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Semiconductor nonlinear etalons

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Previous observations of optical bistability in nonlinear etalons of ZnS, CuCl and GaAs are summarized. Emphasis is placed upon recent results in GaAs: similar room-temperature optical bistability at powers under 10 mW in bulk and multiple quantum-well etalons; room-temperature bistability achieved with a diode laser as a light source; NOR and other logic operations; optical fibre signal regeneration and continuous wave operation.

Semiconductors are atrractive for use as nonlinear media in practical, intrinsic optical bistable devices. Laser light of photon energy slightly below the band edge interacts with these materials via sharp absorption resonances (such as free and bound excitons and biexcitons), which permit fast, room-temperature, low power optical bistability. Furthermore, the absorption coefficients α are of the order of 10 cm^{-1}, which allows $\alpha L \approx 1$ to be achieved in short interaction lengths and thus makes possible the realization of devices 1 μm thick. Here we review our recent progress in semiconductor optical bistability. Results of optical bistability in ZnS, CuCl, and GaAs achieved before the Topical Conference on Optical Bistability (Bowden *et al.* 1984) are summarized briefly. Subsequent results in GaAs are described in greater detail.

Zinc sulphide

Apparently, the first semiconductor to exhibit optical bistability was ZnS (Karpushko & Sinitsyn 1978, 1982). Karpushko and Sinitsyn attribute the nonlinear refraction to a two-photon photorefractive effect, which is large in evaporated thin films and much smaller or non-existent in bulk crystals (Karpushko & Sinitsyn 1978, 1982). Their ZnS etalon was simply a narrow-band interference filter with an intermediate layer of ZnS about λ/n_0 thick (λ is the vacuum wavelength and n_0 is the refractive index of ZnS at λ). The short length and simple fabrication process make ZnS etalons attractive for parallel signal processing. Unfortunately attempts (Weinberger *et al.* 1982; Rushford *et al.* 1983) to reproduce the fast switching times (*ca.* 10 μs) and low intensities (*ca.* 300 W cm^{-1}) claimed (Karpushko & Sinitsyn, personal communication) have achieved only thermal bistability with *ca.* 1 ms switching times and *ca.* 10 kW cm^{-2} intensities. So far we have tried only commercial interference filters, but a study of bistability as a function of growth parameters is under way.

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Copper chloride

Optical bistability achieved with the biexciton resonance (Koch & Haug 1981; Hanamura 1981) in CuCl is of particular interest because of its potential (Hanamura 1981) for picosecond switch-off times. Recently, two groups have reported bistability in CuCl in which the switching times were shorter than the *ca.* 500 ps resolution of the detection systems (Peyghambarian *et al.* 1983; Levy *et al.* 1983, and this symposium; see also Bowden *et al.* 1984). The switch-on intensity of *ca.* 10 MW cm^{-2} for 10 to 30 μm long etalons with *ca.* 90 % reflectivity is considerably higher than first predicted (Koch & Haug 1981). However, it is consistent with a recent numerical calculation (Sarid *et al.* 1983), which includes two effects previously neglected: intensity broadening of the biexciton resonance and background absorption from the wing of the free exciton resonance. Our research is now focused on a streak camera study of the dependence of the switching times upon laser–biexciton detuning to see if switch-off times under 10 ps occur. The high-intensity and low-temperature requirements appear to make CuCl biexcitonic bistability unattractive for signal processing. However, it is noteworthy that if a device could be fabricated with a transverse dimension equal to one wavelength in the material (λ/n_0) it would need only several femtojoules of switching energy if the switching time is in fact only 1 ps. This corresponds to only a few thousand photons, a number approaching the statistical limit (i.e. the minimum number of photons needed to avoid occasional failure of switching due to statistical fluctuations).

Gallum arsenide: room-temperature bistability

Optical bistability in a 4 μm GaAs etalon was reported from 5 to 120 K; it was suggested that a superlattice might permit room-temperature operation because of the increased binding energy of the free exciton (Gibbs *et al.* 1979). Room-temperature bistability was achieved in a multiple quantum well (m.q.w.) etalon consisting of 33.6 nm GaAs layers alternated with 40.1 nm AlGaAs layers for *ca.* 2 μm of GaAs (Gibbs *et al.* 1982). Such a wide well increases the free exciton binding energy to only 6 meV, not that much larger than the 4.2 meV bulk value (Miller *et al.* 1981). Consequently, the bulk sample was tried at room temperature, and bistability was observed; presumably, this was primarily due to better focusing with the dewar removed (Gibbs *et al.* 1982). The bistability was better (lower switch-on power, wider loops) in the m.q.w. etalon.

