High Power Conversion Efficiencies and Scaling Issues for Multimode Vertical-Cavity Top-Surface-Emitting Lasers

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Abstract—We report advances in the power conversion efficiencies of vertical-cavity top-surface-emitting lasers defined by proton implantation. Efficiencies as high as 13.4% and 15.8% have been obtained for single-mode and multimode operation, respectively. Scaling issues are addressed including the size dependence of threshold current, series resistance, lasing output power, and power conversion efficiency. We find that devices between 15 μm and 25 μm diameters show the highest power conversion efficiency due to the threshold current not scaling with the conductance and output power. Device geometries with contact apertures both equal to and less than (overlapping) the active region diameter were investigated.

Vertical-cavity surface-emitting lasers (VCSELs) present a large parameter space for epitaxial designs including the number, location, composition, and thickness of quantum wells in the active region; the composition, thickness, and doping of cladding layers; and the composition, grading, doping, and number of distributed Bragg reflectors (mirrors). Additionally, various active region areas can be defined by implantation or etching. Depending upon application specific requirements, optimum designs are evaluated with regard to appropriate metrics such as threshold current density, threshold voltage, maximum output power density, slope efficiency, series resistance, and power dissipation. All of these parameters impact the electrical to optical power conversion efficiency so that it may be used as a global performance metric prior to the definition of application specific requirements.

VCSEL power conversion efficiencies have increased substantially during the past two years. Peters et al. have achieved a maximum continuous-wave (CW), room-temperature power conversion efficiency of 17.3% in a bottom-emitting, multimode, index-guided device [1]. We have previously reported on proton-implanted, top-emitting VCSELs that exhibited a power conversion efficiency of 12.7% during single-mode operation [2]. In this letter we describe the extension of our earlier work to larger devices in which the maximum CW, room-temperature power conversion efficiency occurs during multimode operation with a value of 15.8%. In addition to modal characteristics, increases in the active region diameter affect the electrical, thermal, and other optical properties of the laser. The associated parameters scale differently with device size resulting in changes in performance metrics. These scaling issues are discussed with respect to their impact on power conversion efficiency.

The epitaxial structure and device processing used in this study were similar to ones described in detail in [2]. The molecular beam epitaxial layers were grown on an n-type GaAs substrate and included a 33 period n-type AlGaAs mirror, a triple InGaAs quantum well in a one-wave cavity of graded AlGaAs, and a 22 period p-type AlGaAs mirror. The mirror alloy composition was graded as described previously [3], and both the silicon and beryllium doping concentrations were decreased near the active region to reduce free carrier absorption [4], [2]. The nominal design wavelength was 980 nm. Two differences from the structure and processing described in [2] are that a delta-doped GaAs cap was not used and the contact metal was alloyed at 350°C prior to the implant. The process employed a relatively thin (2000 Å) AuBe contact metallization to permit ion implantation through the contact. After initial measurements, the finished devices were then annealed at 400°C to reduce implant damage near the contacts and near the junction. This temperature was found to optimize laser efficiency [5].

A variety of device sizes were fabricated on the sample with photoresist implant mask nominal diameters of 10, 15, 25, and 35 μm. This dimension g defines the gain or active region and will be referred to as such in this letter. In general the diameter of the aperture in the metallic contact a was the same as the implant mask (a = g), but devices with g = 15 μm and a = 10 μm as well as g = 35 μm and a = 25 μm were also fabricated. In these special cases where a < g, the metal contact overlaps into unimplanted regions to provide lower contact and lateral spreading resistances; however this is at the expense of output power since part of the gain region is obscured. The cross-section of the completed structure is shown in Fig. 1.

The devices were characterized in wafer form on a probe station. Room-temperature CW light versus current and voltage versus current measurements were made as previously described [2]. The lasing wavelength varied with radial position on the wafer, so measurements were made at a position where the threshold current of small devices was minimum. The lasing wavelength in this area was approximately 970 nm.
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curves intended only as aids to the eye. Error bars indicate the standard
resistance, as a function of device radius. These parameters
shown in Fig. 2.

