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Performance Analysis of Modulation Response of a Designed 1550 nm Oxide Confined Vertical Cavity Surface Emitting Laser

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***Abstract*— This paper aims to present the impact of using oxidized layer and the effect of oxide aperture size on VCSEL's modulation performance. After the introduction of oxidized layer, the characteristics of VCSEL have improved immensely, especially in modulation performance. The peak material gain of $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ MQW VCSEL found from the MATLAB simulation tools has been utilized for investigating the modulation characteristics of the laser model. The optical output power of 27.23 dBm is found at 2.5 mA of current injection. Later, by varying the injection current up to 2.5 mA a maximum frequency of resonance of 10.75 GHz and the equivalent -3dB cut off frequency of 11.85 GHz are achieved. It is seen that with the reduction of oxide aperture size and increase of injection current, the frequency of resonance in addition to the -3dB cut off frequency of the laser increases. The use of oxidized layer and impact of aperture size effect on VCSEL's -3dB cut off frequency.**

***Keywords*— VCSEL, Modulation, Bandwidth, AlGaInAs/InP**

I. INTRODUCTION

VCSEL is well considered to be a vital semiconductor device for fiber optic communication due to the rapid growth and demand for large amounts of information. Researchers and scientists are always looking for the tweak in the VCSEL structure and introduce an oxidized layer with the aperture size scaling. It is seen that, after the introduction of the oxidized layer, better electrical and optical confinement can be achieved which immensely improves the performance characteristics of the VCSEL. High performance oxide confined VCSELs are realized with a view to achieving high material gain, high optical output power, less consumption of power, low threshold current, high -3dB cut off frequency, low cost and good reliability. It is a superior laser diode that revolutionize the optical communications by improving efficiency and increasing data rate [1-2]. The characteristics and reliability of VCSELs are suitable for long distance and high data rate communication systems. At low threshold current, high mirror reflectivity and small active volume of VCSELs allow high speed in data transmission through fiber optic system [3-5].

In this paper, an oxide-confined VCSEL model is presented with a view to 1550 nm operation. The designed model and modulation characteristics of a 1550 nm MQW VCSEL using $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ materials have been found by calculation and simulation. Our analysis provides an insight into VCSEL design optimization for improving the modulation performance with a very little amount of injection current.

II. DESIGN STRUCTURE AND METHODOLOGY

For attaining high performance, a VCSEL whose active region consists three quantum wells of $Al_{0.06}Ga_{0.24}In_{0.70}As$ separated by InP barriers is selected through calculation with the aim of obtaining 1550 nm operation. The active medium of the laser cavity consists of $Al_{0.06}Ga_{0.24}In_{0.70}As$ material with bandgap energy of 0.72 electron volts and refractive index (n_1) of 3.53. The thickness (l_w) of each of the QW is 110 Å. Each of the QW is separated by InP barriers with bandgap energy of 1.351 electron volts and refractive index (n_2) of 3.17, each having a thickness of 155 Å as shown in Fig. 1. In the VCSEL cavity, the active medium is guided by p-cladding and n-cladding layer of $Al_{0.6}Ga_{0.4}As$ materials. For optical confinement, the cladding layers of 1.86 electron volts each are used in the laser cavity, which has a refractive index (n_3) of 3.13.

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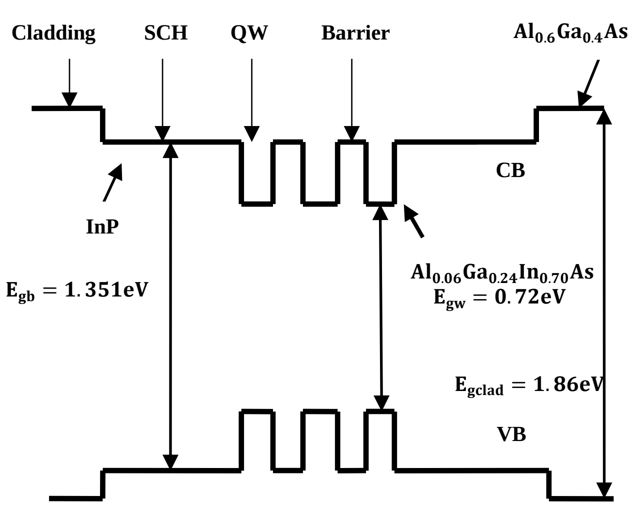

Fig. 1. The cavity structure of a VCSEL containing 3 QW of 110 Å each [2].

