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Design and optimization of DBR in 980 nm bottom-emitting VCSEL

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According to the theory of DBR, with the P-type DBR as an example, the electrical characteristics and optical reflection of the DBR are analyzed by studying the energy band structure with various graded region widths and doping densities. The width and doping density of graded region are decided through a comparative study. The P-type DBR of 980 nm VCSELs is designed with $Al_{0.9}Ga_{0.1}As$ and $Al_{0.1}Ga_{0.9}As$ selected as the high and low refractive index material for the DBR. The 980 nm bottom VCSELs, which consists of 30 pairs P-type DBR and 28 pairs N-type DBR, are then fabricated. In P-type DBR, the width of graded region is 0.02 μm and the uniformity doping concentration is $2.5\times10^{18}cm^{-3}$. Its reflectivity is 99.9%. In N-type DBR, the width of graded region is also 0.02 μm and the uniformity doping concentration is $2\times10^{18}cm^{-3}$. Its reflectivity is 99.3%. The I-V curve shows that the series resistance of the device is about 0.05 Ω. According to the theory of DBR, with the P-type DBR as an example, the electrical characteristics and optical reflection of the DBR are analyzed by studying the energy band structure with various graded region widths and doping densities. The width and doping density of graded region are decided through a comparative study. The P-type DBR of 980 nm VCSELs is designed, with $Al_{0.9}Ga_{0.1}As$ and $Al_{0.1}Ga_{0.9}As$ selected as the high and low refractive index material for the DBR. The 980 nm bottom VCSELs, which consist of 30 pairs P-type DBR and 28 pairs N-type DBR, are then fabricated. In P-type DBR, the width of graded region is 0.02 μm and the uniformity doping concentration is $2.5\times10^{18}cm^{-3}$. Its reflectivity is 99.9%. In N-type DBR, the width of graded region is also 0.02 μm and the uniformity doping concentration is $2\times10^{18}cm^{-3}$. Its reflectivity is 99.3%. The I-V curve shows that the series resistance of the device is about 0.05 Ω.

VCSEL, DBR, component graded, series resistance, reflectivity

1 Introduction

In recent photonics research fields, the vertical cavity surface-emitting lasers (VCSELs) have become one of the hottest topics. The unique geometry of VCSELs results in several significant advantages over their edge-emitting counterparts, including

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a low threshold current, single-longitudinal-mode operation, circular output-beam profile. These advantages make VCSELs quite promising as compact light source for future applications in optical communications, interconnects, optical storage and pump source[1−4].

In general, a VCSEL consists of an active region sandwiched between two distributed bragg reflectors (DBRs)[5]. The thickness of the active region is only tens or hundreds of angstrom, when the resonator length is only in wavelength order in VCSELs. It is difficult to obtain enough gain in such thin active region. Therefore, mirrors with high reflectivity are necessary in VCSELs in order to reduce the loss of the resonant cavity and achieve stimulated emission[6,7]. For these mirrors, typically a multilayer stack consisting of quarter-wavelength dielectric or semiconductor layers with low- and high-index materials is used. Top and bottom DBRs, which constitute a sophisticated Fabry-Perot resonator in VCSELs, provide more than 99% reflectivity. However, the DBRs would reduce the output power seriously as the increased series resistance when the reflectivity becomes higher and higher[8,9]. This phenomenon, which is caused by self-heating, is particularly evident in the P-type DBR[10]. Self-heating, which increases the temperature of the cavity and changes the refractive index and the band gap of each semiconductor layer, will reduce the output power. Thus, the design of DBR structure with a low resistance is very necessary for improving the performance of VCSEL.

This paper focuses on the DBR of 980 nm bottom-emitting laser (Figure 1 shows its schematic structure). The impact of doping concentration and width of graded zone to the characteristics was investigated. A new DBR's structure with low resistance was designed for 980 nm VCSEL. The device with the new DBR's structure shows excellent characteristics.

