Passive cavity surface emitting laser

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Demonstrated is a vertical cavity surface emitting laser (VCSEL) formed by a passive half-wavelength cavity and a quarter-wavelength active gain region, wherein the said gain region resides in one of the VCSEL's distributed Bragg reflectors. The device concept invites extensive opportunities for innovation in the combinations of materials and gain region placements that may be used to construct surface emitting devices.

Introduction: GaAs-based vertical cavity surface emitting lasers (VCSELs) [1] are broadly used in sensing and optical communications. The key advantages of VCSELs include a low threshold current density, high power conversion efficiency, narrow emission spectrum, high temperature stability, planar processing, high yield, and high reliability. More recently, photonic crystal VCSELs [2, 3] opened a way to engineer singlemode polarisation stable VCSELs with large apertures, realise field-coupled arrays, and produce lasers with different emission wavelengths on the same wafer. Yet still the industrial progress of VCSELs is limited by the GaAs-AlGaAs materials system. This system provides a relatively high refractive index step for wavelengths longer than about 750 nm between its binary and quasi-binary members, and thus relatively thin and highly-reflective distributed Bragg reflectors (DBRs) with significant heat conductivity. Despite notable success in basic research [4], industrial applications of InP-, GaSb-, GaN-, and short wavelength (red) GaAs-based VCSELs [5] remain quite limited or in full stasis. For these VCSEL products the main obstacle for broader market penetration is the small step in the refractive indices of the DBRs. As is well known, a small index contrast in monolithic semiconductor DBRs leads to a narrow DBR stopband. The narrow-band DBRs must be grown with extreme precision and a large number of periods to provide the necessary power reflectance for lasing. Moreover, in low index contrast VCSELs the resonant optical field intensity significantly extends outside of the microcavity region. This reduces modal gain and heat conductivity and leads to inefficient devices.

In this Letter we report the performance of oxide-confined 850 nm GaAs-based VCSELs with an InAs submonolayer quantum dot [6] active region incorporated into a high-index $\lambda/4$-thick section of the top DBR, wherein the gain region is displaced five DBR periods from a passive cavity region. The optical field intensity in the VCSEL's cavity is generated by the gain section with a gain maximum spectrally within the forbidden gap of the DBR. The passive resonant cavity can be made of a large variety of materials including dielectric layers that may or may not be lattice matched and have a large refractive index step. The passive resonant cavity may contain for example: metal insertions, materials with a compensated dependence of the refractive index on temperature, an electro-optic or -absorption modulator, a photonic crystal structure, or a nanometre-patterned medium. Since the optical field intensity in the cavity and the width of the field along the vertical and lateral axes can be independently engineered, a large set of materials systems can be used in this approach to fabricate VCSELs.

Experiment: Epitaxial wafers for oxide-confined 850 nm passive cavity surface emitting lasers (PCSELs) were grown by molecular beam epitaxy on (100) (n+)GaAs substrates oriented 2° off towards the nearest <110> plane. The DBRs consist of AlGaAs quarter-wave layers with 43.5 periods for the bottom DBR and 28 periods (including the half-period with the gain elements) for the top DBR. The n-doped half-wave cavity is also composed of AlGaAs materials. The n- and p-type dopants are Si and Be atoms, respectively, and the entire structure is about 9.2 µm thick. In contrast to conventional VCSEL designs where the gain medium is directly introduced into the optical cavity, we placed an InAs submonolayer (SML) quantum dot (QD)-based active region [6] within one of the $\lambda/4$-thick sections of the top DBR. Herein the QD sheets reside in a relatively high-index DBR layer that is the fifth high-index layer in the top DBR from the passive n-doped cavity. Fig. 1*a* shows the calculated refractive index profile and the electric field intensity on resonance for the device structure. Fig. 1*b* shows the measured optical power reflectance spectrum of one spot on the epitaxial wafer. While herein we use 23 DBR periods on top of the $\lambda/4$-thick gain section, clearly it is possible to place the gain elements elsewhere. A detuning between the photoluminescence (PL) intensity maximum of the gain medium and the cavity resonance wavelength for this wafer is about 25 nm. The wafer is fabricated into oxide confined VCSELs as illustrated in Fig. 2 with square mesas, picture-frame top metal contacts, and square oxide apertures with dimensions starting at 1 × 1 µm (1 × 1) and increasing in 0.5 µm steps.

