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Multiple Quantum Well Optical Nonlinearities: Bistability from Increasing Absorption and the Self Electro-Optic Device

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Phil. Trans. R. Soc. Lond. A 1984 **313**, 239-244
doi: 10.1098/rsta.1984.0101

Phil. Trans. R. Soc. Lond. A **313**, 239–244 (1984)
Printed in Great Britain

Multiple quantum well optical nonlinearities: bistability from increasing absorption and the self electro-optic device

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This paper briefly reviews the nonlinear optical and electro-optical properties and applications of GaAs–AlGaAs multiple quantum wells, all of which are compatible with laser diodes or semiconductor electronics or both. They show large nonlinear absorption and refraction (associated with their strong room-temperature exciton resonances) applicable to all-optical devices. They also show large electroabsorptive effects, some of which are unique to the quantum wells at any temperature, which are so strong that optical modulators can be made with micrometre dimensions. A new class of optical bistability (due to increasing absorption) is also reviewed; combination of this with the electroabsorptive effects enables a new mirrorless optical switch called a Self Electro-optic Effect Device (SEED), which sets a new standard for optical switching energies, with energy densities reduced by a factor of six by comparison to even the best resonant cavity devices.

1. Introduction

One problem central to all nonlinear optical processing devices and systems is that of finding suitable nonlinear materials. An ideal material would have a very large and at least reasonably fast nonlinearity, would be easy to use in practical device structures and would be compatible with readily available light sources. Semiconductors at wavelengths near the band edge are attractive because they offer large and moderately fast nonlinearities in relatively convenient materials, although most of the nonlinearities require low temperature operation.

Multiple quantum well (m.q.w.) structures consisting of alternate thin (*ca.* 10 nm) layers of two different semiconductors (for example GaAs and AlGaAs) have recently shown remarkable nonlinear optical effects at room temperature at wavelengths, power levels and timescales compatible with diode lasers (Miller *et al.* 1982, 1983*a*, *b*; Chemla *et al.* 1984; Gibbs *et al.* 1982; Tarng *et al.* 1984). Some of these effects arise from the existence of exceptionally strong room-temperature exciton resonances. These exciton resonances are particularly easy to saturate, giving large nonlinear absorption and nonlinear refraction that make the m.q.w. interesting for all-optical devices. Additionally, it has recently been discovered that m.q.w.s show large electroabsorptive effects at room temperatures with fields both parallel and perpendicular to the layers (Chemla *et al.* 1983; Wood *et al.* 1984, Miller *et al.* 1984*a*). These effects are so large that high speed optical modulators can be made with only micrometres of material (Wood *et al.* 1984). The small energy drive requirements of these modulators makes them also compatible with low power electronic devices.

Recently, a class of mirrorless bistability has been identified (Miller 1984; Miller *et al.* 1984*b*) which relies only on an optical absorption that increases as a material is excited. This has very recently been applied to make a novel hybrid optically bistable device that uses the m.q.w. perpendicular field electro-absorptive effect; this device uses the same piece of m.q.w. simultaneously as both modulator and detector and has consequently been called a Self

Electro-optic Effect Device (SEED) (Miller *et al.* 1984*c*). One remarkable feature of the SEED is the extremely low total switching energy per unit area (*ca.* 20 fJ μm^{-2}). This is achieved without a cavity and represents a sixfold improvement even over the best cavity devices at comparable wavelengths.

In the rest of this paper, the key results of the work on m.q.w. nonlinearities, optical bistability due to increasing absorption and the SEED will be briefly summarized.

2. Nonlinear absorption and refraction

GaAs–AlGaAs is thought to show exciton resonances at room temperature (Ishibashi *et al.* 1982; Miller *et al.* 1982) because the confinement of the exciton in the layer increases its binding energy and phonon broadening is not correspondingly increased (Miller *et al.* 1982; Chemla *et al.* 1984). Excitonic absorption saturation arises from physical processes fundamentally different from those of interband absorption saturation. In the m.q.w., nonlinear absorption and refraction due to excitonic effects can be observed at excitation levels much lower than those required for interband effects (Miller *et al.* 1982; Chemla *et al.* 1984) and the effects can be clearly modelled as being due to changes in exciton broadening, oscillator strength and energy. Detailed measurements were made of nonlinear absorption and degenerate four-wave mixing (d.f.w.m.); from these nonlinear absorption cross section and change in refractive index per excited carrier shown in figure 1 can be deduced. The nonlinearity is so large that, in an

