Surface-emitting microlasers for photonic switching and interchip connections

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Abstract. Vertical-cavity electrically pumped surface-emitting microlasers are formed on GaAs substrates at densities greater than two million per square centimeter. Two wafers were grown with $In_{0.2}Ga_{0.8}As$ active material composing three 80 Å thick quantum wells in one and a single quantum well (SQW) 100 Å thick in the other. Lasing was seen in devices as small as 1.5 μm diameter with $<0.05\ \mu m^3$ active material. SQW microlasers 5 × 5 μm square had room-temperature cw current thresholds as low as 1.5 mA with 983 nm output wavelength. 10 × 10 μm square SQW microlasers were modulated by a pseudorandom bit generator at 1 Gb/s with less than 10^{-10} bit error rate. Pulsed output >170 mW was obtained from a 100 μm square device. The laser output passes through the nominally transparent substrate and out its back side, a configuration well suited for micro-optic integration and photonic switching and interchip connections.

Subject terms: photonic switching and interconnects; low-threshold lasers; surface-emitting lasers; photonic switching; optical logic devices.

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Vertical-cavity surface-emitting lasers[1–4] show promise for a variety of applications. High-power, low-cost laser sources might result from large coherently coupled arrays. Small arrays could accomplish high-speed communication between electronic chips, overcoming a bottleneck that presently limits the speed of computers. In the longer term, arrays of laser-based logic gates may be used for photonic switching in communication networks or for digital or neural computing. In these information processing applications, minimizing the threshold is essential. The lowest threshold edge-emitting lasers[5–7] contain a single quantum well (SQW) and require approximately 0.55 mA. Minimum thresholds will be attained by minimizing the volume of active material in the laser, which in turn requires high-reflectivity mirrors. GaAs-AlAs mirrors grown by molecular beam epitaxy (MBE) have achieved extremely high reflectivity (>99%), high enough to achieve optically pumped lasing in a vertical cavity with an 80 Å thick SQW active layer.[8] Chemically assisted ion beam etching (CAIBE) can form waveguiding pillars in such heterostructures with micron dimensions, and optically pumped lasers with 1.5 μm diameters were demonstrated.[9] Use of these technologies is effective in fabricating[10] ultra-small microlasers (μlasers). In this paper we discuss our initial experiments with μlasers, which achieved room-temperature cw thresholds lower than any previous surface emitters and nearly as low as the best edge emitters and the fastest modulation speed demonstrated for surface emitters.

We have constructed more than one million vertical-cavity electrically pumped surface-emitting μlasers with dimensions of a few μm on a single GaAs chip.[11] 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 centimeter with a typical chip size about 7 × 8 mm.[2] Circular and square-topped devices of various sizes up to 100 μm across were also tested. The lowest thresholds were achieved in a SQW structure and were 1.1 mA pulsed in a 4 μm diameter μlaser and 1.5 mA cw in a 5 μm square device. In most of the chips

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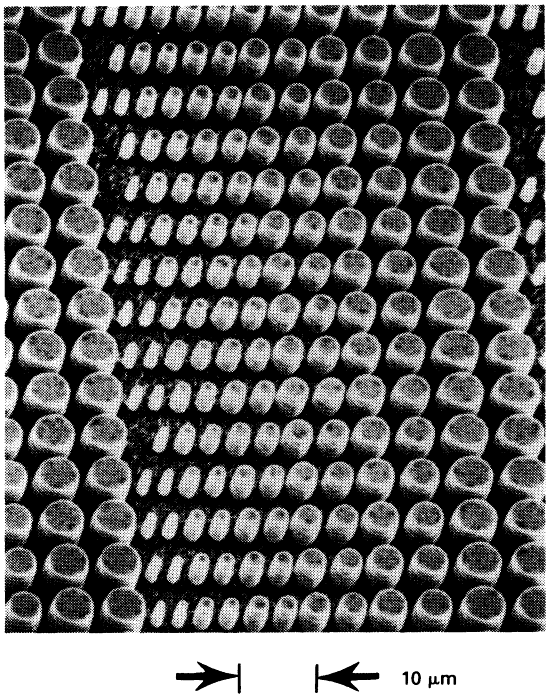

Fig. 1. Small portion of an array of μlasers.

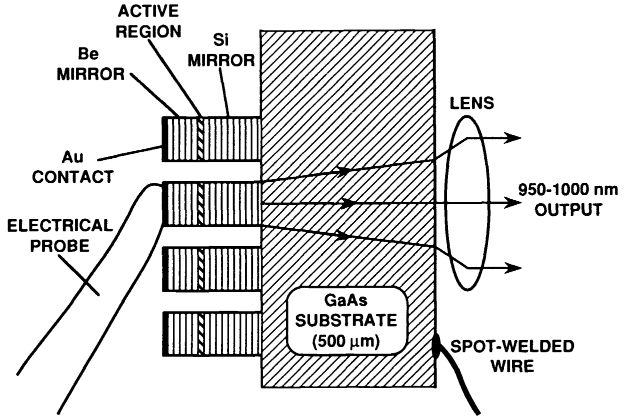

Fig. 2. Schematic of the electrical pumping and optical output. Devices are enlarged to show detail.