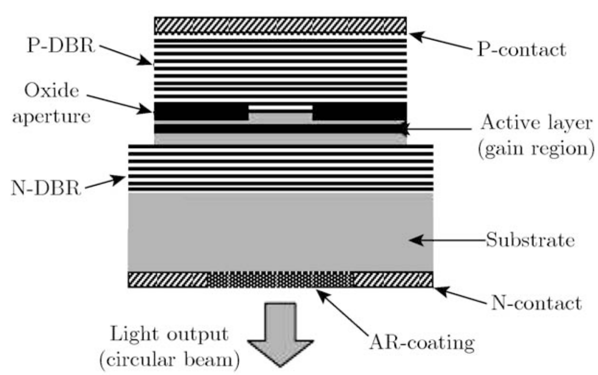

Figure 1 Schematic structure of a bottom-emitting VCSEL.

2 Theory and analysis

When a $\lambda_0/4$ thick thin film is coated, whose refractive index is n_1, on the substrate with refractive index n_g ($n_1 > n_g$), the reflectivity will be greatly increased as the reflected light have the same phase at both interfaces. For the incident light λ_0 with incident angle 0°, the reflectivity is

$$\mathbb{R} = \left[\frac{n_0 - {n_1}^2/n_g}{n_0 + {n_1}^2/n_g}\right]^2. \tag{1}$$

The higher reflectivity could be realized by using alternating material whose optical path length is a quarter of the desired lasing wavelength, and refractive index is different. The reason is that interference of all the reflected lights happens when the lights go back to the front surface with the same phase. In theory, 100% reflectivity is expected to be realized by the above material system. On the assumption that n_H and n_L are refractive indexes of two different materials, respectively, and the outermost layer of the film system is a material with a high refractive index, the reflectivity for the incident light λ_0 with incident angle 0°, when the number of layers is $2N+1$ (N is large enough), is as follows:

$$\mathbb{R} = \left[\frac{1-[n_H/n_L]^{2N}[{n_H}^2/n_g]}{1+[n_H/n_L]^{2N}[{n_H}^2/n_g]}\right]^2 \approx 1-[n_L/n_H]^{2N}[n_g/{n_H}^2]. \tag{2}$$

Theoretically, the reflectivity could be infinitely close to 100% by increasing the amount of film layers. But the maximum of layers is limited by the absorption and dispersion loss in film systems.

In general, DBR consists of m pairs of layers with alternating materials such that the optical path length is a quarter of the desired lasing wavelength. The refractive indexes of alternating material are n_1 and n_2, respectively. When absorption loss is negligible, the reflectivity at desired lasing wavelength is

$$r = \frac{1 - [n_s/n_0][n_1/n_2]^{2m}}{1 + [n_s/n_0][n_1/n_2]^{2m}}. \tag{3}$$

The bandwidth of high reflection region of DBR is

$$\Delta g = 4/\pi \arcsin \frac{n_H - n_L}{n_H + n_L}. \tag{4}$$

Obviously the bandwidth of reflection spectrum is independent of the thickness of film, but only depends upon the difference in refractive indexes between the adjacent films. The larger the difference, the wider the bandwidth of high reflection region.

The parameters of semiconductor multilayer that influence the characteristics of DBR are analyzed in the light of energy band theory. For example, in order to investigate the affection of graded profile, graded width and doping concentration on the hole barrier of P-type DBR, valence band structure of graded region should be calculated at heat equilibrium.

The poisson equation at heat equilibrium reads

$$\nabla \cdot [-\varepsilon[Z]\nabla\phi[Z]] = e[p[Z] - n[Z] + {N_D}^+[Z]], \tag{5}$$

where $\epsilon[Z]$, $\phi[Z]$ and ${N_D}^+[Z]$ are dielectric constant, potential and ionization acceptor, respectively.