Top and bottom Distributed Bragg Reflector mirrors are used in the design which are parallel to the wafer surface [6-8]. In the top DBR stack there are eight layers of Si/SiO_2 and 77 layers of $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ materials in the lower DBR stack. On both sides of the active region p-cladding and n-cladding layer of $Al_{0.6}Ga_{0.4}As$ materials are considered with the aim of improving longitudinal carrier confinement and to make the internal region one wavelength thick [9-11]. An oxidized layer is used above the top p-cladding layer to confine the current with a view to improving laser performance. For achieving very high reflectivity (around 99.99%) this type of model is carefully considered due to shorter cavity length. Current is injected to the device through the top p-contact. The bottom n-contact is connected with InP substrate. An oxidized layer is introduced with aperture diameter with a view to achieving high material gain, high optical output power, less consumption of power, low threshold current and high -3dB cut off frequency. The cross-sectional view of a top emitting AlGaInAs/InP MQW Oxide Confined VCSEL is shown in the following fig.2.

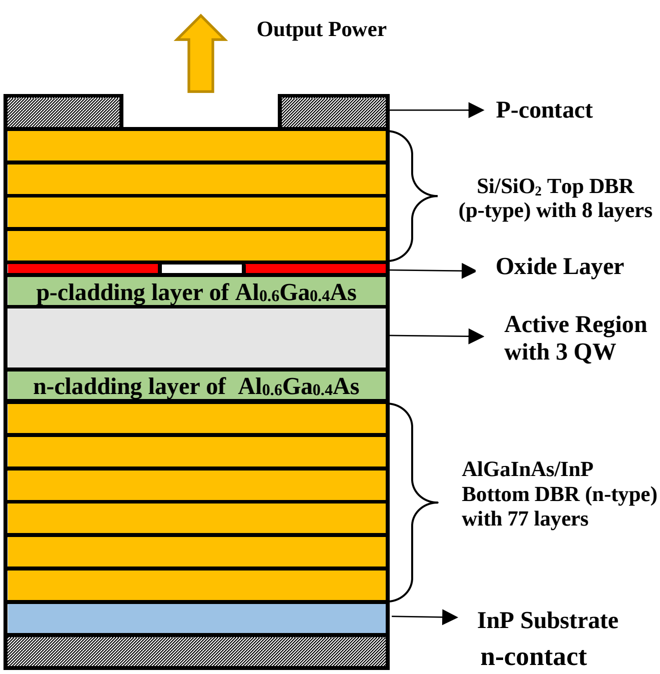

Fig. 2. Cross section view of a top emitting AlGaInAs/InP MQW Oxide Confined VCSEL [3].

III. SIMULATION AND RESULTS

A. Calculation of Material Gain

To design and fabricate a practical laser, the maximum optical gain needs to be considered. This is obtained by calculating the optical gain at the effective wavelength and also by tuning the range around the operating wavelength. For the material gain vs wavelength characteristics, we have used the following gain equation [15],

$$g(E) = \left(\frac{q^2\pi\hbar}{\varepsilon_0 m_0^2 ncE}\right)|M_T|^2\rho_r(f_2 - f_1) \qquad (1)$$

Where, $|M_T|^2$ is denoted as square of the momentum transition matrix element. q is the electron charge, ε_0 is the free air medium permittivity, n is the refractive index of the laser structure, E is the transition energy, c is the speed of light at free air medium, ρ_r is the reduced state of density, m_0 is the electron mass, ħ is the Plank's constant, f_1 and f_2 are the quasi Fermi functions in the conduction and valance band respectively [12-14]. To acquire the plot of material gain vs. wavelength, equation (1) is used. The peak material gain of $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ MQW VCSEL found from the MATLAB simulation has been utilized for the performance optimization of the laser model.

Transition momentum matrix element can be written as [15],

$$|M_T|^2 = \frac{m_0^2 E_g(E_g + \Delta)}{4m_c\left(E_g + \left(\frac{2\Delta}{3}\right)\right)} \qquad (2)$$

Where, Δ is denoted as split-off band potential.

The reduced density of state ρ_r can be calculated for a QW material as [15],

$$\rho_r = \frac{m_r}{\pi\hbar^2 l_w} \qquad (3)$$

Where, l_w is the thickness of each QW.

