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The effect of reflectivity on vcsel output performance

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Abstract

The effect of the reflectivity of the output mirror on the single-mode multi-quantum wells (MQWs) vertical cavity surface emitting lasers (VCSEL) performances is investigated. Relevant VCSEL design with numerous (DBR) pairs has been designed and characterized using laser technology-integrated simulation program ISETCAD. The number of quarter-wave DBR that remaining in the upper mirror could be used to achieve the optimum performance of VCSEL in a top surface emitting geometry, such as maximum output power, threshold current, slope output efficiency, differential quantum efficiency and mode gain.

Keywords: Al GaAs; DBRs; MQWs; VCSEL.
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1. Introduction

In the preceding analysis of the threshold conditions of vertical cavity surface emitting laser (VCSEL), the power reflectivity of mirrors is required to be greater than 0.9 [1-5]. 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 of high-to-low refractive index layers will result in a maximum reflectance greater than 99% [6-9]. A simple equation can be used to calculate the reflectivity of single DBR at normal incidence as in Eq. (1).

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

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where m is the number of the quarter-wave DBR pairs, n_1 and n_2 are the refractive indexes of the two layers in DBR.

The proper DBRs design is crucial for both the optical and electrical performance of the device, high reflectivity DBRs 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 0.996-0.999 while the reflectivity of the bottom DBRs is designed to be 0.99999 [10-12]. In the present paper, the authors tend to present the characteristic features of the reflectivity of the output mirror of 850 nm VCSELs with various output reflector DBR pairs. VCSEL devices with various corresponding p-DBR pairs are simulated using simulation program ISETCAD. The peak output power and the threshold current for each of these devices are determined. This study investigated the increasing on 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 the pair number up to make balance among 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]:

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

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

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]:

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

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

$$\frac{m_{hh}}{m_o} = 0.500 + 0.290x \tag{6}$$

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 λ/4 thicknesses while the upper section of p-DBR pairs was increased by one pair in each step from 15 pairs until 28 pairs, 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 6 nm GaAs quantum wells, 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 $Al_{0.30}Ga_{0.70}As$. When the vertical optical solver is used, perfectly matched layers (PMLs) are used to surround the simulation structure. The PMLs act as wave absorbers to prevent reflections and artificially simulate the radiative boundary condition.

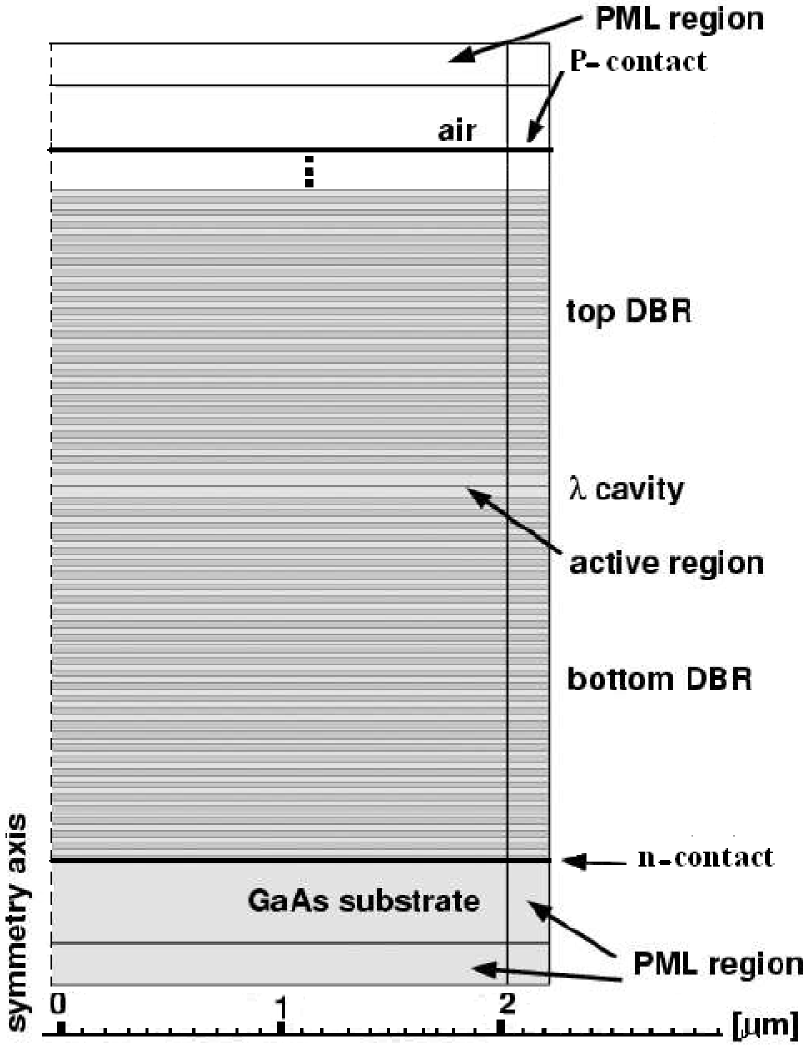

Fig.1. A transverse cross-sectional view of the half portion of cylindrical 850 nm GaAs/AlGaAs top surface emitting VCSEL.

