Continuous Wave Operation of All-Epitaxial InP-Based 1.3µm VCSELs with 57% Differential Quantum Efficiency

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We demonstrate all-epitaxial InP-based 1.3µm VCSELs with a record-high continuous-wave differential quantum efficiency (57%) for single active region long-wavelength devices. Low-loss optical mode confinement is achieved through a selectively etched undercut tunnel-junction aperture. Single-mode continuous-wave lasing was observed up to 87°C and the room-temperature output power was 1.1mW at a current of 4.1mA and a wavelength of 1.305µm.

Introduction: Vertical-cavity surface-emitting lasers (VCSELs) emitting at 1.3µm are attractive light sources for short to mid-range telecommunications and high-speed internet applications. These devices offer many advantages over the existing distributed feedback (DFB) laser infrastructure, including low power consumption, on-wafer testing, low-cost packaging, and high fiber-coupling efficiency.

Recently, long wavelength VCSEL technology has grown to include a wide variety of approaches [1-6]. While excellent results have been reported, the majority of these approaches struggle to demonstrate monolithic all-epitaxial devices that can reliably span the entire 1.3-1.6µm wavelength range. InP-based devices with AsSb-based distributed Bragg reflectors (DBRs) are promising candidates to solve this problem. In previous work, we have reported continuous-wave (CW) lasing up to 88°C with 1.55µm InP-based VCSELs implementing AsSb-based DBRs [7]. In this letter, we demonstrate the first above room-temperature (RT) CW lasing of 1.3µm InP-based VCSELs with AsSb-based DBRs. These devices achieve a high CW differential quantum efficiency (DQE) of 57%. To the authors' knowledge, this is the highest reported DQE value for single active region long-wavelength VCSEL devices. A selectively etched undercut tunnel junction was employed to produce a low-loss thin aperture that achieves simultaneous optical and electrical confinement [8]. Single-mode CW lasing was observed up to 87°C and the RT output power was 1.1mW at a wavelength of 1.305µm.

Device Structure and Fabrication: The VCSEL structure was grown monolithically in a single growth step by solid-source molecular beam epitaxy (MBE). Figure 1 shows a schematic of the bottom-emitting all-epitaxial device with a selectively etched tunnel-junction aperture. The device uses a double intra-cavity contacting scheme to circumvent the high electrical and thermal resistance of the undoped AlGaAsSb DBRs. The top and bottom DBRs are designed to have reflectances of >99.9% and 99.4%, respectively. The VCSEL cavity is 4-λ long and consists of a ½-λ five quantum well $Al_{0.18}In_{0.67}Ga_{0.15}As$ active region with six $Al_{0.24}In_{0.40}Ga_{0.36}As$ barriers clad on both sides by InP layers that facilitate current spreading and heat removal from the device. The active region is designed for peak photoluminescence at 1275nm and contains five 1.0% compressively-strained 7nm quantum wells and six 0.6% tensile-strained 5nm barriers. Embedded in the upper InP cladding layer is a 350Å n^{++}-$Al_{0.29}In_{0.52}Ga_{0.19}As$/$p^{++}$-$Al_{0.29}In_{0.52}Ga_{0.19}As$ tunnel junction (doped Si:3e19cm^{-3}/C:1e20cm^{-3}) that is placed at a standing wave null to minimize absorption loss.

Device fabrication consisted of reactive ion etching (RIE) of the top DBR down to the upper InP cladding layer in Cl_2 plasma. Ni/AuGe/Ni/Au and SiO_2 were then evaporated as the top contact and etch mask, respectively. The upper InP cladding was then etched down to the tunnel-junction layer via RIE in CH_4:H_2:Ar_2. The tunnel junction layer was then selectively undercut with respect to InP with a 10:1 mixture of 1M citric acid and 30% hydrogen peroxide to form the thin air-gap aperture. The selectivity of this etch was observed to be greater than 100 to 1 and the diameter of the tunnel-junction aperture was controlled via observation of removal of sacrificial pillars on the chip. Subsequently, the remaining InP cladding was etched down to the active region via RIE. Finally, the active region was wet etched in citric acid and hydrogen peroxide to expose the bottom InP cladding. Ni/AuGe/Ni/Au was then deposited via electron beam evaporation to form the bottom contact.

