Lateral-Cavity Design for Long-Wavelength Vertical-Cavity Lasers

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ABSTRACT

Long-wavelength vertical-cavity lasers (VCLs) for fiber-optic applications are subject of intense research and development efforts. Several VCL design concepts are currently competing to meet telecommunication specifications. One of the main problems is the demonstration of high-power single-optical-mode lasing at elevated temperature. Both mode and temperature stability strongly depend on the type of aperture layer used for lateral confinement of the VCL micro-cavity. This paper compares different concepts of the lateral cavity design. The trade-offs regarding single-mode lasing, electrical current confinement, and self-heating are discussed in detail.

Keywords: quantum well device, semiconductor laser, vertical-cavity laser, micro-cavity design, numerical simulation.

1 INTRODUCTION

For more than a decade, long-wavelength vertical-cavity lasers (VCLs) for fiber-optic applications are subject of intense research efforts. GaAs-based VCLs emitting at shorter wavelength (0.85 μm) have been commercialized successfully; however, the challenge of transferring this technology to 1.3 μm and 1.55 μm wavelength is often underestimated. Several VCL design concepts are currently competing to meet telecommunication specifications. One of the main problems is the demonstration of high-power single-optical-mode operation at elevated ambient temperature. Both mode and temperature stability strongly depend on the type of aperture layer used for lateral confinement of the VCL micro-cavity (Fig. 1). We present a comparison of different aperture designs, both theoretically and experimentally.

The analysis of this electro-thermal-optical design problem requires a comprehensive simulation of VCL physics. Most previous publications on VCL modeling focus on optical properties and neglect electrical and thermal aspects. The few reports on more comprehensive simulations did not address the design of aperture layers [1,2]. Our quasi-three-dimensional VCL simulation includes a drift-diffusion carrier transport model, band structure and gain calculation for the multi-quantum well active region, computation of the optical VCL modes, as well as heat generation and dissipation.

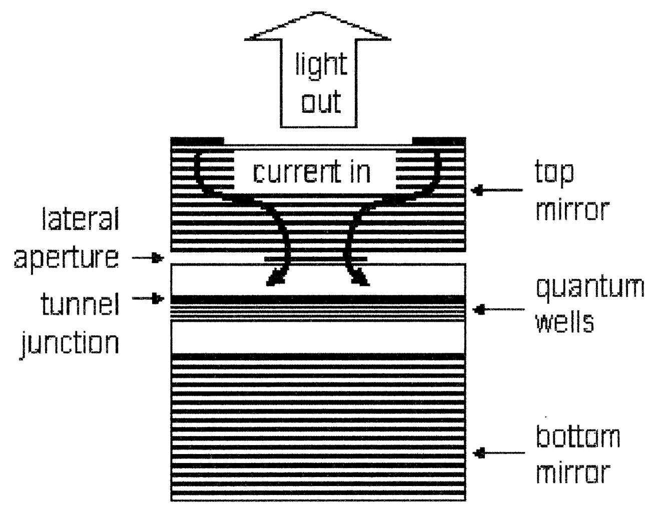

Fig. 1: Schematic structure of our vertical-cavity laser with lateral aperture for optical and current confinement.

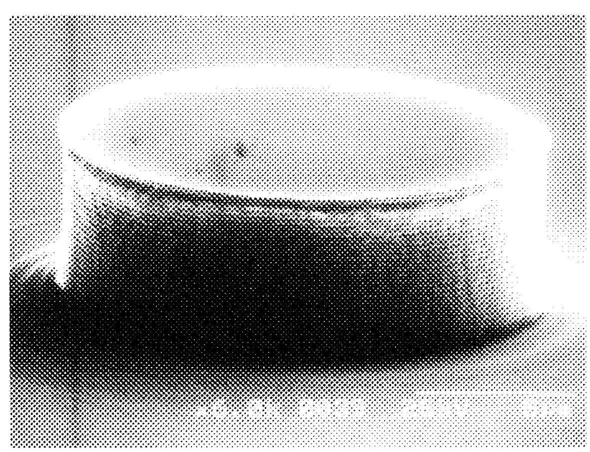

Fig. 2: Fabricated VCL with top mirror pillar etched down for lateral oxidation of the first AlGaAs layer.

2 DEVICE TECHNOLOGY AND EXPERIMENTAL RESULTS

Our VCL technology utilizes GaAs/InP wafer-bonding [3] in order to combine the high reflectivity and high thermal conductivity of AlGaAs/GaAs distributed Bragg reflectors (DBRs) with the superior performance of well established AlGaInAs/InP multi-quantum well (MQW) active regions for laser emission at 1.3μm wavelength. A fabricated device is shown in Fig. 2 and the vertical energy band diagram is given in Fig. 3. AlGaInAs quantum wells are used which offer a larger conduction band offset than traditional InGaAsP quantum wells, thereby reducing the temperature sensitivity. Another requirement for high-temperature operation is an initial (room-temperature) blue-shift of the emission spectrum to compensate for the red shift with higher temperature (Fig. 4) [4].

