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# VCSEL based on InAs Quantum-Dashes with a lasing operation over a 117-nm wavelength span

F. Taleb, C. Levallois, C. Paranthoën, J.-P. Gauthier, N. Chevalier, M. Perrin, Y. Léger, O. De Sagazan and A. Le Corre

**Abstract**—We report an InP based vertical cavity surface emitting lasers (VCSEL) achieving lasing operation between 1529 nm and 1646 nm. This optically-pumped VCSEL includes a wide-gain bandwidth active region based on InAs quantum dashes and wideband dielectric Bragg mirrors. Based on a wedge microcavity design, we obtain a spatial dependence of the resonant wavelength along the wafer, enabling thus to monitor the gain material bandwidth. We demonstrate a 117 nm continuous wavelength variation of the VCSEL emission, a consequence of the important and wide gain afforded by the use of optimized quantum dashes.

**Index Terms**— Quantum dash lasers, Semiconductor lasers, Vertical cavity surface emitting lasers.

## I. INTRODUCTION

WAVELENGTH-TUNABLE vertical-cavity surface-emitting laser (VCSEL) is a promising light source for use in fiber Bragg-grating sensors [1], gas spectroscopy [2], telecommunications [3] and optical coherence tomography systems [4]. For these applications, single-mode laser emission with continuous and a wide wavelength tuning are required. VCSEL is an attractive laser source due to its short cavity design and its inherent longitudinal single-mode behavior to provide a continuous wavelength tuning. However, to achieve a wavelength tuning range higher than 50 nm, wideband Distributed Bragg Reflectors (DBR) and active materials with a large gain bandwidth are also required. Quantum wells (QWs) are predominantly used as a wide-gain material in tunable VCSEL active regions. Recently, continuous wavelength tuning over 100 nm has been demonstrated on electrically pumped or optically pumped VCSELs including QWs and a microelectromechanical-system [4][5]. However, quantum dots (QDs) or quantum dashes (QDHs) are also well suited to be used as wide-gain material in tunable VCSEL. Such nanostructures offer an important inhomogeneous broadening due to their size distribution and are very promising for tunable VCSEL, super luminescent diode (SLD)

or optical amplifiers with a wide-gain bandwidth. Using InP-based QDHs layers at a wavelength of 1.6  $\mu\text{m}$ , a SLD with amplified spontaneous emission bandwidth as wide as 140 nm has already been reported [6]. More recently, optically pumped GaAs-VCSELs including QDs have achieved a 60 nm continuous wavelength variation at 1.25  $\mu\text{m}$  wavelength [7].

In this letter, we present an InP-VCSEL based on InAs QDH nanostructures operating at telecommunication wavelength. In addition to the VCSEL output polarization control related to the QDH we have already evidenced [8][9], we demonstrate that QDH inhomogeneously broadened gain enables a CW VCSEL emission from 1646 nm down to 1529 nm, covering thus a spectral window as large as 117 nm. This result is an experimental evidence of QDH large wavelength gain bandwidth suitable for widely tunable VCSEL applications.

## II. GROWTH AND PROCESSING

VCSEL sample is grown by gas source molecular beam epitaxy on a 2 inches diameter InP(001) substrate. Active region consists of three groups of QDHs layers separated with InP spacers to be located at the position of the microcavity antinodes fields. Each group corresponds to six InAs QDH layers closely separated with 15 nm  $\text{Ga}_{0.2}\text{In}_{0.8}\text{As}_{0.435}\text{P}_{0.565}$  barriers. This quaternary alloy is also used to surround each group of QDHs layers, and acts as absorbing layers for the optical excitation of the device. Careful attention has been paid to design these layer thicknesses for each QDHs group to reach a homogeneous carrier injection within the structure. Details on QDH growth and morphology may be found in reference [8]. To go further, QDH growth has been carefully optimized in order to get a reproducible QDH emission wavelength layer to layer, compensating the natural wavelength shift related to the internal strain field mediation. As a consequence, we obtain a QDH integrated photoluminescence (PL) intensity being even slightly higher than conventional 1.55  $\mu\text{m}$  strained QWs. Details on this optimization will be the subject of another paper. Prior to the processing, PL measurements have been conducted on the VCSEL sample, at a low optical power density of 10 W/cm<sup>2</sup>, and at a 1.064  $\mu\text{m}$  wavelength excitation. Such InP transparent wavelength enables to get PL properties of the three groups of six QDH layers by creating carriers in the GaInAsP barriers. As shown in Fig. 1, the QDHs wavelength emission is rather

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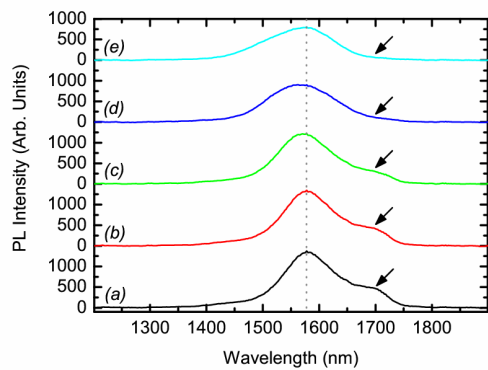


