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Vertical cavity lasers for optical interconnects

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ABSTRACT

Vertical-cavity surface-emitting lasers[1-7] are generating much interest due to their geometric suitability for two-dimensional array fabrication and their potential for achieving ultra-low thresholds. Here, we report on optically- and electrically-pumped microlaser devices. having transverse dimensions of a few microns and active material lengths of a few hundred Å. The very small volumes are a key factor in achieving low thresholds. So far however, surface recombination has prevented us from achieving thresholds much below 1 mA.

1. ELECTRICALLY PUMPED MICROLASERS

We have constructed more than one million electrically-pumped vertical-cavity surface-emitting μlasers with dimensions of a few μm on a single GaAs chip[3]. Cylindrical μlasers have diameters 1, 1.5, 2, 3, 4, and 5 μm with heights about 5.5 μm (Fig. 1). Device density is greater than two million per square cm. Cylindrical and rectangular-shaped devices of various sizes up to 100 μm across were also tested. The lowest thresholds were achieved in a single quantum well (SQW) structure and were 1.1 mA pulsed in a 4-μm diameter μ-laser, and 1.5 mA CW in a 5-μm square device[4]. The latter device, when treated to reduce surface recombination, showed a CW threshold of 1.0 mA. A 5-μm diameter three-quantum-well (3QW) device, similarly treated, had a 0.8 mA pulsed threshold. In most of the chips tested the 5-μm diameter devices had yields of 95-100%. Lasing was observed in 3QW μlasers as small as 1.5-μm in diameter with an active volume $<0.05\ \mu m^3$. In SQW μlasers $10\times10\ \mu m$ square, modulation of pseudorandom data streams at rates of 1 Gb/sec were demonstrated with $<10^{-10}$ bit error rates measured by the receiver. Sinusoidal modulation of 3QW lasers of the same size showed a -3 dB cutoff at >8 GHz.

Molecular beam epitaxy (MBE) was used to grow the two samples. Both substrates were GaAs Si-doped at $3\times10^{18}\ cm^{-3}$ on each of which alternate layers of AlAs and GaAs were grown, forming an interference mirror. These layers, each nominally a 1/4 wave optical thickness at 980 nm, were Si-doped, also at $3\times10^{18}\ cm^{-3}$. In the three-quantum-well (3QW) sample the undoped active region consists of three 80 Å $In_{0.2}Ga_{0.8}As$ quantum wells interleaved with four 100 Å GaAs barriers. The SQW sample had an undoped 100 Å $In_{0.2}Ga_{0.8}As$ active layer. Surrounding each active region are 200 Å compositionally graded undoped $Al_xGa_{1-x}As$ layers. Above and below the graded layer active region complex are spacer regions of doped $Al_{0.5}Ga_{0.5}As$ of thicknesses so that a full wave exists between mirrors. The second mirror was constructed similarly to the first except that Be was used as the dopant at $5\times10^{18}\ cm^{-3}$ density. In the 3QW (SQW) sample the Si-doped mirror had 20 1/2 (23 1/2) half-wave periods while the Be-doped mirror had 12 (15). The well/barrier nature of the heterostructure of the mirrors introduces high electrical resistivity. For this reason both mirrors, the Be-mirror in particular, had superlattices at the interfaces where the carriers had to climb up the potential barriers. The non-abrupt interfaces help reduce the electrical resistance without substantially degrading the reflectivity. Above the Be-doped mirror were grown a ~0.2 wave optical thickness of AlAs/superlattice and a 30-Å GaAs cap, both Be-doped at 5x10^{18} cm^{-3}. For low contact resistance, the cap was also delta-doped with 10^{13} cm^{-2} of Be. The cap layer was covered with unalloyed Au 1500 Å thick.

Standard contact photolithography with liftoff was used to create spots of Ni 1 to 5 μm diameter and 5-200 μm square on the Au. Chemically-assisted ion beam etching (CAIBE) was used to etch through the Au and the 5-6 μm heterostructure, leaving the Ni covered areas[6]. The Ni (etch mask) thickness was about 1500 Å and it barely eroded away. Residual Ni should have no significant effect on laser operation. The other side of substrate was polished and a wire serving as ground was spot welded to it. Positive voltage pulses were applied to the Au caps using a small probe tip of radius ~5 μm. Laser outputs went through the 500-μm-thick substrate and out the polished side. The configuration is shown is Fig. 2.