Bulk bistability compared with m.q.w. bistability

Subsequently, we have compared bulk and m.q.w. devices (well thicknesses 5.3, 15.2, 29.9 and 33.6 nm) including bistability at powers as low as *ca.* 5 mW. This limiting power is so consistent throughout our samples that we believe it provides an accurate measure for present materials and devices. Since the intensity is 3 kW cm^{-2} or less, the optical nonlinearity must be excitonic, not band-to-band. We are studying the apparent contradiction that the bulk and m.q.w. bistabilities look so similar (and the low intensity suggests an exciton nonlinearity), but the m.q.w. exciton features are more prounced because of the increased binding energies. One possible explanation is that unsaturable background absorption from the band tail forces a large detuning below the exciton resonance in both cases; since the maximum change in refractive

index, assuming complete saturation, is proportional to the product of the peak and the width of a two-level transition, the smaller, broader bulk exciton resonance may be as effective as the larger, narrower m.q.w. exciton feature. An understanding of this similarity might result in lower power operation closer to the m.q.w. exciton resonance. Both m.q.w. and bulk crystals have the unusual property of having exciton binding energies E_x less than kT at room temperature, but larger than or comparable to the exciton linewidth Γ_x determined by optical phonon broadening. The condition $E_x > \Gamma_x$ is needed to see the exciton resonance, but the smaller the E_x the smaller the saturation intensity (smaller E_x implies a larger exciton Bohr radius and thus fewer excitations are required to produce one exciton, or carrier, per exciton volume to screen the exciton). GaAs apparently has an unusually small Γ_x permitting low-power room-temperature exciton features, especially pronounced in a m.q.w. crystal. (For a discussion of the nonlinear refraction of a GaAs–AlGaAs m.q.w. crystal see D. A. B. Miller (this symposium).

Bistability by using a diode laser

Room-temperature bistability of a m.q.w. etalon with a diode laser as the only light source emphasizes that these GaAs devices are coming closer to practical operating powers. A m.q.w. crystal consisting of 300 periods of 5.3 nm GaAs and 5.6 nm $Al_{0.3}Ga_{0.7}As$ was grown by molecular beam epitaxy (Gossard 1979) and sandwiched between two mirrors of reflectivity 0.9 and 0.98 to form the Fabry-Perot etalon. A power of 6 mW from a Hitachi HLP 1400 diode laser at 830 nm switches on the etalon at room temperature (Tarng *et al.* 1984).

NOR gate operating on a picosecond timescale

A power of 10 mW per pixel and 10^6 pixels per square centimetre would imply 10 kW cm^{-2} and require much better cooling than that used in electronic systems. It is hoped that further reductions in power will occur when the present limitations are understood. However, such an etalon could be used for picosecond decision-making at a gigahertz repetition rate without thermal problems (Jewell *et al.* 1984 and this symposium). The idea is to use two control pulses followed by a probe pulse. The etalon peak wavelength can be shifted rapidly so that the logic output could occur in a picosecond. For example, if the etalon is initially tuned to the probe wavelength, a NOR gate operation results if each of the control pulses is able to detune the etalon from the probe wavelength (Jewell *et al.* 1984 and this symposium). The carriers must then recombine, which may take a nanosecond or more, and may take longer if thermal or other restrictions require such, but during this dead time there is no light on the etalon to generate heat.

Data regeneration through fibres

Another precursor of actual applications is the demonstration of data regeneration through fibres. Recently the regeneration of a pseudorandom sequence of optical pulses was demonstrated with a GaAs etalon and three fibres 1 km long (Venkatesan *et al.* 1984). A train of rectangular bias pulses was sent through one fibre while the data sequence of picosecond pulses (synchronized with the bias pulses) travelled down a second fibre and both were focused onto the etalon. The transmitted signal was sent through the third fibre and monitored by a photodetector. The following accomplishments were made in the experiment: (i) completely remote

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operation and readout of a bistable device; (ii) all-optical regeneration of optical data; (iii) conversion of data from one wavelength to another; (iv) control of the pulse width of the output by varying the phase delay of the picosecond switching pulses relative to the bias pulses.

Quasi-continuous wave bistability

One impediment to continuous wave applications of GaAs etalons is the regenerative pulsations arising from a competition between thermal and excitonic index changes (Jewell *et al.* 1981). Quasi-continuous wave operation has been obtained by using a diamond heat sink (polished and coated for $R \approx 0.9$) as one mirror of the GaAs etalon. The device stayed on for the entire *ca.* 100 ms duration of the input for most traces, but some showed brief (*ca.* 1 μs) randomly located periods in the lower state. The cause of the undesired switching has not been identified, but it may have been laser mode hopping.

In summary, GaAs continues to appear very promising for optical signal processing because bistability can be seen at room temperature with low powers (*ca.* 10 mW) and fast switching times (switch-on time under 200 ps and probably *ca.* 1 ps; switch-off time under 10 ns, depending upon carrier lifetime). Neither the holding power nor the switch-off time has been minimized, so further improvements are expected. The search for and construction of even better nonlinear materials and devices should continue.

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