Thermal analysis of 980 nm vertical cavity surface emitting lasers with different oxide aperture diameters

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Abstract- In this paper, the thermal analysis of 980 nm vertical cavity surface emitting lasers with different oxide aperture diameters is theoretically performed by using simulation software PICS3D which self-consistently combines three-dimensional simulation of carrier transport, self-heating and optical wave-guiding. Temperature profiles and heat power density were obtained by using a three-dimensional cylindrical heat generation and dissipation model. Simulation results show that Joule heating is the main heat source in the device. The thermal resistance increases significantly with a decrease in oxide aperture size.

Keywords: Thermal analysis, Maximum active region temperature, Oxide aperture, Vertical cavity surface emitting lasers.
1 Introduction

The perpetually increasing demand of our modern society for ever faster access to ever larger amounts of information requires a corresponding permanent increase of the computational power of data center and high-performance computer (HPC) for rapid and efficient data processing and routing. The success of the optical technologies in the HPC applications originates from the decisive advantage of vertical cavity surface emitting lasers (VCSELs) as a high quality laser light source for short-reach optical interconnects with a large number of channels[1]. In the recent years, we have seen impressive progress in the field of high-speed VCSELs emitting around 980 nm. This wavelength has large advantages in the optical interconnects, especially in HPC applications. In order to reach very efficient VCSELs, we need to confine both current and optical field in lateral dimension in a way to have maximum interaction with the active region. One important technique that is widely used in VCSEL is oxide aperture. In confined VCSELs, an Al-containing layer such as AlGaAs is placed in the structure during the growth of Bragg mirrors and active layer. Wet oxidation of this layer at elevated temperature forms a mechanically stable phase of Al₂O₃ which has a low refractive index.

Thermal design is very important for VCSELs. Compared with edge-emitting lasers, VCSELs usually have much smaller active regions and higher threshold current densities, which means that the temperatures of these active regions could be much higher. Low thermal resistance of VCSEL device is one of the most important key factors to improve device management. If VCSEL operating at high temperatures should be realized, thermal phenomena inside of the device becomes one of the crucial laser design aspects. It is of great importance to have a deeper understanding of the thermal processes in VCSELs.

Nanometer scale semiconductor structures are often at the heart of modern optoelectronic devices. Their shrinking size and increasing complexity make computer simulation an important tool for designing better devices that meet ever-rising performance requirements. The current need to apply advanced design software in optoelectronics follows the trend observed in the 1980s with simulation software for silicon devices. Today, software for technology computer-aided design (TCAD) and electronic design automation (EDA) represents a fundamental part of the silicon industry. In optoelectronics, advanced commercial design software has emerged, and it is expected to play an increasingly important role in the near future.

In this paper, the effect of oxide aperture size on 980 nm VCSEL thermal characterization was theoretically investigated by using simulation software PICS3D which self-consistently combines 3D simulation of carrier transport, self-heating and optical wave-guiding.

2 Theoretical Model

A three-dimensional laser model, which combines carrier transport, optical gain computation, wave-guiding and heat-flux, is employed in PICS3D (Photonic Integrated Circuit Simulator in 3D) [2]. The electrical behavior of semiconductor device is described with finite-element drift-diffusion model in this package. The finite-element model of carriers includes Fermi statistics and thermionic of hetero-barriers. Gain calculations are based on 8×8 k.p band structure computations for the strained quantum wells.

2.1 Thermal Simulation

Self-heating often affects the performance of optoelectronic devices. Heat is produced within the device when carriers transfer part of their energy to the crystal lattice. Therefore, the net thermal energy is increased which is measured as increased temperature of Tₜ lattice. Assuming the local thermal equilibrium between the lattice and the carrier, we will have: Tₜ=Tₑ=T_p.

To maintain temperature energy conservation, the heat flux equation should be given by Equation (1):

$$\rho_L C_V \frac{\partial T}{\partial t} = -\nabla \cdot J_{\text{Heat}} + H_{\text{heat}}$$

(1)

Which ρ is physical density; C is specific heat of crystal lattice and H is heat source. The heat source can be separated into contributions from Joule heat, generation / recombination heat, absorption heat and Thomson heat.

3 VCSEL Structure

Figure 1 shows a schematic of the structure for a 980 nm VCSEL. The epitaxial VCSEL structure was grown on GaAs substrate. For this structure the bottom n-type distributed Bragg reflector (DBR) mirror consists of 26 pairs of quarter wavelength GaAs/AlAs layers. The top p-type DBR has 25 pairs of GaAs/Al₉.75Gaₐ₀.25As layers. The cavity contains two In₀.₃Ga₀.₇As quantum wells (QWs) with GaAs barriers. The quantum wells stack is sandwiched between undoped Al₀.₄Ga₀.₆As spacer layers, which act as a waveguide. On the p-side of the structure, the oxide layer is not intentionally doped.
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originated from the enhancement of heat removal through the top DBR.

Figure 5: Calculated temperature profile in lateral position for VCSELs with different oxide aperture diameters

The temperature gradient between the active region and substrate is displayed in the vertical direction in Figure 6. It is indicating a dominant heat removal toward the substrate, and decreasing with the smaller aperture size.

Figure 6: Calculated temperature profile in vertical position for VCSELs with different oxide aperture diameters

The maximum internal temperature, which is caused by the heat generated inside the device, was raised up to 390 K in the active region for VCSEL with 1.5 μm oxide aperture when the heat sink was kept at 293 K. Figure 7 shows the active region temperature rise as a function of oxide aperture diameter. By considering Figure 7, we notice that the heat source density becomes higher with decreasing oxide aperture size. For the narrower oxide aperture, the selectively oxide layer adjacent to the heat generation region extends over the larger area and it prevents the generated heat from spreading out in the lateral direction. Thus, the temperature inside device increased as the oxide aperture diameter decreased. This means that the thermal resistance increased as the oxide aperture diameter decreased.

Figure 7: The temperature rise of a active region vs oxide aperture diameter

Simulation results show that by increasing the oxide aperture diameter, the active region temperature is around ambient temperature 293K. These results are in good agreement with other experimental reports [3].

4 Conclusion

The thermal analysis of 980 nm vertical cavity surface emitting lasers with different oxide aperture diameters is theoretically performed. Simulation results show that Joule heating is the main heat source in device. Downsizing the oxide aperture causes a dramatic increase of the thermal resistance. This is attributed to the reduced initial escape area for the heat generated in the device.

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References