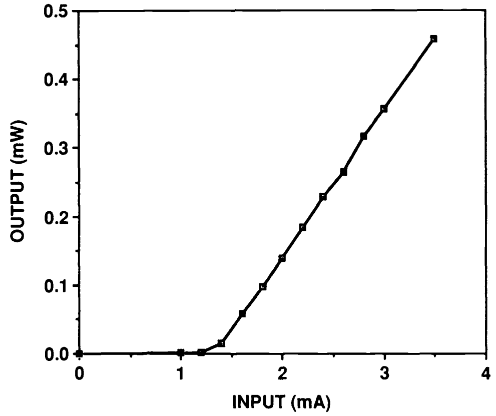

Fig. 3. Pulsed output light vs current in a 3 μm diameter 3QW μlaser. The differential quantum efficiency is ~16%.

tested the 5 μm diameter devices had yields of 95% to 100%. Lasing was observed in three-quantum-well (3QW) μlasers as small as 1.5 μm in diameter with an active volume <0.05 μm^3. Modulation rates of 1 Gb/s were demonstrated with $<10^{-10}$ bit error rates measured by the receiver.

MBE was used to grow the two samples. Both substrates were GaAs Si doped at 3×10^{18} cm^{-3}, on each of which alternate layers of AlAs and GaAs were grown, forming an interference mirror. These layers, each nominally a quarter-wave optical thickness at 980 nm, were Si doped, also at 3×10^{18} cm^{-3}. In the 3QW sample the undoped active region consists of three 80 Å $\mathrm{In_{0.2}Ga_{0.8}As}$ quantum wells interleaved with four 100 Å GaAs barriers. The SQW sample had an undoped 100 Å $\mathrm{In_{0.2}Ga_{0.8}As}$ active layer. Surrounding each active region are 200 Å compositionally graded[12] undoped $\mathrm{Al_xGa_{1-x}As}$ layers. Above and below the graded layer active region complex are spacer regions of doped $\mathrm{Al_{0.5}Ga_{0.5}As}$ 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 5×10^{18} cm^{-3} density. In the 3QW (SQW) sample the Si-doped mirror had 20.5 (23.5) half-wave periods, while the Be-doped 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 at which the carriers had to climb up the potential barriers. The nonabrupt interfaces help reduce the electrical resistance[13] without substantially degrading the reflectivity.[14] Above the Be-doped mirror were grown an ~0.2 wave optical thickness of AlAs/superlattice and a 30 Å GaAs cap, both Be doped at 5×10^{18} cm^{-3}. For low-contact resistance, the cap was also delta doped[15] 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 to 200 μm square on the Au. CAIBE was used to etch through the Au and the 5 to 6 μm heterostructure, leaving the Ni covered areas. 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 in Fig. 2.

All experiments were performed at room temperature. In all structures, 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 μlasers.[9] Figure 3 displays output light at 958 nm versus 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. The 4 μm diameter SQW μlasers had typical pulsed

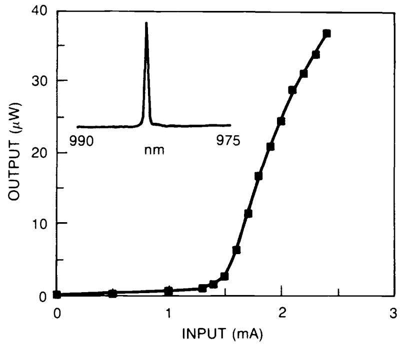

Fig. 4. Room-temperature cw output/input for a 5 μm square μlaser with no applied heatsinking. Inset shows the spectrum with a measured linewidth 3.5 Å equal to the spectrometer resolution.

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.[16] Diffractive losses in the nonwaveguiding bottom mirror were sufficiently small in the ≥5 μm devices to be negligible. Room-temperature cw operation was achieved in these devices with no heatsinking applied. The main heat flow was conduction through the bottom mirror into the substrate. Figure 4 shows the input/output of a 5 μm square device having a 1.5 mA threshold and 5 V 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.

Modulation speeds of 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 suppressed large reflections from the highly resistive devices. 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/s from a 10 μm square laser. Figure 5 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. More recently, sinusoidal modulation experiments were performed (by R. S. Tucker and C. A. Burrus) with the output modulation falling to -3 dB at 8 GHz in a 10×10 μm 3QW μlaser. Micrometer-diameter μlasers packaged in an integrated circuit driver should be capable of many Gb/s operation.

