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**Large-Diameter InGaAs/AlGaAs Vertical-Cavity
Surface-Emitting Lasers with Low Threshold
Current Density Fabricated Using a Simple
Chemical Etch Process**

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Contents

	Page
1. Introduction	5
2. Fabrication Process	5
3. Test Results	8
4. Conclusions	10
Acknowledgements	11
References	11
Distribution	13

Figures

1. Epitaxial structure of vertical cavity surface-emitting laser (VCSEL)	6
2. Reflectance spectra of VCSEL structure	7
3. VCSEL light-output/current characteristics and threshold current density	9
4. VCSEL spectra	10

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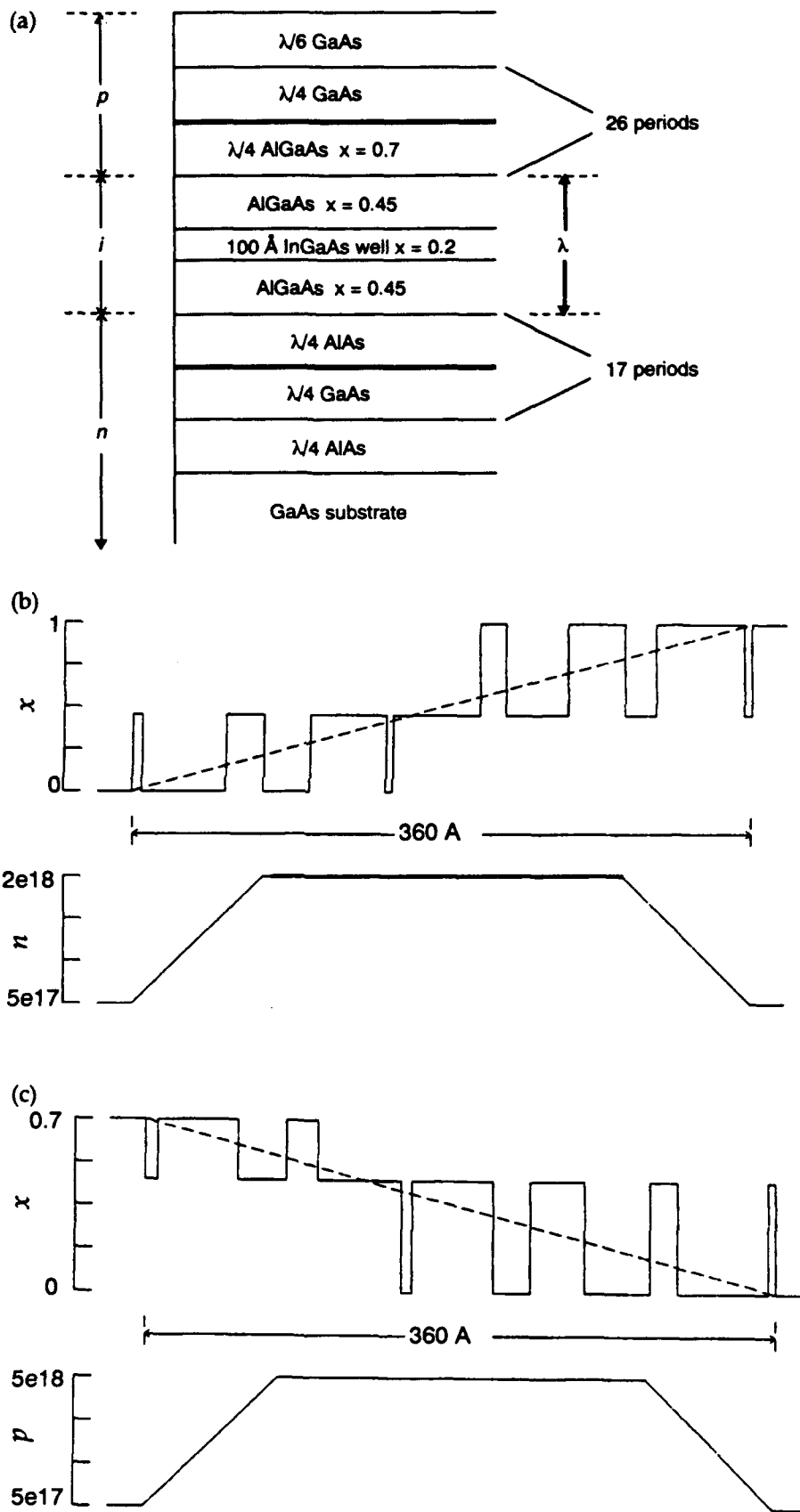
1. Introduction

