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EFFECTS OF GRADING LAYERS ON GaAs VERTICAL CAVITY SURVACE EMITTING LASER PERFORMANCE

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ABSTRACT

This study is an attempt to investigate the effect of grading layers thicknesses and doping on the distributed Bragg reflectors (DBRs) resistivity by using advanced numerical simulation (ISETCAD) . Various VCSEL with and without grading DBRs aredesigned. It was observed increasing the length of grading minimize the voltage drop on the device, especially for p DBR. And total resistance of the device can be further lowered if all grading layers are all highly doped.

Keywords: *VCSEL, DBR, GaAs, Dropping.*

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تأثير الطبقات المتدرجة على اداء ليزر كاليوم ارسنايت ذات انبعاث سطحي لتجويف شاقولي

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الملخص

تم استخدام برنامج المحاكاة العددية المتقدمة لدراسة وتحليل تأثير سمك وتطعيم الطبقات المتدرجة (grading layer) على مقاومة العاكسات Bragg الموزعة. صممت في هذا البحث عدة ليزرات ذات انبعاث سطحي لتجويف شاقولي(VCSEL) مع وبدون الطبقات المتدرجة. و لوحظ ان زيادة طول الطبقات المتدرجة يسبب تقليل في هبوط الفولطية الجهاز، وخاصة في نوعp DBR.كما وجدان المقاومة الكلية للجهاز انخفضت بصورة ملحوظة بعد تطعيم الطبقات المدرجة بشكل اعلى.

الكلمات الدالة: ليزر ذات إنبعاث سطحي لتجويف شاقولي، الطبقات المتدرجة، غاليوم أرسنايت، التطعيم

1. Introduction

The distinctive feature of VCSELs is that laser reflectors are parallel to the epi layers. Since the cavity volume of VCSEL is small, high mirror reflectivity isrequired to compensate the low round trip gain. DBR is the only practical way to realize the high reflectivity [1-6]. DBRs are structures formed from multiple layers of alternating materials with different refractive index. Each interface reflects partial of the optical wave. A high quality reflector is constructed at the wavelength of whichall the reflections combine with constructive interference. Transmission matrix method is a powerful tool to simulate the multilayer structures [7-12].

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Combining the multiple quarter-wavelengths thick high-to-low refractive index layers will result to maximum reflectance greater than 99%. The reflectivity of a single DBR at normal incidence can be calculated using the following equation [13].

$$R = \left(\frac{1 - \left(\frac{n_L}{n_H} \right)^{2n}}{1 + \left(\frac{n_L}{n_H} \right)^{2n}} \right)^2 \qquad (1)$$

where n is the number of the DBR pairs, n_L and n_H arethe low and high refractive indexes of the two layers in DBR, respectively. The DBRs designing criteria arerelated to maximum optical reflectivity, thermal andelectrical conductivity, material index contrast and optical absorption [13]. The analysis of DBRin VCSEL design is critical due to its strong reflectivity effect on all laser fundamental properties; therefore, the attention paid to the optimized distributed Bragg reflectors, which is very important in VCSEL design. The optimization of theDBR structure is fundamentally important to increase theperformance of optical systems based on the VCSEL technology [14-16].In this work the effect of thicknesses and doping concentration of grading layers in DBR on the VCSEL performance using ISE`TCAD software was investigated.

2. VCSEL Design in numerical simulation

When the metal contact is on the outside of DBR, carriers must travel through theDBR structure to reach the active region. Large resistance of DBR multilayers seriously hampers the device’s characteristics. ISETCAD simulation withtransmission matrix method (TMM) was used to analyze the resistance of DBR structure.

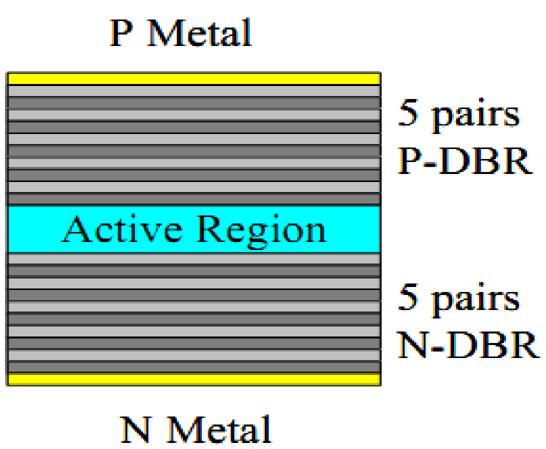

Fig. (1): Schematic diagram of the Structure for DBR Resistance Simulation.

