Novel hybrid optically bistable switch: The quantum well self-electro-optic effect device

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We report a new type of optoelectronic device, a self-electro-optic effect device (SEED), which uses the same GaAs/GaAlAs multiple quantum well material simultaneously as an optical detector and modulator. Using a series resistor and constant voltage bias supply the SEED shows optical bistabilty (OB) of the recently discovered type which relies on increasing absorption and requires no mirrors. OB is seen at room temperature from ~850–860 nm, at powers as low as 670 nW or switching times as short as 400 ns (limited only by power restrictions) with ~1-nJ optical switching energy in a 600-μm-diam device. Total energies per unit area (~18 fJ/μm^2) are substantially lower than any previously reported for OB.

Switching devices using optical inputs and outputs have been the subject of considerable research in recent years. Optical bistability (OB) in particular has received much attention,[1] both as an interesting physical phenomenon and as an attractive method for making optical logic elements. Many methods have been proposed for attaining OB; usually they require a combination of a microscopic nonlinearity with some macroscopic feedback. One problem with most forms of OB has been the difficulty of achieving adequately fast switching times at sufficiently low powers (i.e., low switching energy) to make useful devices. Several approaches have been taken to minimize switching energy. The use of a resonant cavity (such as the Fabry–Perot) helps, but at the expense of increased difficulty of fabrication. Research has also been undertaken to find novel nonlinear materials, especially semiconductors with large nonlinear refractive indices.[2–6] "Hybrid" methods of synthesizing nonlinear optical behavior by combining electro-optic materials with electrical detection and electrical feedback have also been investigated,[7] but these methods usually work at the expense of considerable electrical complexity; even with the best conventional electro-optic materials, devices with interestingly low switching energies[8] have been relatively long (consequently requiring waveguide confinement). Some attempts have also been made to reduce electrical complexity by combining the electrical detector and electro-optic material.[9]

Two recent developments have prepared the way for the novel optically bistable device described in this paper. First, a new type of OB has recently been discovered which relies only on a material whose absorption increases as the material becomes more excited.[10,11] No mirrors or other external feedback are required; the feedback is internal and positive (increasing incident power gives more absorbed power, which excites the material, resulting in increased absorption and hence more absorbed power, and so on). Second, new electroabsorptive processes, much larger than the usual Franz–Keldysh effect seen in conventional semiconductors, are seen in room-temperature GaAs/GaAlAs multiple quantum well (MQW) material.[12–14] In particular, when an electric field is applied perpendicular to the quantum well layers, the band edge absorption, including any exciton resonance peaks, can be shifted to lower photon energies. In a few microns of material, changes in transmission of ~50% can be achieved at modest drive voltages (~8 V).[13] When this field is applied using a reverse-biased *p-i-n* diode with the MQW inside the intrinsic (i) region, the structure also is an efficient photodetector.[14] These recent discoveries are combined in this work to make a hybrid version of OB due to increasing absorption in which the same micron-thick piece of MQW is used as both detector and electroabsorptive modulator. The high sensitivity of this new electroabsorptive effect enables attractive switching energies and speeds without any resonant cavities.

Only a series resistor (R) and a constant voltage bias supply (V_0) must be added to the *p-i-n* diode to make the optically bistable device. The configuration is shown schematically in Fig. 1. We call this combination of MQW modulator and detector a self-electro-optic effect device (SEED). To make the device switch, the incident light wavelength is chosen to be near the exciton resonance position for zero

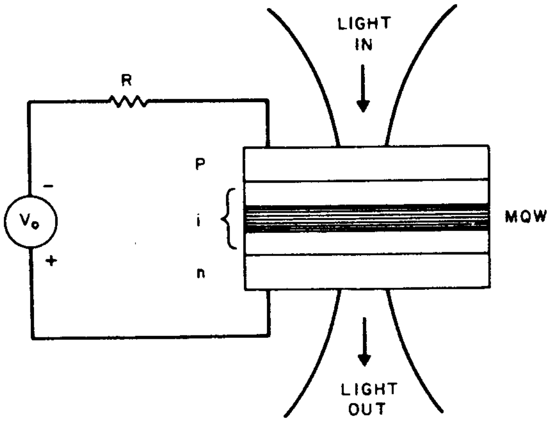

FIG. 1. Schematic of the quantum well SEED.

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voltage across the diode. With low optical power, nearly all the supply voltage is dropped across the diode because there is little photocurrent. This voltage shifts the exciton absorption to longer wavelengths (lower energies) and the optical absorption is relatively low. Increasing the optical power increases the photocurrent, reducing the voltage across the diode. However, this reduced voltage gives increased absorption as the exciton resonances move back, resulting in further increased photocurrent and consequently leading, under the right conditions,[10,11] to regenerative feedback and switching.