3. Simulation results and discussion

To study the effect of output mirror reflectivity on the design of VCSEL extremely, the number of p-DBR pairs subsequent removal of mirror pair in each step from 28 until 16 is investigated, output powers measured at temperatures 250 K, 300 K, and 350 K as shown in Fig.2. It observed that maximum output power decreased with increasing on number of p-DBR pairs of the design at all temperatures. Fig. 3 shows the output power as a function of forward current at temperature 300 k. A strong increment in output power observed at 4.7 mW, 10.6 mW, 18.6 mW and 25.7 mW for 28, 24, 20, and 16 p-DBR pairs respectively. This is attributed to the fact that decreasing in the DBR pairs tend to decrease in the output optical loss (output coupling) of mirrors too (The primary sources of optical loss in VCSELs are the absorption and scattering losses of the mirrors) and this is led to increase in the probability of stimulated emission at a single pass of the cavity which tend to increase in output power.

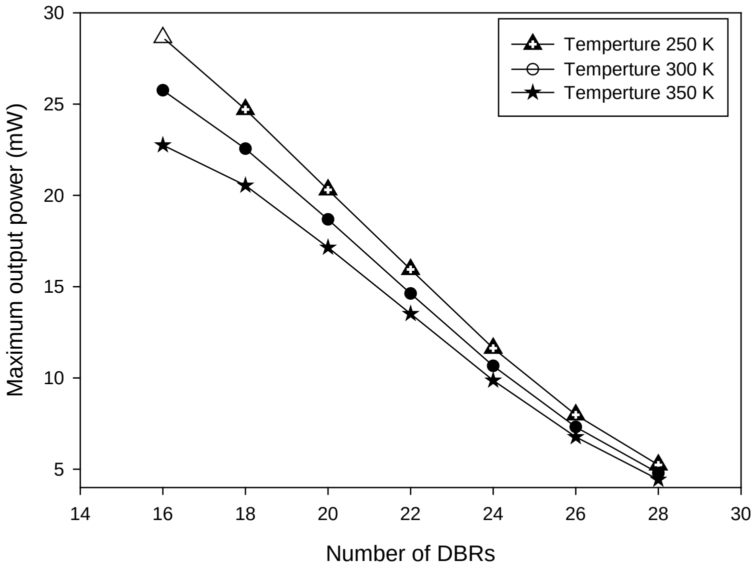

Fig. 2 VCSEL maximum output power as a function of number of DBR pairs at three different temperature.

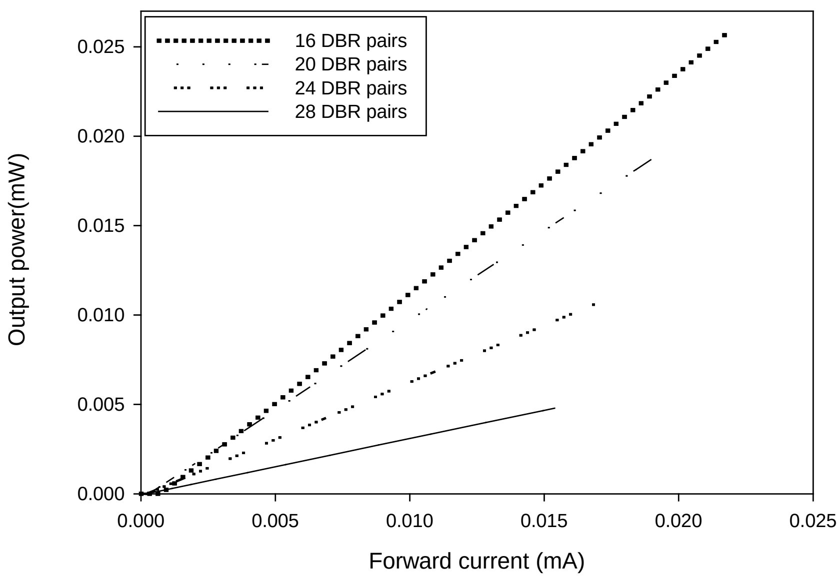

Fig. 3 VCSEL output power as a function of forward current with different number of p-DBR pairs.

Fig. 4 shows VCSEL threshold current as a function of different number of p-DBR pairs. It was observed that the threshold current was increased with decreasing of number of p-DBR pairs due to the increasing of number of carriers inside the active region, which leads to increase the diffraction losses and scattering between the carriers inside active region, which tend to increase the heat inside the VSCEL structure.

