A Single Transverse-Mode Monolithically Integrated Long Vertical-Cavity Surface-Emitting Laser

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***Abstract*—We present a fully monolithic long vertical-cavity surface-emitting laser operating in the fundamental TEM_{00} transverse mode with output powers up to 7.8 mW. The lasing wavelength is 980 nm and the threshold is 9.1 mA. Pump currents from threshold to rollover produce an output beam with an $M^2 < 1.08$. The laser consists of an InGaAs–GaAs–AlGaAs gain region/semiconductor mirror bonded to a 0.5-mm-thick glass substrate with an integrated curved mirror.**

***Index Terms*—Bonding, laser modes, semiconductor lasers, semiconductor laser arrays, surface-emitting lasers.**

I. INTRODUCTION

VERTICAL external-cavity surface-emitting lasers (VECSELs) are capable of high-power single-mode operation at a variety of wavelengths [1], [2]. They are, however, time consuming to fabricate as they require precise alignment of multiple discrete components. In contrast, thousands of vertical-cavity surface-emitting lasers (VCSELs) can be fabricated simultaneously on a single wafer. While they may be easier to mass produce, VCSELs cannot achieve high-power single-mode operation, being limited to a few milliwatts [3]. The monolithically integrated long vertical-cavity surface-emitting lasers (LVCSELs) reported here have many of the advantages possessed by traditional VCSELs such as fabrication of devices in arrays, wafer level testing, and simple packaging. However, they are also capable of high-power single transverse mode operation typical of VECSELs. Due to their low cost, high power, and high quality circular beams appropriate for free space optics or fiber coupling, LVCSELs may find use in optical interconnects, telecommunications, medicine, and as pump sources for optical amplifiers.

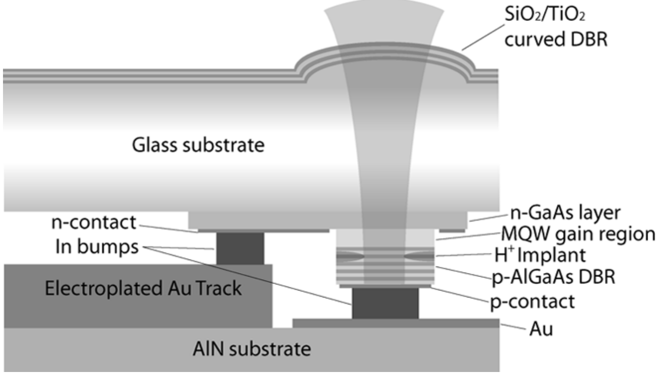

Fig. 1. LVCSEL device structure and AlN heatsink-testbed.

Fig. 1 illustrates the monolithic device structure and its AlN heatsink-testbed. A stable laser cavity is formed between the curved SiO_2–TiO_2 micromirror/output-coupler and the semiconductor distributed Bragg reflector (DBR) bonded to the opposite side of the quartz substrate. The InGaAs quantum-well (QW) gain region sits between the semiconductor DBR and the 0.5-mm-thick glass substrate. The devices are fabricated in arrays and then flip-chip bonded via In bumps to an AlN heatsink for good heat dissipation and electrical testing. Other integrated VECSEL designs have been either optically pumped [4]–[6], therefore, not, strictly speaking, monolithic, or microelectromechanical system-based [6] with cavities hundreds of times shorter than ours. These short cavity devices lack the ability to scale output power by increasing the gain region diameter while maintaining single transverse mode [1]. Thus, this work, to the best of our knowledge, describes the first electrically pumped fully monolithic LVCSEL operating in single transverse mode at up to 7.8 mW of output power at 980 nm. Pump currents from threshold to rollover produce an output beam with an $M^2 < 1.08$. We have previously demonstrated a multitransverse mode LVCSEL in [7].

II. DEVICE DESIGN AND FABRICATION

A. Design

We discuss the analytical design of a stable LVCSEL resonator including choice of the micromirror radius of curvature, glass substrate thickness, and p-type mesa diameter, as well as beam spot size calculations in [7]. The parameters chosen for the device discussed here appear in Table I. The p-type mesa diameter is two times larger than the $1/e$ electric field diameter on the mesa plus 10 μm in order to eliminate any aperture loss due to clipping by the mesa even if the mesa is laterally misaligned several microns. Similarly, the curved mirror diameter is chosen to be over four times larger than the $1/e$ electric field diameter on the curved mirror to avoid aberration caused by the deviation of the curved mirror profile from a parabola away from the curved mirror's center.

