Effect of SiO₂ Reflection Reducing Coating on the Vertical Cavity Surface Emitting Laser

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Abstract. The effects of epitaxis SiO₂ film on the characteristics of DBR reflectivity were simulated, and the reflectivity of graded interface DBR is lower than the abrupt one was studied. 850nm vertical-cavity surface-emitting lasers were fabricated, the DBR is formed by graded heterojunction of AlₓGa₁₋ₓAs, the top and bottom DBR have 22 and 34 pairs of mirror, and current was confined by oxide aperture, and then different thickness of SiO₂ film were grew on the top DBR. and found that a certain thickness (λ/4) of the SiO₂ reflection reducing coating could make the vertical-cavity surface-emitting lasers output power increased about 3-5 mW, the threshold current does not increase obviously, the reason is external quantum efficiency increases more than the threshold current. So the SiO₂ reflection reducing coating does not affect the lasing of lasers and threshold current obviously, but It can significantly improve the output power. The experimental results agree well with the theoretical expectation.

1. Introduction

Vertical cavity emitting laser (VCSEL) has a number of inherent advantages including low threshold current, single longitudinal mode operation, low-divergence circular output beams, broad modulation bandwidth, suitability for monolithic two-dimensional (2-D) integration and compatibility with on-wafer probe testing, and has many potential applications on data transmission in optical network, optical interconnect, optical storage and laser printing [1-2]. The single mode high output power is essential for the application of VCSEL. There have lots of studies on single mode high power VCSEL, such as photonic crystal, holey and surface relief VCSEL etc [3-5]. One critical issue for VCSEL is connected to the very short optical gain region as compared to edge-emitting lasers, hence requiring very high reflectivity (>99%) mirrors to achieve lasing action. This is realized by distributed Bragg reflector (DBR), whose design criteria are related to optical reflectivity, thermal and electrical conductivity, material index contrast and optical absorption. The analysis of DBR is critical in VCSEL design, because their reflectivity strongly affects all laser properties [6], traditional DBR is

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GaAs/AlGaAs growed by alternately, but the abrupt interface of the heterojunction has a higher series resistance which will generate more heat. So recently graded interface heterojunction DBR was appeared, and through altered the reflectivity can affect the characteristics of the VCSEL [7-8]. In this paper, we simulated the reflectivity of abrupt and graded DBR, studied the effects of $\lambda/4$ reflection reducing coating on the reflectivity of DBR and the characteristics of VCSEL. The devices were produced and tested, and agreed well with the theoretical simulation.

2. Device structure and theory

In this Letter, the VCSELs were fabricated from a 3-inch n-type wafer with epitaxial structure consisting of a bottom n-type (Si-doped) 34 pairs DBR, an undoped active region with three GaAs quantum wells, and a similar top (C-doped) 22 pairs DBR. The DBR are formed by graded heterojunction of Al$_x$Ga$_{1-x}$As, the unit period of bottom and top DBR mirrors consisting of 4 layers of Al$_x$Ga$_{1-x}$As (x: 0.9-0.12), Al$_{0.12}$Ga$_{0.88}$As, Al$_x$Ga$_{1-x}$As (x: 0.12-0.9), Al$_{0.9}$Ga$_{0.1}$As. In addition, a 30 nm Al$_{0.99}$Ga$_{0.02}$As oxidization layer was inserted between the top DBR and the active region. The structure is shown in Figure 1 (a). The operation wavelength of the device is designed at 850 nm.

![Figure 1. Structure of the selectively oxidized VCSEL (a) and the actual device photo (b)](image)

The circular mesa was formed by SiCl$_4$/Ar/Cl$_2$ inductively coupled plasma reaction ion etching (ICP-RIE) down close to the active region, using SiO$_2$ as the etching mask. Then the Al$_{0.99}$Ga$_{0.02}$As layer was selectively oxidized to form the current aperture with diameter of 10 and 20 $\mu$m. After that, top ohmic (Ti/Au) ring contacts were patterned and bottom ohmic (AuGeNi/Au) contacts were formed. Then the device was annealed using rapid thermal annealing at 430°C for 35s. The actual VCSEL device photo is shown in Figure 1 (b).

