

ACTIVE ANTI-GUIDE VERTICAL CAVITY SURFACE EMITTING LASERS WITH DIFFUSED QUANTUM WELLS STRUCTURE

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ABSTRACT

The enhancement of single transverse mode operation in vertical cavity surface emitting lasers by using interdiffused quantum wells is proposed and analyzed. It is observed that the influence of self-focusing (arising from carrier spatial hole burning and thermal lensing) on the profile of transverse modes can be minimized by introducing a step diffused quantum wells structure inside the core region of quantum-well active layer. Stable single-mode operation in vertical cavity surface emitting lasers can also be maintained.

INTRODUCTION

An ideal VCSEL should have single longitudinal mode operation, low threshold current and narrow output beam. However, at high power, VCSEL's exhibit multiple transverse modes operation, which is excited by the increase of refractive index arising from self-focusing effect (owing to carrier spatial hole burning and thermal lensing) [1]. This would deteriorate the performance of lasers and should be avoided. Thus, the goal of this paper is to utilize diffused quantum wells (DFQW's) structure of vertical cavity surface emitting lasers (VCSEL's) for the enhancement of high power single-mode operation.

The purpose of using step DFQW's structure can be explained as follows: The step-diffusion is defined selectively within the core region of the QW active layer. A non-uniform stepped refractive index profile is created, resulting in an anti-guiding structure for the transverse modes. Hence, DFQW's structure can compensate the influence of self-focusing and stabilize the profile of transverse modes. Also, the major advantages of utilizing DFQW's structure are that it is simple and compatible with existing fabrication technologies of lasers.

DESIGN AND ANALYSIS

Laser Structure

The schematic diagram of VCSEL with DFQW's structure is as in figure 1. We assume the circular metal contact of the laser has diameter of 10 μm on the p-side for current injection. There is an active layer sandwiched between two undoped spacer layers and two Bragg reflectors. The thickness of each undoped spacer layers is half-wavelength ($\sim 0.1 \mu\text{m}$). The Bragg reflectors are formed by alternate layers of AlGaAs and AlAs, with quarter wavelength thickness dielectric layers on p-side and n-side respectively. The total number of layers on the p-side is 90 ($\sim 5.4 \mu\text{m}$), while on the n-side is 36 ($\sim 2.1 \mu\text{m}$). For the active layer, it consists of three GaAs/Al_{0.3}Ga_{0.7}As QW having total thickness of half-wavelength ($\sim 0.1 \mu\text{m}$).

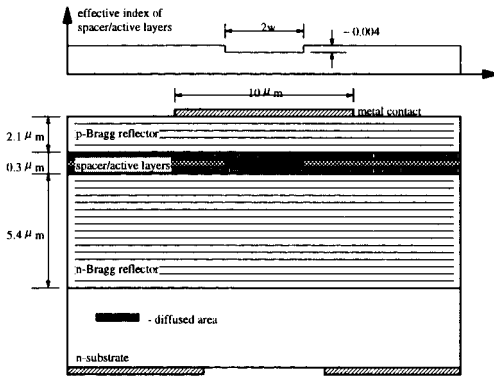


Figure 1 Schematic diagram of a VCSEL with step DFQW's structure

Introduction of DFQW's structure by impurity induced disordering

Step DFQW's structure is introduced along the active layer by compositional impurity induced disordering (IID) of QW. Interdiffusion is applied into the QW's active layer of laser. The implanted ions on the as-growth QW's layers are shielded by the circular mask. After implantation, we apply annealing to induce compositional disordering and to restore the impurities damage. Afterwards, the cladding region is resulted from the area covered by the mask, and the core region is resulted from the diffused area. Consequently, a small refractive index step is established between the core and cladding region. Thus, an anti-index guided structure is obtained. We then grow the spacer layer, p-type Bragg reflector and circular metal contact on the active layer to complete the structure of the device.

For easy penetration of impurities into the active layer, argon is proposed to be the impurity used. It is because argon has deep penetration power ($>2 \mu\text{m}$). Also, its influence on the electrical properties of p-Bragg reflector is less after thermal annealing [2].

Numerical Laser Model

We use k.p method to model the optical gain and refractive index of DFQW's under external carrier injections [3][4]. The QW's active layer under analysis consists of three GaAs-Al_{0.3}Ga_{0.7}As QW's with well width 100Å and barrier thickness 150Å. In the model, the extent of interdiffusion is controlled by the diffusion length of impurities, L_d . It is because the diffusion strength is increased with the magnitude of L_d .

The optical gain spectrum of QW material, G , with a particular set of λ and L_d can be expressed as

$$G(\lambda) = a(\lambda) \log(N / N_0) \quad (1)$$

with $a(\lambda)$ being the gain coefficient and N_0 the carrier concentration at transparency.

