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Proposed enhancement of single mode operation in VCSELs using diffused quantum well structure

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The use of interdiffused quantum wells to enhance single transverse mode operation in vertical cavity surface emitting semiconductor lasers is proposed and analysed theoretically. It is found that by introducing a step diffused quantum well structure inside the core region of a quantum-well active layer, the influence of self-focusing (due to carrier spatial hole burning and thermal lensing) on the profile of transverse modes can be minimized. Therefore, stable single-mode operation in vertical cavity surface emitting lasers can be maintained.

1. Introduction

Single longitudinal mode operation, low threshold current and narrow output beam are promising characteristics of vertical cavity surface emitting lasers (VCSELs) for various applications such as optical communication and computing systems. However, VCSELs exhibit multiple transverse mode operation at high power which deteriorates their performance in fibre-optic applications [1]. This is because multiple transverse modes broaden the optical spectrum such that the modulation bandwidth of communication systems is limited. In addition, the coupling efficiency into single-mode fibres is also decreased with the onset of multiple transverse modes.

The increase in refractive index inside the laser cavity, arising from the influence of self-focusing (due to spatial hole burning of carrier concentration and thermal lensing), excites high order transverse modes [2]. This is because the self-focusing effects collimate transverse modes into the core region of VCSELs such that the threshold gain of the transverse modes is reduced. Hence, multiple transverse mode operation is observed in VCSELs at high power [3].

In order to overcome self-focusing effects, it is suggested that a passive anti-guiding structure for VCSELs can be used to maintain single mode operation [4]. However, organometallic chemical vapour deposition and molecular beam epitaxy which are required for the regrowth of a passive anti-guiding structure are much more complicated than that used for a gain-guided structure [5]. Recently, semiconductor lasers with diffused quantum

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wells (DFQWs) have been proposed for high-power single-longitudinal-mode operation [6]. In this report, a simple DFQWs structure of VCSELs is proposed to preserve single-mode operation. The QW active layer of this laser consists of a step DFQWs structure which can be defined selectively within the core region. This will create a non-uniform stepped refractive index profile such that an anti-guiding structure for the transverse modes is obtained. The purpose of the step DFQWs structure is to compensate the influence of self-focusing and stabilize the profile of transverse modes. The advantages of utilizing DFQWs structure are the simple processing technique and its compatibility with existing fabrication technologies of semiconductor lasers.

2. Proposed VCSELs with diffused quantum well structure

The VCSEL with DFQWs structure under investigation is shown in Fig. 1. It is assumed that the laser has a circular metal contact of diameter 10 μm on the expitaxial side (p-side) for current injection. An active layer is sandwiched between two undoped spacer layers and two Bragg reflectors. The undoped spacer layers each have thickness of half-wavelength (~0.1 μm). The Bragg reflectors are formed by alternate layers of AlAs and AlGaAs with quarter-wavelength thick dielectric layers on both the n- and p-side, respectively. There is a total of 36 layers (~2.1 μm) on the p-side and 90 (~5.4 μm) on the n-side. The active layer consists of three $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells with well width of 10 nm and barrier thickness of 15 nm. It is assumed that the total thickness of the active layer is about half-wavelength (~0.1 μm). Light can be emitted from the n-Bragg reflector through a transparent AlGaAs substrate. Alternatively, light can be emitted from the p-Bragg reflector through an indium tin oxide transparent electrode [7]. In fact, the proposed VCSEL can be either a substrate-emitting type or a top surface-emitting type device.