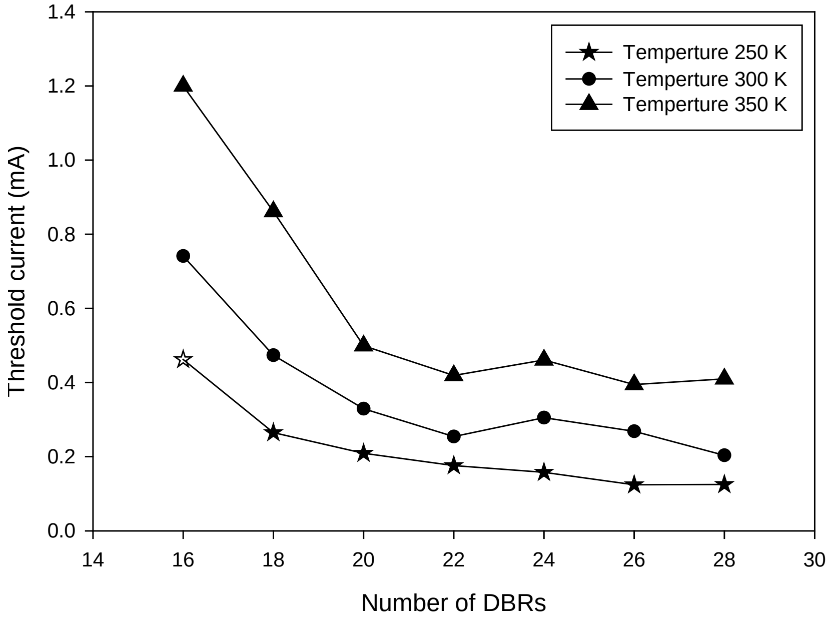

Fig. 4 VCSEL threshold current as a function of number of DBR pairs at three different temperature.

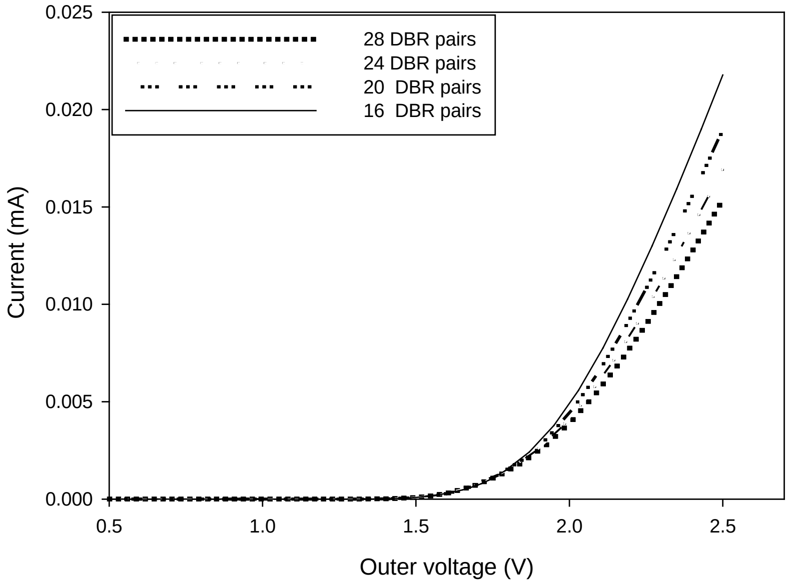

Fig. 5 VCSEL injected current as a function of outer voltage with different number of p-DBR pairs

