Design and Modeling of a high single mode power Long Wavelength InGaAsP Photonic Crystal VCSEL

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Abstract: In the present work, a new vertical cavity surface emitting laser (VCSEL) structure employing combined oxide layer and single defect photonic crystal index guiding layer has been investigated for L-band optical fiber application. The basic design goal was to obtain photonic crystal VCSEL (PhC VCSEL) with the high power, high slope efficiency and low threshold that operate at 1.55-1.6µm wavelength single mode region. By using the combination of photonic crystal and oxide layer, we have achieved high power VCSEL that operated fundamental mode. The influence of the hole etching depth of photonic crystal looking for the highest power and the lowest threshold current is also investigated.

Key words: Modeling, photonic crystal, high power, PhC VCSEL

INTRODUCTION

A crystal is a periodic arrangement of atoms or molecules. The pattern which the atoms or molecules are repeated in space is the crystal lattice. The crystal presents a periodic potential to an electron propagating through it, and both the constituents of the crystal and the geometry of the lattice dictate the conduction properties of the crystal. If the dielectric constants of the materials in the crystal are sufficiently different, and if the absorption of light by the materials is minimum, then the refractions and reflections of light from all the different interfaces can present many of the same phenomena for photons that the atomic potential produces for electrons.

Fig.1 is a schematic representation of several three-dimensional lattices of spheres in a cubic cell. The simplest lattice is formed by the blue spheres at the corners of the cube. If we add the dark red spheres at the centers of the faces, we obtain a face-centered cubic (or fcc) lattice. The fcc lattice vectors are \((x + y)a/2, (y + z)a/2, (x + z)a/2\). Finally, if we add the pink spheres, which represent another fcc lattice that is shifted by \((a/4, a/4, a/4)\) relative to the blue spheres, then we obtain a diamond lattice (Joannopoulos et al., 2008).

Fig. 1: Ball-and-stick (“atomic”) representation of several three-dimensional lattices in a cubic supercell, with a lattice constant a. The blue balls alone form a simple cubic lattice. Adding the dark red balls produces a face-centered cubic (fcc) lattice. Adding the pink balls as well produces a diamond lattice, with stick “bonds” (four bonds per ball).
In recent years, the vertical cavity surface emitting laser has attracted extremely (Iga, 2000). VCSEL is one of the key light source used in high performance optical communication systems where single mode operation, high output power, high speed modulation and low manufacture cost are necessary (Dems et al., 2005). Methods used to achieve single mode operation include oxide apertures less than 3μm in diameter (Hawkins et al., 2002), proton implanted apertures (Morgan et al., 1993), oxide-implant hybrid structures (Lai et al., 2004), shallow surface relief etching (Haglund et al., 2004) or by etching one row of air holes (Furukawa et al., 2004) or a photonic crystal pattern (Yokouchi et al., 2003; Liu et al., 2004) into the top mirror. Employing shallow surface relief etching or by etching one row of air holes or a photonic crystal pattern are approaches for controlling the properties of VCSELS to achieve high-power single-mode operation.

In this paper, we design a high single mode power InGaAsP VCSEL by employing combined oxide layer and single defect photonic crystal index guiding layer for L-band optical fiber application. In the following, we first describe the numerical model. Next the simulated PhC VCSEL structure is introduced. Finally, the conclusions provide common guidelines for designing performance of PhC VCSELS.

2. Theory:

When modeling VCSELs, it is essential to take into account interaction of optical and electrical phenomena that occur during the VCSEL operation. Thus, base of simulation is to solve Poisson and continuity equations for electrons and holes (SILVACO, 2010). Poisson equation is defined by:

$$\nabla \cdot (\varepsilon \nabla \psi) = \rho$$

where $\psi$ is electrostatic potential, $\rho$ is local charge density and $\varepsilon$ is local permittivity. The continuity equations of electron and hole are given by (Piprek, J., 2003):

$$\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q} \nabla \cdot J_n$$

$$\frac{\partial p}{\partial t} = G_p - R_p + \frac{1}{q} \nabla \cdot J_p$$

where $n$ and $p$ are the electron and hole concentration, $J_n$ and $J_p$ are the electron and hole current densities, $G_n$ and $G_p$ are the generation rates for electrons and holes, $R_n$ and $R_p$ are the recombination rates and $q$ is the magnitude of electron charge.

The fundamental semiconductor Eq.(1)-(3) are solved self-consistently together with Helmholtz, lattice heat flow and the photon rate equations. We ignore the polarization effects. Therefore we can use Helmholtz equation to solve Maxwell equations. The applied technique for solution of Helmholtz equation is based on improved effective index model (Hadley, 1995) which shows accuracy for great portion of preliminary problems. This model is very good adapted for simulation of VCSEL structures and it is often called effective frequency method (Wenzel, H. Wunsche, H.-J, 1997). Two-dimensional Helmholtz equation is solved to determine the transverse optical field profile and it is given by (SILVACO, 2010):

$$\nabla^2 E(r, z, \varphi) + \frac{\omega_0}{c^2} \varepsilon(r, z, \varphi, \omega) E(r, z, \varphi) = 0$$

where $\omega$ is the frequency, $\varepsilon(r, z, \varphi, \omega)$ is the complex dielectric permittivity, $E(r, z, \varphi)$ is the optical electric field and $c$ is the speed of light in vacuum.

