InAsP/InGaAsP quantum-well 1.3 μm vertical-cavity surface-emitting lasers

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1.3 μm vertical-cavity surface-emitting lasers based on a novel gain media consisting of InAsP/InGaAsP strain-compensated multiple quantum wells are reported. SiO_2/TiO_2 dielectric thin-film pairs and wafer-bonded GaAs/Al(Ga)As distributed Bragg reflectors are used as the top and bottom cavity mirrors, respectively. The device with a 5 μm-diameter selectively etched tunnel-junction aperture exhibits submilliampere threshold current as low as 0.54 mA and single-transverse mode emission. Maximum output optical power of 1.9 mW was observed in multimode lasing devices.

Introduction: In recent years, much effort has been applied to the development of long-wavelength (1.3–1.6 μm) vertical-cavity surface-emitting lasers (LW-VCSELs) and considerable progress has been achieved [1–6]. Owing to the characteristic of very short cavity-thickness, high-reflectivity distributed Bragg reflectors (DBRs) and high-gain media are very desirable for VCSELs. An optimum optical-quality of the active region is critical to device performance and can be used to alleviate the DBR reflectivity requirements. Based on strain-compensated multiple-quantum-well (SCMQW) design and its large conduction-band-offset (CBO), AlGaInAs QWs have proven to be superior in reduction of Auger recombination, inter-valence band absorption (IVBA) and carrier overflow out of the QW region at elevated temperatures. The AlGaInAs QW active region in conjunction with epitaxial, dielectric and wafer-bonded DBRs [1–6] has promoted high-performance LW-VCSELs, which are better than those using the conventional InGaAsP QWs.

In this Letter, we provide another optional gain medium consisting of InAsP/InGaAsP SCMQWs and first use it to fabricate 1.3 μm VCSELs. This QW system has a high CBO of 0.5–0.7 ΔE_g between that of InGaAsP (0.4 ΔE_g) and AlGaInAs QWs (0.72 ΔE_g) [7, 8], and has been used in 1.3 μm edge-emitting lasers achieving characteristic temperature greater than 90 K [7, 8]. Easy growth and good control of the interface are achieved in this QW material by setting the same composition of group-V elements for wells and barriers. Continuous-wave (CW) submilliampere threshold current as low as 0.54 mA and maximum optical power of 1.9 mW have been demonstrated in our InAsP/InGaAsP QW 1.3 μm VCSELs in which a dielectric thin film and a wafer-bonded DBR are used as the cavity mirrors.

Experiment: Fig. 1 illustrates a schematic of the 1.3 μm VCSEL structure. Both InP and GaAs-based materials were grown by gas-source molecular-beam epitaxy (GSMBE). The 4.25 λ-thick InP-based cavity was directly bonded onto a 32-period GaAs/Al(Ga)As DBR. The SCMQW material consists of seven 6.1 nm-thick InAsP wells with 1.4% compressive-strain and 7.5 nm-thick InGaAsP barriers with 1.1% tensile-strain, and has a photoluminescence (PL) peak wavelength at 1314 nm. An 8-period SiO_2/TiO_2 dielectric thin-film pair with calculated reflectivity of 99.5% acts as the light output mirror. The tunnel junction composed of 20 nm Si-doped n^+-InP (3.0×10^{19} cm^{-3}) and 15 nm C-doped p^+-InAlAs (1.0×10^{20} cm^{-3}) is located at the standing-wave node to minimise absorption loss.

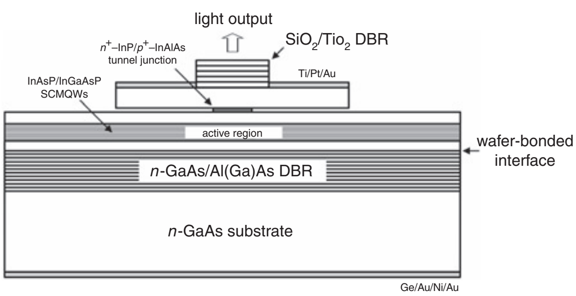

Fig. 1 *Schematic of 1.3 μm VCSEL structure*

During device fabrication, the InP-based cavity and GaAs-based DBR materials were first bonded. For wafer-bonded VCSEL fabrication, the PL efficiency of QWs upon bonding process is critical to device performances. The PL investigation in [9] has indicated that high-temperature thermal stability can be achieved up to 650°C in our InAsP/InGaAsP QW samples. This optimum optical quality of QWs results from the same group-V composition design for wells and barriers. Another important processing for VCSELs is the precise control of the resonance-mode position. As the wafer-bonded half-VCSEL structure forms a Fabry-Pérot (F-P) resonator with the surface air/InP index step serving as the top mirror, easy detection and adjustment of the resonance mode can be accomplished by reflection measurements and chemical etching to the cavity material. Wet-chemical etching was then used to define circular mesas and selectively etching to the InAlAs layer was applied to obtaining thin air-gap tunnel-junction apertures. After isolation of device units by polyimide, the deposition of SiO_2/TiO_2 dielectric thin-film pairs completed the device processing.