Also, we can evaluate the change of refractive index, Δn_r , inside the QW's active layer by considering the variation of gain spectral through Kramers-Kronig dispersion relation[5]. It can be shown that at certain values of L_d and λ_0 , the relation between Δn_r and N is

$$\Delta n_r = d(\lambda) \log(N / N_r) \quad (2)$$

where $d(\lambda)$ and N_r are fitting parameters.

We can analyze the characteristics of transverse modes of VCSEL's by making some modifications on the recently developed model [6]. The Poisson equations for voltage and temperature can be solved by finite difference method self-consistently with the wave equation of optical field and rate equation of carrier concentration. Therefore, the 3-D distribution of voltage and temperature can be included into the model.

In solving the voltage equation, we assume the electrical conductivity of n-Bragg reflector, p-Bragg reflector, spacer/active layer and n-substrate to be $1.5\text{cm}^{-1}\Omega^{-1}$, $7\text{cm}^{-1}\Omega^{-1}$, $3\text{cm}^{-1}\Omega^{-1}$ and $500\text{cm}^{-1}\Omega^{-1}$, respectively. Also, several assumptions are made.

- 1) Charge density is zero.
- 2) Metal contacts are fixed at certain voltage level.
- 3) First derivative of voltage at the surface of device without any metal contact is zero.
- 4) Voltage across p-n junction, V_F , is related to carrier concentration by the following equation:

$$V_F = \frac{1}{q} \left[E_g + k_B T \cdot \log \left\{ (\exp(N / N_C) - 1) (\exp(N / N_V) - 1) \right\} \right] \quad (3)$$

where N is carrier concentration, E_g is bandgap energy of GaAs, N_C and N_V are effective conduction and valence edge density of states respectively and T is temperature.

For the Poisson equation of heat, it is assumed at 300°K , the thermal conductivity of n-Bragg reflector, p-Bragg reflector and spacer/active layer to be equal to $0.07\text{Wcm}^{-1}\text{K}^{-1}$, and that of n-substrate to be $0.45\text{Wcm}^{-1}\text{K}^{-1}$. Also, the boundary conditions are similar to that shown in [1]. Moreover, we assume the reasons for internal heat source are as follows:

- 1) There is joule heating in both p- and n- side Bragg reflectors and spacer layers.
- 2) There is non-radiative recombination spontaneous radiation inside the active layer.

In solving the wave equation, we assume the total absorption and scattering losses of the QW waveguide to be 20cm^{-1} for the case without interdiffusion and to be 30cm^{-1} when with diffusion. By varying the carrier concentration and temperature, the refractive index will change also. The change of refractive index, Δn , is given by

$$\Delta n = \Gamma \Delta n_r + \frac{\partial n}{\partial T} \Delta T \quad (4)$$

where $\partial n / \partial T (=2 \times 10^{-4} \text{K}^{-1})$ is the variation of refractive index with temperature, $\Delta T = T - 300^\circ\text{K}$, and $\Gamma (=0.5)$ is the longitudinal confinement factor taking into account the penetration of standing wave into the spacer layers.

Design Consideration on Diffusion Length and other parameters

Small value of $L_d (<5\text{\AA})$ is preferred for VCSEL with step DFQW's structure. It is because small L_d will not reduce the optical gain and refractive index of the QW active layer significantly. However, large L_d may cause damage to the lattice structure of p- Bragg reflector owing to its high implantation energy ($>5\text{MeV}$).

Practically, L_d is set within a particular range. It is because small value of L_d is difficult to maintain, as L_d is affected by the variation of thickness and quality of p-Bragg reflector. In our investigation, we define an effective value, $\langle L_d \rangle$, to be 3 \AA . Also, the operation wavelength, λ , is set to be $0.85\mu\text{m}$.

For $L_d = 0\text{ \AA}$ or 3 \AA , the values of a , N_0 , background refractive index, d and N_r are shown in Table I. The values of other parameters can be found in references [6] and [7].

Table I Values of parameters

	$L_d = 0\text{ \AA}$	$\langle L_d \rangle = 3\text{ \AA}$
a	1591cm^{-1}	1500cm^{-1}
N_0	$1.94 \times 10^{18}\text{cm}^{-3}$	$1.93 \times 10^{18}\text{cm}^{-3}$
Background refractive index	3.6270	3.6185
d	-0.0283	-0.0279
N_r	$2.06 \times 10^{18}\text{cm}^{-3}$	$2.04 \times 10^{18}\text{cm}^{-3}$

RESULTS

Curves of light power against current are plotted in fig. 2, with radius of diffusion area varying between $3\mu\text{m}$ and $3.8\mu\text{m}$. The dotted and solid curves show the case of VCSEL with diffusion and without diffusion respectively. From the graph, it is observed that a kink is present in both cases with the excitation of first-order mode (LP_{11}). However, when diffusion is introduced and at $w = 3\mu\text{m}$, the kink is seen to shift upward and to the right, resulting in a stable fundamental-mode (LP_{01}) operation at high power.