The light power equation relates electrical and optical models. The photon rate equation is given by (SILVACO, 2010):

$$\frac{dS_m}{dt} = \left( \frac{c}{N_{eff}} G_m - \frac{1}{\tau_{ph_m}} - \frac{cL}{N_{eff}} \right) S_m + R_{sp_m}$$

where $S_m$ is the photon number, $G_m$ is the modal gain, $R_{sp_m}$ the modal spontaneous emission rate, $L$ represents the losses in the laser, $N_{eff}$ is the group effective refractive index, $\tau_{ph_m}$ is the modal photon lifetime and $c$ is the speed of light in vacuum. The $m$ refers to modal number.

Eq.(1)-(5) provide an approach that can account for the mutual dependence of electrical and optical.
3. PhC VCSEL Structure:

Fig. 2 shows the schematic structure of PhC VCSEL device, which is used for simulation. The VCSEL device consists of an active region of six In$_{0.76}$Ga$_{0.24}$As$_{0.82}$P$_{0.18}$ quantum wells and seven In$_{0.48}$Ga$_{0.52}$As$_{0.82}$P$_{0.18}$ barriers, bounded between 30 periods of top and 28 periods of bottom DBR mirrors. The top one is GaAs/Al$_{0.33}$Ga$_{0.67}$As with reflection factor of layers 3.38 and 3.05 respectively and the bottom one is GaAs/AlAs with reflection factor of layers 3.38 and 2.89 respectively. Triangular-lattice air holes are formed in the upper pairs of top DBR. The optical confinement is achieved by seven air holes where the center is missed off to make the defect region, as shown in Fig. 3. The depth of the PhC holes (ed) is determined as the distance between the upper edge of the top DBR and the bottom of the holes.

Fig. 2: Schematic structure of the VCSEL device.

![Schematic structure of the VCSEL device.](image)

Fig. 3: Top view of the triangular-lattice air holes pattern.

**Results:**

In the present work, the influence of the hole etching depth on field intensity profile and device characteristics such as light power versus voltage and voltage versus current and threshold current as a function of the hole etching depth is analyzed. The calculated fundamental mode intensity profile is shown in Fig. 4. The upper row shows that the intensity of fundamental mode for a shallow etching depth (ed=2µm) is increased compared with the ed=0µm case. The bottom row displays the further increases in the etching depth (ed=4µm and ed=6µm) lead to better confinement of light within a single defect in the photonic crystal.
Fig. 4: fundamental mode intensity profile for different quantities of the hole etching depth at \( V=3\,\text{V} \). (a) \( ed=0\,\mu\text{m} \), (b) \( ed=2\,\mu\text{m} \), (c) \( ed=4\,\mu\text{m} \) and (d) \( ed=6\,\mu\text{m} \).

Fig. 5 shows the continuous wave output power as a function of the voltage. Results are for room temperature. As can be seen from Fig. 5, increasing the hole etching depth causes the reduction of the power, which is mainly related to the better confinement of the light within a single defect of the photonic crystal. Maximum power achieved is for shallow hole etching (\( ed=2\,\mu\text{m} \)) because optical loss introduced by the PhC discriminates strong modes. The calculated power at \( V=2.4\,\text{V} \) is 24\,mW, which is larger than previous works that operate at 1.55-1.6\,\mu m\n respectively) (Karim et al., 2001; Kandiah et al., 2008).

Fig. 6 shows the voltage versus current curve for different hole etching depths. The V-I characteristics exhibit higher series resistance with increasing hole etching depth, which should be mainly due to etching on the top DBR.

Fig. 7 shows the threshold current as a function of the hole etching depth. It shows that increasing hole etching depth on the top DBR causes the low threshold current, which should be mainly due to the blocking of the current flow in the region by photonic crystal holes.

Fig. 5: Output power versus voltage for different values of the hole etching depths.
Conclusion:
In this work, a new high power single mode VCSEL structure for application at 1.55-1.6µm wavelength region is introduced. The results indicate that a VCSEL with using the combination of photonic crystal and oxide layer can achieve high single mode power. The influence of the hole etching depth of photonic crystal looking for the highest power and the lowest threshold current is investigated. It was shown that increasing hole etching depth on the top DBR will decrease the threshold current but decrease the power, while high performance can be achieved by choosing appropriate hole etching depth on the top DBR.

REFERENCES