${N_D}^+[Z]$ is expressed as

$${N_D}^+[Z] = \frac{N_D[Z]}{1 + 2\exp[[E_F - E_D[Z]]/[k_B T]]}. \tag{6}$$

$E_D[Z]$ denotes the level of acceptor. The electron and hole density are

$$n[Z] = 2\left[\frac{[m_c[Z]k_B T]}{2\pi\hbar^2}\right]^{3/2} \cdot F_{1/2}\left[\frac{E_F - E_C[Z]}{k_B T}\right], \tag{7}$$

$$p[Z] = 2\left[\frac{[m_h[Z]k_B T]}{2\pi\hbar^2}\right]^{3/2} \cdot F_{1/2}\left[\frac{E_v[Z] - E_F}{k_B T}\right], \tag{8}$$

where k_B denotes Boltzmann constant, T denotes temperature, $F_{1/2}[\eta]$ denotes Femi-Dirac integral. Moreover, in the P-type DBR,

$$E_v[Z] = -e\phi[Z], \tag{9}$$

$$E_c[Z] = E_v[Z] + E_g[Z]. \tag{10}$$

By substituting eqs. (6)–(10) into eq. (5), the change on valence band of P-type DBR could be calculated.

3 Design and optimization of DBR for bottom-emitting 980nm VCSELs

Based on the above analysis, we had designed and optimized the DBR of bottom-emitting VCSEL. Because of the influence of refractive index, absorption loss and material growth, $Al_{0.9}Ga_{0.1}As$ and $Al_{0.1}Ga_{0.9}As$ were selected as the materials of the DBR. The refractive indexes of $Al_{0.9}Ga_{0.1}As$ and $Al_{0.1}Ga_{0.9}As$ are 2.996 and 3.437, respectively. The difference is large enough to obtain the reflectivity needed. Next, we will take the P-type DBR as an example to make a specific analysis. Figure 2 shows the relationship between the DBR's reflectivity and its number of periods. The DBR, doped N-type at a concentration of $2.5\times10^{18}\text{cm}^{-3}$, has a 0.02 μm thick "transition layer". The linear graded DBR's reflectivity is a little lower than that of the abrupt type DBR, but the difference becomes smaller and smaller with the increasing periods amount of the DBR. When the periods are 28, the reflectivities of both of them reach over 99.9%.

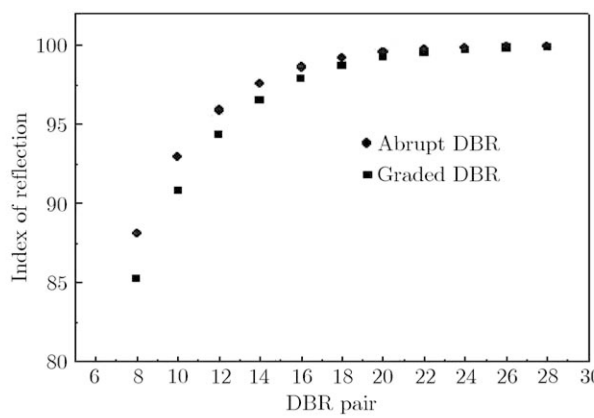

Figure 2 Reflectivity with various pairs of DBR.

Figure 3 shows the valence bands and hole quasi-Fermi levels for 1.5 periods of a P-type DBR. Figure 3(a) and 3(b) show the abrupt DBR and graded DBR with the same doping concentration and bias, respectively. Comparison shows that the hole barrier can be reduced greatly when the graded structure is adopted in the P-type DBR. Therefore, the graded structure of DBR could ef-