The band gap energy for AlGaAs at room temperature is calculated using the direct and indirect energy band gap equations :

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

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

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:

$$\frac{m_e}{m_o} = 0.067 + 0.083x \qquad (4)$$

$$\frac{m_{lh}}{m_o} = 0.087 + 0.063x \qquad \frac{m_{hh}}{m_o} = 0.500 + 0.290x \qquad (5)$$

The schematic diagram of the structures used in the simulation is shown in Fig. (1). This simulation wasused to obtain information of serial resistance ofDBRs used in an 850 nm VCSEL. So the active region is a GaAs QW with $Al_{0.2}GaAs$ as barriers. The active region is one wavelength thick. The active region issandwiched in two 5-pair $Al_{0.15}GaAs/Al_{0.95}GaAs$ DBRs. The bottom DBR is n type and the top DBR is p type. P and n metal contacts are formed on the surfaces of the DBR. The simulated device dimension is 5 µm by 5 µm. Maximum 2 mA current is simulated flowing through the structure. Five different DBR designs are simulated. The DBR dielectric material, thickness and doping information are summarized in Table (1) .

Table (1): DBR Layer Thickness and Doping Used In the Simulation.

Sample	NoGrad	10Grad	10GradHigh	20Grad	20GradHigh
Al0.15GaAs	**59 nm 1E18**	**49 nm 1E18**	**49 nm 1E18**	**39 nm 1E18**	**39 nm 1E18**
Grading	**0 nm**	**10 nm 1E18**	**10 nm 4E18**	**20 nm 1E18**	**20 nm 4E18**
$Al_{0.95}GaAs$	**70 nm 1E18**	**60 nm 1E18**	**60 nm 1E18**	**50 nm 1E18**	**50 nm 1E18**
Grading	**0 nm**	**10 nm 1E18**	**10 nm 1E18**	**20 nm 1E18**	**20 nm 1E18**

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The “No Grad” DBR has no grading between the high refractive index material$Al_{0.15}GaAs$ and low refractive index material $Al_{0.95}GaAs$. The layers are quarter wavelength thick and all the layers are uniformly doped to 1E18 cm^{-3}. The “10Grad” DBR has a 10 nm grading on each interface. The thicknesses of $Al_{0.15}GaAs$ and$Al_{0.95}GaAs$ are reduced accordingly to maintain the periodicity of the DBR. ThisDBR is uniformly doped to 1E18 cm^{-3}. The “10GradHigh” DBR has the same layer structure as the “10Grad” DBR except the doping is 4E18 cm^{-3} in the grading layerswhich the carriers flow from the $Al_{0.15}GaAs$ to $Al_{0.95}GaAs$. The “20Grad” DBR has similar structure as “10Grad” DBR but has 20 nm Grading. The “20GradHigh” DBR is similar to “10GradHigh” DBR buthas 20 nm Grading.

3. Simulation Results and Discussion

Voltage-current curves of various VCSEL Structures are shown in Fig. (2) . It is clearly shown that increasing the grading layer thickness and increasing the doping in grading layerreduce the device resistance. The highest resistance was foundin the “NoGrad” structure.

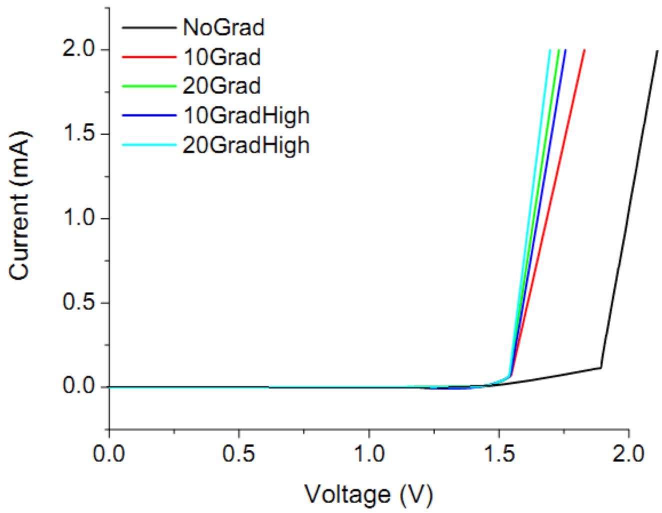

Fig. (2): Simulated Voltage-Current Curves of various VCSEL Structures

The band structure and quasi-Fermi level distribution of “10Grad” structure with 2 mA driving current are shown in Fig. (3) . The black curve is theconduction band structure, the cyan curve is the valence band structure, the greencurve is the electron quasi-Fermi level distribution, and the blue curve is the hole quasi-Fermi level distribution. The voltage drop distribution can be obtained by following the electron quasi-Fermi level in the n side of the device and following the hole quasi-Fermi level in the p side of the device.

