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Monolithic optical logic devices 1.5–5 μm across are defined by ion-beam assisted etching through a GaAs/AlAs Fabry–Perot structure grown by molecular beam epitaxy. They show reduced energy requirements (more than an order of magnitude smaller than the unetched heterostructure), uniform response over small arrays, negligible crosstalk at 3 μm center-center spacing, ~150 ps recovery time, and thermal stability at 82 MHz operating frequency. All experiments were performed at room temperature.

Miniaturization of optical logic devices has long been considered a key to minimizing their energy requirements, and has also been considered difficult (at best) to achieve.[1–4] We have demonstrated a straightforward technique for fabricating arrays of integrated GaAs/AlAs Fabry–Perot étalon devices (microresonators) as small as 1.5 μm in diameter with densities around 10^7 devices/cm^2. Furthermore, submicron devices with densities ~10^8/cm^2 should be possible. The growth of integrated GaAs-AlAs nonlinear étalons by molecular beam epitaxy[5] (MBE) offers much improved manufacturability and uniformity over previous semiconductor étalon fabrication techniques[6] which involved sandwiching semiconductor films between dielectric mirrors. From the sample of Ref. 5 we have formed close-packed arrays of monolithic "posts" or microresonators 1.5–5 μm across by ion-beam-assisted etching[7] and have performed optical NOR/OR gating experiments on them using picosecond pump and probe pulses. These microresonators represent a qualitative advance over the GaAs devices reported by Lee *et al.*[8] In that work pixels 9×9 μm square were formed by etching the active material only, and then sandwiching between dielectric mirrors in the usual way.[6] Growth of integrated devices by epitaxial techniques such as MBE allows us to etch right through both mirrors and the active material. This is critical since in an optimized nonlinear étalon the dielectric mirrors comprise most of the total thickness. Diffractive beam spreading, normally to 5–10 μm diameter in GaAs étalons, is therefore defeated throughout the entire device. The lateral optical confinement in these waveguiding structures allows efficient operation with diameters as small as one can focus the light. Reduction of energy requirements is expected due to the decreased volume of interaction. Further energy reduction may occur since restriction on the allowed transverse modes of the device should result in a narrower transmission peak. Elimination of carrier diffusion[9,10] out of the devices should allow them to be spaced very closely. Finally, surface recombination[8,11] on the *sidewalls* of the microresonators should produce fast relaxation times. Our experimental results show more than an order of magnitude reduction in energy requirements, essentially uniform response over arrays at least several pixels across in each dimension, practically no crosstalk with 3 μm *center-center spacing*, ~150 ps full recovery time, and thermal stability at 82 MHz operating frequency.

The MBE growth upon a GaAs substrate comprised 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 4 μm. This design yields approximately equal mirror reflectivities (~90%) when the structure is intact on the substrate. Since the GaAs substrate has significant absorption at the wavelengths used, transmission was not monitored and the reflection was taken as the output. No attempt was made to achieve uniformity in the growth and the 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 ~1 μm/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.

For the optical measurements we used an 82-MHz mode-locked Nd:YAG laser and two frequency doublers

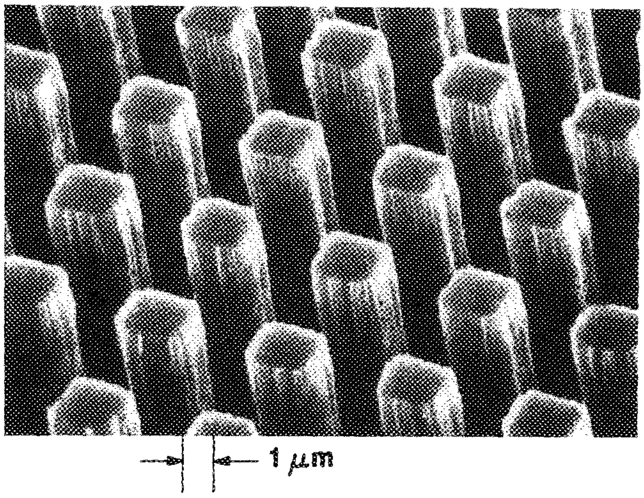

FIG. 1. Small section of the array showing ~2 μm devices used in the experiments.

(the second acting on the leftover fundamental beam from the first doubler, thus yielding two second-harmonic beams) to achieve synchronously pumped mode-locked operation of two LDS 821 dye lasers. The pulses were 5–10 ps long and the wavelengths were tunable from ~ 780 to 950 nm (with mirror exchanges). A Burleigh piezoelectrically driven "inchworm" XYZ translator positioned the array of microresonators with high precision. The pump beam could be temporally varied over 330 ps to measure relaxation phenomena. A fast avalanche photodiode (APD) monitored the reflected output; however, the temporal resolution was ~ 15 ps determined by the pulse durations. Our $f/1.1$ (numerical aperture $\mathrm{NA} = 0.41$) Fujinon LSR-F35B lens has a theoretical full width from zero to zero (FWZZ, i.e., the *entire* central lobe of the Airy disk) of $2.64\,\mu$m for the focused beam at 890 nm wavelength.