The development of vertical-cavity surface-emitting lasers (VCSELs) [1] has enabled III-V semiconductor technology to be applied to certain optical information processing architectures. This development, coupled with the realization of optoelectronic integration, has made feasible the development of so-called "smart pixels," wherein a combination of optical and electronic devices can perform certain logical and computational functions with purely optical inputs and outputs [2]. There are a number of advantages of III-V semiconductor multi-layer structures for these applications, not the least of which is that a large number of devices can be packaged into a very small volume. Consequently a large amount of information can be processed quickly and simultaneously, and therefore the theoretical advantage of optical processing (i.e., massive parallelism) can be realized in an actual system. A further advantage of III-V semiconductor structures is that optical sources, detectors, modulators, and switches can be fabricated from the same semiconductors and can eventually be integrated on the same chip. However, a number of physical and technological obstacles need to be overcome before smart-pixel technology can be made practical, including the complexity of fabrication for the VCSELs reported to date and the difficulties with precise control of layer thicknesses and compositions. Solutions to these problems are critical for obtaining robust optimal devices with a high degree of uniformity over 2D arrays.

2. Fabrication Process

In this report we demonstrate a simple fabrication process for large-diameter InGaAs/AlGaAs VCSELs that involves only a single wet-chemical-etching step and that produces lasers with low threshold current densities and favorable optical characteristics. The structure (see fig. 1(a)), grown by molecular-beam epitaxy (MBE), consists of two Bragg mirrors (21 periods of $(\lambda/4 \text{ GaAs})/(\lambda/4 \text{ AlAs})$ for the n -doped lower mirror and 26 periods of $(\lambda/4 \text{ GaAs})/(\lambda/4 \text{ Al}_{0.7}\text{Ga}_{0.3}\text{As})$ for the p -doped upper mirror), with a single $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ quantum well in the center of a one-wavelength-thick $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ optical cavity. Figures 1(b) and 1(c) show details of the n - and p -doped layers, respectively. In designing the mirrors, we have provided digital grading of the alloy composition [3,4] and an increase in doping at the interfaces [5] where the optical field has a zero to reduce the series resistance of the VCSELs. Before growing the structure, we grew a standard edge-emitting laser with the same $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ strained single-quantum-well active region as the

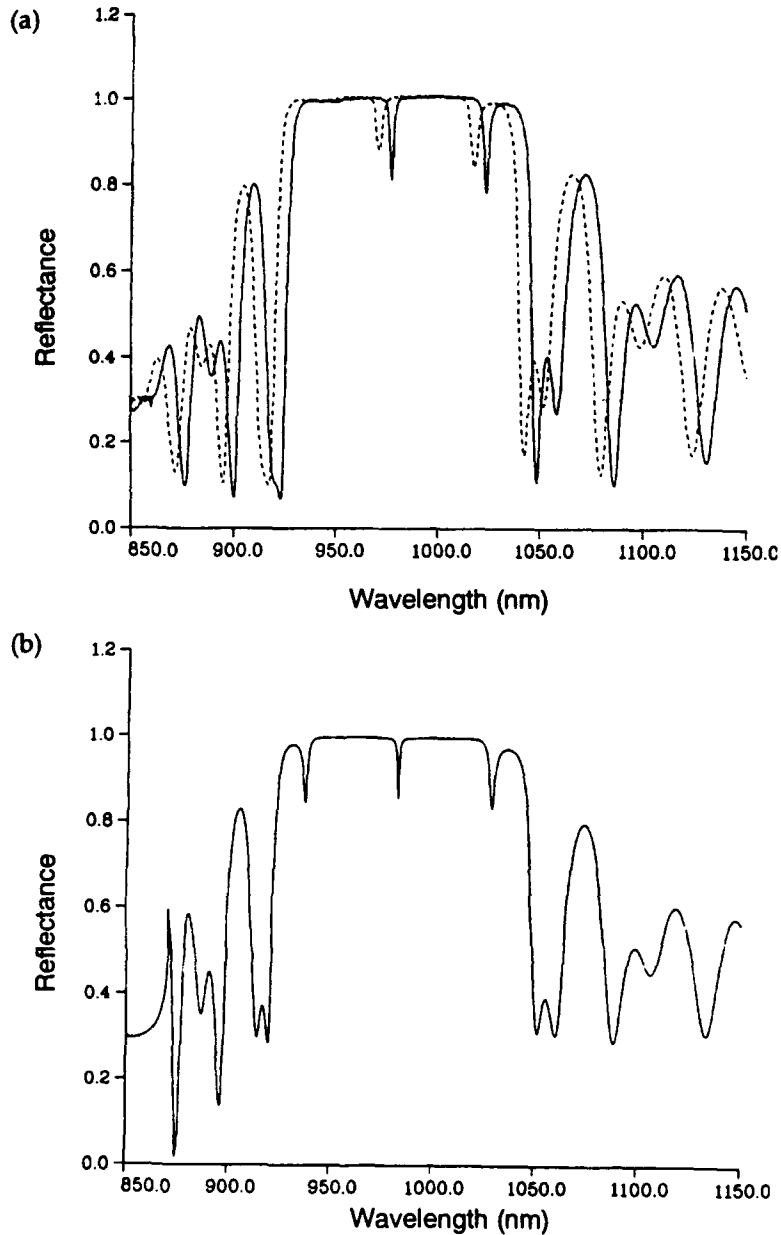
Figure 1. Epitaxial structure of VCSEL:
(a) Overall structure,
(b) details of n -type mirror,
 showing $\text{Al}_x\text{Ga}_{1-x}\text{As}$ mole fraction x and doping profile as a function of position, and
(c) details of p -type mirror,
 showing $\text{Al}_x\text{Ga}_{1-x}\text{As}$ mole fraction x and doping profile as a function of position.



