GaInNAs(Sb) vertical-cavity surface-emitting lasers at 1.460 μm

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We demonstrate a top emitting, electrically pumped, GaInNAsSb vertical-cavity surface-emitting laser (VCSEL) grown monolithically on GaAs, lasing pulsed at a wavelength of 1.460 μm, at a chuck temperature of $-10\,°\mathrm{C}$, with a threshold current of 550 mA (16 kA/cm^2) and a duty cycle of 0.1% for large mesas. Dilute nitrides, such as GaInNAs, have proven effective for lasers operating at 1.31 μm, but reaching longer wavelengths has proven difficult due to defects from low-temperature growth, surface roughening, and nitrogen-related defects. Reduction of oxygen contamination and careful attention to plasma conditions allow a similar extension to laser wavelength, by minimizing crystal defects introduced during growth. This is the first VCSEL on GaAs beyond 1.31 μm to date. © *2004 American Vacuum Society.* [DOI: 10.1116/1.1714940]

I. INTRODUCTION

Next-generation fiber networks and optical interconnects all require inexpensive small-band-gap lasers with wavelengths in the range of 1.2–1.6 μm, particularly vertical-cavity surface-emitting lasers (VCSELs). VCSELs offer significant advantages over edge-emitting diode lasers, such as wafer-scale testing and packaging, increased immunity to feedback, and two-dimensional arrays, with or without flip-chip bonding to complementary metal–oxide–semiconductor circuits. The distributed Bragg reflector (DBR) mirrors in a VCSEL also offer some degree of temperature stability, because the Fabry–Pérot cavity and mirror resonances shift only slowly with temperature compared to the peak gain of the active region. GaAs substrates offer several significant advantages for making VCSELs. They are relatively inexpensive, with mature processing available and good thermal conductivity. Most importantly, they offer a highly reflective, lattice-matched DBR through the use of alternating AlGaAs/GaAs layers, complete with a stable and selective oxide for making current apertures.[1]

In 1996, Kondow[2] discovered that nitrogen would decrease the band gap of GaAs, leading to the first continuous wave (cw) VCSELs at 1.2 and 1.3 μm.[3] Other approaches have included GaAsSb quantum wells (QWs)[4] and InAs quantum dots.[5] GaInNAs and related materials have recently been extended to allow bulk luminescence at wavelengths even beyond 1.6 μm and lasers near 1.5 μm. We demonstrate VCSELs operating pulsed at 1.460 μm when cooled to $-10\,°\mathrm{C}$. Although wavelengths near 1.55 μm are currently covered by InP-based edge-emitting lasers, these suffer from poor carrier confinement at high temperatures, compounded by poor thermal conductivity in the material. Also, although VCSELs have been fabricated on InP over a large range of wavelengths,[6] intensive backend processing was required for these methods, presenting difficulties for manufacturing.

In GaInNAs, nitrogen appears to introduce a highly localized resonant state in the conduction band of GaAs, and band anticrossing pushes the conduction-band edge down into the band gap.[7] In addition, because nitrogen is a small and highly electronegative atom forming short bonds, it reduces the lattice constant when incorporated in other III–V semiconductors. This allows for strain compensation, both within a layer, such as lattice-matched GaInNAs, and also with alternating compressive and tensile strained layers, such as GaNAs barriers surrounding high-indium GaInNAs quantum wells on GaAs.[8] However, although nitrogen dramatically decreases the band gap of the material, it also brings a host of associated defects, such as $\mathrm{As}_{\mathrm{Ga}}$, $(\mathrm{N{-}N})_{\mathrm{As}}$, vacancies, and other point defects. (See, for example, Krispin[9] for a list of many possible defects, with citations.) Identifying and removing[10] the sources of these defects has proven to be crucial to the development of our 1.5 μm edge-emitting lasers and the VCSELs presented here.

