

# Symmetric self-electro-optic effect device: Optical set-reset latch

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We demonstrate an integrated symmetric self-electro-optic effect device consisting of two quantum well *p-i-n* diodes electrically connected in series. The device acts as a bistable optical memory element with individual set (*S*) and reset (*R*) inputs and complementary outputs (optical *S-R* latch). The switching point is determined by the *ratio* of the two inputs, making the device insensitive to optical power supply fluctuations when both power beams are derived from the same source. The device also shows time-sequential gain, in that the state can be set using low-power beams and read out with subsequent high-power beams. The device showed bistability for voltages greater than 3 V, incident optical switching energy densities of  $\sim 16 \text{ fJ}/\mu\text{m}^2$ , and was tested to a switching time of 40 ns.

The potential use of optics in telecommunications switching and computing has generated considerable interest in recent years. One approach is to use planar two-dimensional arrays of logic or memory devices interconnected with free-space optics. One proposed class of devices uses Fabry-Perot étalons containing semiconductor nonlinear refractive materials.<sup>1-4</sup> Uniform operation over different areas of the resonator<sup>3</sup> and fast switching times<sup>4</sup> have been demonstrated. Another device is the quantum well self-electro-optic effect device (SEED).<sup>5-8</sup> 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. This effect has been called the quantum confined Stark effect (QCSE).<sup>9,10</sup> Combining the QCSE with optical detection within the same structure can cause optoelectronic feedback and bistability. Uniform arrays of bistable integrated diode-biased SEED's (D-SEED's)<sup>7</sup> as large as  $6 \times 6$  (Ref. 8) have been demonstrated.

A problem with optically bistable systems is that, to obtain the gain necessary for cascaded logic, the devices need to be biased very close to their switching transition. Such critical biasing imposes very strict tolerances on the uniformity of the devices and the bias beam powers. One solution is to operate an étalon (without bistability) with two wavelengths.<sup>3,11</sup> This requires two different devices, one to down-convert and the other to up-convert wavelengths. The device that we demonstrate here, the symmetric SEED (S-SEED) is optically bistable, but is bistable in the *ratio* of two beam powers, rather than any absolute power. When both beams are derived from the same source, source power fluctuations are, therefore, unimportant. Furthermore, the device does not need to be biased close to a switching point to give gain, so that uniformity of bias beams is not critical. It can show time-sequential gain by being switched at low power and read out at high power. Such time-sequential operation also gives good input/output isolation, because a small reflection back onto the device will not change its state. Hence this device offers a potential solution to some of the major problems of optical bistability for logic.

The D-SEED previously demonstrated<sup>7,8</sup> consists of a

*p-i-n* diode with quantum wells in the intrinsic region vertically integrated in series with another photodiode that is used for the load. The load photodiode is transparent to the wavelengths used for the quantum wells ( $\sim 850 \text{ nm}$ ) but absorbs all of the incident light for wavelengths less than 750 nm. When a He-Ne laser is used to "bias" the photodiode load, the array behaves as a set of nearly identical bistable devices whose switching power and speed can be set over many decades by adjusting the intensity of the He-Ne laser. In addition, the array can operate as a dynamic memory where the state of the device is preserved when both the bias and the infrared beams are removed. The stored state may be read out sometime later (up to 30 s) by simultaneously increasing the two beams.<sup>8</sup> In the symmetric SEED, the load is a second *p-i-n* diode with multiple quantum wells in the intrinsic region. Since the two diodes are identical, either diode can be considered as the load of the other. The basic physical mechanisms in the D-SEED and the S-SEED are therefore similar, but the ability to work with two complementary beams at the same wavelength greatly increases the usefulness of the S-SEED.

The schematic diagram and physical layout of the device are shown in Fig. 1. The material was grown by molecular beam epitaxy on a Si-doped *n*-type GaAs substrate. The *p* region was grown as a fine-period GaAs/AlGaAs superlattice as in the integrated D-SEED to improve the quality of the material. The structure, which is *n-i-p-i-n*, results in two back-to-back diodes between the substrate and the top *n* regions. The multiple quantum well *p-i-n* diodes (on top) are connected "horizontally" by an external connection rather than "vertically" during growth as in the D-SEED, circumventing the problem that limited the speed of the D-SEED, namely, the limited current that could be carried by the internal ohmic contact in that structure. The isolation diodes (bottom), comprised of the AlGaAs *i* and *n* and superlattice *p* regions, ensure electrical isolation between the *p* regions of the two quantum well diodes. In operation, both of the isolation diodes are always reverse biased by connecting the substrate to a positive voltage. The quantum well diodes are made by etching separate mesas and electrically connected