Results: Figure 2 shows the CW light and voltage versus current (LIV) curve at 20°C for a device with a 22μm pillar and a 6μm tunnel-junction aperture. This is the first reported RT CW lasing of a 1.3μm InP-based VCSEL with AsSb-based DBRs. Moreover, the 57% DQE and resulting low required drive current are new milestones. High DQE values are desirable to achieve maximum device output powers at low bias and modulation currents. For this device, over 1mW output power was demonstrated at the low current of

3.5mA. The high DQE value is attributed to the implementation of the 350Å low-loss air-gap tunnel-junction aperture placed at a standing wave null. The low effective index contrast ($\Delta n = 0.01$) afforded by this aperture provides good optical mode confinement with no scattering loss from the rough DBR sidewalls. Figure 3 shows the CW lasing spectrum of the device at a bias of 4mA. Single-mode lasing was observed up to the maximum output power and the lasing wavelength at this bias was 1.305µm. The side-mode suppression ratio (SMSR) was 42dB. These results clearly indicate the effective optical confinement achieved by the thin tunnel-junction aperture.

Figure 4 displays the light versus current (LI) curves for various stage temperatures. The maximum CW lasing temperature achieved was observed to be 87°C. The wavy nature of the LI curves can be attributed to substrate reflections due to an imperfect anti-reflection coating on the bottom-emitting device. AlInGaAs active regions have been shown to operate up to 134°C with a large (~60nm) gain peak to cavity-mode offset [2]. For these devices, the highest temperature operation of 87°C can be partly attributed to the relatively small (~30nm) offset, which was designed for optimum room-temperature device performance. The thermal impedance of the device was measured to be less than 2°C/mW, indicating that for a potential compromise in RT performance, higher temperature operation would be possible with larger gain peak to cavity-mode offsets.

Conclusion: We have demonstrated the first above room-temperature CW lasing for an InP-based 1.3µm VCSEL with AsSb-based DBRs. These all-epitaxial devices achieved a record-high CW differential quantum efficiency (57%). Effective optical mode guiding and current confinement was achieved via a thin selectively etched tunnel-junction aperture. Single-mode operation was observed up to the maximum output power of 1.1mW at 20°C and showed a SMSR of 42dB. The maximum CW lasing temperature was shown to be 87°C. The lasing wavelength at 20°C for the maximum output power was 1.305µm.

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Figure 1:

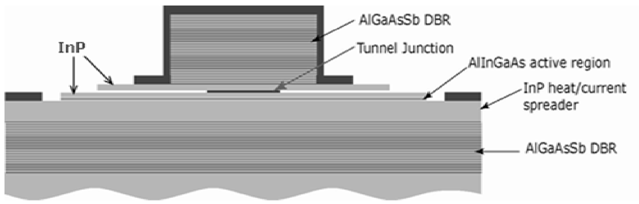
AlGaAsSb DBR
InP
Tunnel Junction
AlInGaAs active region
InP heat/current
spreader
AlGaAsSb DBR

Figure 2:

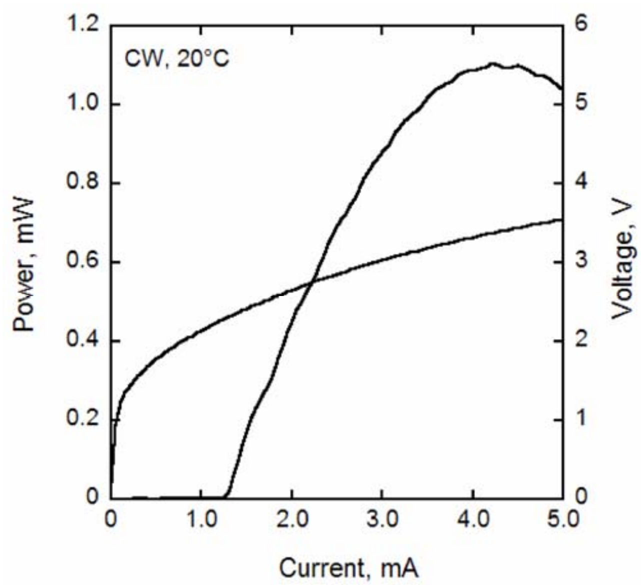
CW, 20°C
Power, mW
Voltage, V
Current, mA
1.2
1.0
0.8
0.6
0.4
0.2
0
6
5
4
3
2
1
0
0
1.0
2.0
3.0
4.0
5.0