In our experiments we have used a krypton-pumped LDS 821 cw dye laser, although the powers and wavelengths are clearly compatible with a diode laser source. The sample used has fifty 95-Å GaAs quantum well layers separated by 98-Å GaAlAs barrier layers, all with no intentional doping. This MQW material is within the intrinsic region of a *p-i-n* diode structure grown by molecular beam epitaxy on a GaAs substrate; contact and buffer regions are made of GaAlAs and GaAs/GaAlAs superlattice materials which are substantially transparent at the wavelengths of interest here. The material is etched to give a 600-μm-diam mesa, a gold ring contact with a 100-μm-diam hole is applied to the top surface, and the GaAs substrate is removed underneath this hole to give a clear optical path perpendicularly through the layers. This sample is similar to those previously used for modulators[13] and is described in greater detail elsewhere.[13] When a reverse bias is applied to this structure, the absorption spectrum near the band-gap energy shifts to lower energies with some broadening as has been described.[13,14] However, our measurements also show that, with reverse bias, the internal quantum efficiency of the structure as a detector is high with one carrier pair collected for each absorbed photon within experimental error.[14] Only at reverse bias $\lesssim 2$ V does the quantum efficiency drop off, probably because the depletion region then does not extend completely through the MQW.

Figure 2(a) (solid line) shows the measured (external) responsivity S of the sample as a function of reverse bias; this measurement is made at 1.456 eV (851.7 nm) which is approximately the zero bias energy of the heavy hole exciton resonance. As the reverse bias is increased, the responsivity first increases as depletion becomes complete and then decreases as the exciton absorption peak moves to lower energy. The subsequent feature between 8 and 16 V is due to the light hole exciton resonance similarly moving past the measuring wavelength.

To calculate the input/output characteristic, we solve two simultaneous equations. The first is

$$S = S(V), \tag{1}$$

where $S(V)$ is the measured responsivity [the solid line in Fig. 2(a)]. The second is $V = V_0 - RSP$, where P is the optical input power and V is the voltage across the diode, i.e.,

$$S = (V_0 - V)/RP. \tag{2}$$

The graphical solution is straightforward [Fig. 2(a)] with Eq. (2) giving straight lines (shown dashed) of decreasing (negative) slope for increasing P. Bistability results from the multiple intersections of straight line and curve. We can also calculate S and V as a function of P by choosing V, deducing S from Eq. (1) and P from Eq. (2). For reverse bias $\gtrsim 2$ V, the optical absorption closely follows the responsivity; to make a more accurate calculation, however, we have measured the transmission $T(V)$ [Fig. 2(b)] from which we can deduce the output power $P_{\text{out}} (\equiv PT)$ for each V and P and, hence, the whole theoretical input/output characteristic [Fig. 2(c)].

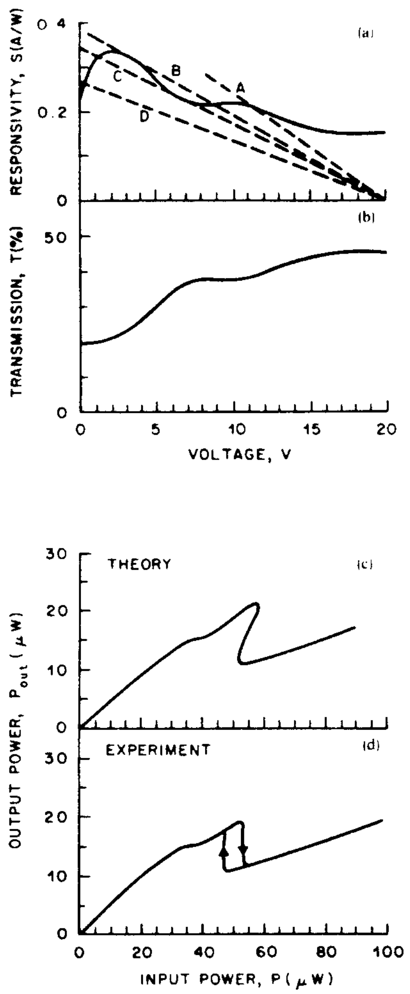

FIG. 2. (a) The solid line is the measured responsivity at 851.7 nm with reverse bias, V [Eq. (1)]. The dashed lines A–D correspond to the constraint imposed by the external circuit [Eq. (2)] for increasing power P ($V_0 = 20$ V). Lines A and D show only one intersection (i.e., only one solution); all lines between B and C show three intersection points, corresponding to bistability (the middle solution is unstable). (b) shows the measured optical transmission of the device with voltage at 851.7 nm (c) shows the theoretical optical input/output characteristic calculated using the measured responsivity and transmission with $R = 1$ MΩ and $V_0 = 20$ V as described in the text; there are no fitted parameters. (d) shows the measured optical input/output characteristic at 851.7 nm with $R = 1$ MΩ and $V_0 = 20$ V.