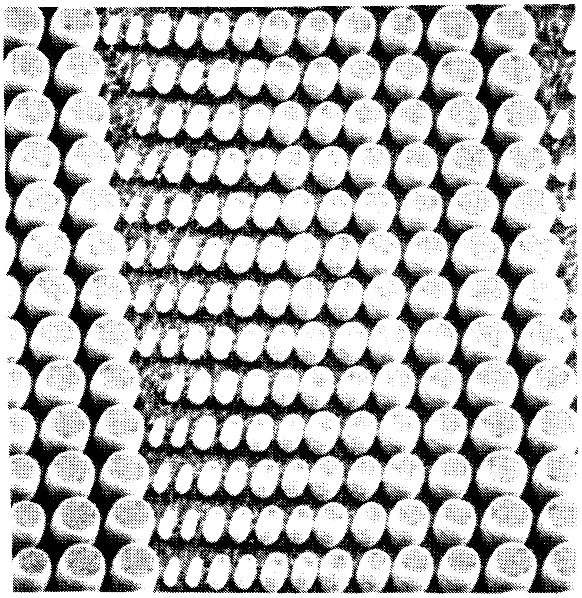

Fig.1 - Small portion of an array of μlasers.

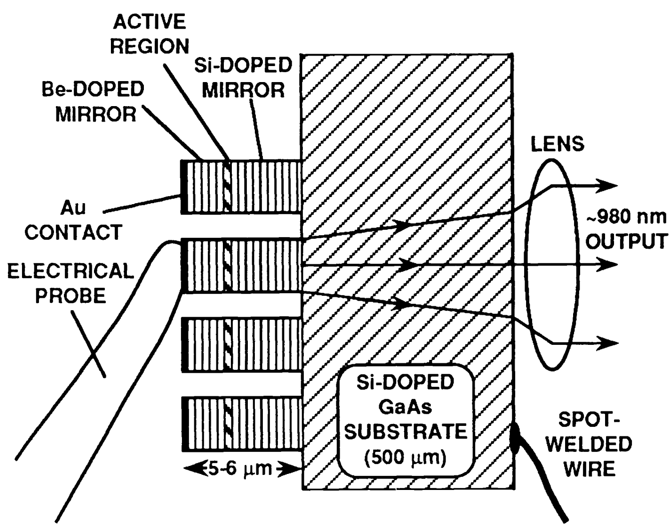

Fig. 2 - Schematic of the electrical pumping and optical output. Devices are enlarged to show detail.

1.1 Microlaser Results

All experiments were performed at room temperature. For all lasers below threshold the luminescence was unpolarized, while above threshold the laser light was linearly polarized. Slight asymmetry in the structures, rather than crystal orientation appears to cause the polarization as with previous optically-pumped microlasers[8]. Figure 3 displays output light at 958 nm vs. driving current for a 3-μm 3QW μlaser on the first chip tested. Voltage pulses were 50 ns long at low duty cycle. The measured single-facet differential quantum efficiency was about 16% despite some absorption of the laser output in the doped substrate. At threshold the voltage was about 15 V rising to 20 V at 3.5 mA. The 5-μm 3QW μlasers required about 8 V and 2 mA for threshold. 4-μm diameter SQW μlasers had typical pulsed thresholds of 1.1 mA with ~7 % differential quantum efficiency. Other devices were etched to a level slightly below the active layer, resulting in lower electrical resistance and higher thermal conductivity[4]. Diffractive losses in the non-waveguiding part of the bottom mirror were sufficiently small in ≥ 5 μm devices to be negligible. Room-temperature CW operation was achieved in these devices with no heat-sinking applied. The main heat flow was conduction through the bottom mirror into the substrate. Fig. 4 shows the input/output of a 5-μm square device having a 1.5 mA threshold and 5 volts applied. The wavelength was 983 nm with a measured width of 3.5 Å limited by the spectrometer resolution. A 7-μm diameter 3QW laser had a CW threshold 2.5 mA at 4 V and output over 0.3 mW with 6 mA current. The same device, at 1% duty cycle, had 18 mW peak output power and >28 % differential quantum efficiency (Fig. 5).