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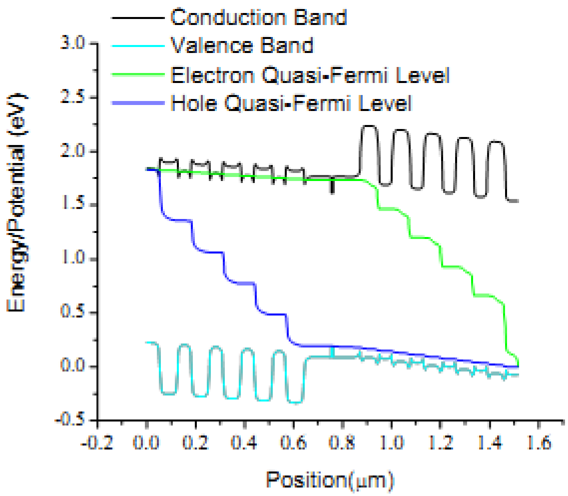

Fig. (3): Band Diagram and Quasi-Fermi Level Distribution of "10Grad" Structure

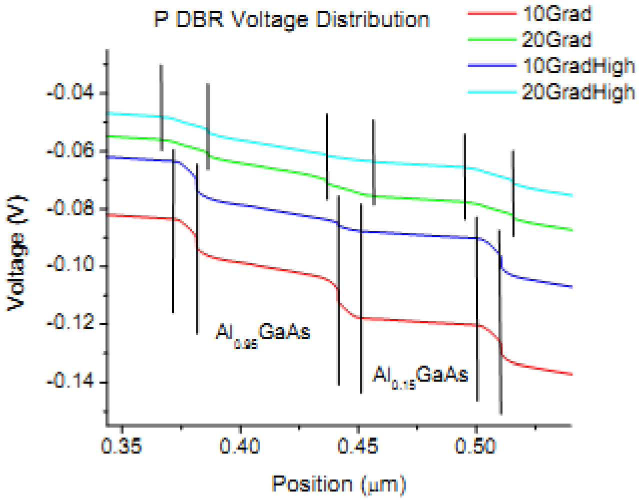

Fig. (4): Simulated Voltage Distribution in P-DBRs

The voltage distributions in the p DBRs are shown in Fig. (4). The four curves corresponding to four graded DBR structures are presented. They are markedby different colors according to the legends in the graph. Vertical black lines mark the positions of interfaces. For all these curves, the zero voltage points are located inthe QW at the 0 µm position which is not shown. Holes flow from right to left in this drawing. Similar drawings for n DBRs are shown in Fig. (5) . The zero voltage points are still located in the QW at the 0 µm position. Electrons flow from left to right in the drawing. Fig. (4) and Fig. (5) are plotted with the same scale for the convenience of comparison.

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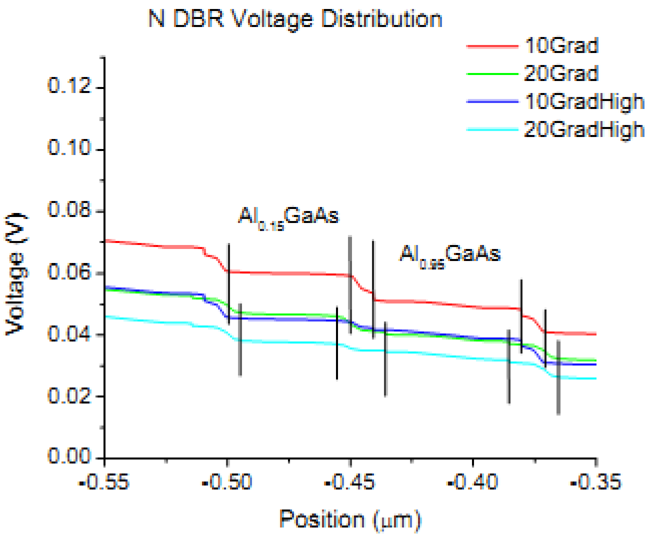

Fig. (5): Simulated Voltage Distributions N-DBRs

Voltage drops in all layers of simulated DBRs are summarized in Table (2) . The Grading (LH) is the grading from $Al_{0.15}GaAs$ to $Al_{0.95}GaAs$ in the current flow direction. The Grading (HL) is from $Al_{0.95}GaAs$ to $Al_{0.15}GaAs$ in the current flow direction. Compared to n DBR, p DBR has higher voltage drop due to heavy effective mass and low mobility. Increasing the length of grading minimize thevoltage drop, especially for p DBR. Increasing the doping in the grading also helps to lower the voltage drop. Total resistance of the device can be further lowered if all grading layers are all highly doped. However, there is a tradeoff between the DBRresistance and free carrier absorption. Other than grading layers, p-$Al_{0.95}GaAs$ alsocontributes to the high voltage drop due to high bulk resistance.