The reduced effective mass, m_r in a material system can be calculated by the masses on the conduction and valence band of m_c and m_v respectively as [15],

$$\frac{1}{m_r} = \frac{1}{m_c} + \frac{1}{m_v} \qquad (4)$$

The material gains for the 1550 nm $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ 110 Å quantum well laser is obtained by changing wavelength. The achieved result is shown in the following fig. 3.

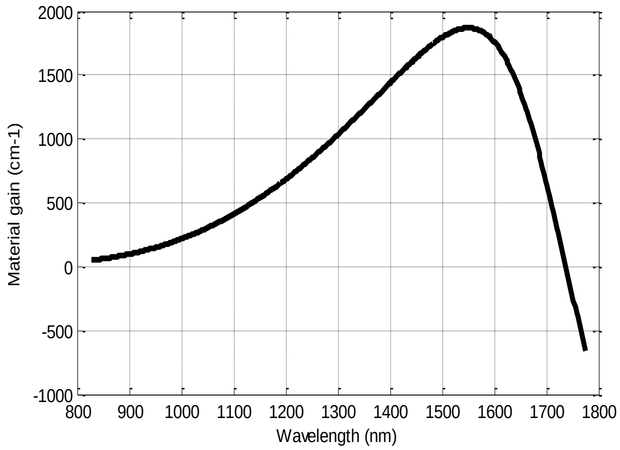

Fig. 3. Plot of Material gain vs. Wavelength of the AlGaInAs/InP 110Å MQW VCSEL at 300 K. A peak gain for the $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ material of 1878 cm^{-1} is obtained at 1550 nm.

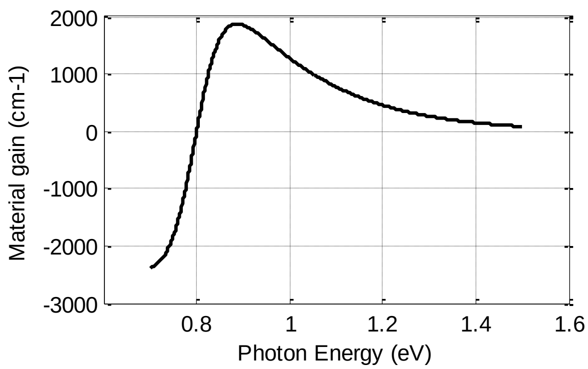

Fig. 4. Plot of Material gain vs. Photon Energy of the AlGaInAs/InP 110Å MQW VCSEL at 300 K [2].

From the Fig. 3 it is seen that the material gain of the laser increases with the increase of wavelength. Maximum material gain is found as 1878 cm^{-1} at 1550 nm wavelength. After this region the material gain is decreased in accordance with the increase of the wavelength.

B. Calculation of Output Power

The obtained value of peak material gain is used in output power calculation. We have used the following expression to calculate the output power (P_0) of the laser [9-10],

$$P_o = \frac{\alpha_m h\upsilon\eta_i}{qg\Gamma}(I - I_{th}) \tag{5}$$

where, mirror loss coefficient is denoted as α_m , The Planck constant, h is a physical constant, υ is the frequency of lasing, electron of charge is q, the material gain is g, Γ is the confinement factor, η_i is the current injection efficiency, I is the injection current and I_{th} is the threshold current of the laser [2]. The plot of output power vs. wavelength is shown in Fig. 5.

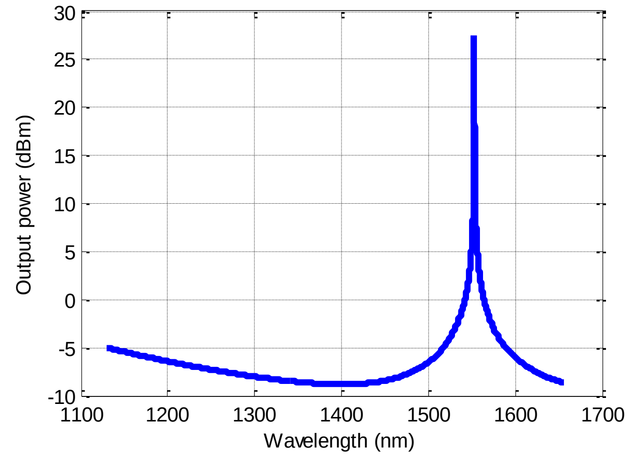

Fig. 5. Plot of power output vs. wavelength of the $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ 110Å MQW VCSEL at 300 K.