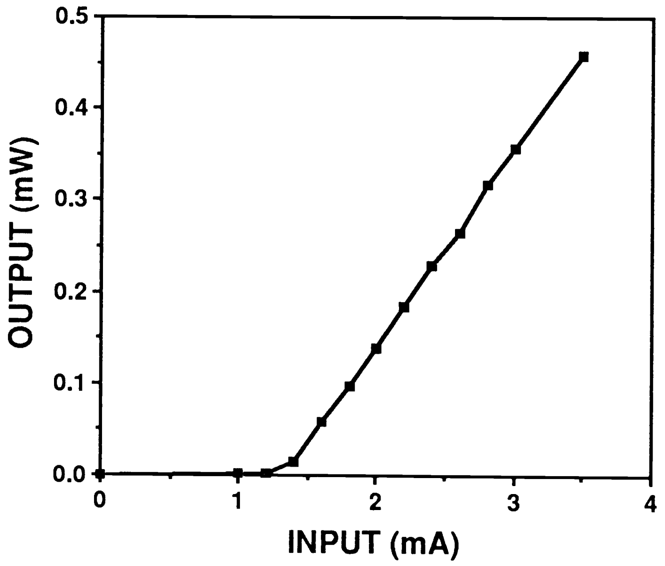

Fig. 3 - Pulsed output light vs. current in a 3-μm diameter 3QW μlaser. Differential quantum efficiency is ~16 %.

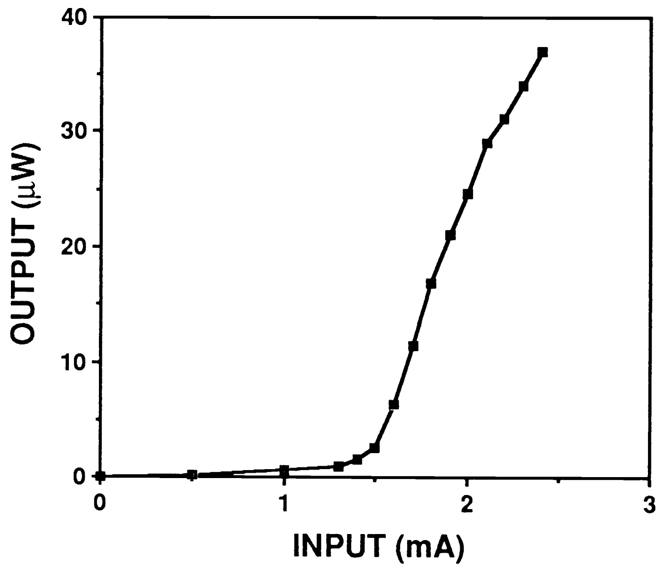

Fig. 4 - Room-temperature CW input/output for a 5-μm diameter SQW μlaser with no applied heatsinking.

Modulation speeds of the CW-operating SQW lasers were tested using a 3 GHz coaxial probe tip and a pseudorandom pulse generator. A 50 Ω resistor and 0.1 μf chip capacitor wired onto the probe tip supressed large reflections from the highly resistive devices. The data was continuously incident on the μlaser with no gating. Despite electrical limitations due to detector speed and long wire lengths we obtained bit error rates $<10^{-10}$ at a modulation speed of 1 Gb/sec from a 10 μm square laser. Fig. 6 shows the wide open eye diagram and the direct laser output. We saw a clear trend of smaller μlasers showing faster modulation capability presumably due to their lower capacitance. Due to the probe tip size and spacing of the devices we were unable to contact the 5-μm lasers without also touching the larger ones. Sinusoidal modulation experiments were performed on 10 μm square 3QW lasers with very low inductance mountings. To a CW bias current was added a small sinusoidal modulation. Modulation of the laser output was then monitored as a function of the current modulation frequency. A typical result is shown in Fig. 7 with the output modulation falling to -3 dB at >8 GHz. The same devices showed gain switching times of about 25 ps produced by a 2 GHz sinusoidal current pump and observed with a streak camera. Micron-diameter μlasers packaged in an integrated circuit driver should be capable of many Gb/sec operation.

