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Lasing characteristics of GaAs microresonators

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Lasing characteristics of optically pumped 1.5-μm-diam GaAs-AlAs microresonators are reported. Room-temperature thresholds of 9 pJ were observed. Uniform outputs were obtained from a simultaneously driven 2×2 array.

For future chip-to-chip data transfer and other data communication applications, ultra-low-threshold high-speed lasers represent a promising technology.[1,2] Clearly, high reflectivity cavity mirrors are desirable for lowering thresholds as demonstrated for quantum well lasers in Ref. 2. The choice of surface- or edge-emitting geometries may depend on a particular application. Surface-emitting geometries with vertical cavities are well suited for high finesse[3] (high reflectivity) structures as well as for precisely controlled short cavity lengths.[4,5] Here we report the lasing characteristics of optically pumped GaAs-AlAs microresonators[5,6] fabricated by molecular beam epitaxy (MBE) and ion beam assisted etching.

The MBE growth upon a GaAs substrate consists of 9 1/2 pairs of AlAs/GaAs layers 813 Å/594 Å thick (quarter-wave-stack mirror) followed by a 1.6 μm GaAs spacer and 7 more AlAs/GaAs pairs for a total thickness of $\sim 4\,\mu$m. This design yields approximately equal mirror reflectivities of 90% at the lasing wavelength when the structure is intact on the substrate. Pump wavelengths were outside the mirrors' stopband. We deliberately grew layers so that the GaAs and AlAs thicknesses varied over the sample area. The etching was accomplished in a 5:2 Ar:Cl_2 gas mixture at 8×10^{-4} Torr. With 1500 V between the electrodes the etch rate was $\sim 1\,\mu$m/min. As seen in Fig. 1 the devices have vertical walls despite the deep etch and extreme variation (0–100%) in Al concentration. The mask contained circular and square features 1.5–5 μm across which were transferred to the wafer by contact optical lithography.

The sample was designed for optical bistability,[6] not for optically pumped lasers. As seen in Fig. 2, the top mirror contains GaAs and, therefore, absorbed some of the incident pump light. We believe that lasing mainly occurred in the 1.6 μm GaAs spacer layer with some contribution from nearby GaAs in the top mirror. Surfaces left after our etching have high surface recombination velocities, producing[5] carrier lifetimes of ~ 100 ps. Pump pulses were of ~ 10 ps duration; thus our inputs and outputs are given in energy units.

Pump pulses were produced by a mode-locked dye laser synchronously pumped by a mode-locked Nd:YAG laser running at 82 MHz continually. Output pulse energies were ~ 125 pJ at 809 nm wavelength. This wavelength is at a reflection minimum of the input (top) mirror and produced the lowest thresholds. The absorbing GaAs substrate was not removed. Lasing outputs were observed only through the top pump input mirror (Fig. 2). The pump beam was focused onto microresonators using a 0.41 numerical aperture lens.[7]

Figure 3 shows the output/input curve for a microresonator with 9 pJ threshold and $>10\%$ single-facet slope efficiency. The reduction in slope efficiency at pump energies >20 pJ may be due to any or a combination of effects, such as dynamic cavity tuning due to pump induced refractive index changes or transverse mode competition or degradation of the alignment. Thresholds remained constant when the pump pulse width was varied between 5 and 20 ps, consistent with a carrier recombination time of ~ 100 ps.

Typical spectra are shown in Fig. 4 just above and many times threshold (~ 110 pJ). As the pump energy was increased from theshold, the laser spectrum broadened towards shorter wavelengths. In this case an acoustic-optic modulator gating the pump pulses allowed only one lasing pulse approximately every 30 μs. The observed broadening, therefore, must occur during each lasing pulse. We attribute these frequency shifts to refractive index changes during the lasing action as explained by Marcuse and Wiesenfeld.[8] At higher pump energies, higher order transverse modes appear as seen in Fig. 4 at ~ 8630 Å and probably at ~ 8480 Å. The mode at ~ 8630 Å cannot be a different longitudinal mode because the microresonator length is too small. The same remark probably applies at 8480 Å.

