SIMULATION OF A SINGLE-MODE TUNNEL-JUNCTION-BASED LONG-WAVELENGTH VCSEL

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Abstract

We investigate the physics of an internal device for a high-performance, vertical-cavity surface-emitting laser operating at 1.305 μm. Experimental results are analyzed using as the simulation software a photonic-integrated-circuit simulator in 3D (PICS3D), which is a state-of-the-art 3D simulator for surface- and edge-emitting laser diodes, semiconductor optical amplifiers, and other similar active waveguide devices. The 2D/3D semiconductor equations are coupled to the optical modes in both lateral and longitudinal directions. Optical properties such as the quantum well/wire/dot optical gain and spontaneous emission rates are computed self-consistently. Careful adjustments of material parameters led to an excellent agreement between simulation and measurements. Simulation results show that the maximum output power is limited by electron leakage from quantum wells.

Keywords: long-wavelength vertical-cavity surface-emitting laser, simulation, electron current leakage, quantum wells.

1. Introduction

In vertical-cavity surface-emitting lasers (VCSELs), the optical cavity is formed by mirrors above and below the active region [1]. The laser beam is emitted in a vertical direction and typically exhibits a circular beam shape, ideal for coupling with optical fibers. With the light passing through the active layers in a vertical direction, gain is achieved over a short distance, and amplification per photon round trip is made small. Therefore, the mirrors need to be highly reflective to balance the short axial length of the gain region. The high reflectivity is provided by distributed Bragg reflectors (DBRs) with two alternating layers of high refractive-index contrast. With quarter-wavelength layer thickness, the reflected waves from all DBR interfaces add up constructively, enabling the DBR reflectance to be above 99% [2].

The VCSEL offers many potential advantages compared with traditional in-plane lasers. The most significant advantage of the VCSEL is its small size, lower power consumption, high-speed modulation, and compatibility with low-cost, wafer-scale fabrication and testing methods. Long-wavelength VCSELs
emitting in the range 1300–1600 nm are considered to be attractive light sources for use in short-to-
mid-range optical fiber communication. Despite the obvious commercial incentives, long-wavelength 
VCSELs undergo a more deliberate development in comparison with short-wavelength counterparts [3]. 
The main constraint is the unsatisfactory high-temperature operation. Inherent material qualities of 
InP–InGaAsP, such as low characteristic temperatures, high Auger recombination rates, and high inter-
valence-band absorption have slowed down the rate of progress. The lack of a robust perforation technique 
on InP has limited the operating efficiency. DBRs with high thermal conductivity, high reflectivity, and 
high electrical conductivity have proved to be complicated to fabricate on InP. Long-wavelength VCSEL 
technology has grown to include a wide variety of approaches [4–6].

While excellent results have been reported, the majority of these approaches struggle to demonstrate 
monolithic devices that can reliably span the entire 1.3–1.6 μm wavelength. One approach is to use 
InGaAlAs active regions coupled with AlGaAsSb DBRs [7, 8]. The InGaAlAs active regions, being 
lattice-matched to InP, have demonstrated a reliable high-gain operation over a full long-wavelength 
region with excellent temperature performance. The AlGaAsSb DBRs are also lattice-matched to InP 
and offer high reflectivity over a broad range of wavelengths, thus, enabling wavelength selection from 1.3 
to 1.6 μm. Indeed, the available refractive-index contrast is Δn = 0.4 compared with that of Δn = 0.49 
for the GaAs/AlGaAs system [9].

In this paper, we demonstrate a self-consistent, physics-based, three-dimensional simulation of con-
tinuous wave performance above room temperature at 1.305 μm for an InP-based VCSEL implementing 
AsSb-based DBR and performance limiting internal mechanisms. By calibrating material parameters, 
excellent agreement with measured device characteristics is achieved. The VCSEL structure and exper-
imental results have been reported in [10,11].

This paper is organized as follows.

In Secs. 2 and 3, we introduce the theoretical models and material parameters used in this study. We 
discuss the calibration of material parameters in Sec. 4 and present the simulation results in Sec. 5.

2. Theoretical Models

We focus mainly on a single-mode, tunnel-junction, bottom-emitting VCSEL structure. Figure 1 
shows a schematic of the structure for a 1.3 μm VCSEL.

The VCSEL was grown monolithically by the 
solid-source molecular-beam epitaxy in a single 
growth step. A double intra-cavity contacting scheme is employed to circumvent the high 
electrical and thermal resistances of the AsSb-
based DBRs. The AllnGaAs active region contains 
five 1.0% compressively strained 7 nm quantum 
wells and six 0.6% tensile strained 5 nm barriers. 
Claddings both sides of the active region are InP 
layers, n-doped at 5 × 10¹⁷ cm⁻³, that facilitate cur-
rent spreading and heat removal in the device. The total cavity thickness is 4λ. The device contains 
a 2 × 10¹⁹ cm⁻³ n⁺⁺–In₅₂Al₂₉Ga₁₉As/2 × 10²⁰ cm⁻³ p⁺⁺–In₅₂Al₂₉Ga₁₉As tunnel-junction layer. The 
lateral diameter is 7 μm. Because the tunnel junction converts holes to electrons, the p-type layers can be replaced by n-type layers, with optical absorption losses being considerably reduced. In addition,