VCSEL. This waveguide laser showed an extremely low transparency current density of 70 A/cm^2 , with an emission wavelength of about 1000 nm .*

Figure 2(a) shows the measured reflectance spectra at points near the center (solid line) and edge (dashed line) of the wafer; comparison of these two spectra shows that the layer thicknesses in the MBE-grown structure are uniform to considerably better than a percent over the area of the 2-in. wafer. For comparison, in fig. 2(b) we show the results of a computer simulation of the reflectance, where

Figure 2. Reflectance spectra of VCSEL structure: (a) Experimental reflectance spectra for areas near the center (solid line) and edge (dashed line) of the 2-in. wafer; (b) calculated reflectance spectrum.



*The edge-emitting laser has $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ surrounding the quantum well rather than $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ as in the VCSEL; thus its well is shallower, and the emission wavelength longer, than the VCSEL.

we use the refractive-index interpolation of Adachi [6] to model the optical properties of the GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers and where we have neglected the $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ well.

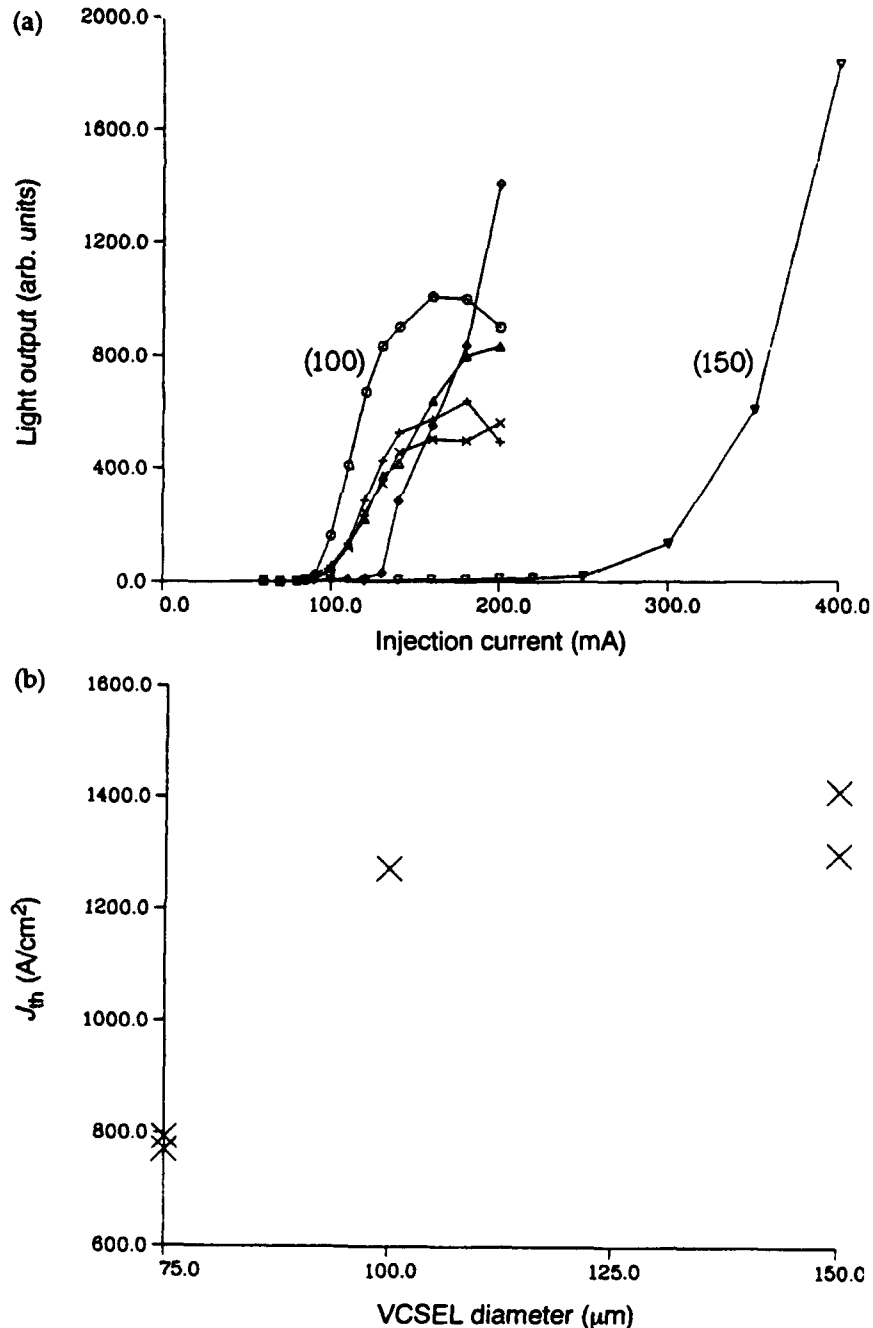
A piece of the MBE-grown wafer was polished on the back, and *n*-type (Au/Sn/Au) contact pads were deposited on the corners of the piece and annealed, thus leaving most of the back transparent for light output. Then *p*-type (Au/Cr/Au) contacts in the form of circular disks ranging from 25 to 150 μm in diameter were evaporated onto the upper surface of the wafer through a mask. These disks also served as masks in a one-step, self-aligned wet chemical etching process (8:1:1 $\text{H}_2\text{O}_2:\text{H}_2\text{SO}_4:\text{H}_2\text{O}$) that removed about 4 μm of material (i.e., to slightly below the $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ well). Examination of the resulting mesas using a scanning electron microscope showed that they were undercut, as expected for an isotropic chemical etch. The wafer piece was mounted in a metal package (attached with solder to the rear corner contacts) with a large hole