Figure 3:

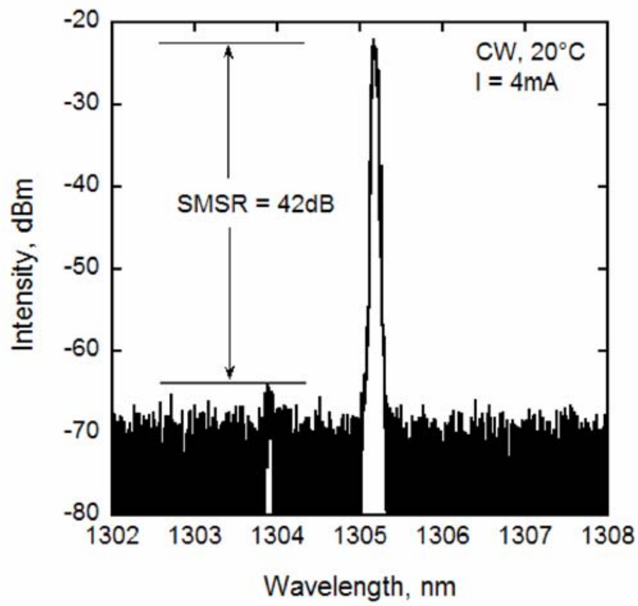
CW, 20°C
I = 4mA
SMSR = 42dB
Intensity, dBm
Wavelength, nm
-20
-30
-40
-50
-60
-70
-80
1302
1303
1304
1305
1306
1307
1308

Figure 4:

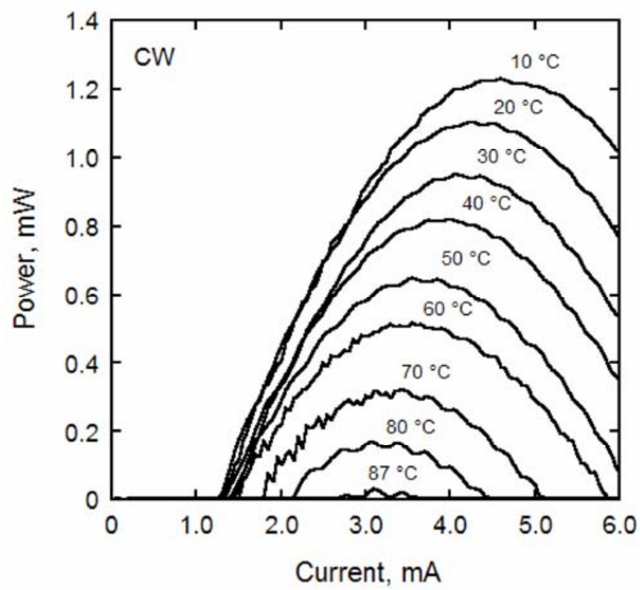
CW
10 °C
20 °C
30 °C
40 °C
50 °C
60 °C
70 °C
80 °C
87 °C
Power, mW
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
1.0
2.0
3.0
4.0
5.0
6.0
Current, mA

Figure Captions

Fig. 1 Schematic of bottom-emitting 1.3μm VCSEL structure showing thin tunnel-junction aperture.

Fig. 2 CW LIV curve of device with 57% differential quantum efficiency at room temperature.

Fig. 3 CW lasing spectrum at 4mA of 1.3μm VCSEL device, showing single-mode operation with a 42dB SMSR.

Fig. 4 LI curves for various stage temperatures, showing CW lasing up to 87°C and over 1mW output power at 20°C achieved below 4mA.