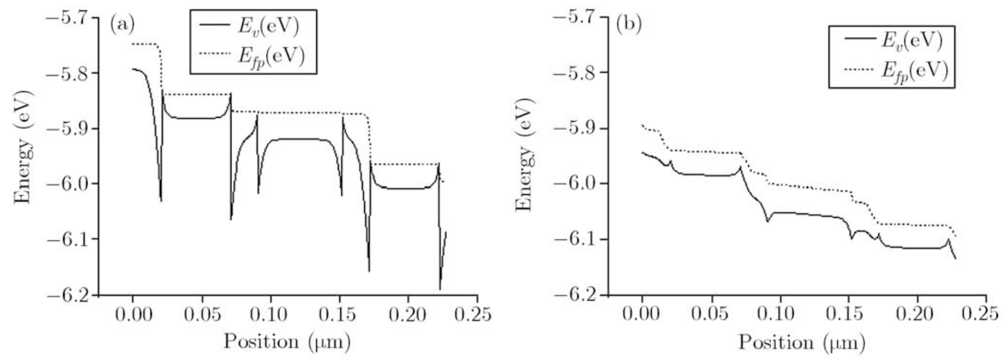

Figure 3 (a) Valence and quasi-Fermi band of 1.5 periods abrupt P-type DBR; (b) valence and quasi-Fermi band of 1.5 periods graded P-type DBR.

fectively reduce the series resistance and suppress the thermal effect, thus improving the performance and reliability of the device.

The width and doping concentration of the graded region would exert effect on the performance of DBR greatly, so it is necessary to study them in detail. Figure 4 compares the valence bands for 1.5 periods of a P-type DBR with doping concentration $2.5\times10^{18}\text{cm}^{-3}$ and various widths of the graded region. As is evident in Figure 4, when the width increases from 0.01 to 0.03 μm, the barrier of hole reduces gradually. But with the increasing width, the reduction of barrier declines. For example, when the width of graded region varies from 0.025 to 0.03 μm, there is a little difference in structure of valence bands.

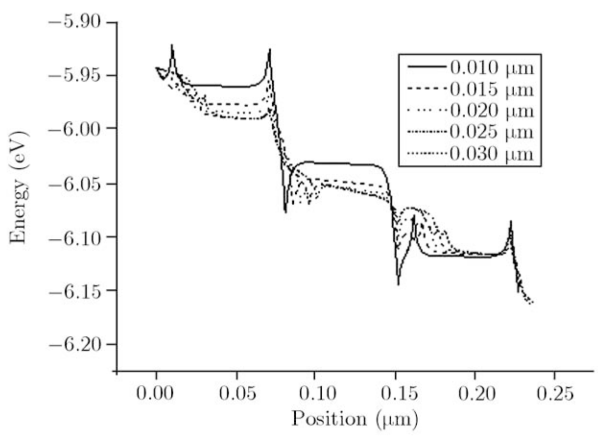

Figure 4 Valence band of 1.5 periods P-type DBR with various widths of graded region.

Figure 5 shows the current densities of 30 periods DBR with three different widths of graded region. It is obvious that current density increases by about 3.6 times when the width of graded region increases from 0.01 to 0.02 μm. But the current density increases only by about 0.6 times when the width increased from 0.02 to 0.03 μm. Figure 4 also shows that the resistance of DBR is reduced greatly and the reduction declines with increasing width of graded region.

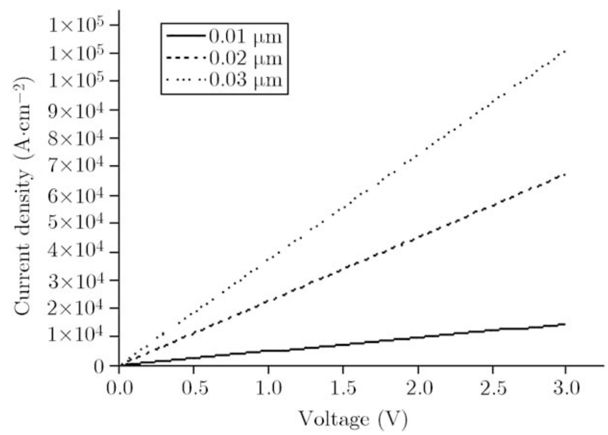

Figure 5 Voltage-current density curves of P-type DBR.

The reflection spectrum of the DBR is simulated with constant doping concentration and various widths of graded region. Figure 6 shows the results of simulation. The bandwidth of the high reflectivity section becomes narrower when the width of graded region widens. This phenomenon could be explained by formula (4). As the width of graded region increases gradually, the change of refractive index in graded region is slowed down. If two changed sections are selected as the two tiers, which have high and low refractive index, respectively, the difference in refractive index between these two tiers will be smaller. Thus, the bandwidth of the high reflectivity section will be narrower. So in order to obtain appropriate bandwidth, the width of graded region should not be increased unlimitedly.