Fig. 2. (a) The average threshold currents (circles) and series resistances
(squares) and (b) the maximum power (circles) and maximum power conver­
sion efficiencies (squares) for VeSELs as a function of the active region radius
(r = g/2) for VCSELs as a function of the active region radius (r = g/2). The
solid symbols indicate devices with equal aperture and active region
radii (a = g) while the open symbols indicate devices with a reduced
aperture (a < g). The solid line indicates the fit of $R_s = A/r + B/(\pi r^2)$
to the resistance data for devices with $a = g$. The dashed lines are polynomial
curves intended only as aids to the eye. Error bars indicate the standard
deviation of the data.

were measured and the average statistics for these devices are
shown in Fig. 2.

Fig. 2(a) shows two parameters, threshold current and series
resistance, as a function of device radius. These parameters
affect power conversion efficiency, and it is useful to analyze
their dependence on device size. Ideally, in the absence
of edge effects and current crowding, the threshold current
density should be constant giving a threshold current that is
proportional to the active region area. The threshold current
density was calculated as the ratio of threshold current to active
area even though the current density varies radially within the
active region [6], [7]. The two largest VCSELS, 25 and 35
$\mu$m in diameter, have approximately equal threshold current
densities of 1 kA/cm². However, the smaller devices have
much higher threshold current densities. This is partly due
effects that require additional currents which scale with the
device circumference, such as nonradiative recombination
that occurs at the periphery of the implant. Interestingly, the
data in Fig. 2(a) shows not only an increase in threshold
current density for smaller devices, but even an increase in the
threshold current for the smallest (10 $\mu$m diameter) device.
Peripheral currents alone cannot account for this behavior;
rather there must be increased optical losses (diffraction and
unabsorbed spontaneous emission) associated with the smallest
device. It is also noteworthy that the lasers employing a contact
aperture smaller than the gain region (a < g) have smaller
thresholds than devices with the same gain region and contact
aperture diameter (a = g) as previously observed by others
[8]. Metal overlying a portion of the active region may reduce
the optical loss and thus decrease the threshold current.

The device resistance as plotted in Fig. 2(a) was taken
from a linear fit of the current versus voltage curves between
the lasing threshold and maximum output power points on the
curves. The current versus voltage relationship is quite
linear in this range and extrapolates to approximately 1.4 V.
Decreasing the aperture diameter to be less than the gain
region diameter (a < g) reduces the resistance slightly in
comparison to the devices with $a = g$. The reduction comes
from reduced lateral current flow and lower contact resistance
[2], [8]. The data for resistance of the four device sizes with
$a = g$ have been fit with the expression $R_s = A/r + B/(\pi r^2)$
for gain region radius $r = g/2$ where the first term accounts
for constriction or spreading, lateral, and contact resistances
that scale inversely with radius and where the second term
corresponds to a uniform vertical current flow resistance that
scales inversely with the gain area. The best fit is obtained with
coefficient values of $A + 0.066 \text{Q-cm}$ and $B = 2.6 \times 10^{-5} \text{Q-}
\text{cm}^2$. Using these coefficients, the two terms would be equal
for $r = 1.3 \mu$m; thus the $1/r$ term dominates for all the device
sizes in the present study. This highlights the importance of
enhancing lateral as well as vertical conductivity in VCSEL
mirror stacks.

Fig. 2(b) shows two performance metrics, maximum power
and maximum power conversion efficiency, as functions of the
device size. While the maximum output power of the
lasers increases with gain region size, it does not increase as
rapidly as the gain region area so that the effective maximum
power intensity decreases with size. In fact, the maximum
power approaches a linear relationship in radius for the larger
devices. This is a result of current crowding that concentrates
the carriers and thus power at the periphery of the device under
high level injection conditions [6], [7].

Since the junction impedance is much higher under the
lower level injection conditions near threshold, the current
injection is more uniform and the threshold current is
approximately proportional to the area of large devices as noted
been obtained in single-mode and multimode operation of a 15 \textmu m proton implant. Values as high as 13.4% and 15.8% have been reported as indicative of current crowding at the periphery of the device. This occurs because contact, lateral, and substrate spreading resistance contributions are greater than the vertical mirror resistance. The lasers also show an increase in threshold current for small devices indicating increased optical losses and constant threshold current densities for the largest devices. The disparity between the scaling of the threshold current and the effective device area results in optimum efficiencies for intermediate sized devices. Larger devices would benefit from better current injection uniformity, through reduced lateral resistance and perhaps transparent conducting contacts such as indium-tin-oxide or cadmium-tin-oxide [11], and from improved heat-sinking.

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**REFERENCES**