Transverse mode selection is achieved by forcing one mode to see more net gain than any other mode. Carrier dynamics, gain

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TABLE I
DEVICE DIMENSIONS

Symbol	Quantity	Value
t_{glass}	Glass Substrate Thickness	0.5mm
ROC	Micro-mirror Radius of Curvature	1.0mm
d_{mesa}	p-type GaAs Mesa Diameter	52 µm
d_{mirror}	Curved Micro-mirror Diameter	320 µm
w_{mesa}	e^{-1} Electric field diameter on the Mesa	21 µm
w_{mirror}	e^{-1} Electric field diameter on the curved mirror	50 µm
d_{imp}	Implant aperture diameter	21 µm

saturation, and thermal effects make transverse mode selection theory somewhat complicated [8], but the basic idea is straightforward. We select the fundamental TEM$_{00}$ mode by confining our pump current and, thus, our gain area with an H^+ implant. The transverse mode which overlaps the spatial gain profile best, will see the most net gain and be selected to lase over all other modes. The implant aperture diameter was chosen to be the $1/e$ diameter of the electric field on the mesa, or 21 μm. Since the mesa and curved mirror diameters are so large, clipping of the beam from these apertures plays no role in mode selection.

Finally, the laser was designed to have very little longitudinal mode filtering. In a traditional VCSEL, the cavity is so short that only one longitudinal mode overlaps with the gain. However, we do not place a strong partial mirror at the fused-silica/GaAs interface, so we avoid selecting such a single longitudinal mode. In our device, many longitudinal modes may overlap with the gain spectrum; therefore, many of them may lase simultaneously. This wide lasing bandwidth is desirable for mode-locking as the time duration of a mode-locked pulse is inversely proportional to its bandwidth.

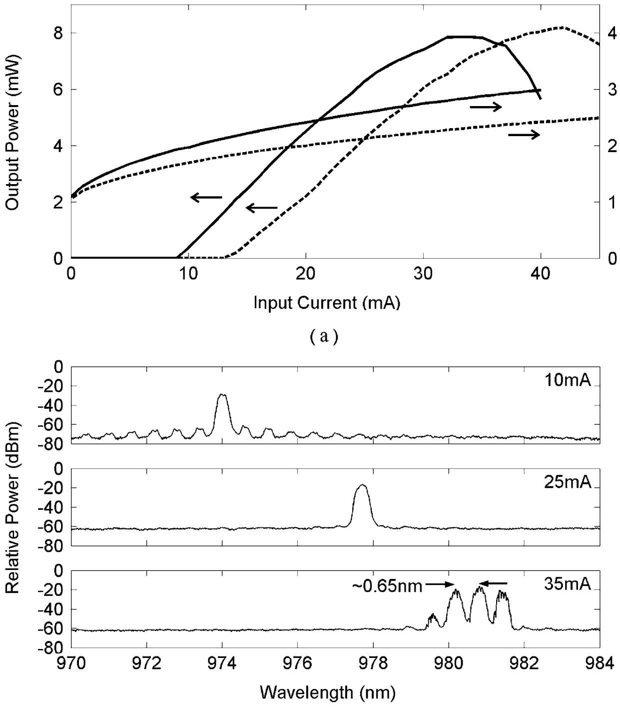
B. Fabrication

The process flow follows what has been reported previously in [7] with two major exceptions. First, a 360-keV 4e14 ion/cm^2 H^+ ion implant was performed directly after the GaAs substrate removal step in order to confine the pump current flow [9]. The 360-keV implant energy places the implant peak 3.1 μm deep into the p-DBR, well above the QW depth of ~5 μm. The implant mask was lithographically defined in 10-μm-thick photoresist and aligned to the centers of the curved micromirrors. Second, the 98.5% reflecting SiO$_2$–TiO$_2$ DBR was sputtered on the curved micromirrors as the last step before flip-chip bonding to the AlN heatsink-testbeds.

III. EXPERIMENTAL RESULTS

Fig. 2 shows the light output–current (L–I) curve and spectrum for the device described in Table I. The maximum output power is 7.8 mW, the threshold current is 9.1 mA, and the differential quantum efficiency is 33%. The beam maintains an M^2 value less than 1.08 for all pump currents from threshold to rollover. The M^2 value was measured by fitting spot size versus distance data to the standard equation for Gaussian beam propagation

$$w(z) = w_0\sqrt{1 + \left(\frac{M^2\lambda z}{\pi w_0^2}\right)^2} \quad (1)$$



(a)

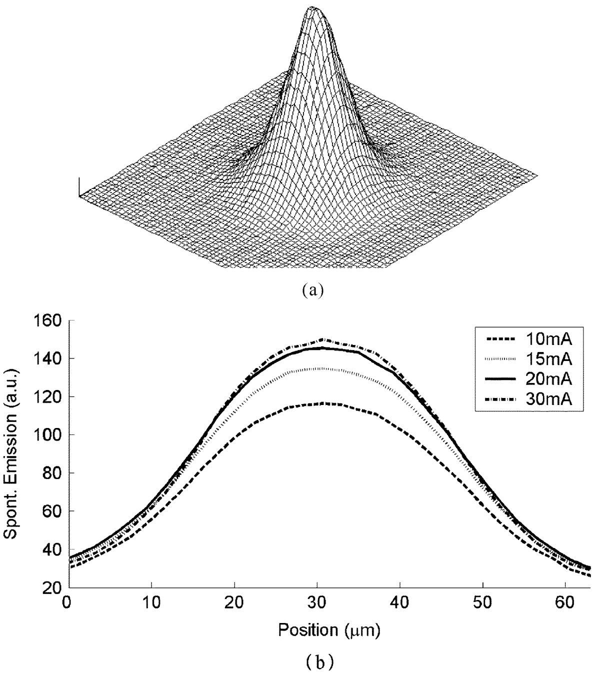
(b)