The step DFQWs structure can be realized along the active layer by compositional-induced disordering of QW. Impurities can be implanted across the p-Bragg reflector into

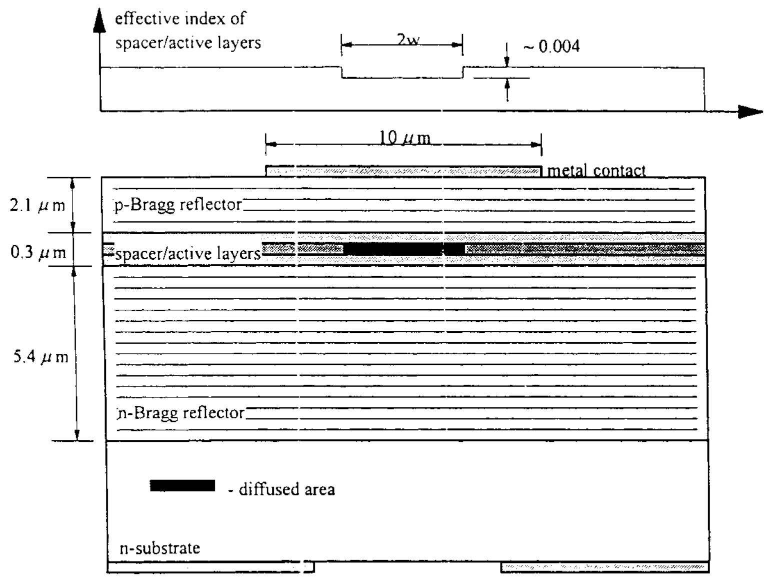

Figure 1 Schematic diagram of a VCSEL with a step DFQWs structure.

the active layer through a circular hollow mask. It must be noted that the thickness of the p-Bragg reflector and the impurity used should be carefully selected. Otherwise, the penetration of impurity into the active layer may not be possible. From our theoretical prediction, it is shown that argon can be utilized to realize a DFQWs structure in VCSELs. This is because argon has (i) deep penetration depth ($>2\ \mu m$) and (ii) little influence on the electrical properties of the p-Bragg reflector after thermal annealing [8].

3. Theoretical model and parameters

In order to analyse the performance of VCSELs, the optical gain and refractive index of DFQWs under external carrier injections are modelled by the $k \cdot p$ method. The material considered in this calculation, which is similar to that given in [6], is the as-grown and interdiffusion modified $Al_{0.3}Ga_{0.7}As/GaAs$ single QW structure with a well width of 10 nm. The DFQW is approximated by an error function and the extent of interdiffusion is characterized by a diffusion length L_d (where $L_d = 0$ represents the as-grown QW). The optical gain, G, at a particular wavelength λ and L_d can be expressed as [6]

$$G(\lambda) = a(\lambda)\ \log(N/N_o) \tag{1}$$

where $a(\lambda)$ is a fitted parameter and N_o is the carrier concentration at transparency. The background refractive index, $n_r(\lambda)$, of the DFQW can also be obtained from [6]. In addition, the carrier induced index change, Δn_r, can be approximated by [6]

$$\Delta n_r(\lambda) = \mathrm{d}(\lambda)\ \log(N/N_r) \tag{2}$$

where $\mathrm{d}(\lambda)$ and N_r are the corresponding fitted parameters.

The transverse mode characteristics of VCSELs can be analysed by using the recently developed model [9] with some modifications. In order to take into account the three-dimensional distribution of voltage and temperature, the Poisson equations for voltage and temperature are solved self-consistently with the wave equation of the optical field and the rate equation of the carrier concentration by a finite difference method. In solving the Poisson equation of voltage, the corresponding boundary conditions are assumed as follows: (i) charge density is set to zero, (ii) metal contacts are fixed at a certain voltage level, (iii) the first derivative of voltage at the device surface without any metal contact is set to zero, and (iv) the voltage across the p–n junction, V_F, can be related to the carrier concentration by