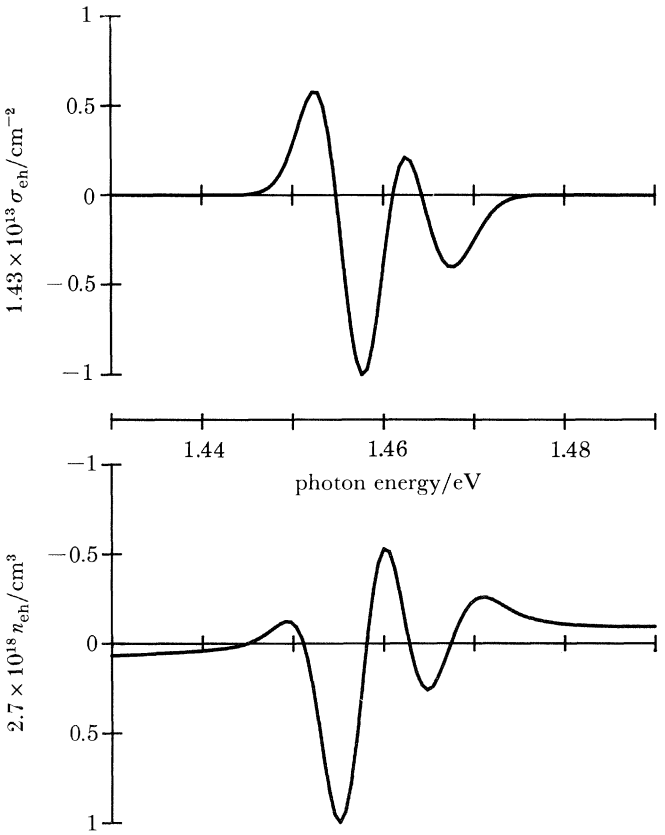

FIGURE 1. Absorption saturation cross section, σ_{eh} and change in refractive index per excited carrier pair n_{eh} (in the vicinity of the exciton resonances), as deduced from nonlinear absorption and degenerate four-wave mixing spectra (Chemla *et al.* 1984).

important practical demonstration, it was possible to achieve d.f.w.m. in a 1.26 μm thick sample by using only a continuous wave laser diode. These nonlinear effects have recovery times of up to 30 ns, which may be shortened by diffusion of carriers or otherwise (Miller *et al.* 1983*a*, *b*; Chemla *et al.* 1984). They are attractive for d.f.w.m., saturable absorption and optically bistable devices (Gibbs *et al.* 1982; Tarng *et al.* 1984) although it has proved difficult to exploit them to their full potential for optical bistability, probably because of high linear absorption in the band tail region. The physical mechanism of the excitonic nonlinear absorption is thought to be screening of potential excitons by free carriers; the free carriers may be created directly or by the phonon ionization of excitons (Miller *et al.* 1982; Chemla *et al.* 1984).

3. Electroabsorption

Figure 2 shows the effect of electric fields applied (*a*) parallel and (*b*) perpendicular to the m.q.w. layers (Chemla *et al.* 1983; Wood *et al.* 1984; Miller *et al.* 1984*c*). For parallel fields the dominant effect appears to be Stark broadening, i.e. the exciton is field-ionized by the applied field, reducing its lifetime and hence broadening the optical transition (Miller *et al.* 1984*c*). This broadening is very significant with electric fields of *ca.* 10^4 V cm^{-1}, which corresponds to a potential drop of greater than one binding energy (*ca.* 9 meV) across the exciton diameter (*ca.* 12 nm); this is a severe perturbation but is relatively easily applied with high purity material. For perpendicular fields, the dominant effect is a shift of the spectrum to lower energies (Wood *et al.* 1984; Miller *et al.* 1984*c*); the small apparent broadening may be due to field inhomogeneity in the sample. This shift is readily seen with fields over 3×10^4 V cm^{-1} and is thought to arise (Miller *et al.* 1984*c*) from a shift in the confined energy levels of the carrier sub-bands in the wells (Bastard *et al.* 1982; Miller *et al.* 1984*c*) with a small

