Energy Scaling and Subnanosecond Switching of Symmetric Self-Electrooptic Effect Devices

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Abstract—**We demonstrate the scaling of switching energy with device area for four sizes of symmetric self-electrooptic effect devices, the smallest of which has a switching energy of 3.6 pJ. We also demonstrate switching speeds of ~2 ns at 15 V bias and ~860 ps at 22 V bias by using mode-locked (6 ps) pulses, although the energies in these pulses were somewhat higher, because of saturation of the quantum well material. Making the device area only moderately larger than the spot size is suggested as a method of avoiding this saturation.**

THE FUTURE success of photonic switching and optical computing depends, at least to some degree, on the ability to find a suitable device with fast switching times and low-optical power requirements. One class of proposed devices are the quantum well self-electrooptic effect devices (SEED's) [1]–[11]. SEED's rely on changes in the optical absorption that can be induced by changes in an electric field perpendicular to the thin semiconductor layers in quantum well material by way of the quantum-confined Stark effect (QCSE) [12]. Combining the QCSE and optical detection within the same structure, for example by putting quantum wells in the intrinsic region of a reverse biased p-i-n diode, can cause optoelectronic feedback and bistability. A host of functionalities can be obtained by combining these quantum well p-i-n diodes with resistors [2], [3], photodiodes [3]–[5], field effect transistors [6], bipolar transistors [1], [11], and other quantum well p-i-n diodes [7]–[10]. Although many of the devices have demonstrated low-switching energies *per unit area,* the devices that have been reported in the literature thus far are large and thus have optical switching energies in the hundreds of picojoules and switching speeds in the tens of nanoseconds. To achieve the best possible performance, a device must work at lower energies as the devices are made smaller. Diode-biased SEED's [4], [5] have shown performance scaling in going from $(200\ \mu m)^2$ to $(60\ \mu m)^2$ mesa sizes. In this paper, we present the energy scaling of four sizes of symmetric self-electrooptic effect devices (S-SEED's) [7], [8], the smallest of which has a switching energy of ~3.6 pJ. In a different experiment, we also demonstrate switching speeds of 2 ns at 15 V and 860 ps at 22 V using pulses from a mode-locked dye laser, although the energies in these pulses were higher.

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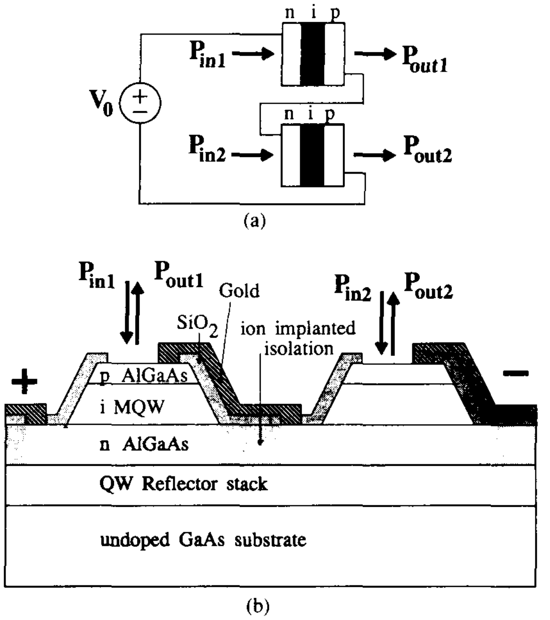

Fig. 1. The symmetric SEED: (a) Schematic diagram. (b) Physical layout of devices used in the experiments (not to scale). Epitaxial layer dopings, compositions, and thicknesses (from bottom to top): reflector stack: 15 periods of alternating undoped AlAs 723 Å and $Al_{0.11}Ga_{0.89}As$ 599 Å with top $Al_{0.11}Ga_{0.89}As$ layer of 1198 Å; anode n = $5 \times 10^{18}/cm^3$ $Al_{0.11}Ga_{0.89}As$ 5000 Å; buffer: undoped $Al_{0.11}Ga_{0.89}As$ 5000 Å; MQWS: undoped 60.5 periods (60 wells 61 barriers) $Al_{0.30}Ga_{0.70}As$ 60 Å and GaAs 100 Å; buffer: undoped $Al_{0.11}Ga_{0.89}As$ 200 Å; cathode: p = $1 \times 10^{19}/cm^3$ $Al_{0.11}Ga_{0.89}As$ 3000 Å; total thickness ~3.93 μm.

The S-SEED consists of two quantum well p-i-n diodes electrically connected in series as shown in Fig. 1(a). It acts as an optically bistable memory element with individual set and reset capabilities and complementary outputs (an optical set-reset latch), and can also operate as a differential logic gate [13]. The S-SEED is very attractive for systems experiments, because the switching point is determined by the ratio of the two inputs, thus the device is insensitive to power supply fluctuations if both input beams are derived from the same laser. The device also has time-sequential gain in that the state of the device can be set using relatively weak beams and subsequently read out using higher power clock beams. Since the application of the input signals and appearance of the output signals occur at different times, the device has input/output isolation as well.