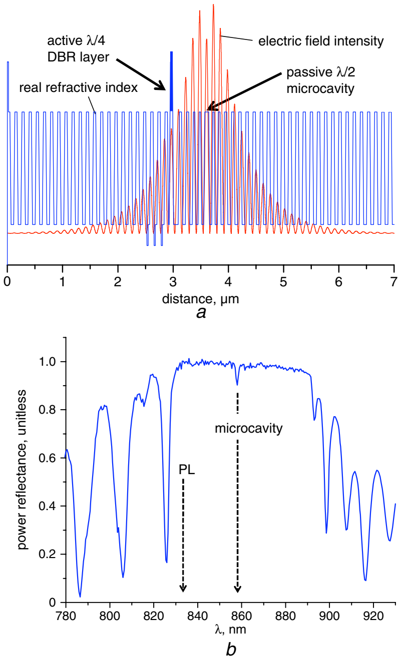

Fig. 1 *Calculated real refractive index and electric field intensity both against distance for passive cavity surface emitting laser studied in this work (Fig. 1a); measured room-temperature optical power reflectance spectrum of as-grown epitaxial wafer (Fig. 1b)*

Arrows in (Fig. 1*b*) indicate approximate cavity (etalon) wavelength and wavelength of photoluminescence (PL) intensity maximum of gain medium. Etalon-to-gain detuning is roughly 25 nm

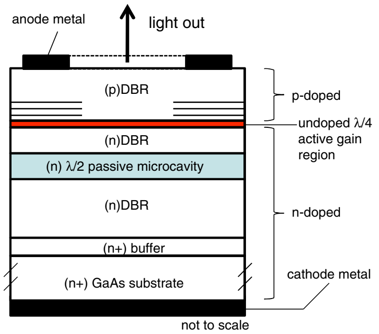

Fig. 2 *Simplified schematic diagram of fabricated passive cavity surface emitting laser*

Characterisation: Fig. 3 shows the room-temperature continuous-wave light-current (Fig. 3*a*) and current-voltage (Fig. 3*b*) characteristics of our devices. The differential slope efficiency reaches 25%. The differential resistance is about 100Ω for the 6 × 6 VCSELs, and $50-70\Omega$ for the 8 × 8–10 × 10 VCSELs, respectively. These series resistances are comparable to those measured in VCSELs grown by metal organic chemical vapour deposition with carbon doping [7]. The threshold current density is about $12-14\ \mathrm{kA/cm^2}$ for oxide apertures exceeding the 8 × 8 oxide geometry. We attribute a relatively high threshold current density primarily to the very significant spectral detuning between the cavity etalon wavelength and the PL gain maximum wavelength of the SML QDs, wherein a significant thermal shift of the gain is required to match these two wavelengths [8, 9].

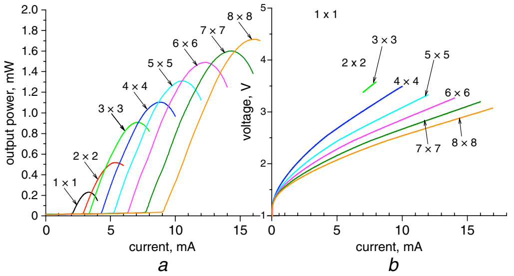

Fig. 3 *Measured light power-current (L-I) (Fig. 3a); current-voltage (I-V) characteristics of passive cavity VCSELs (Fig. 3b)*

Dimensions of VCSEL square oxide apertures vary from 1 × 1 µm (1 × 1) to 8 × 8 µm (8 × 8). Maximum differential slope efficiency is 25%

Fig. 4 shows the maximum output power against oxide aperture side length, and we note that the 8 × 8 VCSEL produces the highest output power. Fig. 4 also shows the emission spectra of the 1 × 1 and 2 × 2 VCSELs at peak output power. The 1 × 1 device emits in a single mode up to the roll-over power, whereas the 2 × 2 VCSEL is clearly emitting multiple modes. From this data we estimate that the overheating of the junction region of our VCSELs is about 100K. This value approximately matches the temperature shift of the bandgap needed for the gain peak of the SML QDs gain region to match the resonant cavity wavelength.

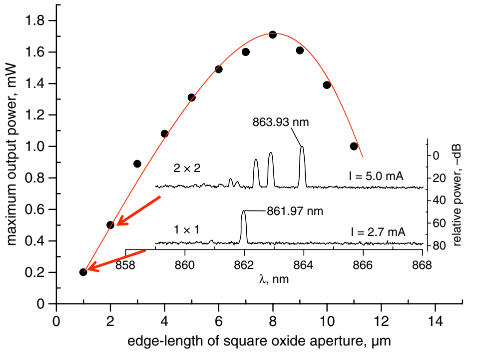

Fig. 4 *Measured maximum output power against square oxide aperture size (dots)*

Inset: Measured emission spectra of 1 × 1 µm (1 × 1) and 2 × 2 µm (2 × 2) oxide confined PCSELs at 2.7 and 5.0 mA drive current, respectively

Conclusions: We have demonstrated a non-obvious variation of a vertical surface emitting optoelectronic device suitable for continuous-wave operation up to high junction temperatures and suitable for a large variety of passive cavity designs. We expect that the possibility to apply different materials and processing techniques to engineer the passive cavity may be a key advantage for a wide range of nanometre-scale photonic devices and can result for example in high performance InP-, GaAs-, GaSb- or GaN-based surface emitting lasers, standard and resonant cavity light emitting diodes (LEDs), and broad spectral range intersubband quantum cascade lasers. Another advantage of this device concept is the possibility to avoid a thermal shift of the emission wavelength or conversely create broadly wavelength tunable VCSELs using cavity materials with a refractive index highly sensitive to electro-optic, piezoelectric, or thermal effects.

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One or more of the Figures in this Letter are available in colour online.

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