Fig. 2. (a) L–I and voltage–current curves for the 21-μm-diameter implant device (—) and a 31-μm-diameter implant device (· · ·). (b) Lasing spectrum of the 21-μm-diameter implant device. For clarity, only three currents are shown. The spacing between longitudinal modes is ~0.65 nm which corresponds to the axial mode spacing of a 0.5-mm fused-silica cavity. In the 35-mA spectrum, we believe that the increased pump current has broadened the spectral width of the gain minus loss curve enough to support multiple longitudinal modes above threshold.

where z is distance, w is spotsize, w_0 is the minimum spot size, λ is wavelength, and M^2 is the beam parameter of interest. Spot sizes were measured with a commercial charged coupled device beam analyzer system.

The low M^2 value of 1.08 not only demonstrates the effectiveness of our lithographic cavity alignment technique but it may also explain the small bumps or wiggles in the L–I curve [Fig. 2(a)]. These kinds of bumps are usually associated with transverse mode-hoping [9]. Since we know the transverse mode is stable because of the low M^2 value, the bumps in the L–I curve can be explained by longitudinal mode-hopping. As the pump current increases and the gain peak moves to longer wavelength, the lasing longitudinal modes will also hop to longer wavelength. This can be seen in Fig. 2(b). As the wavelength hops, the L–I curve will wiggle reflecting the changing overlap of the lasing wavelengths and the gain.

The choice of implant diameter is critical for achieving TEM$_{00}$ operation. Since there is no hard aperturing in this device (see Section II-A), the transverse mode profile of the laser is determined by the overlap of the resonator modes with the transverse gain profile. A laser was fabricated with similar device dimensions to those in Table I but with an implant diameter of 31 μm corresponding to 1.5 times the $1/e$ diameter of the electric field spot on the mesa. The 21-μm device described in Table I maintained fundamental transverse mode operation through rollover indicating a good overlap of only the TEM$_{00}$ mode with the transverse gain profile. The 31-μm-diameter



(a)

(b)

Fig. 3. (a) Optical mode at 30 mA for the 21-μm-diameter implant device. (b) Spontaneous emission profiles at various currents for a 31-μm implant diameter device. These profiles were obtained from a chip which did not have any curved mirrors or a dielectric DBR coating.

implant device lased in the fundamental mode at low pump currents (<20 mA) but degraded to a higher order transverse mode at larger pump currents. Spontaneous emission profiles for the 31-μm implant device, which are indicative of its carrier density profile, are shown in Fig. 3. Profiles for the 21-μm implant device are similar. The profiles show overall higher concentration, and therefore gain, at the center than at the edges, thus helping in the selection of the fundamental transverse mode. The mechanisms responsible for the degradation of the transverse mode profile at higher pump currents are discussed elsewhere [8].

In comparing the 21- and 31-μm implanted devices, we also notice that the rollover current for the 31-μm device is larger [see Fig. 2(a)]. In our device, rollover is caused by the reduction of gain at higher temperature so it is reasonable to assume that the peak temperatures in both devices at rollover are similar. Since the device with the smaller diameter implant rolls over first at 33 mA, its peak temperature must increase more per unit input current. We believe that this additional heat comes in part from a comparative increase in Joule heating due to the constriction of the current through the narrower implant aperture increasing the device's series resistance. Using the current–voltage data in Fig. 2(a), we find that the 21-μm implant diameter device has a series resistance of 22 Ω while that of the 31-μm implant device is only 16 Ω. The 21-μm implant device may also reach a higher peak temperature more easily because the narrower implant concentrates the heat generation in a smaller area. Increasing both the diameter of the implant and the beam spot size on the GaAs mesa may improve the thermal performance of the device and allow us to reach higher powers while maintaining single mode.

IV. CONCLUSION

We have presented a fully monolithic LVCSEL operating in the fundamental TEM_{00} transverse mode with output powers up to 7.8 mW. The long cavity allows the device to achieve fundamental mode high-power performance beyond that achievable by traditional VCSELs. The device structure and fabrication steps are also applicable to other kinds of semiconductor gain materials opening the possibility of creating devices which operate throughout a wide range of wavelengths. Furthermore, the long cavity structure may prove interesting for mode-locking at repetition rates in the tens of gigahertz.

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