We have measured the input/output characteristics by amplitude modulating the incident light beam with an acousto-optic modulator and displaying the input and output powers, as monitored by silicon photodiodes, on the X and Y axes of an oscilloscope. Figure 2(d) shows the experimental result with $R = 1$ MΩ and $V_0 = 20$ V at 851.7 nm [the same parameters were used for the theory, Fig. 2(c)]. Bistability is clearly seen, and the result is in very good agreement with the theory with no fitted parameters.

The capacitance of this device[13] is $C \sim 20$ pF and the

TABLE I. Measured switching times and powers with $V_0 = 20$ V at 853.0 nm using various resistors. RC time constants are calculated using $C = 20$ pF. τ_a is the 10%–90% switching time for high-to-low transmission, measured with slowly varying input powers. P_s is the incident power at the high-to-low transition. Switching times are accurate only within a factor of 2 due to laser noise.

Resistance (R)	Switching power (P_s)	Switching time (τ_a)	RC time constant	Switching energy ($P_s \times \tau_a$)
100 MΩ	670 nW	1.5 ms	2 ms	1.0 nJ
10 MΩ	6.5 μW	180 μs	200 μs	1.2 nJ
1 MΩ	66 μW	20 μs	20 μs	1.3 nJ
100 kΩ	660 μW	2.5 μs	2 μs	1.7 nJ
22 kΩ	3.7 mW	400 ns	440 ns	1.5 nJ

measured switching time from high to low transmission states, τ_a, is dominated by the RC time constant as is shown in the results in Table I. Switching times were measured by ramping the input optical power up and down and measuring the optical rise and fall times of the transmitted light at the switching transitions. The switching power is proportional to $1/R$ (from the above theory), which leads to the measured speed/power trade off seen in Table I. The switching transition from low-to-high transmission also shows "critical slowing down,"[15] with switching being delayed by up to five times the switch-on time τ_a, when the input power is ramped rapidly. Critical slowing down was also observed in the thermal OB due to increasing absorption.[10] At $V_0 > 25$ V we can also observe OB due to the light hole exciton resonance and can resolve two overlapping bistable regions.

One of the remarkable features of this device is the broad range of parameters with which it will operate. The switching power and speed can be chosen over a range of nearly 10^4 as shown in Table I. We also find that OB can be seen for all V_0 from 15 V to the highest voltage used (40 V). The operation is insensitive to incident light spot size from $< 10\,\mu$m diameter up to the maximum mechanically allowed ($\sim 100\,\mu$m); this is to be expected since the device operation depends on power, not intensity. The switching is remarkably insensitive to wavelength; we observe OB from 850.1 to 861.8 nm with $V_0 = 20$ V with less than 40% shift in the switching powers. The device also works equally well with multiline output from the laser (e.g., 850–853 nm); this is to be expected as theoretically this device should not require coherent light. Furthermore, it is possible to set and reset the device electrically; increases and decreases ~ 0.8 V can switch the device to high and low transmission states respectively near 20-V bias and the device is also electrically bistable at constant optical power.

Switching power and speed limits are clearly important for any practical switch. The present device is large (600 μm) by optical standards and consequently has a large capacitance and only a moderately low switching energy, i.e., power × time (~ 1 nJ incident optical energy and $\gtrsim 4$ nJ calculated dissipated electrical energy at 20-V bias during the switching. However, the switching energies per unit area are remarkably low (~ 4 fJ/μm^2 incident optical and $\lesssim 14$ fJ/μm^2 electrical); optical and total switching energies per unit area (comparing our total device area to optical spot sizes in other devices when appropriate) are lower by factors of ~ 30 and ~ 6, respectively, than the lowest measured optical energy per unit area for any OB device at a comparable wavelength.[8] The scaled total energy requirement of our device in the physical limit (i.e., ~ 1 fJ in a λ^2/n^2 device) is comparable to or better than the best scaled high-finesse resonant cavity OB devices[16] despite the absence of a resonant cavity to reduce switching energy. The low energies and absence of cavities make this device particularly attractive for switching arrays. Our maximum switching speed was dictated by a conservative maximum operating power rather than any fundamental limit. With smaller devices, therefore, faster, lower energy operation should be possible. The device has already been operated as a modulator with response times in the range of 2 ns,[13] and as a detector with $\lesssim 10$-ns response times.

In conclusion, we have demonstrated a novel hybrid optically bistable device utilizing multiple quantum well material simultaneously as both a modulator and detector. The circuit is electrically very simple, the device requires no mirrors or other external optical feedback, it operates over a broad range of conditions readily compatible with semiconductor light sources, it shows inverting logic operation, and smaller, scaled devices offer the possibility of attractively low switching energies.

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