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

where N is the carrier concentration, E_g is the bandgap energy of GaAs, T is the temperature, and N_C and N_V are the effective conduction and valence edge density of states, respectively. The electrical conductivity of the n-Bragg reflector, p-Bragg reflector, spacer/active layer and n-substrate are equal to $1.5\,\mathrm{cm^{-1}\,\Omega^{-1}}, 7\,\mathrm{cm^{-1}\,\Omega^{-1}}, 3\,\mathrm{cm^{-1}\,\Omega^{-1}}$ and $500\,\mathrm{cm^{-1}\,\Omega^{-1}}$, respectively. In solving the heat equation, it is assumed that the internal heat source is caused by (i) Joule heating in both p- and n-side Bragg reflectors and spacer layers and (ii) non-radiative recombination spontaneous radiation inside the active layer. The boundary conditions are similar to those given in [2] with the materials' thermal conductivity assumed to be temperature dependent (i.e. proportional to $T^{-1.2}$). The thermal conductivity of the n-Bragg reflector, the p-Bragg reflector and the spacer/active layer are assumed to be equal to $0.07\ \mathrm{W\,cm^{-1}\,K^{-1}}$, and the thermal conductivity of the n-substrate equal to 0.45 W cm^{-1} K^{-1}, at 300 K. In solving the wave equation, the change of refractive index, Δn, due to the change of carrier concentration and temperature is given by

$$\Delta n = \Gamma \Delta n_{\mathrm{r}} + \frac{\partial n}{\partial T} \Delta T \tag{4}$$

where $\partial n/\partial T$ $(=2 \times 10^{-4}\,\mathrm{K}^{-1})$ is the change of refractive index with temperature and $\Delta T = T - 300\,\mathrm{K}$. Γ $(=0.5)$ is the longitudinal confinement factor which takes into account the penetration of the standing wave (with peak located at the active layer) into the spacer layers for the calculation of the transverse modes. The total absorption and scattering losses of the QW waveguide are assumed to be $20\,\mathrm{cm}^{-1}$ for the case without interdiffusion but equal to $30\,\mathrm{cm}^{-1}$ for the case with interdiffusion.

4. Design considerations of diffusion length

For the proposed VCSEL with step DFQWs structure, only small L_{d} $(\leq 0.5\,\mathrm{nm})$ is desired. This is because a small value of L_{d} will not significantly reduce the optical gain and the refractive index of the QW active layer. However, a large value of L_{d} requires a high implantation energy $(> 5\,\mathrm{MeV})$ which may damage the lattice structure of the p-Bragg reflector even after thermal annealing. On the other hand, it is difficult to maintain L_{d} at a particularly small value due to the fluctuation of thickness and the quality of the p-Bragg reflector. In practice, it will be easier to control L_{d} within a particular range (e.g. $0 \leq L_{\mathrm{d}} \leq 0.5\,\mathrm{nm}$). In our investigation, an effective value, $\langle L_{\mathrm{d}} \rangle$, is defined in order to take into account any uncertainty in L_{d}. It is assumed that $\langle L_{\mathrm{d}} \rangle$ is approximately equal to 0.3 nm. The operating wavelength of the laser is chosen to be $\lambda = 0.85\,\mu\mathrm{m}$. The value of a and N_{o} for the case $L_{\mathrm{d}} = 0$ are equal to $1591\,\mathrm{cm}^{-1}$ and $1.94 \times 10^{18}\,\mathrm{cm}^{-3}$, and for the case $\langle L_{\mathrm{d}} \rangle = 0.3\,\mathrm{nm}$, they are equal to $1500\,\mathrm{cm}^{-1}$ and $1.93 \times 10^{18}\,\mathrm{cm}^{-3}$, respectively. The background refractive index is equal to 3.6270 for $L_{\mathrm{d}} = 0$ and 3.6185 for $\langle L_{\mathrm{d}} \rangle = 0.3\,\mathrm{nm}$. The effective step-change of refractive index of the anti-guided structure is thus equal to 0.004. The parameters d and N_{r} for the case $L_{\mathrm{d}} = 0$ are equal to -0.0283 and $2.06 \times 10^{18}\,\mathrm{cm}^{-3}$, and for the case $\langle L_{\mathrm{d}} \rangle = 0.3\,\mathrm{nm}$, they are equal to -0.0279 and $2.04 \times 10^{18}\,\mathrm{cm}^{-3}$, respectively. Other device parameters can be found in [6, 9].