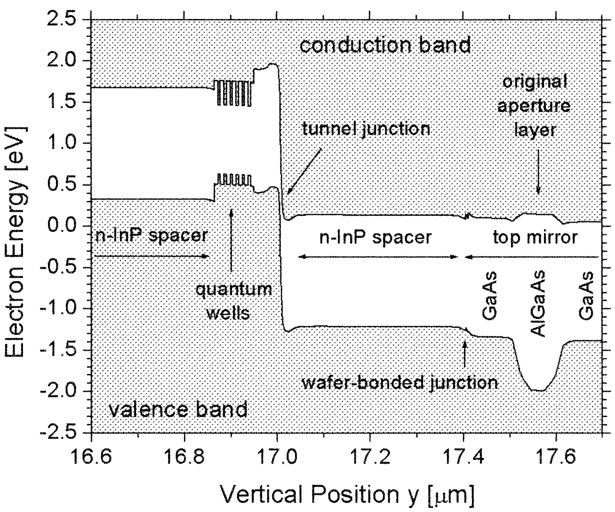

Fig. 3: Energy band diagram at the vertical VCL axis for the original oxide aperture design.

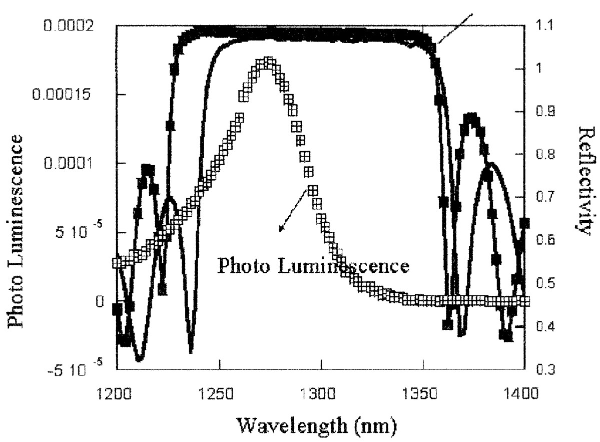

Fig. 4: Mirror reflectivity spectra and multi-quantum well photoluminescence spectrum measured at room temperature.

A special feature of our VCL design is the inclusion of an AlInAs/InP tunnel-junction on top of the MQW which helps to reduce the use of absorbing *p*-doped layers in our device. The AlInAs layer also serves as an electron barrier (Fig. 3). Based on this design, we have recently fabricated wafer-bonded tunnel-junction 1.3-μm VCLs employing a common aluminum-oxide aperture within the top mirror (Figs. 1, 3). However, the measured VCL output power is very low. Reasons and alternatives are investigated in the following. Two different lateral cavity designs are compared which employ the same vertical cavity structure: (A) the original oxide aperture and (B) an air aperture created by lateral etching of the MQW active region.

3 SIMULATION AND ANALYSIS

3.1 Optical Modes

The vertical design of the optical cavity is illustrated in Fig. 5. Both the fused interfaces and the tunnel junctions are located at optical nulls to minimize optical losses. Our initial design uses relatively thick InP spacer layers in order to improve the heat dissipation and to allow for higher operating temperatures.

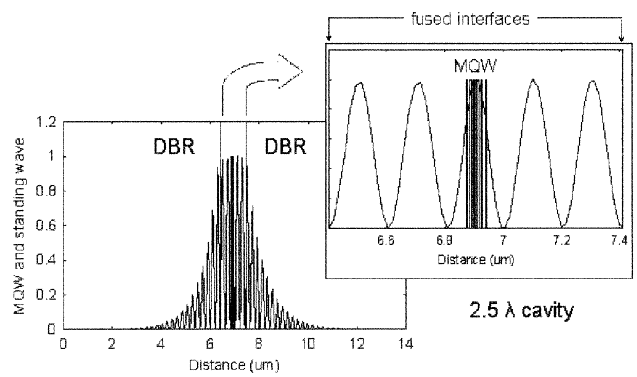

Fig. 5: Vertical profile of the standing optical wave within the VCL (inset: magnification of the InP based active region between the two GaAs based mirrors).

