion

A numerical study has been preformed for the VCSEL operating at 415 nm region of the electromagnetic spectrum. Relevant VCSEL design with numerous doping concentrations has been designed and characterized using ISETCAD simulation. In this paper, it has been recognized that reduced doping level in the n-DBR has a significant impact. Decreased doping throughout the n-type mirror produced significantly higher external quantum efficiency and lower threshold current

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