This MBE-grown étalon was not designed for high performance or even for this kind of gating. Prior to etching the lowest pump energy required for 5:1 contrast was ~ 20 pJ.[5] So far we have achieved similar or better response with a 1.5-pJ pump, more than an order of magnitude lower. The probe energy was 10 pJ or ~ 7 times *larger* than the pump. Figure 2 (upper trace) shows a NOR gate response to the 1.5 pJ input in a $\sim 1.75\,\mu$m pixel. In this and the following traces the left side of the pulse train shows the gate output with no input while the right side has the input present. The 35 ns "slope" in the response is due entirely to the acousto-optic modulator and has nothing to do with the actual device speeds. Wavelengths are typically 850 nm for the input (pump) beam and 890 nm for the probe due to this étalon design. Pulsed operation such as this generally has the input and output at different wavelengths and a pair of complementary gates must be achieved for use in a practical system. Complementarity is most conveniently achievable using an isolated resonance but is also possible by working on the bandtail of conventional semiconductors. With a "sandwiched" GaAs étalon we have achieved 5:1 contrast gating with the probe beam 30–50 Å *shorter* and ~ 8 times *more* intense than the input beam. The wide range of pixel sizes was chosen for this first experiment since we did not know how well the light would interact with or couple into the microresonators. Results indicate that a $\sim 2.5\,\mu$m diameter is optimum for this setup, consistent with the expected focusing ability. Larger pixels tend to require more energy, and smaller ones require essentially the same *incident* energies. Since the smallest ones are smaller than the FWZZ of the focused beams, much light is scattered and the amount of light actually coupled into the device is reduced. Preliminary measurements on these devices show maximum reflectivity from ~ 15 to $> 50\%$ and gain factors up to 3 or 4. Tighter focusing into smaller posts of better design should yield much better performance.

The post sizes were designed to be constant in one direction which was parallel to the gradient of the étalon thickness. Despite the fact that this direction gives the fastest variation in response, for medium to large pixels (i.e., $> 2.5\,\mu$m) we could move at least several pixels in either direction (totals are $\geqslant 8$ pixels or $\geqslant 40\,\mu$m) without significant change in response. In the orthogonal direction (smallest thickness variation) the pixel size changed every four pixels, but uniform responses were often obtained for same-size pixels. To look for crosstalk, the pump and probe were first aligned on one pixel yielding a 5:1 contrast NOR gate. Then with the pump centered on an adjacent pixel *only 3 μm away* on either side practically no response could be seen (Fig. 3). This was expected[9] since the vertical boundaries should eliminate long range carrier diffusion and also reduce diffraction. Previously, spacings of $\geqslant 10\,\mu$m showed comparable signs of crosstalk.[9]

Prior to etching it was not possible to employ surface recombination[8,11] to speed up the recovery of the MBE-grown étalon and with > 300 ps delay (between pump and probe) *no sign of recovery* was seen. It presumably took several nanoseconds as in earlier GaAs devices.[12] Recombination on the sidewalls of the microresonators, however, yielded *nearly full recovery* in as little as 150 ps (Fig. 2, lower trace has the probe delayed 150 ps relative to the upper

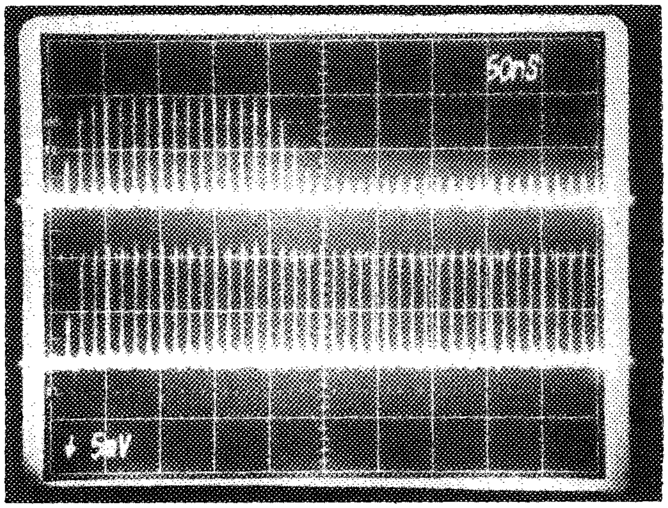

FIG. 2. (Upper) Response of a $\sim 1.75\,\mu$m device to 1.5 pJ input pulses. The left side is the output with no input (data) present and the right side is the output *with* input present. (Lower) Same as upper but with probe pulses delayed 150 ps.