5. Numerical results

Figure 2 shows the light/current curves of VCSELs with and without a step DFQWs structure. In the investigation, the radius of the diffusion area, w, is varied between 3 and $5\,\mu\mathrm{m}$. It is observed that a kink occurs in the light/current curves with the excitation of the first order mode (LP_{11}). With a suitable value of w (i.e. $w = 3\,\mu\mathrm{m}$), the kink is shifted upward and stable fundamental mode (LP_{01}) operation can be maintained at a higher power level. Figure 3 compares the refractive index profile of lasers, with and without a step DFQWs structure, operating at 1 mW output power. The refractive index profile at threshold for a gain-guided structure (i.e. without step DFQWs structure) is also shown in the figure. As we can see for the case without step DFQWs structure, the refractive index of the active layer increases near the centre of the core. Due to the self-focusing effects, transverse modes move towards the centre region and LP_{11} is excited. On the other hand, the increase in refractive index is counteracted by the step DFQWs structure with $w = 3\,\mu\mathrm{m}$ such that single transverse mode operation is maintained.

It must be noted that self-focusing effects have a greater influence on the profile of transverse modes in DFQWs laser than on the device proposed in [4] (i.e. the total

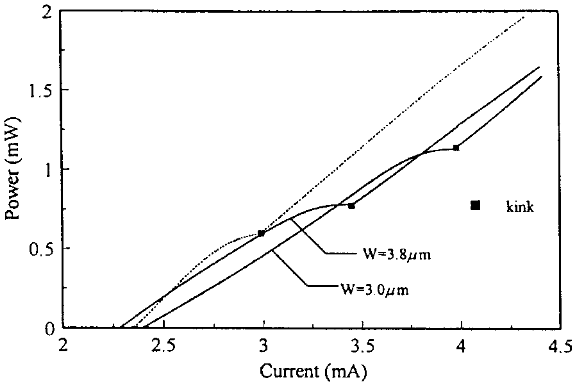

Figure 2 Light/current characteristics of VCSELs without (dotted line) and with (solid line) a step DFQWs structure.

longitudinal length of the passive anti-guiding structure is much longer than the thickness of active layer). Therefore, the value of w is a critical parameter in determining single-mode operation in VCSELs with a step DFQWs structure. It is found that the selection of w is based on the profile of the LP_{11} mode. Figure 4 shows the profile of LP_{01} and LP_{11} modes with and without a step DFQWs structure. For a DFQWs laser with $w \leq 3\,\mu m$, kinks appear in the profiles of the LP_{01} and LP_{11} modes. However, single mode operation can be maintained at high power due to the deformation of the transverse modes. It is noted that the LP_{11} mode for a gain-guided structure exhibits a peak at $w = 3\,\mu m$. For DFQWs lasers with $w > 3.8\,\mu m$, no kink is observed and their profiles are similar to that of the gain-guided structure.

Figure 5 shows the variation of the LP_{11} mode with the injection current. It is observed that self-focusing effects have less influence on the LP_{11} mode of a DFQWs laser with $w = 3\,\mu m$. As we can see, the volume of the LP_{11} mode inside the cladding region is not varied by the injection current such that stable operation of the LP_{01} mode can be achieved. However, the beam-width of the LP_{11} mode is reduced significantly by self-focusing effects for a DFQWs laser with $w > 3.8\,\mu m$ or a gain-guided structure. As a result, the threshold gain of the LP_{11} mode is reduced. From the analysis given above, it is noted that the optimum value of w may be equal to or less than the position of the peak of the LP_{11} mode supported by the gain-guided structure.