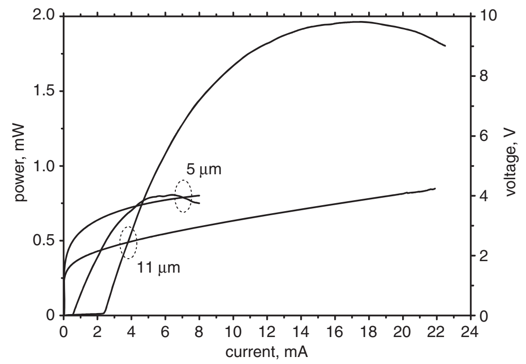

Fig. 2 *RT-CW L-I-V characteristics of 5- and 11 μm-aperture devices*

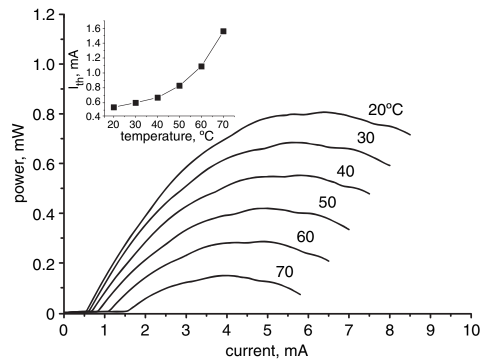

Fig. 3 *Light output characteristics of 5 μm-aperture device at various stage temperatures*

Inset: threshold current against temperature

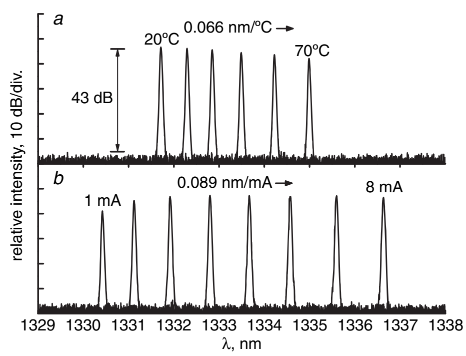

Fig. 4 *Emission spectra of 5 μm-aperture device with different stage temperatures from 20 to 80°C with 10°C steps at injection current of 2.5 mA, and different injection currents from 1 to 8 mA with 1 mA steps at 20°C*

a Stage temperatures from 20 to 80°C with 10°C steps at injection current of 2.5 mA
b Injection currents from 1 to 8 mA with 1 mA steps at 20°C

Results and discussion: Fig. 2 shows light-current-voltage (*L-I-V*) characteristics of the VCSELs at room-temperature (RT, 20°C) and CW operation. The threshold currents (I_{th}) are 0.54 and 2.3 mA for devices with a 5 and an 11 μm-diameter aperture, respectively, and peak optical powers are 0.8 and 1.9 mW, respectively. The slope efficiency is between 0.27 and 0.32 W/A. Multimode behaviour was observed in the 11 μm-aperture device. The submilliampere threshold characteristic indicates good performance of top and bottom mirrors, low optical loss of bonding interface and high optical gain of InAsP/InGaAsP QWs. Fig. 3 illustrates temperature-dependent output optical characteristics of the 5 μm-aperture device. The increasing of threshold current with stage temperatures suggests potential improvement of performance by better matching of resonance mode and QW PL peak wavelength. Single-transverse mode emission was observed in this aperture-size device, as shown in Fig. 4. The measured sidemode suppression ratio (SMSR) has a maximum value of 43 dB and is still above 39 dB at 70°C.

From Fig. 4*a*, temperature rising leads to the red-shift of the lasing mode at a rate of 0.066 nm/°C, which is lower than the reported shift rate (0.1 nm/°C) [10]. PL measurements [11] of InAsP/InGaAsP SCMQWs have shown that its PL peak wavelength moves with temperature at a relatively lower rate (0.4 nm/°C) than that of [10] (0.5 nm/°C) as well. Thus a different mode-gain offset design from [10] should be optimised for further performance improvement. We can see from Fig. 4*b* that an increasing of injection current from 1 to 8 mA leads to a wavelength tuning range up to 6.2 nm. By considering the temperature rising effect on red-shift of the lasing mode, it is equivalent to a temperature rise of 94°C. An even larger tuning range can be realised with much greater current injected. The average wavelength-tuning rate is measured as large as 0.89 nm/mA. The emission line shape is unchanged in the whole measurement of changing stage temperatures and injection currents.

Conclusion: By using the InP-based InAsP/InGaAsP SCMQW active region, we have demonstrated CW operation of 1.3 μm VCSELs. This QW material has a high-temperature thermal stability up to 650°C and is fit for wafer-bonded VCSEL processing. By using dielectric SiO_2/TiO_2 thin-film and wafer-bonded GaAs/Al(Ga)As DBR as the cavity mirrors, CW submilliampere threshold current as low as 0.54 mA and maximum optical power of 1.9 mW have been realised. The slope efficiency is between 0.27 and 0.32 W/A. The 5 μm-aperture device exhibits single-transverse mode emission with a maximum SMSR of 43 dB. These results indicate that the InAsP/InGaAsP QW active region is attractive as an optional gain medium to the AlGaInAs QWs for high-performance LW-VCSELs.

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