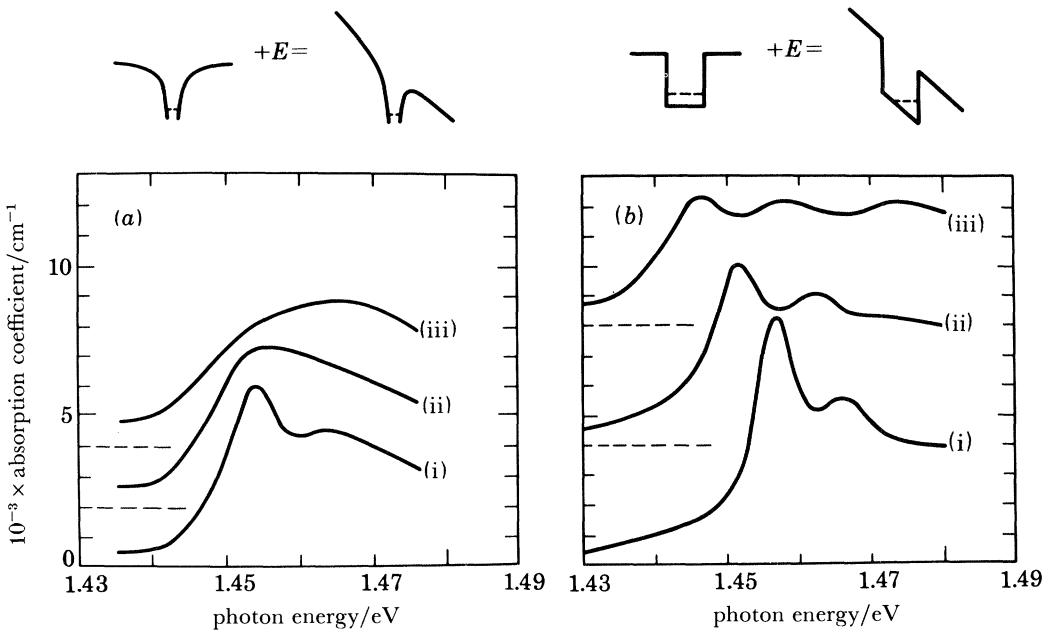

Figure 2. Absorption spectra with applied field, *E*. (*a*) Field parallel to the layers: (i) 0 V cm^{-1}; (ii) 1.6×10^4 V cm^{-1}; (iii) 4.8×10^4 V cm^{-1}. Sketch above: schematic diagram of Coulomb potential of exciton. (*b*) Field perpendicular to the layers: (i) *ca.* $1 \times 10^+$ V cm^{-1}; (ii) *ca.* 4.7×10^4 V cm^{-1}; (iii) *ca.* 7.3×10^4 V cm^{-1}. Sketch above: schematic diagram of quantum well potential (Miller *et al.* 1984*c*).

correction for the change in exciton binding energy (Miller *et al.* 1984*c*). (The exciton does not field ionize because it is held together by the walls of the quantum well.) This effect is distinct from and much larger than the Franz–Keldysh effect normally seen in bulk semiconductors because it arises from perturbations of large (*ca.* 10 nm) envelope functions with small associated energies (*ca.* 5–30 meV) and is unique to the m.q.w. at any temperature.

Both parallel and perpendicular field effects produce large changes in transmission (about 50% in samples only micrometres thick). They are not limited by recombination times; in practice they are limited so far by the time taken to apply the electric field (for example, by *RC* time constants) and the fundamental limit is likely to be an uncertainty time up to 1 ps. A novel high speed modulator (up to 2 ns) has already been demonstrated (Wood *et al.* 1984).

4. Optical bistability due to increasing absorption

It has recently been pointed out (Miller *et al.* 1984*a*; Miller 1984) that a common principle underlies several previously independent theoretical discussions (Kaplan 1982; Hajto & Janossy 1983; Hopf *et al.* 1984) and experimental demonstrations (Hajto & Janossy 1983; Bohnert *et al.* 1983) of mirrorless optical bistability in diverse, specific, physical systems. The principle relies on an increase of absorption as the material becomes more excited. Increased incident optical power gives increased absorbed power and hence increased excitation of the material; this gives increased absorption, which gives further increased excitation and hence further increased absorption. Under the right conditions (Miller *et al.* 1984*a*; Miller 1984), this positive feedback leads to switching and bistability. Good agreement is found between theory and experiment in a simple thermal system (Miller *et al.* 1984*a*). The theory is particularly simple and general, is readily interpreted graphically (Hajto & Janossy 1983, Miller *et al.* 1984*a*), and simple conclusions can be drawn about limiting switching powers and the width of the bistable region (Miller 1984).