With the pump beam aligned for minimum threshold, the output had the appearance of a TEM_{00} mode. However, with a slight misalignment, a TEM_{01} mode (double-lobed) lased with a higher threshold instead; other transverse modes were not observed. Microlaser outputs were always

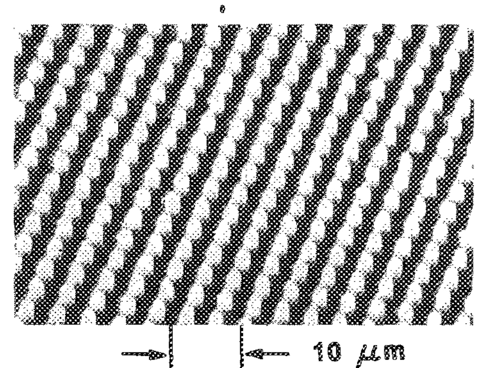

FIG. 1. Small section of an array of microresonators.

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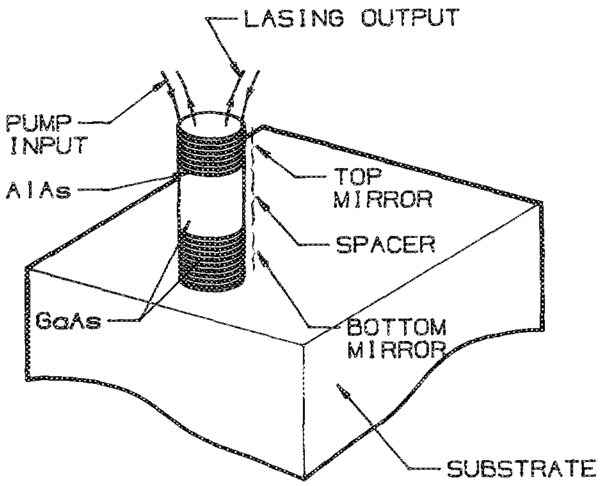

FIG. 2. Schematic diagram of lasing microresonator. Dark regions represent AlAs; lighter regions represent GaAs.

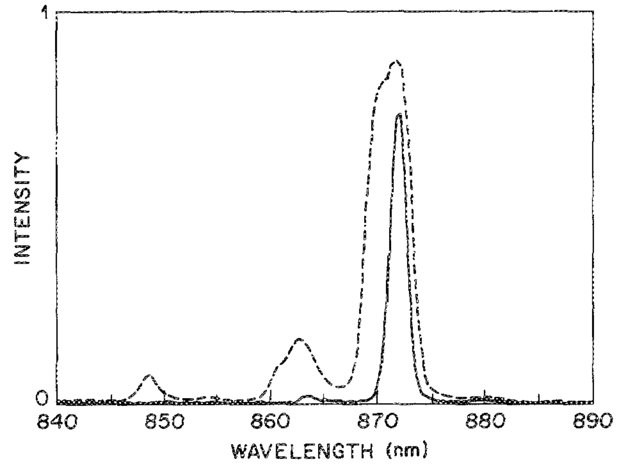

FIG. 4. Typical spectra for a single microlaser near (solid) and well above (dotted) threshold. The vertical scales differ.

observed to be linearly polarized with an orientation which varied apparently randomly from one microlaser to another. This is surely due to slight asymmetries in the microresonators. Rotating the pump polarization had no apparent effect on the lasing output polarization. Polarization direction could be controllable by using rectangularly or elliptically shaped devices.

Using two Wollaston prisms with a quarter-wave plate between them, a 2×2 array of pump beams was produced which drove four simultaneously lasing microresonators as seen in Fig. 5. The microlaser array center-to-center spacing was 9 μm, at the corners of a 4×4 array of microresonators having 3 μm center-to-center spacing. Each pump input was about 15 pJ. A spectrum of the four outputs combined has the same appearance as the just above threshold spectrum of Fig. 4 with a 25 Å linewidth.