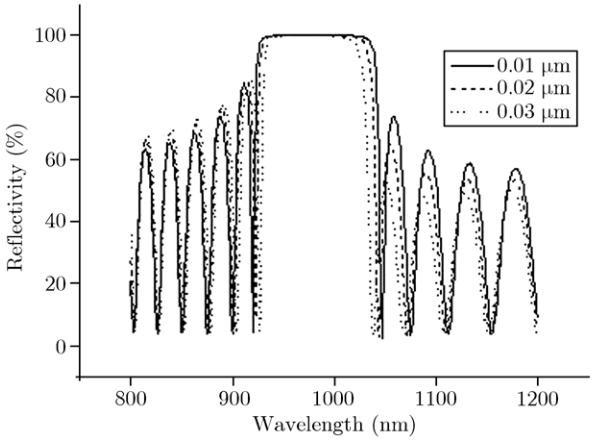

Figure 6 Reflectivity spectrum of P-type DBR with various widths of graded region.

Moreover, the doping concentration has a strong effect on the barrier of DBR. We investigate the phenomena in two cases. One is changing the doping concentration of all the DBR tiers. The other is only changing the doping concentration of graded region. Figure 7 shows the valence bands for different doping concentrations. The solid line denotes the valence band of using $2.5\times10^{18}\text{cm}^{-3}$ doping concentration for all the DBR tiers, while the dashed line denotes the valence band with a $3.5\times10^{18}\text{cm}^{-3}$ doping concentration. The hole barrier reduces by 5.3 meV with the increasing doping concentration. The dissimilarity between Figure 8 and Figure 7 is that only the doping concentration of graded region is increased to $3.5\times10^{18}\text{cm}^{-3}$ in Figure 8. But it is observed that the hole barrier reduces by 9.7 meV. In other words, only changing the doping concentration of the graded region is a better way to effectively reduce the hole barrier. However, the light absorption of DBR will be enhanced by the exorbitant doping concentration and it is very difficult to grow semiconductor materials with high-doping. Thus an appropriate doping concentration should be selected in devices.

Based on the above analysis, the structure of DBRs is designed for 980 nm bottom-emitting VCSEL. Considering the light absorption of DBR, P-type DBR, in which the width of graded region is 0.02 μm and the uniformity doping concentration is $2.5\times10^{18}\text{cm}^{-3}$, consists of 30 pairs $Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As$. Its reflectivity is 99.9%. N-type DBR, in which the width of graded region is also 0.02 μm and the uniformity doping concentration is $2\times10^{18}\text{cm}^{-3}$, consists of 28 pairs $Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As$. Its reflectivity is 99.3%. The VCSELs we fabricated have the bottom-emitting structure, so the reflectivity of P-type DBR is higher than that of N-type DBR. Figure 9 compares the experimental data and theoretical values of reflectivity of P-type DBR. The errors in thickness of each tier in DBR, which occur when

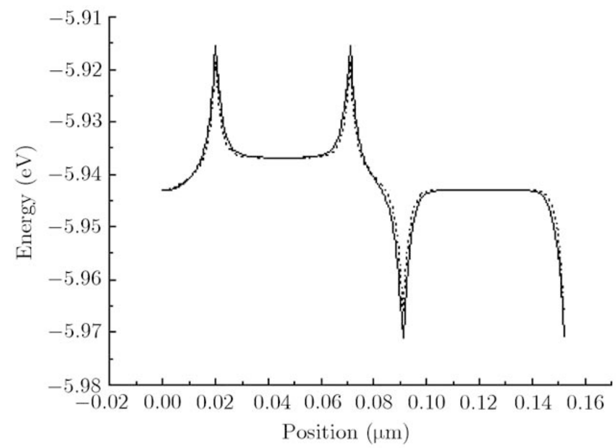

Figure 7 Reflectivity spectrum of P-type DBR with various widths of graded region.