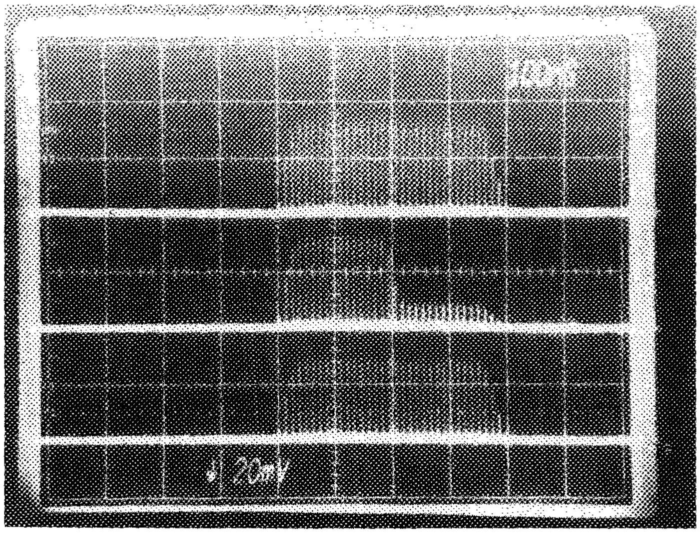

FIG. 3. Response of a 1.5-μm pixel with the probe beam constantly on one pixel and the input centered on the adjacent pixel to the left (top), on the same pixel (center), one pixel to the right (bottom). Center-center separation is $3\,\mu$m.

trace). As expected the recovery was fastest for the smallest pixels, but it also varied with the etching parameters. Probably sidewall surface recombination is quite sensitive to the etching process and consequent material damage on the sides. It is worthwhile to note that sidewall recombination should also work for multiple quantum well semiconductors, not just in bulk material.

Most data were taken with offset modulated pulse trains ~300 ns long (to observe both high and low outputs at a glance) and widely spread to avoid thermal effects. However, heating effects appear to be minimal since the response of a 5:1 contrast NOR was very similar with the pulses on *continually* at the 82 MHz mode-locked repetition rate as it was in the "thermal-free" (~300 ns pulse train envelope) case (Fig. 4). The device still functions as a NOR gate; however, the detector output shows a noticeable drop for the "high" signal when going from low to high duty cycle as seen in the figure. Saturation of the APD is believed to account for at least most of the difference since a similar drop was seen when the device was replaced by a highly reflecting mirror.

In conclusion, we have demonstrated a qualitative advance in étalon optical logic device technology which improves most of the key device characteristics such as energy, speed, uniformity, and crosstalk. In no way does the performance appear to be degraded; only good focusing is required. Since the diameter of a diffraction-limited spot scales with wavelength, submicron-diameter devices *still using* GaAs should be achievable by focusing through a high refractive index material. For example, light with a vacuum wavelength, λ, of 0.88 μm, has in GaP (with an index $n > 3.1$) a wavelength in the medium of only $< 0.3\,\mu$m. This offers another *order-of-magnitude reduction* in device areas, allowing them to approach $(\lambda / n)^2$. These first experiments with microresonators have confirmed our expectations of reductions in energy requirements, crosstalk, and recovery times. The thermal stability at 82 MHz gives additional encouragement to their eventual practicality. Of course, we will eventually want to run them much faster and will undoubtedly have to deal with thermal dissipation. Exactly what percentage of the light actually coupled into the devices is not known. Microresonators designed for transmitted outputs (with the substrate removed) should allow much more accurate quantitative measurements. It would be quite surprising, however, if these first attempts resulted in optimized coupling. High performance étalon designs, optimized coupling, good fabrication of still smaller devices, and possibly some reduction of operating temperature should allow us to push these devices close to the fundamental and statistical limits of performance.[1,3]

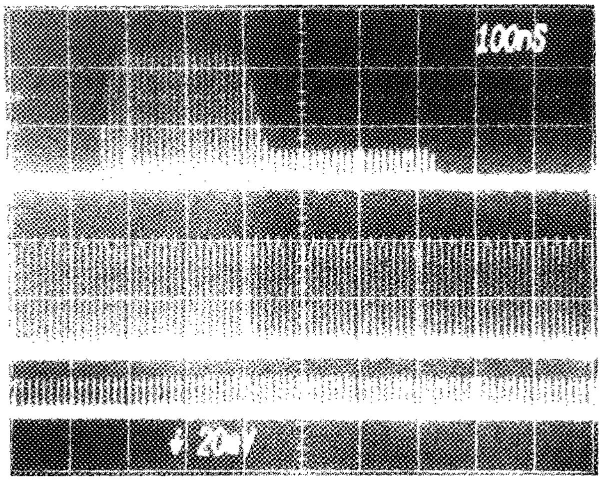

FIG. 4. Output of a 1.5-μm device with the usual ~300 ns pulse trains (top), probe on continually with the input blocked (center), both input and probe on continually (bottom). The decrease in the "high" signal level when going from low to high duty signal is mostly due to detector saturation rather than device heating.

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