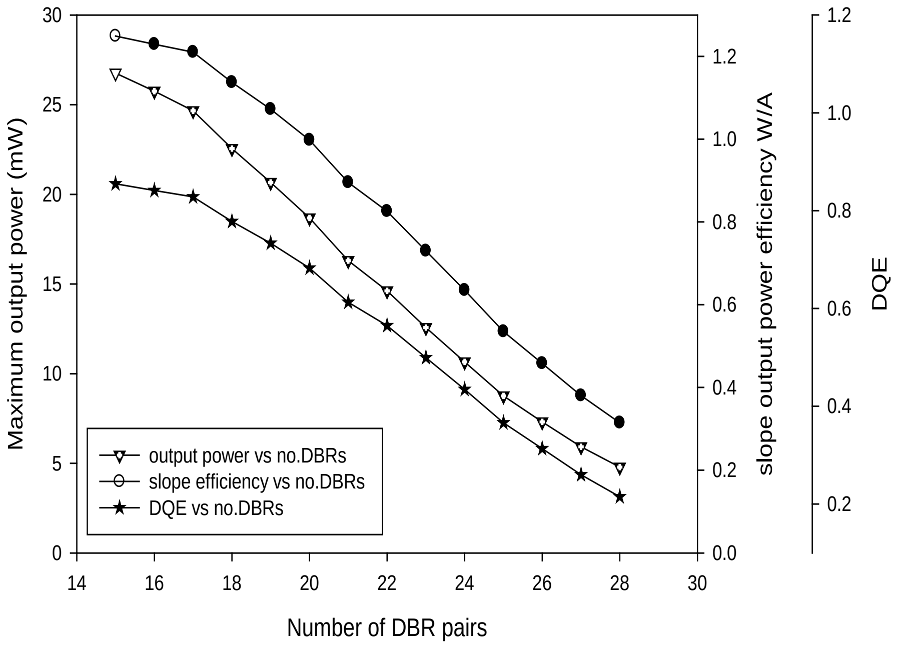

Fig. 6 VCSEL maximum output power, slope efficiency, differential quantum efficiency as a function different number of p-DBR pairs.

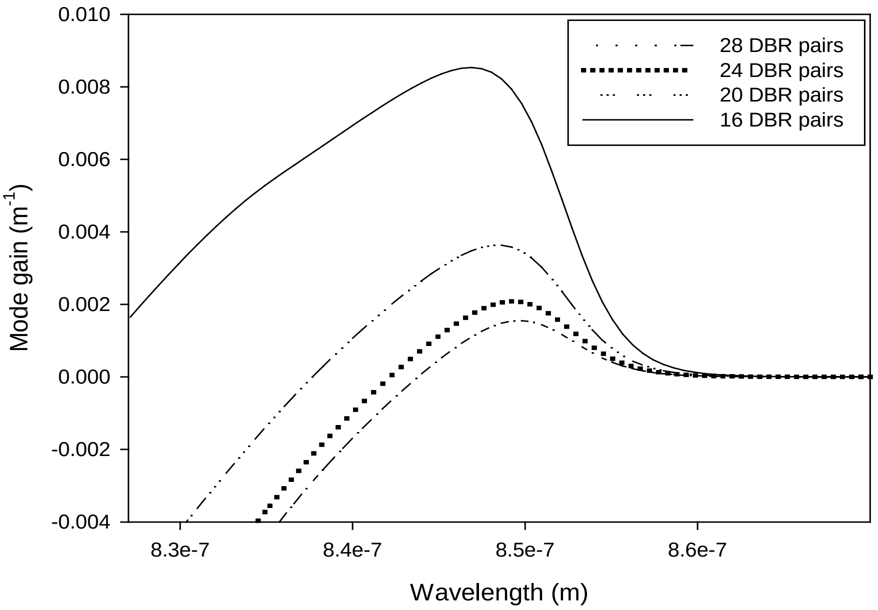

Fig. 7 VCSEL mode gain as a function wavelength with different number of p-DBR pairs.

Fig. 5 shows VCSEL injected current as a function of outer voltage for different number of p-DBR pairs. It was observed that the injected current was increased with decreasing of number of p-DBR pairs due to the increasing of number of carriers inside the active region, which leads to increase the diffraction losses and scattering between the carriers inside active region, which cause to increase the injected current at the same turn off voltage.

The variation of the slope efficiency, and differential quantum efficiency (DQE) with the output mirror DBR pairs is shown in Fig. 6. It was found that in the case of increment on number of DBR pairs, the output slope efficiency and DQE decreased, due to the increasing on optical losses (absorption and scattering losses of mirrors) as well as the heat generation by electrical series resistance of the DBR pairs which made less efficiency of the device. The optical mode gain of the VCSEL has calculated as a function of Q-factor (i.e., as a function of the of number DBR pairs). Increasing on the number of DBR pairs leads to increase on the Q-factor of the cavity and narrows on width of its resonance (better wavelength selectivity) as shown in fig. 7, but it also reduces the peak of mode gain which is gone lower for both the slope and differential quantum efficiency, as shown in Fig. 6.

4. Conclusion

The effect of the various number of p-DBR pairs on output performance of GaAs MQWs VCSEL is numerically investigated using simulation program ISETCAD. The influence of the output mirror reflectivity on the output power, threshold current, gain, slope and differential quantum efficiency is observed**.** In the study, we found the starting VCSEL structure used 28 upper DBR pairs and achieves a record low threshold current of a VCSEL of 0.2037 mW. With the subsequent removal of mirror pairs, the maximum slope efficiency of 124.93 percent and differential quantum efficiency of 85.48 percent is achieved with 15 upper DBR pairs for which the threshold current has increased to 1.4201 mW while further decreasing on the upper mirror reflectivity tend to increase the output coupling. The increasing on threshold current limits of the device performance is presumably due to the heating. We observed that the number of quarter-wave DBR remaining in the upper mirror can be selected to achieve optimum performance for the VCSEL in a top surface emitting geometry.

Acknowledgement

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