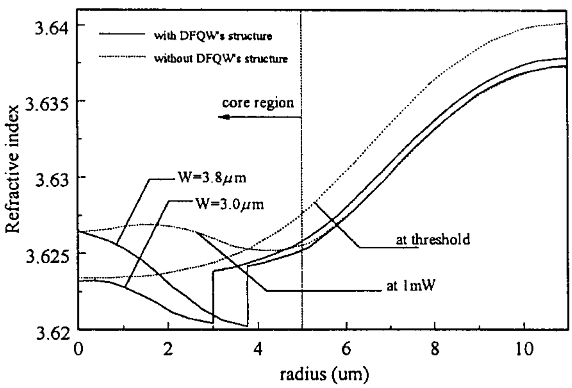

Figure 3 The transverse distribution of the refractive index inside the active layer of a VCSEL (i) with (solid line) and (ii) without (dotted line) a step DFQWs structure. The output power of the devices is set to 1 mW.

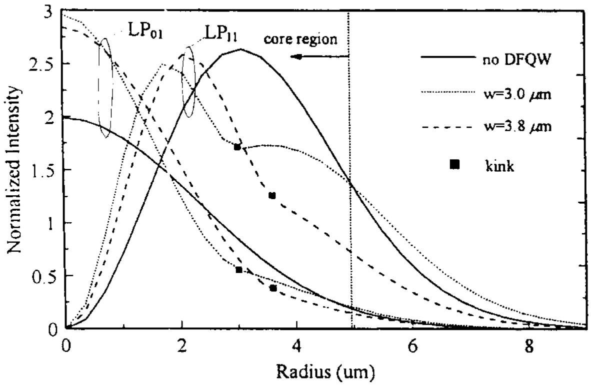

Figure 4 The transverse distribution of transverse modes (i.e. LP_{01} and LP_{11}) of VCSELs (i) with (solid line) and (ii) without (dotted line) a step DFQWs structure. The devices are biased at threshold.

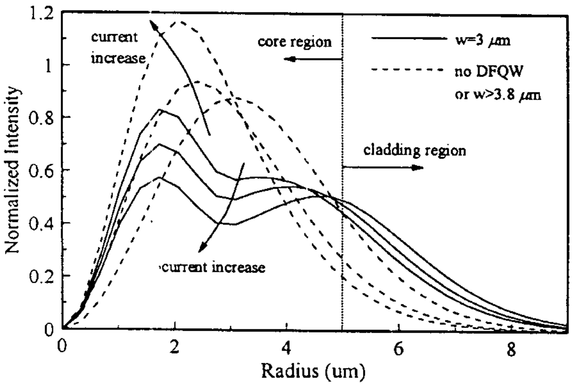

Figure 5 Variation of LP_{11} mode with injection current increase from I_{th} to 1.6 I_{th} where I_{th} is the threshold current.

6. Discussion and conclusion

It is shown in the above calculation that the maximum output power (i.e. to maintain single transverse mode operation) of VCSELs with DFQWs structure is relatively low (i.e. 1 mW). In fact, the low value of the maximum output power is attributed to the original design of the gain-guided structure and is independent of the DFQWs structure. The geometrical structure of VCSELs, used in the above calculation, has not been optimized for high maximum output power. This is because the main obejective of this report is to verify the possibility of using a DFQWs structure for VCSELs to maintain single transverse mode operation at high power.

The use of a passive anti-guiding design to enhance single mode operation in VCSELs has been demonstrated [4]. However, the fabrication technique for a passive anti-guiding design is much more complicated than the method proposed in this report. Therefore, we can conclude that the DFQWs structure has the advantages over the passive anti-guiding design, of (i) a simple processing technique and (ii) low production cost.

In conclusion, the enhancement of single-mode operation in VCSELs by using a step DFQWs structure along the core region of the QW active layer is verified theoretically. Results show that the maximum output power for stable LP_{01} mode operation can be doubled. Stable LP_{01} mode operation is achieved by deforming the profile of the LP_{11} mode such that its optical loss inside the cladding region remains unchanged at high injection current. The step DFQWs structure can be achieved by impurity-induced disordering in the active layer.

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