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Speed and effectiveness of windowless GaAs étalons as optical logic gates

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The effectiveness of surface recombination in speeding up the relaxation of a GaAs étalon is reported. Various thickness (1.5, 0.5, 0.3, 0.13 μm) bulk GaAs windowless samples were fabricated and tested as optical logic gates. Times for complete recovery of transmission lie between 400 and 30 ps. The response shows a roughly linear increase in speed as the sample thickness decreases, consistent with surface recombination being the dominant relaxation mechanism. A very fast cycle time of 70 ps is demonstrated using a 0.3-μm-thick windowless GaAs étalon as an all-optical logic device. Proton-bombarded samples show slower recovery and poorer contrast, and they require more gating energy.

There has been increasing interest in all-optical computing, because this technology may exploit the massive parallelism and global interconnectivity of light. It will be even more exciting if individual optically active elements can be operated faster than their electronic counterparts. Then even a small number of very fast optical logic elements could be used for some specialized applications and the computing power of the parallel machines would be further increased. The main factor limiting the repetition rate of most semiconductor devices is the carrier relaxation (switch-off) time rather than the turn-on time.[1] There are several ways to speed up the carrier relaxation time. For example, proton bombardment and impurity doping have enhanced the speed of many optoelectronic devices.[2-4] Devices made of amorphous semiconductors and windowless GaAs also show very fast response.[5-7]

In this letter, "windowless" GaAs samples and proton-bombarded samples are tested. Recently, it was demonstrated that bulk GaAs with no top AlGaAs layer ("windowless") showed fast recovery in a nonlinear optical gating experiment.[6,7] This increase in speed was attributed to much faster surface recombination at the GaAs/dielectric mirror interface than at a GaAs/AlGaAs interface. If surface recombination is a dominant recombination mechanism, faster carrier relaxation should be expected for thinner windowless GaAs crystals. In order to better understand the physical mechanisms and the practical limitations on the speed of windowless GaAs nonlinear optical gates, samples of various thicknesses are needed. Bulk GaAs samples of different thicknesses (1.5, 0.5, 0.30, 0.135 μm) having one AlGaAs window (the etch-stop layer) were prepared by molecular beam epitaxy (MBE); the remaining $Al_{0.7}Ga_{0.3}As$ window was removed by inserting the sample in a concentrated HCl solution for several minutes to make it really windowless (neither top nor bottom AlGaAs window). The nonlinear Fabry–Perot étalons were fabricated using these windowless GaAs crystals as nonlinear media sandwiched between identical dielectric mirrors. The dielectric mirrors were designed to have high reflectivity ($\simeq$98%) around 890 nm for high finesse and low reflectivity ($\simeq$30%) around 800 nm for efficient use of the pump beam.

Picosecond pump-and-probe techniques were employed to resolve the fast recovery of these windowless GaAs optical logic gates at room temperature. Two mode-locked dye (LDS 821) lasers pumped synchronously by the second harmonic of a mode-locked Nd:YAG laser were used for the measurement. The full widths at half-maximum of the pulses were about 5–10 ps and this limited the temporal resolution of the pump-and-probe measurement to 25 ps. The spot diameter at the étalon was about 10 μm. The pump and probe beam wavelengths were set at about 800 and 890 nm, respectively. Variable optical delay and split-and-delay (Fig.1) were introduced in the pump beam to map out the relaxation characteristics and to demonstrate fast repetitive gating.