Fig. 1. PL spectra at 300K under an incident power of  $10\text{W}/\text{cm}^2$  and a  $1.064\ \mu\text{m}$  laser wavelength measured at different positions from the center of the wafer to its edge. Spectra (a), (b), (c), (d) and (e) correspond to PL measurements at a distance of 5, 7.5, 10, 12.5 and 20 mm from the wafer center respectively. The vertical dotted line located at 1575 nm is only a guide for the eyes.

constant and centered at 1575 nm on the 2-inch InP substrate. Note that the arrow indicating a PL shoulder, is not ascribed to QDH but related to an underneath InGaAs stop-etch required in our VCSEL fabrication process. The PL linewidth slightly increases from 116 to 130 nm, and the overall integrated intensity decreases only by a factor of 1.6, from measurements done respectively from the center up to the edges of the wafer. Considering those PL measurements, we can assume that over the whole surface of the wafer, the QDH properties are nearly identical. This VCSEL active region based on such QDHs has been grown on a 1500 nm thick InP phase layer including a thickness gradient. This gradient has been created by a voluntary interruption of the sample rotation during the growth to achieve a cavity length decreasing from the center up to the edge of the wafer. This wedge cavity is expected to present a thickness variation estimated to be around 10%, being appropriate to induce a significant variation of the resonant wavelength.

After the growth of the QDHs based active region, the VCSEL cavity is formed with wideband dielectric DBRs to allow a laser emission on a large spectral width. A first dielectric DBR constituted of six pairs of amorphous Si (a-Si) and amorphous SiN (a-SiN) is deposited by magnetron sputtering on the wafer. Considering the important optical index contrast of 1.85 and the optical losses of these layers, with optical simulations based on transfer matrix method we estimate the reflectivity to be greater than 99.5% at  $1.55\ \mu\text{m}$ , over a stopband of 250 nm for our bottom DBR including six periods. Thus, metallic layers of Ti and Au are deposited onto this first DBR and a  $50\ \mu\text{m}$  thick copper film is electro-plated to form a metallic substrate. The whole InP substrate is then removed by mechanical and selective chemical etching. Finally, the InGaAs stop-etch layer is also removed by chemical etching, and a second dielectric DBR including four periods is deposited on the wedge cavity.

### III. QUANTUM-DASH VCSEL CHARACTERIZATION

The Fig. 2 inset represents the schematic view of the QDH

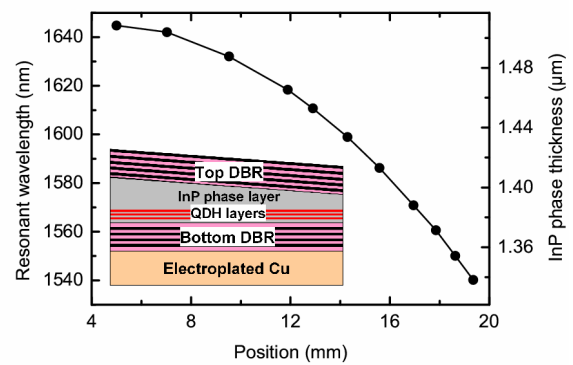


Fig. 2. Resonant wavelength of the VCSEL cavity as a function of position on the wafer. Positions indicated in mm correspond to the distance from the wafer center. Inset is a schematic cross-section of the fabricated QDH VCSEL.

VCSEL when fabrication process is completed. Prior to lasers characterizations, spontaneous emission from our device has been measured at room-temperature (RT) by pumping the QDH active region with a 980 nm continuous-wave (CW) laser diode. Those measurements have been done at low excitation power ( $< 5\ \text{mW}$ ) on a  $15\ \mu\text{m}$  diameter ( $1/e^2$  width) focused spot. Resonant wavelength and free spectral range as function of the position on the wafer have been analyzed to deduce the effective thickness gradient of the InP phase layer. A plot of the measured resonant wavelength and the deduced InP phase thickness as a function of the position on the wafer is shown in Fig. 2. The x-axis represents the radial position of the wafer from the center at 0 mm to the edge of the VCSEL sample at 20 mm. Resonant wavelength continuously decreases from 1645 down to 1540 nm, corresponding in a 165 nm decrease of the InP phase thickness, close to the 10% variation expected.