II. VERTICAL-CAVITY SURFACE-EMITTING LASER GROWTH AND PROCESSING

A schematic diagram of the VCSEL is shown in Fig. 1. The VCSEL consists of a bottom mirror, cavity, and top mirror, all epitaxially grown on $n+$ GaAs. The bottom mirror was composed of 29 alternating pairs of silicon-doped $\mathrm{Al}_{0.92}\mathrm{Ga}_{0.08}\mathrm{As}$ and GaAs, making a DBR. The cavity was a one-lambda thick layer of GaAs, designed for 1.485 μm, with three (QWs) at the center. The QWs were based on edge-emitting lasers which operated at wavelengths from 1.49 to 1.51 μm.[11] The QWs were 7 nm $\mathrm{Ga}_{0.62}\mathrm{In}_{0.38}\mathrm{N}_{0.016}\mathrm{As}_{0.958}\mathrm{Sb}_{0.026}$ with 20 nm GaNAs barriers below, between, and above the QWs. The composition reported here was determined from calculations by Volz based on secondary ion mass spectroscopy, x-ray diffraction, Rutherford backscattering (RBS), and nuclear reaction analysis-RBS.[12] The top DBR was p doped with carbon, and 24 pairs thick. A thin digital alloy of 98% aluminum was included as part of the second AlGaAs layer from the cavity. Nitrogen was supplied by an SVT Associates rf plasma cell at 300 W and 0.5 sccm. The Sb flux was 1.15×10^{-7} Torr, and the arsenic overpressure was 20 times the group-III flux in the quantum wells and 15 times elsewhere. Because the nitride molecular-beam epitaxy (MBE) system did not have

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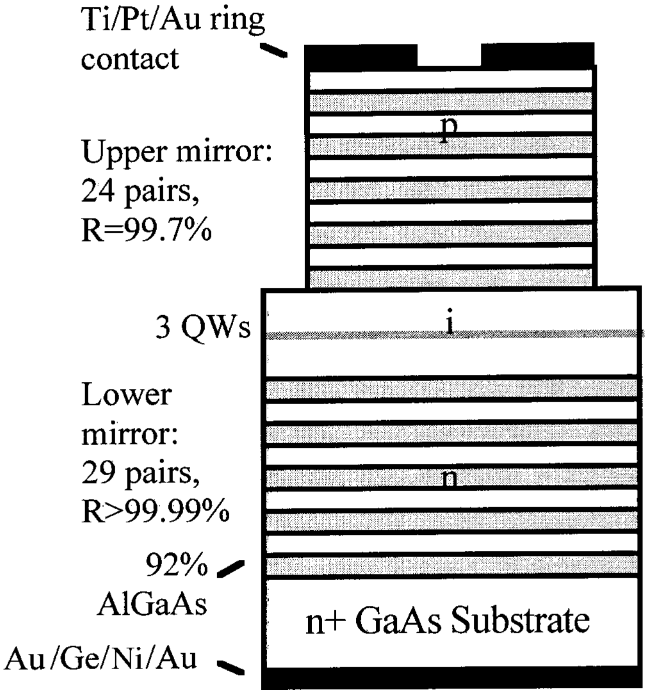

FIG. 1. Schematic cross section of VCSEL.

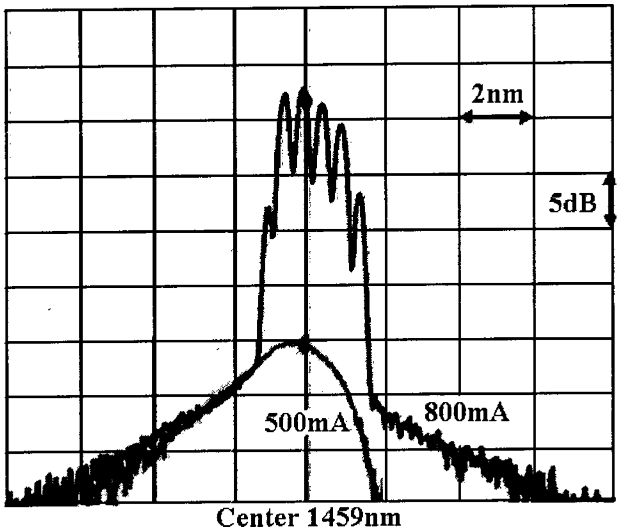

FIG. 2. Fiber-coupled spectrum of VCSEL pulsed at 500 mA (lower curve) and 800 mA (upper curve), showing onset of stimulated emission. Operated at 0.1% duty cycle and −10 °C, with 66 μm current aperture.

enough ports for multiple AlGaAs compositions, the DBRs were grown in a separate MBE machine and transferred under an ultrahigh vacuum.