drilled in the back to permit light output, and several devices of each size were wire bonded. Current-voltage characteristics showed that 75-, 100-, and 150- μm -diam devices consistently showed favorable characteristics, including series resistances below 50 Ω ; in contrast, wire bonds to the 25- and 50- μm -diam devices failed to adhere to the contacts.

3. Test Results

The VCSELs were tested using a voltage source producing pulses typically 0.1 μs in duration at a 10-kHz repetition rate (i.e., a 0.1-percent duty cycle) connected to one of the VCSELs in series with a 50- Ω resistor and a 0.5- Ω test resistor; the voltage drop across the 0.5- Ω resistor determined the current through the VCSEL. For most of the power-current (L-I) characterization and for far-field measurements, a silicon photodiode was used as the detector. For spectral characterization (and for L-I characterization at a single wavelength), the output from the VCSEL was focussed onto the entrance slit of a 0.75-m monochromator (100- μm entrance and exit slits), dispersed through the monochromator, and imaged onto a liquid-nitrogen-cooled InAs photodetector. Figure 3(a) shows the L-I characteristics for several of the 100- μm -diam VCSELs and for one of the 150- μm -diam VCSELs. All the devices tested show sharp thresholds. In figure 3(b) we show the threshold current density J_{th} (i.e., the threshold current divided by the area) plotted as a function of the VCSEL diameter. J_{th} decreases with decreasing device diameter, possibly indicating the influence of parasitic transverse modes on the device operation. (The number of available transverse modes decreases

with decreasing device size.) Undercutting by the etch effectively decreases the device diameter, but this decrease is insufficient to account for the dependence of J_{th} on diameter. J_{th} is below 800 A/cm^2 for the $75\text{-}\mu\text{m}$ -diam VCSELs; we expect it to decrease even further with decreasing diameter. Testing this hypothesis will require a better wire bonding procedure or possibly using the more complex dry-etching or proton-implantation techniques to fabricate smaller VCSELs. Nevertheless, the results obtained here are comparable to the best obtained in similar structures [7].

