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Streak-camera observation of 200-ps recovery of an optical gate in a windowless GaAs étalon array

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Fast recovery (<200 ps) of an optical gate at room temperature in a GaAs étalon is observed by eliminating the top AlGaAs window and defining $9\times 9\ \mu\text{m}^2$ pixels. This recovery time is at least an order of magnitude shorter than that for previous étalons consisting of AlGaAs/GaAs/AlGaAs heterostructures. The fast recovery is attributed to faster surface recombination of carriers at the GaAs-dielectric mirror interface as compared to that at a GaAs-AlGaAs interface.

There has been increasing interest in the research and development of optical logic devices to utilize the parallelism and interconnectivity advantages of light.[1] It has been demonstrated that a GaAs nonlinear étalon can perform NOR, NAND, XOR, OR, and AND operations with proper initial detunings at 82 MHz.[2] Recently, using a GaAs nonlinear étalon, it was shown that an optical NOR gate can change its transmission state from HIGH to LOW in about 1 ps.[3] However, to perform another NOR operation on the same optical gate one must wait several nanoseconds for carriers generated by optical pulses to recombine. In other words, the maximum operating frequency for these devices is limited by carrier relaxation time rather than turn-on time.

Several ways to reduce the carrier recombination time have been proposed. One is to introduce artificial recombination centers inside the crystal by proton bombardment. This method resulted in a nonlinear optical response time of 150 ps in an AlGaAs/GaAs/AlGaAs multiple quantum well structure.[4] But greater damage degrades the exciton feature and changes the band-edge structure as well. Another proposal is to use fast surface recombination of free carriers at an interface of GaAs-air (or dielectric mirror). In AlGaAs/GaAs/AlGaAs heterostructures the AlGaAs-GaAs interface is so well lattice matched that free carriers feel only a quantum mechanical potential barrier at this interface. At a GaAs-air interface, free carriers encounter a very sharp lattice discontinuity and recombine very fast at the high-density surface states. It is reported that the exciton and the band-edge structure are still preserved for very thin ($0.5\ \mu$m) windowless GaAs at low temperature.[5] For 1.5-μm-thick windowless samples used in the experiment, exciton features are observed in the linear absorption spectrum of the band edge even at room temperature. Here it is shown that elimination of the top AlGaAs window from the conventional AlGaAs/GaAs/AlGaAs heterostructure reduces the carrier lifetime by about two orders of magnitude. Typical carrier lifetimes for bulk GaAs are about 30 ns,[6] but typical recovery times for GaAs nonlinear étalons are several nanoseconds[2]; this is attributed to the diffusion of carriers from a small focused spot of about $10\ \mu$m in diameter.[7]

The sample was grown by molecular beam epitaxy and consists of $1.5\ \mu$m bulk GaAs and $0.25\ \mu$m AlGaAs, without the top AlGaAs window. Figure 1 shows the 2D array of $9\times 9\ \mu\text{m}^2$ GaAs pixels with $20\ \mu$m center-to-center spacing defined by reactive ion etching.[8] The array was sandwiched between high reflectivity (94/94%) dielectric mirrors. For the purpose of comparison, an étalon was made from the same bulk crystal without etching an array. Instrument widths for the étalons are 6–8 nm and finesses are 4–5, showing some spatial variation on the sample.

The input light source is an 82-MHz mode-locked argon laser operating at 514.5 nm with a pulse width of 180 ps. To decrease the average input power and to reduce the thermal effects on the sample, an acousto-optic modulator (AOM-1) was used to gate the mode-locked pulse train (see Fig. 2).