The materials that comprise the two p-i-n diodes in the devices used in these experiments [8] are grown on top of a dielectric mirror, so that the output signals are reflected off the device, similar to a reflection quantum well modulator that has been previously reported [14]. This approach was chosen primarily because the device is easier to fabricate, although additional benefits include better heat conduction because the back of the chip can be mounted directly to a heat sink and better contrast ratio because the optical beams pass through the quantum well regions twice. An illustration of the device is shown in Fig. 1(b). The wafers were grown by molecular beam epitaxy. The individual diodes were formed by etching down to the n layer, and isolated using ion implantation. Ohmic contacts, deposition of an insulator, and interconnect metallization completed the fabrication. The mesa sizes vary from 100 μm × 100 μm to 13.5 μm × 14 μm, with corresponding optical window sizes from 40 μm × 80 μm to 5 μm × 10 μm. All windows were anti-reflection coated. All four device sizes were packaged together on the same chip.

The required optical switching energy was measured for each device size by applying a single low-power pulse to one p-i-n diode at a time. When the pulse is initially present, that output is in its high state, and after a period of time the output switches to its low state as illustrated in Fig. 2. By integrating the power in the pulse until switching occurs, we know the amount of energy that was supplied. A later pulse incident on the other p-i-n diode returns the device to its original state. Because the device can hold its state when both signals are removed, the two pulses need not overlap. The pulses generated by current-modulating AlGaAs semiconductor laser diodes had a rise-time ~15 ns, although this is not observable from Fig. 2 because the device begins switching before the pulse reaches its final value. By looking at the unswitched pulse, we determined that the average power integrated over the first 15 ns was 2/3 of the peak power. A summary of the measurements of the different device sizes is shown in Table I. The fastest switching time observed in this group of measurements was 14 ns from the beginning of the applied pulse with a peak power of only ~400 μW. There was some contrast ratio degradation at power levels greater than ~200 μW, because of saturation of the quantum well material. All of the devices had switching energy densities between 6.5 and 10.5 fJ/μm^2.

The theoretical required optical switching energy is found by calculating the time it takes to charge the capacitance of the quantum well diodes with the photocurrent. Using Kirchoff's current law at the center node of the two diodes [see Fig. 1(a)], we get:

$$P_{\mathrm{in}_1} S(V) - P_{\mathrm{in}_2} S(V_0 - V) + C\frac{dV}{dt} - C\frac{d(V_0 - V)}{dt} = 0. \quad (1)$$

where C is the capacitance of a single p-i-n diode, P_{in_1} and P_{in_2} are the input powers incident on the first and second diodes, respectively, $S(V)$ and $S(V_0 - V)$ are the responsivities of the two diodes, V_0 is the power supply voltage, and V is the voltage across the top p-i-n diode. Since this expression is difficult to calculate directly, we assume that the responsivity of the two diodes is constant and given by $\bar{S}$ and dV/dt is equal to the voltage swing (V_0 plus the forward bias voltage V_f) divided by the switching time Δt. Since only one signal is present, $P_{\mathrm{in}_2} = 0$. The product of P_{in_1} and Δt gives us an

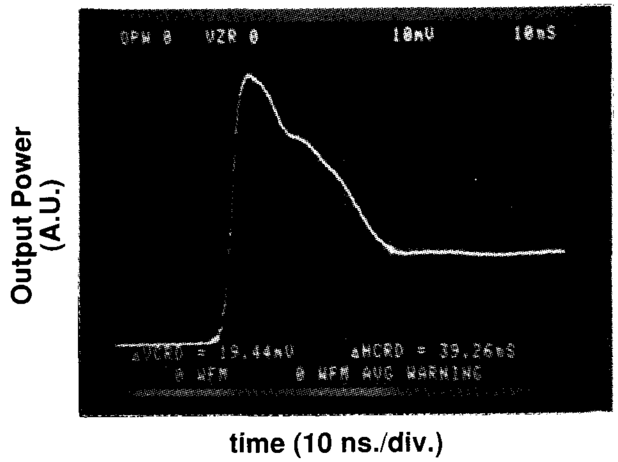

Fig. 2. Output from one p-i-n diode after the application of a pulse with a 15 ns rise-time and a 100 μW peak power showing the switching of the device at a voltage of 15 V and $\lambda \sim$ 850 nm. During the pulse, no signal is present on the other p-i-n diode. A similar pulse delayed in time is used to "reset" the state of the device.