This class of bistability shows several exceptional features (Miller *et al.* 1984*a*; Miller 1984): (i) it requires no mirrors or other optical feedback and hence does not require coherent light; (ii) the switching is to a *higher* absorption (and hence *lower* transmission) state; (iii) it requires a material whose absorption increases as the real state of excitation of the material is increased. Although the 'state of excitation' may be parameterized in many different ways (for example, temperature rise (Miller *et al.* 1984*a*, Hajto & Janossy 1983), kinetic energy (Kaplan 1982), population inversion (Hopf *et al.* 1984), band gap renormalization (Bohnert *et al.* 1983) and, as discussed later, voltage change (Miller *et al.* 1984*b*)), the nonlinearity must be 'dynamic', and no susceptibility rigorously expandable in a power series only of the optical electric field (with constant coefficients) can give this bistability.

This bistability is important in its own right, but also happens to be the class exploited in the hybrid device now discussed.

5. The optically bistable SEED

The samples used to measure the perpendicular field electroabsorption (Miller *et al.* 1984*c*) and to demonstrate fast modulators (Wood *et al.* 1984) used a p-i-n diode structure in which the m.q.w. material was contained in the intrinsic region. All other parts of the structure were transparent. Such a structure also serves as an efficient photodetector (Miller *et al.* 1984*c*), with

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the responsivity depending on the absorption of the m.q.w., which in turn depends on the voltage of the m.q.w. If the photocurrent alters the voltage, then modulator and detector feed back on one another, giving a Self Electro-optic Effect Device (SEED) (Miller *et al.* 1984*b*).

Connecting the p-i-n diode through a large series resistor to a constant reverse bias supply can give an optically bistable SEED. The wavelength of the light source shining through the SEED is chosen near the zero-field heavy-hole exciton-peak position. With no incident optical power, the diode is reverse biased, the exciton peak is moved to lower energy and the absorption is comparatively low. With increasing power, a photocurrent is generated that drops a voltage across the resistor, reducing the voltage across the diode and thereby shifting the exciton absorption back towards the operating wavelength and increasing the absorption and photocurrent. Optical bistability is then seen through the mechanism described in §4. Figure 3 shows the observed bistability together with a theroetical model, based on measured transmission and responsivity, with no fitted parameters.

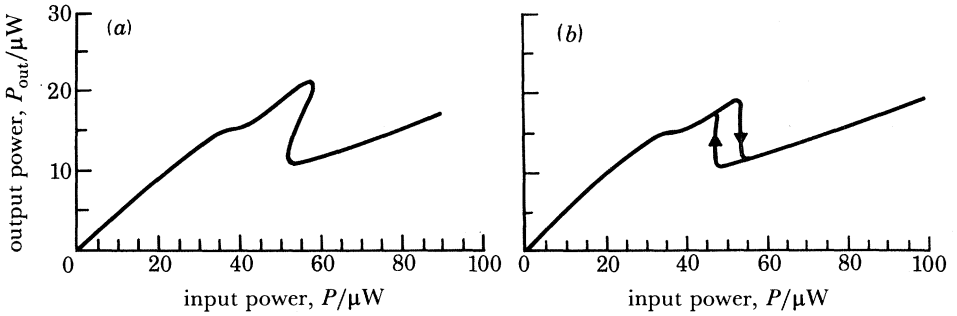

FIGURE 3. THEORY (*a*) and experiment (*b*) for SEED optical bistability (Miller *et al.* 1984*b*) and with 1 MΩ resistor and 20 V bias supply at 851.7 nm.