The peak intensity of output power of the $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ 110 Å QW VCSEL is obtained as 27.23 dBm for the value of current injection of 2.5 mA at 1550 nm wavelength as shown in Fig. 5.

C. Computation of Threshold Current

Threshold current of a laser can be written as [9-10],

$$I_{th} = \frac{qV_a N_{th}}{\eta_i \tau_c} \tag{6}$$

where, V_a is the active volume, N_{th} is the threshold carrier density, η_i is the current injection efficiency, τ_c is the carrier lifetime. For the injection current efficiency (η_i) of 0.8, the carrier lifetime, τ_c = 2.63 × 10^{-9} sec and threshold carrier density, N_{th} = 1.98×10^{18} the threshold current is found to be 0.32 mA.

D. Calculation of Differential Quantum Efficiency

The differential quantum efficiency of the laser is expressed as [2-3],

$$\eta_d = \eta_i \frac{\alpha_m}{\{(<\alpha_i>) + \alpha_m\}} \tag{7}$$

where, α_i is denoted as inherent absorption loss coefficient, α_m is the mirror loss. By considering inherent absorption loss coefficient [2-3], α_m =20 cm^{-1} due to absorption in the $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ material of the cavity the calculated value of differential quantum efficiency of the designed $Al_{0.09}Ga_{0.38}In_{0.53}As/InP$ MQW VCSEL is obtained as 20%.

TABLE I
KEY PARAMETERS OF THE DESIGNED VCSEL

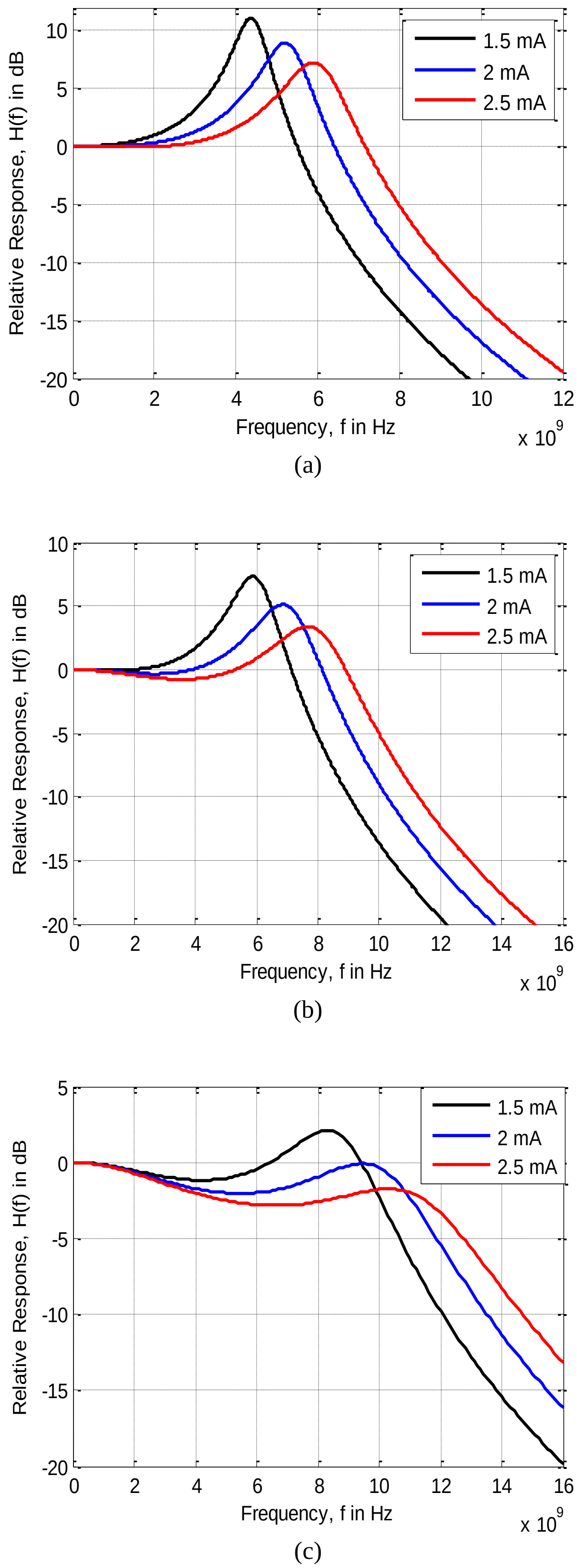

Fig. 6. Modulation response at different injection currents for oxidized aperture diameter of (a) 9 µm, (b) 7 µm and (c) 5 µm.