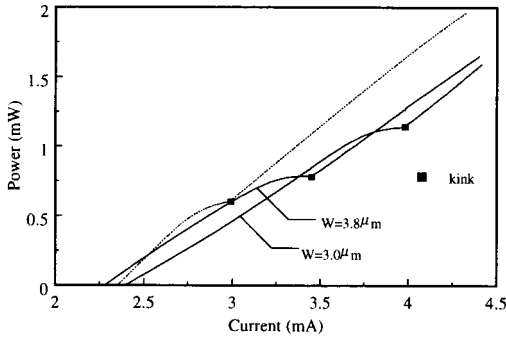


Figure 2 Light/current characteristics of VCSEL's without (dotted line) and with (solid line) a step DFQW structure

The variation of refractive index with change in radius is shown in Fig. 3. The output power is set to 1 mW . As seen from the plot, lasers without step-diffused QW's structure exhibit continuous increase of refractive index near the center of the core region. This can be explained by the self-focusing effect arising from spatial hole burning and thermal lensing. As a result, optical field with transverse modes is shifted towards the center region and the LP_{01} mode is excited. However, for lasers with step-diffusion introduced and at $w = 3\mu\text{m}$, no

increase of refractive index is observed, as it is counteracted by the step-diffused QW's structure. Thus, single-transverse-mode operation can be maintained.

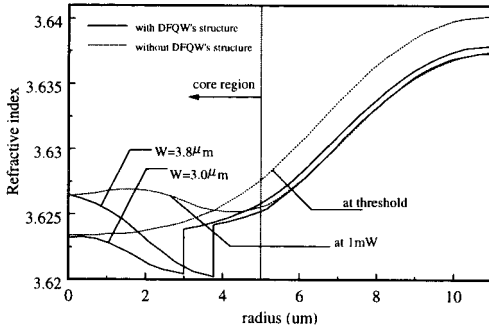


Figure 3 Transverse distribution of refractive index of VCSEL's without (dotted line) and with (solid line) a step DFQW structure at output power of 1 mW

The profile of normalized intensity of LP_{01} mode and LP_{11} mode is shown in Fig. 4. From the graph, it can be seen that for DFQW's lasers with $w \leq 3 \mu\text{m}$, a kink appears in both the LP_{01} and LP_{11} modes. However, for DFQW's lasers with $w > 3 \mu\text{m}$ and for lasers without diffusion, no kink is observed. The profile of the transverse modes is deformed so as to minimize the influence of self-focusing.

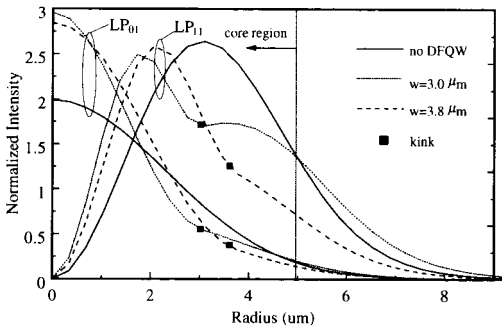


Figure 4 Profile of LP_{01} and LP_{11} modes for VCSEL's with and without DFQW's structure at threshold

A graph of normalized intensity of LP_{11} mode against radius at different injection level is shown in fig. 5. It can be seen that for DFQW's lasers with $w = 3 \mu\text{m}$, the effect of self-focusing is less than that for lasers without diffusion. The beam-width of LP_{11} mode is reduced significantly by self-focusing effect for lasers without diffusion. Also, we can observe that the volume of LP_{11} mode inside the cladding region remains unchanged with increasing injection current. Thus, stable operation of LP_{01} mode is maintained.

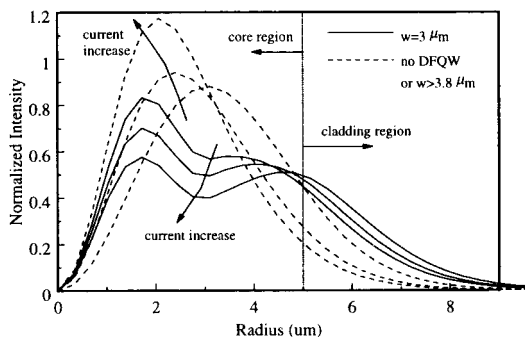


Figure 5 Variation of LP₁₁ mode with injection current increased from I_{th} to $1.6 I_{th}$ where I_{th} is the threshold current

CONCLUSIONS

The enhancement of single transverse mode operation of VCSEL by using DFQW's structure is analyzed. Impurity induced disordering (IID) is used to introduce step DFQW's structure as it is simple and requires low cost. From our investigation, it is found that the optical loss in cladding region remains unchanged at high injection current. Thus stable LP₀₁ mode operation can be maintained. Also, the output power of stable LP₀₁ mode operation is doubled by using the proposed device. On the whole, VCSEL with DFQW's structure requires only simple fabrication process and low production cost, and can produce high yield rate and satisfactory performance.

ACKNOWLEDGMENTS

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