Plasma conditions were optimized to minimize plasma damage during growth. A conventional lift-off process was used to define metal rings for the top contacts, and top and bottom metal were deposited in an evaporator. Unfortunately, the liftoff failed to remove the metal at the center of each mesa until the metal was thinned using aqua regia ($1{:}3\ HNO_3{:}HCl$). This step significantly damaged the metal and the wafer surface, leading to rough sidewalls and surfaces and adding significant scattering loss to the VCSELs. Even with the aqua regia etch, very few mesas smaller than 62 μm in diameter lifted off. Also, because the selective oxidation layer was too thin, it did not significantly oxidize, so rather than a single current-confining layer the top DBR oxidized uniformly about 10 μm inward. This added optical scattering losses and series resistance to the top DBR. The VCSELs were mounted epi-side-up on a copper chuck, cooled by a thermoelectric cooler, for testing.

III. VERTICAL-CAVITY SURFACE-EMITTING LASER RESULTS

Despite the above difficulties, the VCSELs lased in pulsed mode when cooled to a chuck temperature of −10 °C. Figure 2 shows the fiber-coupled power, as a function of wavelength, at 500 mA and 800 mA of peak current, showing the onset of stimulated emission. The VCSELs were pulsed at 0.1% duty cycle, with 2 μm pulses at a 500 Hz repetition rate. Multiple transverse modes are visible above threshold, due to the large 66 μm current aperture size of the VCSELs. The threshold current I_{th}, was 543 mA (pulsed), corresponding to current density J_{th} of 16 kA/cm^2, or 5.3 kA/cm^2 per QW. The VCSELs QWs were identical to the single QW from our earlier cw 1.49 μm edge-emitting lasers. Due to the lower operating temperature and a short cavity, the VCSELs lased at 1.46 μm, a significantly shorter wavelength. Microcavity emission from a similar structure showed that the growth of the top DBR only partially annealed the active region, but an additional rapid thermal anneal was required for peak photoluminescence.

Figure 3 shows a luminescence verse current curve. Neighboring VCSELs produced up to 33 μW peak (not shown). This modest power is surprisingly high given the problems outlined above and also the mismatch between the cavity resonance and the actual emission wavelength (gain peak). It is expected that better mounting techniques will reduce the need for such low cooling temperatures.

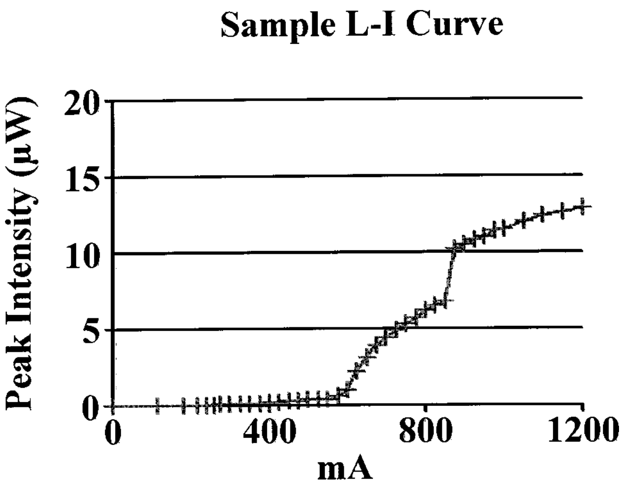

FIG. 3. Luminescence vs current curve. This particular device showed a kink at approximately 800 mA due to the onset of higher-order transverse modes.

IV. CONCLUSIONS

We have demonstrated the first VCSEL beyond 1.31 μm to date, operating at a wavelength of 1.46 μm in electrically pulsed mode. The VCSEL had a threshold current density of 16 kA/cm^2 for three QWs (5.3 kA/cm^2 per QW) on a large mesa size with a current aperture inner diameter of 66 μm, and operating at a chuck temperature of $-10\,°$C. The high thresholds are believed to be the result of poor processing techniques. We believe this validates our change in growth technique, which has been submitted for publication. Identifying and removing the sources of defects in our wafers were fundamental tasks in our ability to produce edge emitters and VCSELs near 1.5 μm.

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