Figure 2 shows a typical optical NOR gate response with complete recovery (within 5% of the original transmission level) in 200 ps for a 0.5-μm thickness windowless GaAs étalon. When one probes the nonlinear étalon right after the pump pulses ($t = 0$ ps), transmission of probe pulses is LOW. The transmission returns to its original transmission level after all the carriers recombine ($t = 200$ ps). The measured complete recovery times lie between 400 and 30 ps depending on the sample thickness and, to some extent, the location on the sample. The response shows a roughly linear increase in speed as the sample thickness decreases, consistent with surface recombination being the dominant relaxation mechanism. Here the complete recovery time is the time after which the optical gate can be reused; it is about twice as long as the $1/e$ carrier relaxation time. A 0.5-μm-thick sample showed complete recovery times as fast as 150 ps with 16 pJ gating energy. A 0.3-μm-thick sample showed even faster complete recovery (down to about 60 ps) with 20 pJ gating energy. This increased speed promises another advantage of windowless étalons for parallel processing. For a carrier re-

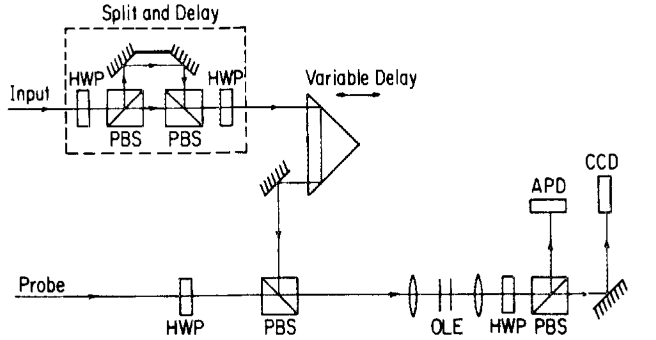

FIG. 1. Experimental setup: PBS, polarization beamsplitter; OLE, optical logic étalon; APD, detector; CCD, TV monitor. The dashed-in portions are used with the appropriate experiments.

combination time of < 100 ps, transverse carrier diffusion[8] is almost negligible for a spot size of $10\,\mu$m, and crosstalk due to diffusion would be virtually eliminated for parallel operation of such devices.

The minimum energy required for the NOR gate operation in a 0.5-μm étalon is 7 pJ which is comparable to the lowest energy required (3 pJ) in a much slower (about 5 ns complete recovery time) multiple quantum well (MQW) sample of the same GaAs thickness for similar contrast (5:1).[9] As the sample thickness becomes very thin (<0.3 μm), the required gating energy increases due to the limited absorptivity-length product. In terms of gating energy, a thickness of 0.5 μm seems to be optimum for current étalon designs. We also compared band-edge structures of the 0.5-μm-thick *windowless* GaAs sample[10] and a 0.435-μm-thick GaAs sample *with windows* at 77 K and both of them showed very similar exciton and band-edge structures in spite of the more than an order of magnitude difference in carrier relaxation times. Presumably this is because the exciton lifetime[11] is much shorter (<1 ps) than the carrier lifetime in either sample. In general, these devices require about 10–20 pJ of input energy to obtain optical gating with reasonable contrast (5:1).

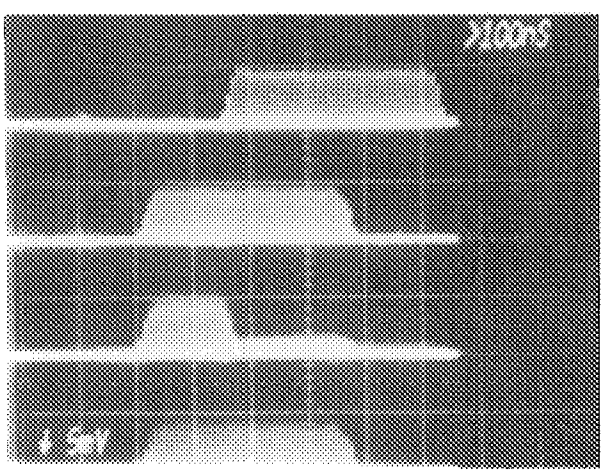

FIG. 2. Response of a windowless optical NOR gate. (a) Pump pulse envelope, (b) probe pulse envelope with no pump pulses. (c) Each probe pulse is incident just after the corresponding pump pulse; the probe beam transmission is driven LOW by pump pulses (NOR gating). (d) Each probe pulse is incident 200 ps after the corresponding pump pulse; the probe beam transmission has completely recovered to its original level.