The three-dimensional (3D) computation of the optical modes is one of most challenging tasks of VCL simulation, especially when lateral confinement layers are included. Besides the desired mode confinement, such layers cause undesired optical losses by photon scattering at the aperture. Many more or less sophisticated optical VCL models have been published, several of which are compared in [5]. We here use a frequency domain finite element approach as developed at the Swiss Federal Institute of Technology [6]. A 2D profile of the calculated fundamental mode is shown in Fig. 6. Lateral mode confinement is achieved by the oxide aperture. Higher-order lateral modes may also exist in the VCL cavity, which experience different optical losses caused by the aperture. The optical gain provided by the MQW needs to compensate for the optical losses in order for each mode to reach the lasing threshold. Practically, it is of great interest to maximize the lasing power from the fundamental mode while keeping all other modes below threshold (single-mode operation). The maximum single-mode power is limited by the threshold (loss) of the higher-order modes (Fig. 7). The mode discrimination can be enhanced by increasing the optical loss for higher-order modes.

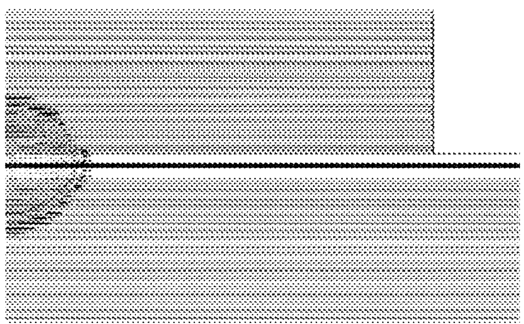

Fig. 6: Two-dimensional VCL cross-section showing the fundamental optical mode (00) as confined by the oxide aperture layer (the left-hand side border is the VCL axis).

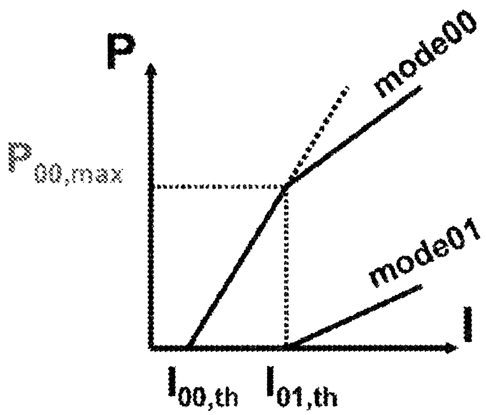

Fig. 7: Schematic plot of the optical power P vs. injection current I for the fundamental (00) and the first-order mode (01). $P_{00,max}$ is the maximum single-mode power.

We calculated optical losses and maximum single-mode lasing power for (A) an oxide aperture and (B) an air aperture (Fig. 8). With small apertures, the maximum power is similar for both the cases and it hardly changes with increasing oxide aperture (Fig. 8A). However, the maximum single-mode power increases substantially with increasing air aperture (Fig. 8B). This improvement can be attributed to the relatively high difference in optical loss for both modes. At 9 μm aperture radius, the calculated photon lifetime of the fundamental mode is about 117 ps for both cases, while the lifetime of the 01 mode is (A) 107 ps and (B) 89 ps. These lifetimes represent photon losses due to emission and scattering, internal absorption is neglected here. The air aperture is advantageous as it inflicts higher scattering losses on the 01 mode than the oxide aperture.

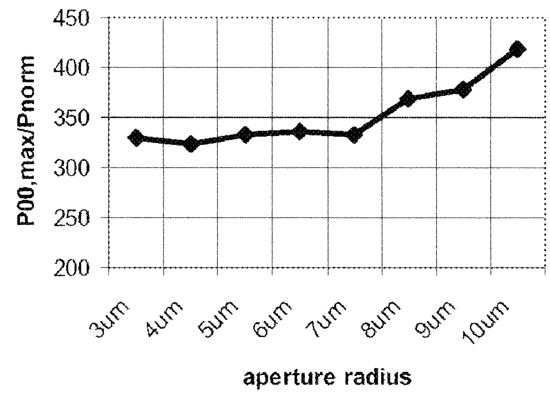

Fig. 8A: Normalized maximum single-mode power vs. aperture radius for a 80 nm thick oxide aperture placed at the peak of the standing wave.

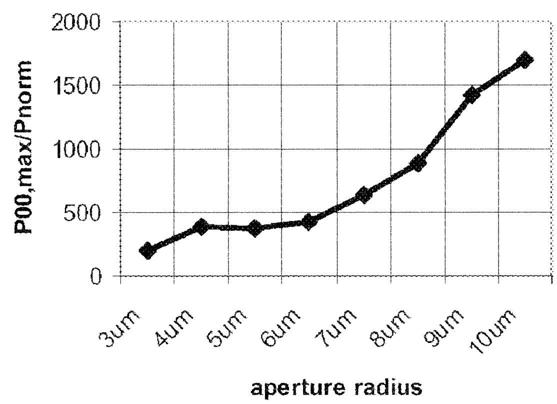

Fig. 8B: Normalized maximum single-mode power vs. aperture radius for an 86 nm thick MQW air aperture.