By deflecting a long train of pump pulses with the acoustic-optic modulator to drive a microlaser, the laser output was observed to shift to longer wavelengths. Near threshold, the shift was 25 Å corresponding to a 10 °C temperature rise. By observing the amount of shift with pump pulse train length, we found that equilibration occurred after about 15 μs.

The ultra-low-threshold laser reported by Lau *et al.*[2] had an energy threshold of 1 pJ, only nine times smaller than ours. We emphasize that our result came from a first attempt with structures not designed for optimal lasing characteristics. We anticipate dramatic reductions in threshold with the following straightforward improvements: (1) nonabsorbing mirrors, (2) higher[3] finesse, (3) use of quantum well materials, and (4) reduction[9,10] of cross-sectional area by as much as a factor of 36. The factor 36 corresponds to a diameter of 0.25 μm. There are no confined propagating modes for GaAs diameters less than ~0.22 μm. For chip-to-chip communication, lasers should be electrically driven. The improvements listed above will also improve such electrically

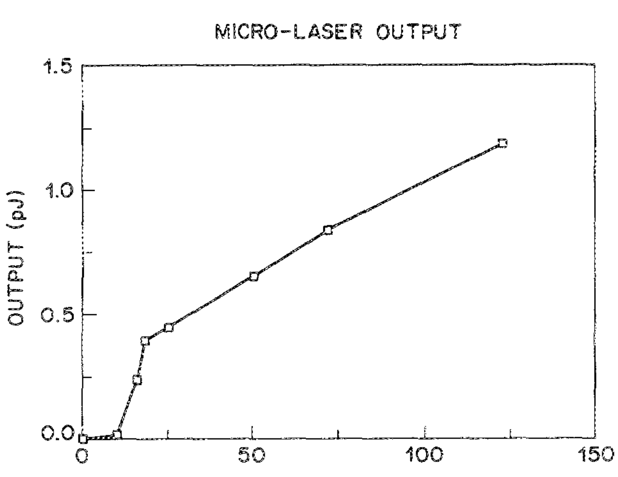

FIG. 3. Output/input curve for a microlaser. A 9 pJ threshold and > 10% single-facet slope efficiency near threshold was observed.

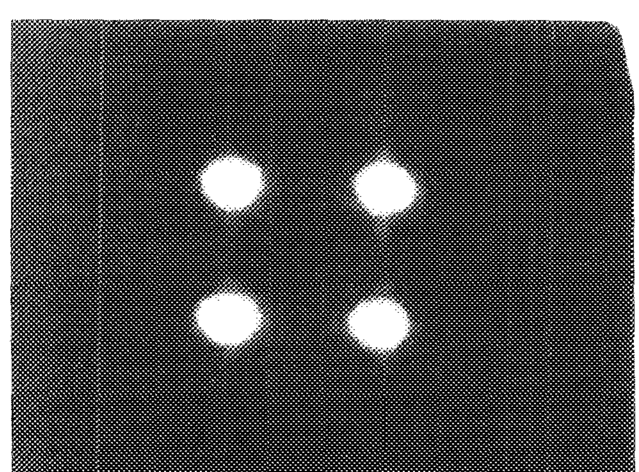

FIG. 5. 2×2 array of simultaneously pumped microlaser outputs. The lasing microlasers are on the corners of a 9 μm $\times$ 9 μm square. Microlasers form a square lattice with 3 μm spacing.

driven lasers with good ohmic contacts.[11] If long carrier lifetimes are desired, the surface recombination velocity can be greatly reduced as demonstrated by Yablonovitch *et al.*[12] Finally cavities with wavelength dimensions can exhibit enhanced spontaneous emission,[13] resulting in still lower thresholds.

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