The highest power obtained was 170 mW peak and about 4 mW average from a 100 μm × 100 μm (10^4 μm^2) device. Since this size is much larger than the diffractive spreading area of about 400 μm^2 expected from our cavity effective thickness and finesse,[8] the light output was nonuniform. Nearly as much peak power was obtained by Zinkiewicz et al. in a 35 μm diameter structure.[17] Higher power with greater efficiency is expected from two-dimensional arrays of lasers, 10 to 20 μm in diameter, which are coherently coupled by an external mirror located at a Talbot self-imaging plane.[18,19]

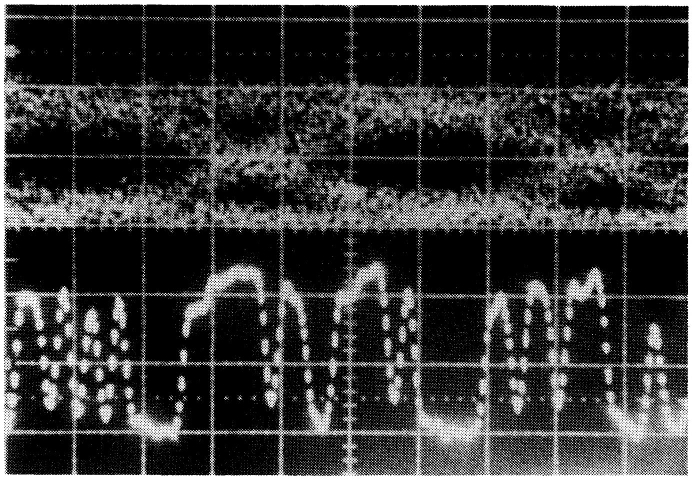

Fig. 5. (Upper trace) Eye diagram of 1.0 Gb/s modulation of a 10 μm square SQW laser by a pseudorandom bit generator; time scale is 200 ps/div. (Lower trace) Direct laser output of the data on 5 ns/div scale.

We saw lasing in μlasers as small as 1.5 μm diameter with an active material volume less than 0.05 μm^3 in the 3QW sample. They typically required 2.3 mA and 27 V for threshold. The current is higher than that required for the 3 and 5 μm devices because surface recombination[20] 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 voltages and currents can be greatly reduced in μlasers. Techniques are developing that can suppress surface recombination.[21] This should increase the carrier lifetimes by more than an order of magnitude in the smallest μlasers, thus decreasing both current and excess voltage by a similar amount. Since these wafers are the first two we tried, they are not optimized, and optical absorption in the cavity is believed to be the main cause for threshold current densities >1 kA/cm^2 in all of the devices. Quantum efficiencies can also be improved. Since the absorption coefficient in our substrate is around 10 cm^{-1} and its thickness is ~500 μm, we expect only 60% transmission through it and we expect our measured values of output to be reduced by this factor. Optical pumping in undoped structures containing a SQW[8] and multiple quantum wells with periodic gain[22,23] have yielded quantum efficiencies much higher[24] than the devices reported here. This is due to the smaller ratio of mirror transmission to absorption loss in the present structures. Since the best edge emitters require only on the order of 100 A/cm^2 there is much room for optimization to reduce both the current and voltages. Lateral current injection could overcome both problems of absorption (since the mirrors would not need to be doped) and high resistance, but it requires much more sophisticated fabrication. Application of some or all of the above techniques should produce μlasers with thresholds less than 10 μA.

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.[25] 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.[26,27] These processes are non-labor-intensive and will help minimize packaging costs. Furthermore, the high numerical apertures,

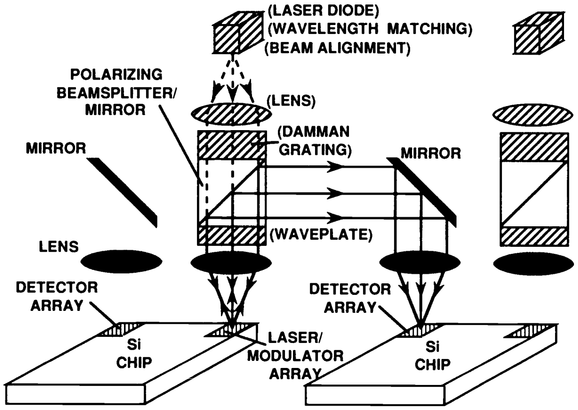

Fig. 6. Example of free-space minimum-component PICC layout for lasers or modulators. Components marked by diagonal hatching (with labels in parentheses) are eliminated when lasers are used instead of modulators and the polarizing beamsplitter is replaced by a simple mirror. Wavelength matching and beam alignment of the external laser diode to the modulators become unnecessary also.

made possible by the very high refractive index of semiconductors, are ideal for coupling in or out of ultra-small devices.[25,28] Extremely compact optical systems to image data from one array of devices to another with transit times $\sim$10 ps or less[25] can be built with this technology.