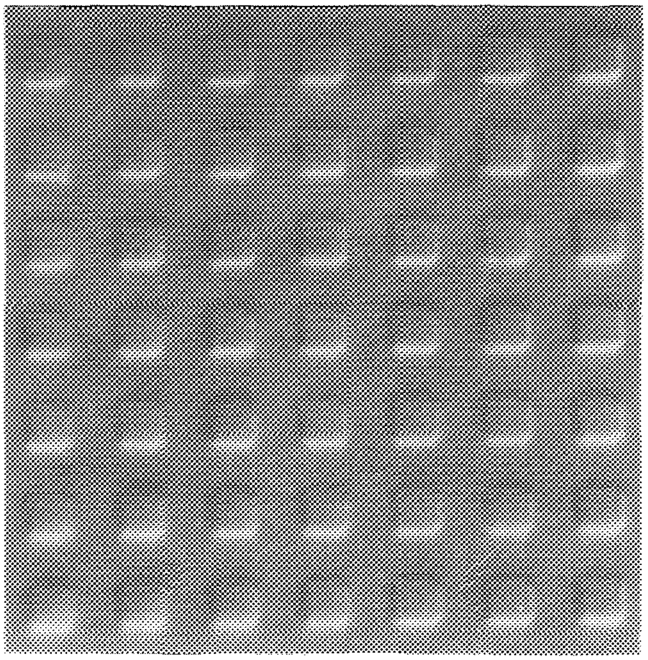

FIG. 1. 2D array of $9\times 9\ \mu\text{m}^2$ pixels prepared by reactive ion etching.

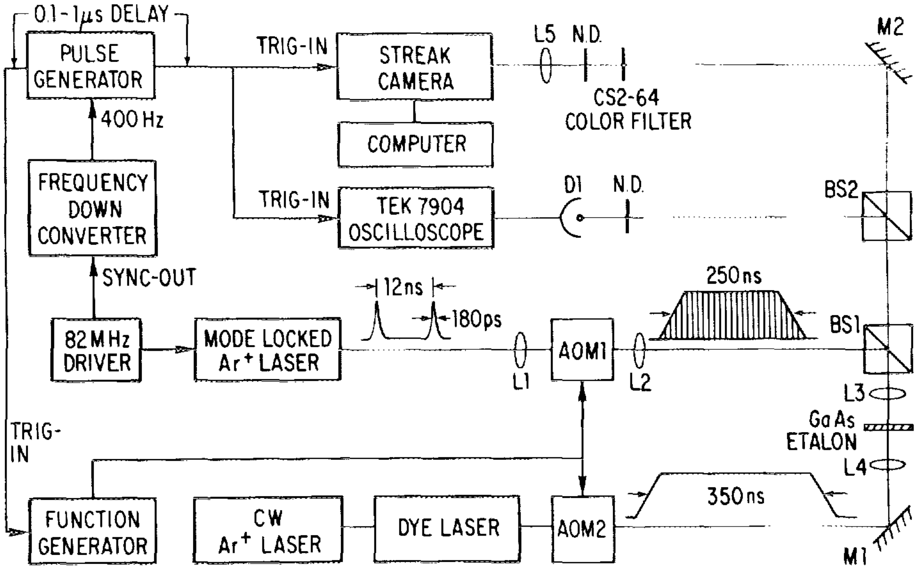

FIG. 2. Experimental setup.

Each packet is 250 ns in duration at a repetition rate of 400 Hz. The other acousto-optic modulator (AOM-2) is driven by the same function generator used for AOM-1 to synchronize the input with the probe. The probe wavelength is tuned to the long-wavelength end of the LDS-821 dye gain curve (885–889 nm) to reduce band-edge background absorption. The main triggering source is obtained by frequency down-converting the SYNC-OUT signal from the mode-locker driver. This main trigger signal is input to the pulse generator to supply trigger signals for AOM-1, AOM-2, the sampling oscilloscope, and the streak camera with proper delays for the different instruments. A fast photodetector [full width at half-maximum (FWHM) 500 ps] is used for the initial alignments. Then the streak camera is used to resolve the detector-limited response of fast optical gates and is interfaced to the computer for data acquisition. The resolution of the streak camera is 5 ps.