A 70 ps cycle time was demonstrated using a 0.3-μm windowless sample in an optical AND gate by splitting the pump beam into two and delaying one of them 70 ps relative to the other. In other words, the optical gate answers two logic questions separated by less than 70 ps (Fig. 3). The responses of the two successive inputs are virtually identical with slight differences being attributed mainly to difficulty in maintaining uniform alignment and incident energy. A 0.135-μm-thick sample has also shown optical recovery times as fast as 30 ps but with much higher energy requirements. The recovery times vary widely within each sample. We cautiously attribute this to the variation in surface quality over the samples.

Proton-bombarded MQW samples of GaAs were also tested for comparison purposes. The MQW GaAs MBE sample consists of 100 periods of 152 Å GaAs layers alternated with 104 Å AlGaAs layers. The dosages are 3×10^{11}, 1×10^{12}, 3×10^{12}, 1×10^{13}, 3×10^{13}, and 1×10^{14} protons/cm^2. The energy of the bombarding protons was 2 MeV; these relatively high-energy protons can penetrate the GaAs crystal to depth of 20–30 μm so that reasonably uniform damage would be introduced throughout the MQW samples used in the experiment. The samples were not annealed after bombardment. Up to the third highest dosage (1×10^{13} protons/cm^2), no significant increase in speed was observed. Thus diffusion limits the optical gate recovery time up to this level. At the same level at which the speed begins to increase, the modulation depth (contrast) for optical gates becomes shallower even with more gating energy than used for windowless samples. This implies unfavorable changes in exciton and band-edge structures from proton bombardment,[12] consistent with the previous observation by Silberberg *et al.*[4] We were unable to compare directly the changes at the band edge for these different-dosage MQW samples due to the wedge introduced during the original MBE growth process. The wedge introduced variations in GaAs well thickness and AlGaAs barrier thickness, resulting in a 40 Å shift in the position of the exciton resonance. The most heavily bombarded sample (1×10^{14} protons/cm^2) showed 270 ps complete recovery time, but the contrast was severely degraded (2:1) even with relatively high gating energy (40 pJ), as shown in Fig. 4.

In summary, surface recombination is shown to be a very effective way of speeding up optical gate recovery without significantly degrading its contrast (nonlinearity), and windowless GaAs samples are shown to be better than pro-

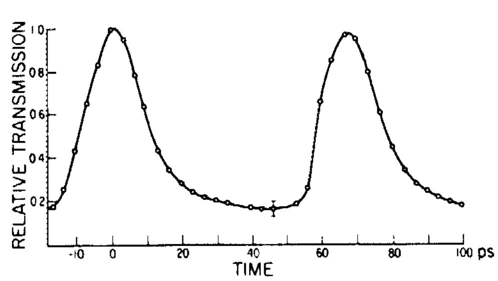

FIG. 3. 70 ps cycle time of the 0.3-μm windowless GaAs étalon (20 pJ/input) operated as an AND gate.

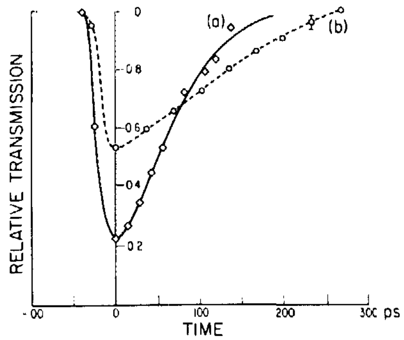

FIG. 4. Comparison of NOR-gate responses. (a) 0.5-μm windowless GaAs étalon with 16 pJ input, (b) proton-damaged GaAs étalon (1×10^{14} protons/cm^2) with 40 pJ input.

ton-damaged samples in response time, energy, and contrast. Also 70 ps cycle time of an all-optical logic device was demonstrated, showing the possibility of 14 giga-bit operations/second. This is the fastest all-optical cycle time ever reported, to our knowledge.

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