The suitability of optics, from an energy standpoint, for performing communications of data over all but the shortest distances (i.e., between nearby gates) is discussed by Miller.[29] Other analyses are given by Goodman et al.[30] and by Feldman et al.[31] Tsang[32] has demonstrated a free-space optical interconnection between boards with a 1 Gb/s data rate and determined the alignment tolerances necessary for reliable operation. Most schemes for optical communication between chips involve either lasers or electro-optic modulators. Symmetric self-electro-optic effect device based modulators working at GaAs wavelengths have become available in the last few years,[33] and photonic interchip connections (PICC) based on them have been constructed.[34,35] Since lasers are light sources that directly convert electronic data into optical signals, they have several distinct advantages over modulators. A minimum-component "free-space" PICC arrangement [34,35] using lasers or modulators is shown in Fig. 6. PICC schemes that rely on any type of modulator necessarily involve components such as external laser sources, Damman gratings to split the beam into many beams, quarter-wave plates, and polarizing beamsplitters. These components, which tend to be expensive and difficult to assemble, are not needed in a laser-based PICC system. Alignment of the external laser is no longer an issue, nor is its precise wavelength matching to the modulator response. These advantages are present whether the interconnection uses free space or fibers, and the arguments are also valid in comparing requirements for free-space optical computing systems. All-optical logic devices[36] may be viewed as optically driven optical modulators needing the same external lasers, polarizers, etc. as electro-optic modulators.[25] To be practical, however, the laser operating energy per bit of information transmitted must be much lower than that required for electronic connections and at least comparable to modulator energy requirements. Competitive PICC lasers should have thresholds on the order of 100 μA or less with switching times $\sim$100 ps and $\leq$5 V applied. We expect these goals to be achieved and surpassed in near-future developments of μlasers. Microlasers for optical logic devices have even higher performance requirements.

In conclusion, we have demonstrated the smallest lasers made so far. The active volume is as low as 0.05 μm^3 compared with $>$1 μm^3 for edge emitters and $>$10 μm^3 for all previous surface emitters, while the entire μlaser is only 1.5 μm diameter by 5.5 μm long. Room-temperature cw thresholds of 1.5 mA are the lowest demonstrated in surface emitters despite a lack of efficient heatsinking and are only a few times greater than that for the most highly optimized edge emitters. Modulation speeds in excess of 1 Gb/s by pseudorandom pulse generators are the fastest demonstrated for any surface emitter. Orders-of-magnitude improvement is expected in the thresholds of the smallest μlasers through reducing absorption and passivating the sidewalls to suppress surface recombination.

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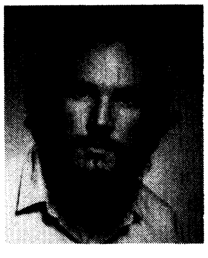
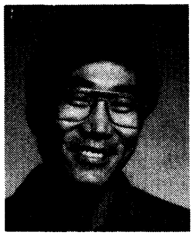


Jack Jewell has been working on optical computing logic devices for more than nine years, beginning at the University of Arizona, where he completed his Ph.D. in optical sciences. He then started work at AT&T Bell Laboratories in 1984. Since late 1986, in collaboration with Bellcore, Dr. Jewell has investigated GaAs "microresonators," first as all-optical gates, and most recently as electrically pumped microlasers.



Yong H. Lee was born in Ahndong, Korea, in 1955. He graduated from Seoul National University in 1977. Dr. Lee received the MS degree in applied physics from the Korea Advanced Institute of Science and Technology in 1979 and the Ph.D. degree in optical sciences from the University of Arizona in 1986. In 1987, he joined the Optical Computing Research Department of AT&T Bell Laboratories, where he has been working on optical logic devices, MQW GaAs dispersive modulators, and semiconductor optical nonlinearities. Dr. Lee is currently involved in research on 2-D arrays of very low threshold surface emitting microlasers and their application to optical switching and computing.

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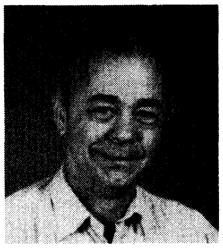

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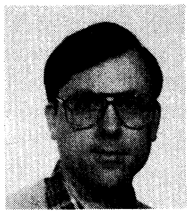
N. Anders Olsson is currently head of the Solid State and Quantum Optics Research Department at AT&T Bell Laboratories. His current research interests include optical amplifiers, coherent communication, and narrow linewidth semiconductor laser sources. Dr. Olsson received his MS in applied physics from Chalmers University of Technology, Gothenburg, Sweden, and his Ph.D. in electrical engineering from Cornell University in 1975 and 1982, respectively. Between 1975 and 1977 he was with Schlumberger Overseas SA, Singapore.



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