Figure 3. (a) Light-output/current (L-I) characteristics of four $100\text{-}\mu\text{m}$ -diam VCSELs and one $150\text{-}\mu\text{m}$ -diam VCSEL; (b) threshold current density J_{th} plotted as a function of VCSEL diameter.

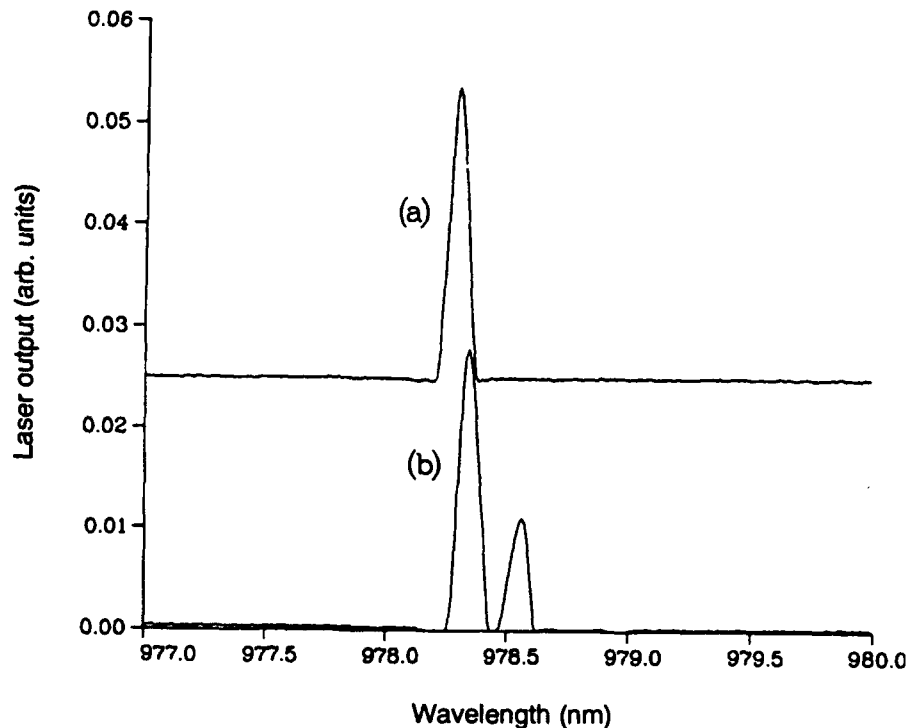


Typical spectra for 100- μm -diam VCSELs are shown in figure 4. In figure 4(a) we show a spectrum recorded under typical testing conditions—i.e., with 100- μs pulses. Under these conditions we are unable to resolve more than one mode, and the laser output shows a definite polarization (which is not necessarily coincident with one of the crystallographic axes). In addition, the far-field pattern consists of a single Gaussian-like mode with a full width at half maximum of less than 4° . In contrast, when the laser is driven with longer pulses (typically greater than 0.5- μs pulses; see fig. 4(b)), more than one mode can often be resolved, with some of the mode polarizations rotated 90° relative to the others. Examination of the laser output with a boxcar integrator indicates that the laser is switching from one mode to the other (and from one polarization to the other) as time progresses. As the pulse duration increases, the output power decreases and eventually goes to zero. We propose that these phenomena result from heating of the VCSEL active region and would not occur with properly heat-sunk devices.

4. Conclusions

We have shown that a simple fabrication process involving only a single wet-chemical-etch step can produce VCSELs with favorable operating characteristics, including threshold current densities as low as 800 A/cm^2 . At present we are fabricating smaller VCSEL structures from our MBE-grown structure using both ion etching

Figure 4. VCSEL spectra for (a) laser operating with a short ($1 \mu\text{s}$) pulse, showing an *apparent* single-mode operation and (b) laser operating with a long ($> 0.5 \mu\text{s}$) pulse, showing more than one mode.



and proton implantation to define devices. We also intend to examine a second $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ VCSEL structure, fabricated as described here, which has a substantial offset between wavelengths corresponding to the gain maximum and the cavity resonance. This structure should be more tolerant of heating effects [8] and may exhibit improved characteristics at high operating currents and longer pulse widths.

Acknowledgements

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