TABLE I
SWITCHING SPEED AS A FUNCTION OF PEAK POWER FOR THE DIFFERENT SIZE DEVICES AT A POWER SUPPLY VOLTAGE OF 15 V AND $\lambda \sim$ 850 nm

device size (μm)	Power (μW)	Δt (ns)	E_{meas} (pJ)	$E_{meas}/\mu m^2$ (fJ)	$E_{calc}/\mu m^2$ (fJ)
100 x 100	200	750	149	7.5	5.9
	400	361	142	7.1	
60 x 60	200	357	71	9.8	
	400	145	56	7.7	
30 x 30	100	130	12.5	6.9	
	200	63	11.6	6.5	
13.5 x 14	50	80	3.7	9.7	
	100	39	3.4	8.9	
	200	24	3.8	10.5	
	400	14	3.6	9.5	

approximate expression for the optical switching energy:

$$E_{\mathrm{opt}} = \Delta t P_{\mathrm{in}_1} = \frac{2C(V_0 + 2V_f)}{\bar{S}}. \quad (2)$$

The capacitance of each diode is 115 aF/μm^2, V_0 is 15 V, V_f is 1 V, and $\bar{S}$ is equal to ~0.33. The calculated value of optical switching energy density of 5.9 fJ/μm^2 agrees reasonably well with the measured data, although the smallest devices have slightly higher energy densities. In these small devices, some of the energy fell outside the optical window and the parasitic capacitances are a greater percentage of the total capacitance.

To apply more power to the device in a shorter time, the smallest devices were switched using ~6 ps pulses separated by 13.2 ns from an argon-ion-pumped Styryl 9 mode-locked laser. The pulsed signal was split in two equal paths and each path was routed to one diode of the S-SEED with one of the paths delayed ~5 ns relative to the other. The output from a CW laser diode was routed to both diodes of the S-SEED to monitor the output. The spot sizes were slightly larger than 5 μm in diameter. The device switched in ~2 ns at 15 V and ~860 ps at 22 V as shown in Fig. 3, although the optical energies in the pulses were ~18 and ~21 pJ, respectively, considerably more than the ~3.5 pJ measured in the earlier experiment. This is partly because some of the optical energy fell outside of the optical window, but mostly because the quantum efficiency of the devices is reduced for these short intense pulses due to saturation of the quantum well material.

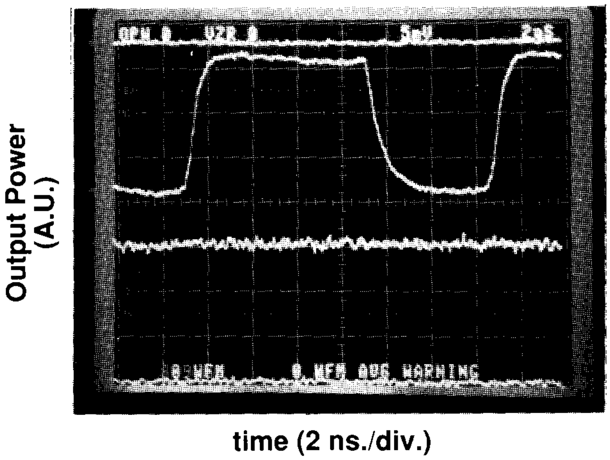

Fig. 3. Output power of one of the CW laser diode beams after being switched by the 6 ps (21 pJ) pulses with the device biased at 22 V. Also shown are the output power levels when the device was switched by blocking one of the beams and the input pulsed signals removed. Bottom horizontal line is the detector output with no signal present (baseline) and the top two horizontal lines show the device in the "low" and "high" states, respectively. Average power in the incident CW signals were ~ 180 μW.

If we assume that a carrier density $\gtrsim 10^{17}/\text{cm}^3$ will start to cause saturation to occur [15], this limits the allowed energy of the optical pulse in the extreme case where all of the switching energy is injected in a time that is short compared to the device switching time. The number of carriers generated from an incident optical pulse with energy E_{opt} is given by

$$N = \frac{\eta(V)}{h\nu} \left[1 - e^{-2\alpha(V)L}\right] E_{\text{opt}} \tag{3}$$

where N is the number of carriers where saturation begins, $\eta(V)$ is the quantum efficiency (number of electron-hole pairs generated per photon absorbed), L is the thickness of the sample, and $[1 - e^{-2\alpha(V)L}]$ is the fraction of incident photons that are absorbed. Assuming one electron-hole pair per photon absorbed, 50 percent absorption in the material (at 15 V bias), and a photon energy of 1.45 eV, saturation should begin to occur at an incident energy density of 46 fJ/μm^2. Since the spot sizes in these experiments were about $(5\ \mu\text{m})^2$, saturation should occur at an input energy of 901 fJ. Because this is four times less than the required switching energy of the device, saturation occurs and more incident energy is required to generate the charge required to switch the device than would be the case without saturation. The key to solving this problem is to reduce the device capacitance as much as possible while maintaining the same size optical window. Since the measured switching energy is less than 10 fJ/μm^2 of device area, the device area can be up to four times larger than the spot size, and these pulses will switch the devices without saturating. In these experiments, however, the device area was ~ 10 times the spot area. Operating the devices at lower voltages should help reduce this saturation problem as well, since less charge is required for switching.

In conclusion, we have demonstrated the scaling of optical switching energy with device size for four sizes of symmetric self-electrooptic effect devices, the smallest with a switching energy of 3.6 pJ. By using mode-locked 6 ps pulses to switch the devices, we have measured switching times below 1 ns. The energy in these pulses was somewhat higher than expected, probably because of saturation of the material. We finally suggested that reducing the device size so that it is only moderately larger that the spot size would allow even mode-locked pulses to switch the device without saturation occurring.

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