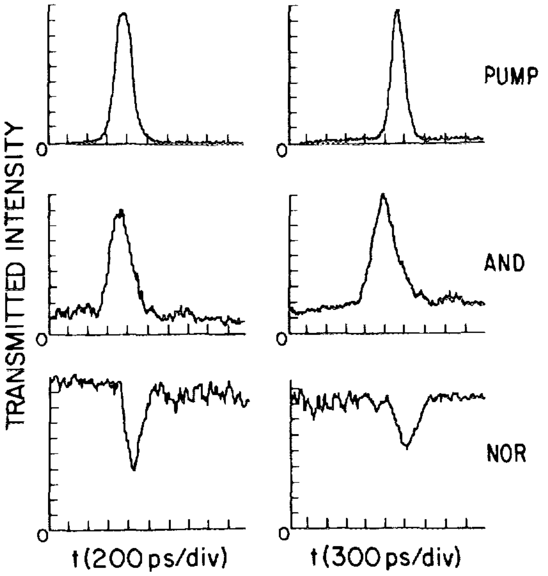

FIG. 3. Streak-camera traces of the pump, AND, and NOR gate for one 9×9 μm^2 pixel of the GaAs étalon with no GaAlAs window (left) and for a single spot on a similar GaAs étalon in which no pixels were defined by reactive ion etching (right). The base lines are taken with the probe beam blocked.

Figure 3 displays the steak-camera traces of the optical gates for one pixel of the 2D array. Generally, the optical gate response does not change appreciably with respect to probe wavelength within 1/10 of an instrument width. In both NOR and AND gates, the recovery of the optical gates is completely finished in less than 200 ps. By comparing the FWHM for the input pulse (180 ps) and the gate response (250 ps), one can deduce an 80-ps carrier relaxation time by deconvolving the input pulse from the Fabry–Perot characteristic curve. The NOR gate contrast in Fig. 3 appears to be less than that of the AND gate. This may be attributed to greater background scattering onto the streak camera's diode array for the high-to-low intensity transition of the NOR gate. Also the pump and probe work together in the AND gate, while in the NOR gate they work against each other.

The recovery of the gates for the étalon prepared from the same windowless GaAs/AlGaAs structure but without an array is also fast with a FWHM of 350 ps. The carrier relaxation time for this sample is 180 ps. This fast relaxation cannot be explained by the carrier diffusion, considering the spot size of 10 μm in the experiment. The surface recombination velocity at a GaAs-air interface is 5×10^5 cm/s (Ref. 7) and from this one calculates a surface recombination time of 300 ps in reasonable agreement with the data. The gating action for the array sample is faster than that of the sample without an array. The faster recovery of the $9 \times 9 \times 1.5\ \mu m^3$ pixel array results from an average decrease in the distance a carrier must diffuse before encountering a surface recombination site. A crude estimate of this effect suggests that it may not account for all of the reduction in recovery time, so we do not rule out the possibility that reactive ion etching may introduce a very thin damage layer along the etched side[8] that would speed up the recombination of carriers at the sides even further. Measurement on enough samples to be statistically meaningful will be necessary to determine if etching enhances recombination. In any case, isolating the individual pixels by defining an array not only increases the speed but also eliminates diffusion crosstalk.

The gate input energy of 1 nJ is much larger than that of recent gates. This is due to the thicker sample, smaller finesse, and the higher incident photon energy than the previous 82-MHz low-energy sample.[2] The higher photon energy introduced a thermal problem during the experiments. Consequently, observations were limited to the first five to ten pulses in each pulse packet. This thermal problem could be solved by introducing a mirror with higher reflectivity at the probe wavelength and higher transmission at the input wavelength and by matching the input to the exciton wavelength (minimizing the temperature of carriers generated by the input pulse). Recently, it has been shown, using picosecond pump-and-probe techniques, that the gate input energy can be reduced to 7 pJ in similar windowless GaAs samples.[9] Simultaneous operation of 100×100 pixels at 1 GHz rate would yield 10^{13} bit operations per second. Assuming 7 pJ energy per operation, heat load of < 70 W/cm^2 is generated, which is less than the maximum reasonable to contemplate based on electronics experience.

In conclusion, fast recovery of optical logic gates is achieved by eliminating the top AlGaAs window and hence increasing the surface recombination at the GaAs-dielectric mirror interface. Definition of an array on this windowless sample results in the fastest full recovery time of < 200 ps, which is more than an order of magnitude faster than previous GaAs optical logic gates.

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