The resulting optical device can be operated over a very wide range of parameters. With a 600 μm diameter device, switching powers of 670 nW (at 1.5 ms switching time) to 3.7 mW (at 400 ns switching time) have been observed between 850 and 860 nm. Switching times are *RC* time-constant limited, and are expected to be proportionally smaller for smaller area devices. However, the most remarkable feature of the device is the switching energy per unit area (4 fJ μm^{-2} for incident optical and up to 14 fJ μm^{-2} for electrical). Even the total switching energy per unit area is lower than any previously reported optical switching energy per unit area at a comparable wavelength (*ca.* 120 fJ μm^{-2}) by a factor of over six, despite the fact that the SEED uses no cavity to reduce switching energy. The reason for this fundamentally lower energy stems from the very small volume and moderate field requirements of the m.q.w. perpendicular field electroabsorptive effect; the switching energy reduces mainly to the stored electrostatic energy in the reverse-biased diode.

6. CONCLUSIONS

In summary, the m.q.w. shows itself to be a remarkable material for optical devices, both for all-optical nonlinearities and electro-optical effects. In electroabsorption it opens up new opportunities not accessible with any other material at any temperature. All these phenomena are seen at room temperature at power levels, wavelengths, voltages and timescales compatible

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

with laser diodes and other semiconductor optoelectronic and electronic devices. A new class of optical bistability has also been identified and applied to demonstrate the SEED by using the quantum wells to give a device that sets new standards in optical switching energy and represents a significant advance towards practical optical switching and processing.

References

Bastard, G., Mendez, E. E., Chang, L. L. & Esaki, L. 1982 *Phys. Rev.* B **28**, 3241–3245.

Bohnert, K., Kalt, H. & Klingshirn, C. 1983 *Appl. Phys. Lett.* **43**, 1088–1090.

Chemla, D. S., Damen, T. C., Miller, D. A. B., Gossard, A. C. & Wiegmann, W. 1983 *Appl. Phys. Lett.* **42**, 864–866.

Chemla, D. S., Miller, D. A. B., Smith, P. W., Gossard, A. C. & Wiegmann, W. 1984 *IEEE J. Quantum Electron.* **20**, 265–275.

Gibbs, H. M., Tarng, S. S., Jewell, J. L., Weinberger, D. A., Tai, K., Gossard, A. C., McCall, S. L., Passner, A. & Wiegmann, W. 1982 *Appl. Phys. Lett.* **41**, 221–222.

Hajto, T. & Janossy, I. 1983 *Phil. Mag.* B**47**, 347–366.

Hopf, F. A., Bowden, C. M. & Louisell, W. 1984 *Phys. Rev.* A **29**, 2591–2596.

Ishibashi, T., Tarucha, S. & Okamoto, H. 1982 *Inst Phys. Conf. Ser.* **63**, 587–588.

Kaplan, A. E. 1981 *Phys. Rev. Lett.* **48**, 138–141.

Miller, D. A. B. 1984 (Submitted to *J. opt. Soc. Am.* B.)

Miller D. A. B., Chemla, D. S., Eilenberger, D. J., Smith, P. W., Gossard, A. C. & Tsang, W. T. 1982 *Appl. Phys. Lett.* **41**, 679–681.

Miller, D. A. B., Chemla, D. S., Eilenberger, D. J., Smith, P. W., Gossard, A. C. & Wiegmann, W. 1983*a* *Appl. Phys. Lett.* **42**, 925–927.

Miller, D. A. B., Chemla, D. S., Smith, P. W., Gossard, A. C. & Wiegmann, W. 1983*b* *Optics Lett.* **8**, 477–479.

Miller, D. A. B., Gossard, A. C. & Wiegmann, W. 1984*a* *Optics Lett.* **9**, 162–164.

Miller, D. A. B., Chemla, D. S., Damen, T. C., Gossard, A. C., Wiegmann, W., Wood, T. H. & Burrus, C. A. 1984*b* *Appl. Phys. Lett.* **45**, 13–15.

Miller, D. A. B., Chemla, D. S., Damen, T. C., Gossard, A. C., Wiegmann, W., Wood, T. H. & Burrus, C. A. 1984*c* (In preparation.)

Tarng, S. S., Gibbs, H. M., Jewell, J. L., Peyghambarian, N., Gossard, A. C., Venkatesan, T. & Wiegmann, W. 1984 *Appl. Phys. Lett.* **44**, 360–361.

Wood, T. H., Burrus, C. A., Miller, D. A. B., Chemla, D. S., Damen, T. C., Gossard, A. C. & Weigmann, W. 1984 *Appl. Phys. Lett.* **44**, 16–18.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES