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The effect of number of distributed Bragg reflectors on VCSEL output performance

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The effect of the various number of p-DBR pairs on output performance of GaAs MQWs VCSEL is numerically investigated using ISETCAD simulation program. Relevant VCSEL design with numerous (DBR) pairs has been designed and characterized. It was observed that the number of quarter-wave DBR remaining in the upper mirror can be chosen to achieve optimum performance for the VCSEL in a top surface emitting geometry, such as maximum output power, threshold current, slope output efficiency and differential quantum efficiency and mode gain.

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1. Introduction

In the preceding analysis of the threshold conditions of VCSEL, the power reflectivity of mirrors is required to be greater than 0.9 [1, 2]. High reflectivity can be obtained by coating an almost perfect conductor (i.e., with large but finite conductivity) on the surface of the confinement layer. However, semiconductor multilayered mirrors with high reflectivity and low absorption loss, which is called distributed Bragg reflectors (DBRs) are utilized in VCSELs. DBRs consist of epitaxially grown of repeating pairs of quarter-wavelength-thick high and low-refractive index semiconductor layers. Therefore, combining the multiple quarter-wavelengths thick high-to-low refractive index layers will result in a maximum reflectance greater than 99% [3-5]. A simple equation can be used to calculate the reflectivity of single DBR at normal incidence as in the following equation:

$$R = \left[\frac{1 - \left(\frac{n_1}{n_2} \right)^{2m}}{1 + \left(\frac{n_1}{n_2} \right)^{2m}} \right]^2 \tag{1}$$

where m is the number of the quarter-wave DBR pairs, n_1 and n_2 are the refractive indexes of the two layers of DBR. The proper DBRs design is crucial for both the optical and electrical performance of the device; high reflectivity DRBs are required for achieving lasing in short-cavity (one-λ cavity length) VCSELs. For lasing from the top DBRs, the reflectivity of the top DBRs is usually designed to be around 0.996 - 0.999, while the reflectivity of the bottom DBRs is designed to be above 0.99999 [6, 7]. In the present paper, the authors aim to present the characteristic features of the reflectivity of the output mirror of 850 nm VCSELs with various output reflector DBR pairs. For this, VCSEL devices with various corresponding p-DBR pairs are simulated by using ISETCAD simulation program. The peak output power and the threshold current for each of these devices are determined. In the study, we investigate that by increasing DBR pairs, the DBR reflectivity was increased and so did the cavity Q-factor, which can reduce device lasing threshold. However, the external differential quantum efficiency was inversely related to top mirror reflectivity. So, the optical output of the device also decreases with increased p-type mirrors pairs. A suitable DBR design is carefully pick for the pair number so as to balance between low lasing threshold current, high output power, and high efficiency.

2. VCSEL design in numerical simulations

The ISETCAD program of laser simulation was used. Finite element (FE) with vertical solver is employed to solve the optical and electrical problems inside the VCSEL structure. The band gap energy for AlGaAs at room temperature is calculated using the direct and indirect energy band gap equations [9]:

$$Eg(x)_{dir} = 1.424 + 1.247x \text{ eV} \quad x < 0.45 \text{ (direct energy band gap)} \tag{2}$$

$$Eg(x)_{ind} = 1.900 + 1.250x + 0.143x^2 \text{ eV} \quad x \geq 0.45 \text{ (indirect energy band gap)} \tag{3}$$

The electrons, light and heavy holes effective masses for AlGaAs active layer are used in our simulation which can be calculated by the following equations [10]:

$$\frac{m_e}{m_o} = 0.067 + 0.083x \tag{4}$$

$$\frac{m_{lh}}{m_o} = 0.087 + 0.063x \tag{5}$$

$$\frac{m_{hh}}{m_o} = 0.500 + 0.290x \qquad (6)$$

A schematic diagram of 850 nm GaAs/AlGaAs top surface emitting VCSEL laser structure is shown in Fig. 1. In our design, the device has been constructed with n^+-GaAs substrate followed by n^+-DBR. In order to get a good performance of the device, $Al_{0.20}Ga_{0.80}As$ (having high refractive index ~ 3.492) and $Al_{0.90}Ga_{0.10}As$ (having low refractive index ~ 3.062) materials were used for the p^- and n^+- type DBRs, respectively. The lower section of the device contains thirty-eight pairs of n-DBRs with $\lambda/4$ thicknesses, while the upper section of p-DBR pairs was subsequent removal of two mirror pairs in each step from 29 until 15, while the doping concentration for both n and p-types DBRs was $5\times10^{+17}$ cm^{-3}. The active medium with λ-cavity length consists of four GaAs quantum wells with thickness of 6 nm, separated by five $Al_{0.20}Ga_{0.80}As$ barriers with thickness of 12 nm. The multiple quantum well (MQW) was sandwiched by two spacers of $Al_{0.30}Ga_{0.70}As$.

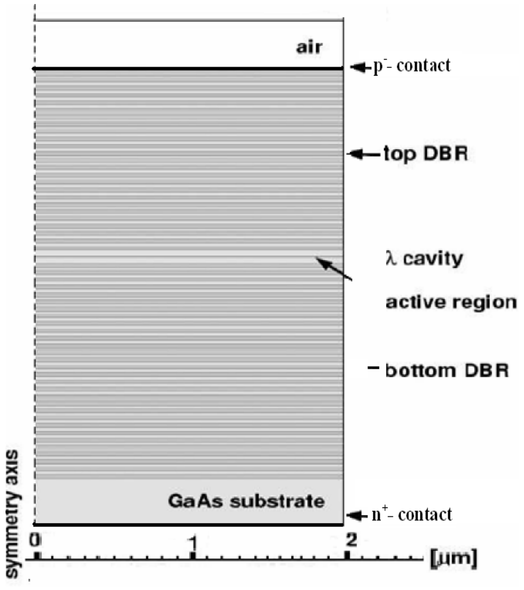

Fig. 1. A transverse cross-sectional view of the half portion of 850 nm GaAs/AlGaAs top surface emitting VCSEL.

3. Simulation results and discussion

To study the effect of output mirror reflectivity on the design of VCSEL, the number of p-DBR pairs subsequent removal of two mirror pairs in each step from 29 until 15 is investigated, while the reflectivity of the bottom n-DBRs is designed to be 38 pairs, which is ≈ 99.999 % .

Fig. 2 and Fig. 3 illustrated the effect of VCSEL reflectivity of the top p-DBRs on carriers' density (electrons and holes) distribution inside the MQWs active region. The right side of the diagram is n-side and left side is p-side of the GaAs VCSEL. The horizontal axis is the distance along the crystal growth direction in side the active medium. It can be seen that with increase of the p-DBR pairs of VCSEL, a rapid increase for both of electrons and holes carriers' density were observed. This is attributed to the fact that decreasing of the DBR pairs lead to decreasing the coupling losses of mirrors. The primary sources of optical loss in VCSELs are the absorption and scattering losses of the DBR pairs and this leads to increase in the carriers' density (holes, electrons) inside the active region. More carriers density can be confined inside the active region also lead to increases in the optical material gain inside the quantum well layers as shown in Fig. 4. Fig. 4 also shows optical material gain inside the quantum well layers increased with increasing p-DBR pairs of GaAs VCSEL due to the increase in probability of stimulated emission in a single pass of the cavity which is increase of the gain inside the MQWs active region.

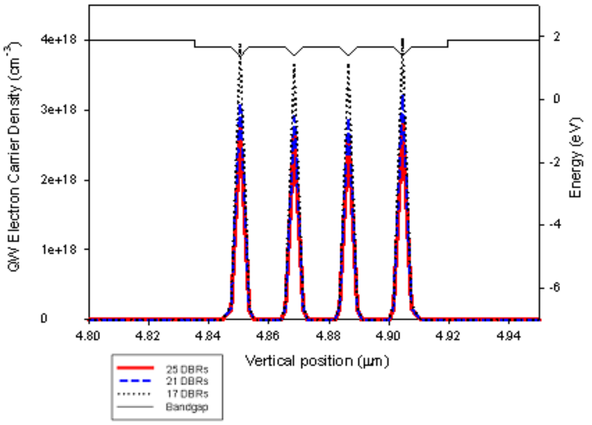

Fig. 2. Electron carrier's density distribution inside the MQWs active region as a function of number of p-DBR pairs at temperature of 300 K.

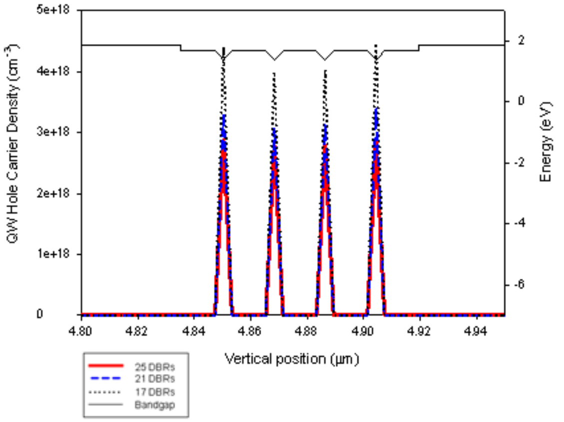

Fig. 3. Hole carriers density distribution inside the MQWs active region as a function of different number of p-DBR pairs at temperature of 300 K.

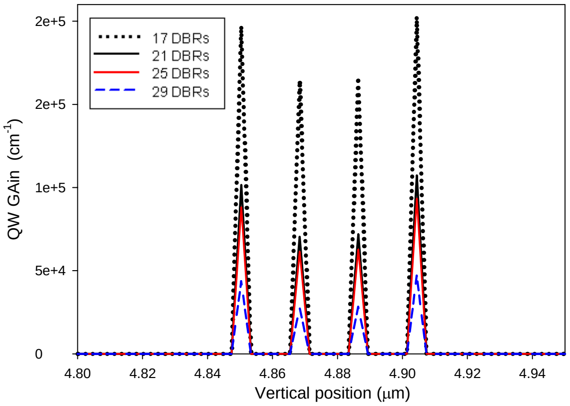

Fig. 4. Optical material gain inside MQWs of our VCSEL structure as a function of different number of p-DBR pairs at temperature of 300 K.

Fig. 5 shows the maximum output power and threshold current as a function of different number of p-DBR pairs. Fig. 6 shows output power as a function of forward current at temperature of 300 K. We observed an increase in output power as 0.447, 0.945, 1.513, 1.571 mW at 29, 25, 21, and 17 p-DBR pairs, respectively, while it decreased to 0.850 at 15 p-DBR pairs. This is attributed to the fact that decreasing in the DBR pairs lead to decreasing the coupling losses of mirrors. This leads to increase in the carriers density (holes, electrons) inside the active region which leads to increase in probability of stimulated emission in a single pass of the cavity therefore output power was increased. But it was observed that the output power will be decreased at 15 p-DBR pairs to 0.850 mW and that is attributed to the fact that the active region was saturated with carriers and some of the carriers would escape from the MQWs active region which cause the decrease in the output power, as shown in Fig. 5.

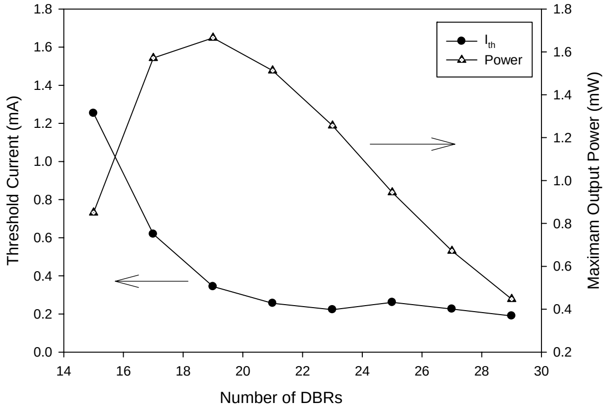

Fig. 5. VCSEL maximum output power as a function different number of p-DBR pairs at temperature of 300 K.

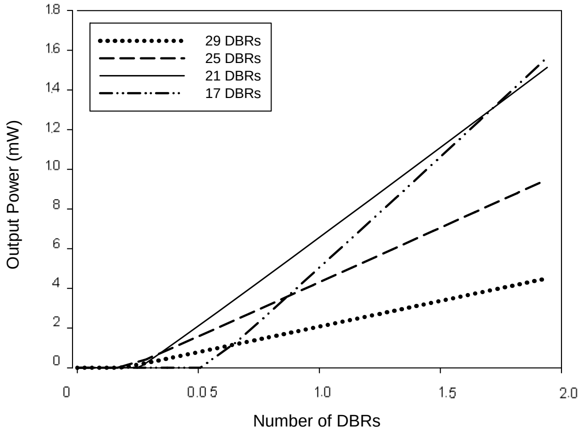

Fig. 6. VCSEL output power as a function of forward current with different number of p-DBR pairs.

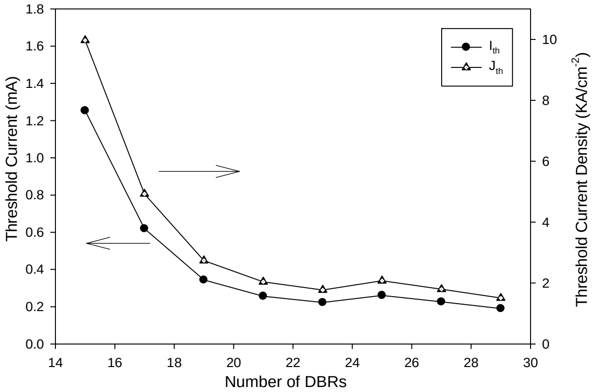

Fig. 7. VCSEL threshold current and threshold current density as a function of different number of p-DBR pairs.

Fig. 7 shows VCSEL threshold current and threshold current density as a function of different number of p-DBR pairs. It was observed that both of the threshold current and threshold current density were increased with decreasing number of p-DBR pairs due to the increasing of number of carriers inside the active region, which leads to increasing of the diffraction losses and scattering between the carriers inside active region, which cause the increase of the heat inside the VSCEL structure. The variation of the slope efficiency, and differential quantum efficiency (DQE) with the output mirror DBR pairs is shown in Fig. 8. It was found that by the increasing number of DBR pairs, the output slope efficiency and DQE decreased, due to increasing of optical losses (absorption and scattering losses of mirrors) as well as the heat generation by electrical series resistance of the DBR pairs which made the efficiency of the device less.

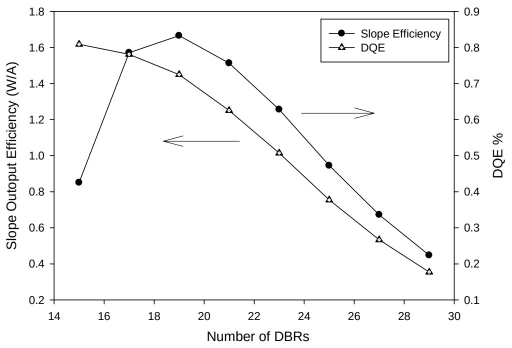

Fig. 8. VCSEL maximum output power, slope efficiency, differential quantum efficiency as a function of different number of p-DBR pairs.

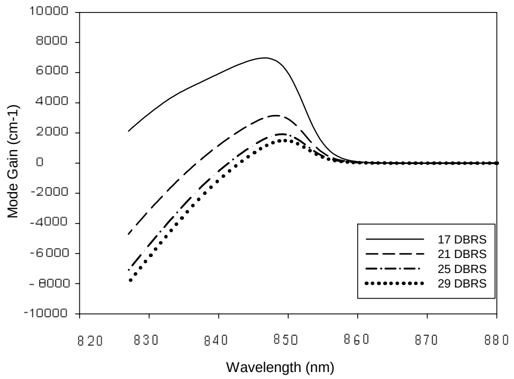

Fig. 9. VCSEL mode gain as a function wavelength with different number of p-DBR pairs.

Fig. 9 shows VCSEL mode gain as a function of wavelength with different number of p-DBR pairs. The optical mode gain of the VCSEL has been calculated as a function of Q factor (i.e., as a function of the of number DBR pairs). Increasing in the number of DBR pair's increase the Q factor of the cavity and narrows the width of its resonance (better wavelength selectivity) but it also reduces the peak of mode gain which goes lower in both the slope and differential quantum efficiency, as shown in Fig. 8.

4. Conclusions

The effect of the reflectivity of the output mirror of the single-mode multi-quantum wells (MQWs) GaAs-vertical cavity surface emitting lasers (VCSEL) performances is investigated. The influence of the output mirror reflectivity on the output power, threshold current, gain, slope and differential quantum efficiency is observed**.** This study found that the starting VCSEL structure uses 29 upper DBR pairs and achieves a record low threshold current of a VCSEL of 0.203 mW. An increase in output power by subsequent removal of two mirror pairs from 29 to17 pairs can be observed; this is attributed to the fact that decreasing in the DBR pairs lead to decreasing the coupling losses of mirrors. This leads to increase in the carriers' density (holes, electrons) inside the active region, which cause the increase in probability of stimulated emission in a single pass of the cavity. Therefore output power was increased. But it was observed that the output power will be decreased at 15 p-DBR pairs to 0.850 mW and that is attributed to the fact that the active region was saturated with carriers and some of the carriers would escape from the MQWs active region, which cause the decrease in the output power. The maximum slope efficiency, differential quantum efficiency and threshold current were increased while further decrease in the upper mirror reflectivity increases the output coupling. The increasing threshold current limits the device performance, presumably due to heating.

Acknowledgements

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