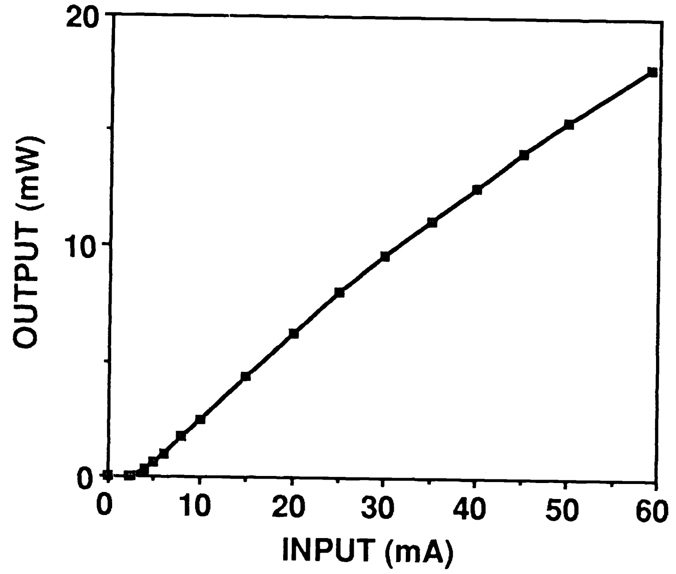

Fig 5 - Peak input/output for a 7-μm diameter 3QW μlaser run at 1 % duty cycle. Differential quantum efficiency is $\sim$28 %.

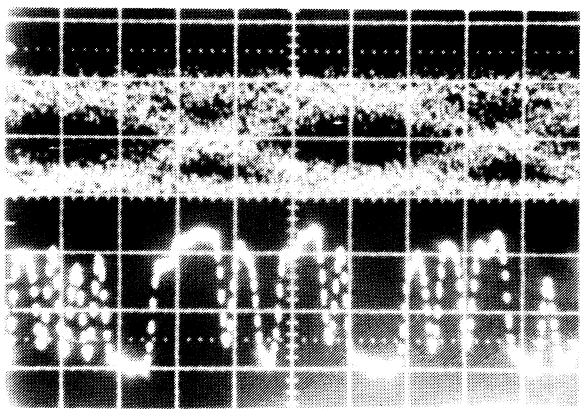

Fig. 6 - (Upper trace) Eye diagram of 1.0 Gb/sec modulation of a 10-μm$\times$10-μm SQW μlaser. Time scale is 200 ps/div. (Lower trace) Direct laser output of the continuous stream of pseudorandom bit-generated data. (5 ns/div)

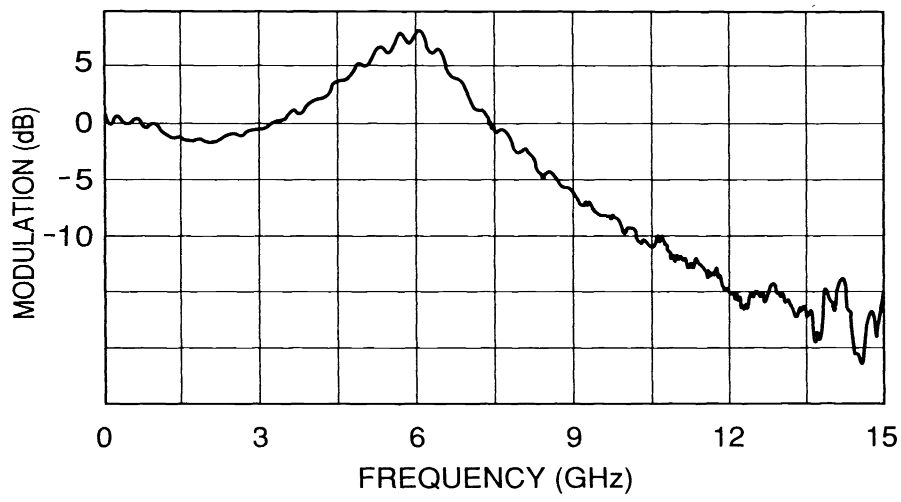

Fig. 7 - Modulation vs. frequency for a continuously-driven 10-μm square 3QW laser. The -3 dB cutoff is $\sim$3 GHz.

We saw lasing in μlasers as small as 1.5 μm diameter with an active material volume less than $0.05\mu m^3$ in the 3QW sample. They typically required 2.3 mA and 27 volts for threshold. The current is higher than that required for the 3- and 5-μm devices because surface recombination[10] on the sidewalls greatly reduces the carrier lifetimes. The expected 1/e lifetime in 1.5 μm diameter devices is $<$100 ps if the recombination velocity in $In_{0.2}Ga_{0.8}As$ is as large as that of GaAs. The high current density coupled with the high resistance of this small diameter causes the 27 V requirement.