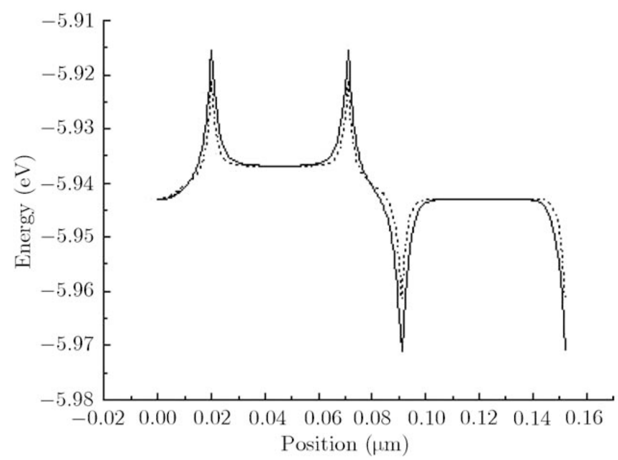

Figure 8 Valence band of 1 period P-type DBR by only changing the doping concentration of graded region.

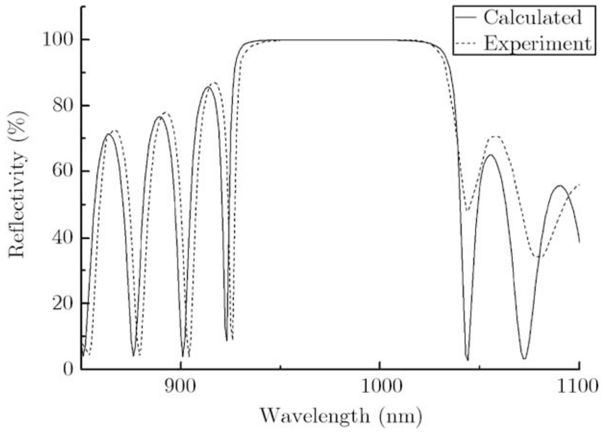

Figure 9 comparison of calculated and experimental result of reflectivity spectrum.

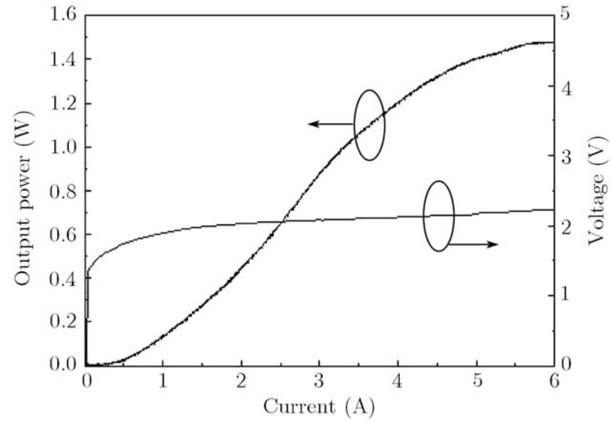

Figure 10 *L-I* and *V-I* curves of VCSEL with new DBR structure.

the DBR is grown, result in the differences in reflectivity between experimental data and theoretical values. But it is measured that the reflectivity is as high as 99.9% at 980 nm, which is satisfactory.

Figure 10 shows the output characteristics of VCSEL under the continuous current. The series resistance calculated with I-V curve is 0.05 Ω.

4 Conclusion

According to the theory of DBR, the electrical characteristics and optical reflection of the DBR have been analyzed by studying the energy band structure with various graded region widths and doping densities. With the P-type DBR as an example, the graded region width and doping density are chosen through a comparative study. The P-type DBR of 980 nm VCSELs is designed, when $Al_{0.9}Ga_{0.1}As$ and $Al_{0.1}Ga_{0.9}As$ are selected as the high and low refractive index material for the DBR. The 980 nm bottom VCSELs are then fabricated with the structure decided above, whose I-V curve shows that the series resistance of the device is about 0.05.

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