Table (2): Simulated Voltage Drops in DBR layers

Sample / Material	10Grad	20Grad	10GradHigh	20GradHigh
p-$Al_{0.15}GaAs$	0.002	0.002	0.002	0.002
p-Grading (LH)	0.013	0.006	0.004	0.002
p-$Al_{0.95}GaAs$	0.009	0.007	0.009	0.007
p-Grading (HL)	0.013	0.005	0.013	0.005
P Total	**0.037**	**0.020**	**0.028**	**0.016**
n-$Al_{0.15}GaAs$	0.001	0.001	0.001	0.001
n-Grading (LH)	0.008	0.006	0.002	0.002
n-$Al_{0.95}GaAs$	0.003	0.002	0.003	0.002
n-Grading (HL)	0.007	0.007	0.007	0.007
N Total	**0.019**	**0.015**	**0.013**	**0.011**

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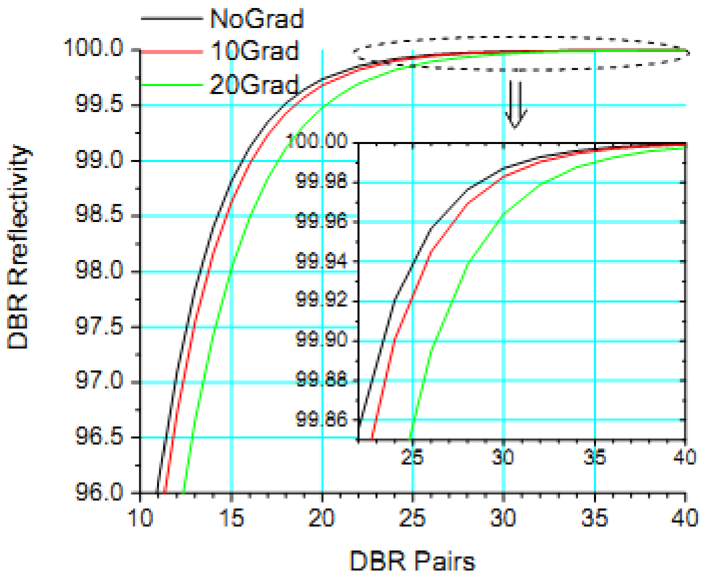

Fig. (6): Influence of Grading on DBR Reflectivity

Using the grading instead of the abrupt junction in DBR decreases the resistivity, but it also influences the reflectivity. The reflectivity of $Al_{0.15}GaAs$-$Al_{0.95}GaAs$ DBRs with no grading, with 10 nm grading, and with 20 nm grading is shown in Fig. (6) . According to the simulation, in order to reach the reflectivity of 99%, the number of DBR pairs need to be 16, 17, and 18 respectively for these three DBRs. In order to reach the reflectivity of 99.99%, 31, 32 and 35 pairs of DBRs are required respectively. Although the DBR resistivity increases linearly with the number of DBR pairs, the reduction of the DBR resistivity due to a wide grading is much larger. Other than DBR reflectivity, there is also another trade off between the free carrier absorption and the DBR resistivity. Doped DBR introduces the freecarrier absorption especially in the p DBR side. In order to minimize the free carrier loss, few pairs of p DBR close to the active region may intentionally be doped less.The DBR resistivity is sacrificed to lower the loss in this case.

4. Conclusions

Finally, the comparison of the effect of thicknesses and doping concentration of grading layers inDBR on the VCSEL performance was included. It was observed that by using the grading layers instead of the abrupt junction in DBR decreases the resistivity, but it also influences the reflectivity of the device. Compared to n DBR, p DBR has higher voltage drop due to heavy effective mass and low mobility. Increasing the length of grading minimize thevoltage drop, especially for p DBR. Increasing the doping in the grading also helps to lower the voltage drop. Total resistance of the device can be further lowered if all grading layers are all highly doped.

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