Considering the optical waves of the VCSELs were propagated along the vertical direction of the DBR, so we did not consider the entrance ray angle. According to $E$ and $H$ are continuously in the two side of the interface, we can obtain the transmission matrix method from Fresnel formula [9-10].

$$
\begin{bmatrix}
E_0 \\
H_0
\end{bmatrix} =
\begin{bmatrix}
\cos(kd + iad) & i/n_1 \sin(kd + iad) \\
n_1 \sin(kd + iad) & \cos(kd + iad)
\end{bmatrix}
\begin{bmatrix}
E_2 \\
H_2
\end{bmatrix} = M
\begin{bmatrix}
E_2 \\
H_2
\end{bmatrix}
$$

(1)

Where $k = 2\pi/\lambda$, $E_0$, $E_2$ are the electric-field intensity vector of the first film, $H_0$, $H_2$ are the intensity vector of magnetic field of the first film, $\lambda$ is the wavelength in vacuo, $n_1$ is the index of refraction of the single dielectric film layer, $d_i$ is the thickness of the single dielectric film layer, a is the absorption coefficient, the DBR multiplayer structure is shown in Figure 2.
The transmission matrix of every DBR layer is $M_i$, for the total layer of DBR, the overall transmission is described as equation (2), and the amplitude reflectivity of the DBR can be deduced as equation (3).

\[
M = \prod_i M_i = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}
\]

\[
r = \frac{n_0 m_{11} + n_0 n_s m_{12} - m_{21} - n_s m_{22}}{n_0 m_{11} + n_0 n_s m_{12} + m_{21} + n_s m_{22}}
\]

Where $M_{ij}$ is the element of the matrix $M$, $n_0$ is the index of refraction in vacuo, $n_s$ is the index of refraction of the substrate. According to the reflectivity of the amplitude $r$ and the power $R$: $r = |R|^2$ ($\phi$ is the phase change on reflection), so the refractive ratio is described as $R = \left| R \right|^2$, then we can calculate the reflectance spectrum. Assume there are $m$ pairs of $\lambda/4$ thickness multilayer DBR, the index of refraction of the two adjacent layers are $n_1$ and $n_2$, and absorbed coefficient is 0, so the wavelength reflectivity of DBR is described by equation (4). From that we can obtain the power reflectivity which is described by equation (5), and the more the change of index of refraction the higher reflection of power.

\[
r_{vv} = \frac{1 - \frac{n_2}{n_0} \left( \frac{n_1}{n_2} \right)^{2m}}{1 + \frac{n_2}{n_0} \left( \frac{n_1}{n_2} \right)^{2m}}
\]

\[
R = \tanh 2 \left[ \frac{1}{2} \ln \left( \frac{n_o}{n_s} \right) + m \ln \left( \frac{n_1}{n_2} \right) \right]
\]

Then the 850nm VCSEL structure which includes the refractive index with linearly graded Al composition from equation (6)-(11) was simulated. where $n$ denotes the refractive of $Al_xGa_{1-x}As$, $x$ is the composition of Al, $E$ is optical energy, $E_0$ is effective oscillated energy, $E_d$ is dispersion energy, $E_g$ is band gap energy, the equations for $E_0$, $E_d$ and $E_g$ as the function of alloy composition yield [11].
\[ n^2(E) = 1 + \frac{E_d}{E_0} + \frac{E_d^2}{E_0^2} E^2 + \eta E^4 \ln \left( \frac{2E_0^2 - E_g^2 - E^2}{E_g^2 - E^2} \right) \] (6)

\[ \eta = \frac{\pi E_d}{2E_0^2 (E_0^2 - E_g^2)} \] (7)

\[ E = \hbar \omega \]

\[ E_0 = 3.65 + 0.871x + 0.179x^2 \] (9)

\[ E_d = 36.1 - 2.45x \] (10)

\[ E_g = 1.424 + 1.266x + 0.26x^2 \] (11)

The schematic diagrams of unit period in top and bottom DBR mirrors is mentioned hereinbefore, the simulated results of top 22 pairs DBR is shown in Figure 3, we can see the reflectively of abrupt interface DBR is higher than graded one with the same pairs of DBR. That is because the index of refraction change between adjacent DBR layers of graded DBR is less than abrupt one, so the reflection of the whole DBR is lower.