Parameter Type	Value
Confinement Factor (Γ)	0.0396
Average refractive index , (n_{avg})	3.30
Split off band potential (Δ)	0.361
Number of quantum well (N_{qw})	3
Quantum well thickness (L_w)	110 Å
Differential quantum efficiency (η_d)	0.20
Injection current efficiency(η_i)	0.80
Lifetime of carrier (τ_c)	2.63×10^{-9} sec
Peak material gain coefficient (g_0)	1878.3 cm-1
Temperature (T)	300 K
Differential gain (a)	10×10^{-16} cm^2
Stationary electronic mass (m_0)	9.1×10^{-31} kg
Effective mass of electron (m_e)	0.0568m_0
Hole effective mass (m_h)	0.3678m_0
Inherent absorption loss (α_i)	20 cm^{-1}
Mirror reflectivity (R)	0.9999
Threshold Carrier density (N_{th})	1.9758×10^{18} cm^{-3}
Current threshold (I_{th})	0.50 mA
Lifetime of photon (τ_p)	4.1252×10^{-12} sec
Mirror loss (α_m)	6.6651 cm^{-1}

E. Modulation Response Analysis

The modulation performance characteristics of the oxide confined VCSEL model has been obtained through the three-pole transfer function equation as stated below [17-18],

$$H(f) = const \cdot \frac{f_R^2}{f_R^2 - f^2 + j\frac{f}{2\pi}\gamma} \cdot \frac{1}{1 + j\left(\frac{f}{f_p}\right)} \qquad (8)$$

where, f_R is denoted as frequency of resonance, f_p is the parasitic cutoff frequency and γ is the decaying parameter. The frequency of resonance, f_R can be expressed as [2,16],

$$f_R = \frac{1}{2\pi}\sqrt{\frac{\Gamma v_g a \eta_i}{q v_a}(I - I_{th})} \qquad (9)$$

For parasitic cutoff frequency, $f_p = 4$ GHz using equation (8), the relative response of the oxide confined VCSEL has been simulated by changing frequency for various values of injection current and oxide aperture size. The outcomes are plotted as shown in Fig. 6. It is seen that with the reduction of oxide aperture size and increase of injection current, the frequency of resonance in addition to the -3dB cut off frequency of the laser increases. Thus, higher modulation bandwidth enables the laser for long distance optical communication. Key results obtained at different injection current by varying oxide aperture size is given on Table I I. From Table I I, it is seen that by varying the current injection up to 2.5 mA a maximum frequency of resonance of 10.75 GHz and the equivalent modulation bandwidth of 11.85 GHz are obtained which makes the laser capable for high speed operation.

TABLE I I

KEY RESULTS OBTAINED AT DIFFERENT INJECTION CURRENT BY VARYING OXIDE APERTURE SIZE

Injection Current, I	**Oxide Aperture Size**	**Resonance frequency, f_R (GHz)**	**-3dB cut off frequency, f_{-3dB} (GHz)**
1.5 mA	9µm	4.51	5.89
	7µm	5.90	7.65
	5µm	8.65	10.25
2 mA	9µm	5.22	6.84
	7µm	6.86	8.67
	5µm	9.60	11.25
2.5 mA	9µm	5.96	7.63
	7µm	7.82	9.53
	5µm	10.75	11.85

IV. CONCLUSION

The superior performance of $Al_{0.06}Ga_{0.24}In_{0.70}As/InP$ oxide confined vertical-cavity surface-emitting laser (VCSEL) was demonstrated both mathematically and simulation. Oxide layer has been introduced in VCSEL technology for attaining better performance and characteristics. It is seen that with the increasing of oxide aperture size, -3dB cut off frequency decreases but for the same oxide aperture size of increasing current injection, modulation performance improves. So, the use of oxidized layer and impact of aperture size effect on VCSEL's -3dB cut off frequency. Thus, high performance oxide confined VCSELs were realized with a view to achieving high material gain, high optical output power, less consumption of power, low threshold current, high -3dB cut off frequency, low cost and good reliability. All of these benefits enable the oxide confined VCSEL capable for performing well after the fabrication.

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