3.2 Current and Carrier Confinement

The poor performance of the oxide-confined VCL can be attributed to strong lateral current spreading between oxide aperture and MQW active region (cf. Fig. 1). This is mainly attributed to the high mobility of electrons and to the electrical resistance of bonded and tunnel junctions. After passing the aperture, electrons spread out laterally before they reach the MQW. Figure 9 shows the lateral profile of the vertical electron current entering the tunnel junction. The air aperture perfectly confines the current to the optical mode while the oxide aperture allows for significant lateral current spreading. Carriers outside the optical mode do not contribute to the modal optical gain. Due to the large amount of wasted carriers, the threshold current calculated for the oxide aperture is more than five times higher than with the air aperture (pulsed operation without self-heating).

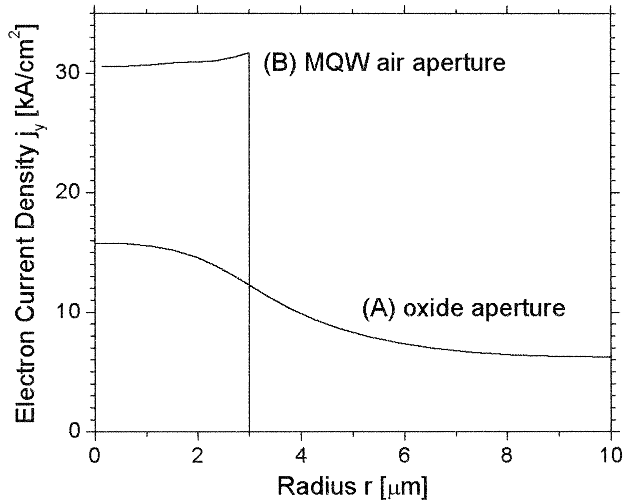

Fig. 9: Profile of the vertical electron current at the tunnel junction for 3μm aperture radius.

3.3 Self-Heating

The electrical resistance of interfaces and bulk layers as well as nonradiative recombination in the active layers are main heat sources in VCLs. Joule heating strongly depends on the local current density which is highest in the aperture plane. Downsizing the aperture causes a dramatic increase in the VCL's thermal resistance as the initial escape area of the heat is reduced [7].

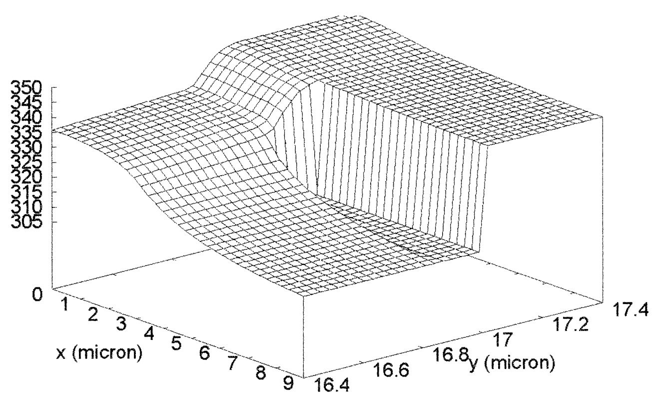

Fig. 10: 2D surface plot of the lattice temperature T(x,y) [K] between the mirrors (the laser axis is at x=0, the ambient and air gap temperature is 300 K).

The calculated temperature distribution in the center part of the VCL is shown in Fig. 10 for an air aperture radius of 3 μm . Heat generated above the MQW needs to flow through the active region to reach the bottom heat sink. At 1.4 mW output power, the temperature rise within the MQW is $\Delta T = 52$ K.

With 3 μm oxide aperture, more than double the current is needed to reach the same output power, leading to an even stronger self-heating ($\Delta T = 60$ K), despite the better heat dissipation.

4 SUMMARY

The low output power of the original oxide-confined VCL is shown to be mainly attributed to poor current confinement, which leads to higher threshold current and increased self-heating. In addition, the optical mode discrimination is small, restricting the maximum achievable single-mode output power.

An alternative lateral confinement scheme, the under-etching of the MQW layers, promises improved laser performance: (1) the mode discrimination by aperture scattering losses is enhances, allowing for higher single-mode power; (2) effective current confinement to the optical mode reduces the threshold current significantly; (3) less current is required for any given output power, which reduces the self-heating of the VCL despite the higher thermal resistance.

A third lateral cavity design is currently under investigation, which employs patterned wafer-bonding in order to have better control of the aperture size and to reduce the thermal resistance. First results will be reported at the meeting.

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