With the optical set-up described above, laser experiments in CW operation at RT have been performed at different positions on the VCSEL sample. Output spectra have been monitored with an optical spectrum analyzer by moving the

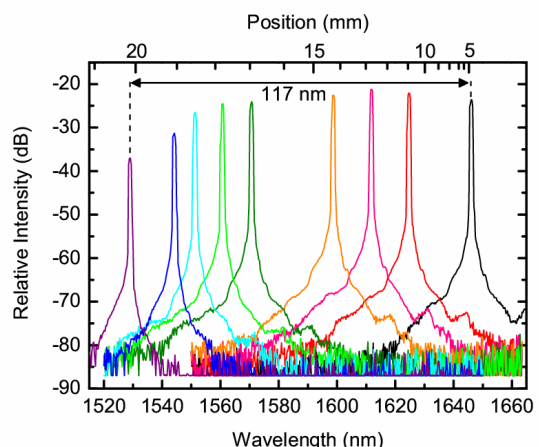


Fig. 3. VCSEL output spectra (300K, CW) measured above threshold at a constant pump power, for different position across the wafer (from 5 up to 20 mm, from right to left respectively). The upper scale relies on the dependence of the position from the center of the wafer and the cavity resonant wavelength. The arrows illustrate the wide wavelength span of the VCSEL emission.

pump spot along the radius of the wafer. The different lasing spectra, shown in Fig. 3, have been recorded above threshold at a 15 mW constant absorbed pump power (corresponding to a  $8.5 \text{ kW/cm}^2$  pump power density). Close to the center of the wafer, the longest lasing wavelength measured is 1646 nm. In agreement with spontaneous emission measurements, as the distance from the center increases, resonant wavelength is reduced, and lasing wavelength continuously decreases. Close to 16 mm from the wafer center, laser emission wavelengths are measured to be close to 1585 nm. But because of numerous defects on the top DBR related to processing artifacts, VCSEL laser performances are poor, and data were not considered in the following. At the edge of the VCSEL sample, the shortest lasing wavelength measured is 1529 nm, demonstrating a CW laser emission at RT in a very large spectral window of 117 nm. Note that as previously demonstrated for such QDH based VCSEL, the output VCSEL intensity exhibits a stable and polarized laser emission over the whole spectral range, with a polarization ratio greater than 25 dB along the [1-10] crystallographic direction [8][9] (not shown here). Fig. 4 shows the output power versus incident pump power curves recorded for a few lasing wavelengths of the Fig. 3.

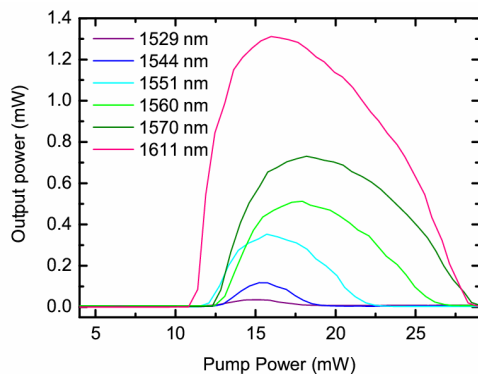


Fig. 4. CW VCSEL output power versus incident pump power for different positions across the wafer.

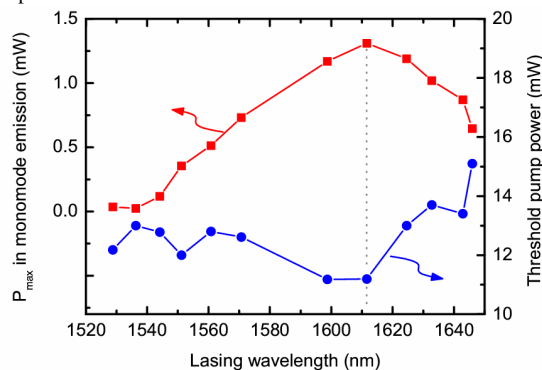


Fig. 5. Evolution of laser thresholds and maximum output powers (in monomode emission) as a function of emitted wavelength measured in CW operation.

As it can be seen, the laser slope efficiencies and thresholds depend on the emitted wavelength. The maximum achievable singlemode output power is mainly limited by thermal rollover and the pump spot diameter of  $15 \mu\text{m}$ . For several emitted wavelengths, at a pump power greater than 17 mW, higher-order transverse modes appear and VCSEL emission becomes

multimode. The maximum achievable singlemode output powers and lasing thresholds for the different wavelengths are reported in Fig. 5. Minimum threshold and maximum output power have been obtained at a position of 13 mm away from the wafer center, corresponding to a lasing wavelength of 1611 nm. Considering thus, the maximal achieved output power minus 3-dB window, the threshold variation does not exceed 10%, and the spectral window is covering the [1570-1640] nm range. Finally, from room temperature until the highest operation temperature of  $50^\circ\text{C}$ , we estimate the characteristic temperature  $T_0$  to be 73 K

#### IV. CONCLUSION

A  $1.6 \mu\text{m}$  InP VCSEL continuous wavelength variation of 117 nm has been demonstrated, combining the use of a QDH active region, wideband dielectric DBRs and a wedge cavity. These experiment evidences the large and wide gain afforded by inhomogeneous QDH nanostructures. In association with a wavelength tuning mechanism, QDH VCSEL are expected to achieve very large tuning, exceeding 100 nm, without any specific gain engineering of this active region.

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