![Figure 3. The spectra of top DBR of abrupt and grade interface](image)

We calculated the effect of SiO₂ film on the DBR, so we had studied the reflection of the DBR with \( \lambda/2, \lambda/4 \) thickness of SiO₂, the simulated results are shown in Figure 4. At the high reflective zone, epitaxsis \( \lambda/2 \) thickness of SiO₂ has the same reflectivity as with no SiO₂, but \( \lambda/4 \) thickness of SiO₂ can minish the reflectivity at the high reflectance zone.

![Figure 4. The reflectance spectrum of top DBR and with epitaxis\( \lambda/2 \) thickness of SiO₂ (a) The reflectance spectrum of top DBR and with epitaxis\( \lambda/4 \) thickness of SiO₂ (b)](image)
3. Result and discussion

We fabricated the VCSELs, and epitaxis different thickness of SiO$_2$, we tested the output power and threshold current of the VCSELs, the results are shown in Figure 5 (a) and (b). we obtained that, when the oxide aperture is 10 $\mu$m, the output power of VCSEL with $\lambda/4$ SiO$_2$ is higher than the without one about 3 mW, and when the oxide aperture is 20$\mu$m, the output power of VCSEL with $\lambda/4$ SiO$_2$ is higher than the without one about 4.5 mW.

![Figure 5](image)

**Figure 5.** VCSEL oxide aperture 10$\mu$m, the output power and threshold current with SiO$_2$ is 8.3 mW and 0.5 mA, the without one is 5.3 mW and 0.5 mA (a) oxide aperture 20$\mu$m, the output power and threshold current with SiO$_2$ is 15.9 mW and 1.6 mA the without one is 11.4 mW and 1.5 mA (b)

The output power is increased with a small decreases of the DBR reflectivity, because the decreases reflectivity of DBR cause the increases of the loss of cavity face, the loss of top DBR cavity face is the output power, but the threshold current did not increase, from the equation (12) we know that, the increasing of the $R_2$ (the loss of top DBR cavity face) affects the threshold current weakly.

$$J_{th} = \frac{N_w J_0}{\eta_{int}} \exp \left\{ \frac{\alpha_{cav} + \frac{1}{2\Gamma_w} \ln \frac{1}{\Gamma_w R_1 \Gamma_z R_2}}{N_w \Gamma_w \Gamma_z g_0} \right\}$$  (12)

$R_1$ and $R_2$ are the reflectivity of bottom ($N = 34$) and top ($N = 22$) DBR mirror, respectively, $N_w$ is the number of active region quantum wells, and $\Gamma_w$ and $\Gamma_z$ are lateral and longitudinal confinement factors, respectively. Moreover, $L_{cav}$ is the laser cavity length, $\alpha_{cav}$ is the optical cavity loss, $g_0$ is the material gain coefficient, $J_0$ is the transparency current density and $\eta_{int}$ is the internal quantum efficiency.

4. Conclusion

The reflectivity of graded interface DBR is lower than the abrupt one was studied, and the effects of epitaxis SiO$_2$ film on the characteristics of DBR reflectivity were simulated. 850nm oxidation confined VCSELs were fabricated, then epitaxis different thickness of SiO$_2$ film on the top DBR, and found that a certain thickness ($\lambda/4$) of the SiO$_2$ reflection reducing coating can make the output power of VCSELs increases dramatically, the threshold current not increases obviously. From the theoretical simulation and experimental we can obtain that, the reflection reducing coating can increases the output power of VCSELs, then it can be used in the single mode VCSELs, such as photonic crystal VCSEL, holey VCSEL, to increase the output power.
5. References

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