Both the current thresholds and voltages can be greatly reduced in μlasers. Techniques are developing which can supress surface recombination[9]. We have tried a Se-based chemical passivation on some deeply etched 3QW lasers. Figure 8 shows the characteristic for pulsed operation with submilliamp threshold in a 5-μm diameter μlaser. The 0.8 mA threshold is only about a factor of two less than the threshold before the chemical treatment, a much smaller improvement than hoped for. The improvement appears to be fairly permanent since it has not degraded for more than 6 months. True passivation of the sidewalls should have produced a larger improvement; also the solution used was not expected to last more than a few days. Most likely the chemical simply removed part of the outer sidewall material which had been damaged by the CAIBE processing, and any true passivation did not last long enough for us to observe. 2-μm diameter devices do still lase with 1.0 mA pulsed threshold. Another group[7] using SQW structures similar to ours has achieved 0.7 mA CW threshold at room temperature without passivation.

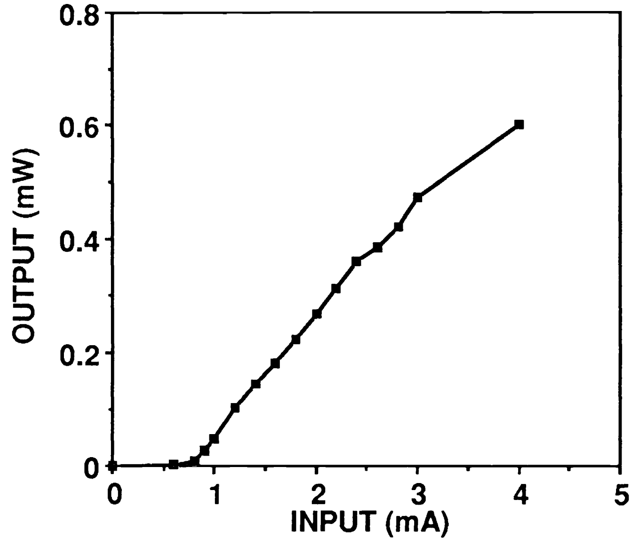

Fig. 8 - Pulsed light/current response with 0.8 mA threshold for a 5-μm diameter 3QW μlaser with some damaged sidewall material removed by chemical etching. Threshold before treatment was 1.5 mA.

The ability to pass the laser output through the substrate allows us to use the geometry of Fig. 2, which is well-suited for micro-optic integration[11]. The output collecting lens can be replaced by lenslets with diameters on the order of 100 μm formed on the substrate back side by etching processes. These processes are non-labor-intensive and will help minimize packaging costs. Furthermore the high numerical apertures, made possible by the very high refractive index of semiconductors, are ideal for coupling in or out of ultra-small devices. Extremely compact optical systems to image data from one array of devices to another with transit times $\sim$10 ps or less[11] can be built with this technology.

2. OPTICALLY PUMPED MICROLASERS

We previously reported the characteristics of optically pumped microlasers[8] with thick (1.6 μm) bulk GaAs active regions and diameters as small as 1.5 μm. Now we have preliminary results of structures with a single $In_{0.2}Ga_{0.8}As$ quantum well and diameters down to about 0.5 μm. Even in these smallest structures, lasing is observed in a single transverse and longitudinal mode. Nearby 1- and 2-μm diameter devices showed a multitude of transverse modes, as expected from previous work on micron and submicron diameter microresonators[12]. It is encouraging that in such small cavities (0.5 μm diameter is smaller than the light's wavelength in air) the losses are still low enough to allow lasing with a single quantum well active layer. In half-micron and smaller-diameter cavities the fraction of photons spontaneously emitted into the laser mode can be orders of magnitude larger than for conventional lasers[13] and even approach unity. This effect can result in extremely low thresholds with speeds much higher than could be achieved in larger cavities.

3. CONCLUSION

We have shown that it is possible to fabricate μlasers in quantities of $> 10^6$ on centimeter size chips. The yields for devices about 5 μm diameter is very high, thresholds are in the mA range and speeds >1 Gb/sec have been demonstrated. Passivation should result in $\sim$10 μA thresholds. Series resistance in the mirrors needs to be reduced to realize practical devices. The $\sim$0.96 μm wavelength is well-suited for microoptic integration with GaAs lenslets.

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