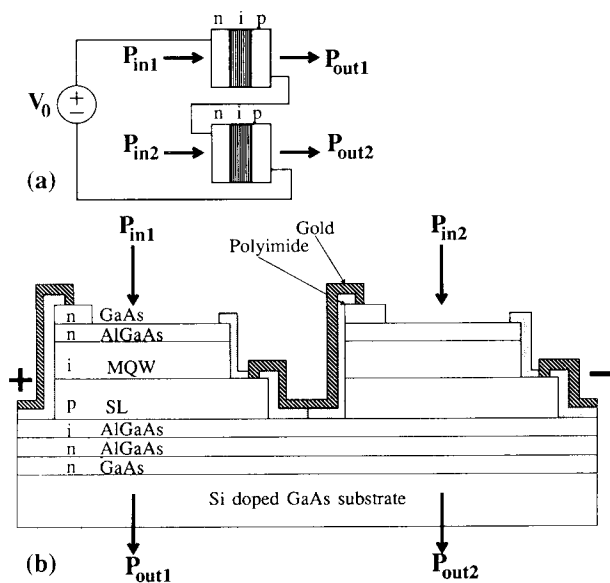


FIG. 1. Symmetric SEED: (a) schematic diagram and (b) physical layout (not to scale). The Al mole fraction in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  is 0.4. Epitaxial layer thicknesses and dopings (from bottom to top):  $n$ -GaAs ( $0.17\text{ }\mu\text{m}$ ,  $n = 10^{18}\text{ cm}^{-3}$ );  $i$ -AlGaAs ( $1.92\text{ }\mu\text{m}$ );  $p$ -superlattice (SL) (250 periods of alternate  $25\text{ }\text{\AA}$  AlGaAs and  $21\text{ }\text{\AA}$  GaAs,  $p = 10^{18}\text{ cm}^{-3}$ );  $i$ -multiple quantum wells (MQW) (63 periods of alternate  $80\text{ }\text{\AA}$  AlGaAs and  $105\text{ }\text{\AA}$  GaAs layers);  $n$ -AlGaAs ( $0.64\text{ }\mu\text{m}$ ,  $n = 10^{18}\text{ cm}^{-3}$ ); and  $n$ -GaAs ( $0.105\text{ }\mu\text{m}$ ,  $n = 10^{18}\text{ cm}^{-3}$ ). Both the GaAs substrate and the GaAs buffer layer are removed by a selective etch under the device active area.

using ohmic contacts and evaporated gold over a polyimide insulator. The mesas are  $\sim 200\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$  on  $400\text{ }\mu\text{m}$  centers, and the optical window is  $\sim 100\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ . The substrate is cleaved into separate  $1 \times 2$  arrays that are packaged individually. The electrical connections to the device are made using silver epoxy to hold the bond wires to the gold metallization. The GaAs substrate and buffer layer are etched away underneath the optical windows, and an antireflection coating is applied.

The operation of the device can be understood through the use of load lines as shown in Fig. 2. By solving for the voltages across the quantum well diodes as a function of the two input power levels, we can determine the optical transmission of the two diodes and hence the input/output characteristics. As shown in Ref. 6, the device is bistable when

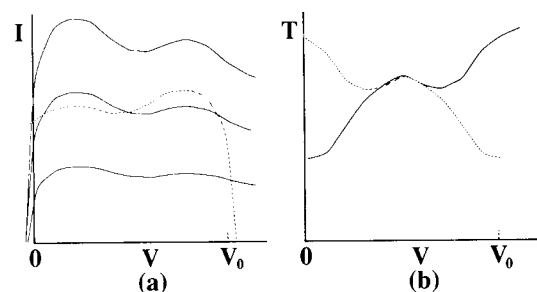


FIG. 2. Characteristics of both quantum well diodes. (a) Solid curves are the photocurrent vs voltage for a quantum well diode at three different input intensities. Dashed line is the photocurrent on the load quantum well diode vs voltage on the first quantum well diode for an input intensity on the load diode equal to that incident on the first diode in the middle curve. (b) Solid curve is the transmission vs voltage for the first quantum well diode. Dashed curve is the transmission of the load quantum well diode vs the voltage on the first diode.

there are three intersection points, and this will only occur if we operate the device at a wavelength where there is a region of decreasing absorption (and therefore decreasing current) for increasing voltage. Furthermore, the device will only be bistable when the optical input power levels are comparable, and will have only a single state when the power in one diode greatly exceeds the power in the other. Figure 2 also shows that if we increase (or decrease) the optical input power levels into both devices by the same factor (for example doubling both input power levels) or by the same fixed amount, the voltage at which the current-voltage curves intersect will not change, and hence the state of the device will not change. This allows us to set the state of the device using low-power beams of different intensities and then read out the state of the device using higher-power beams of equal intensities, thus achieving time-sequential gain.

The measured input/output characteristics of the device shown in Fig. 3 agree with the calculated results using the method described above. The characteristics were measured using an argon-ion-laser-pumped styryl 9 dye laser, although some measurements were also made using a com-

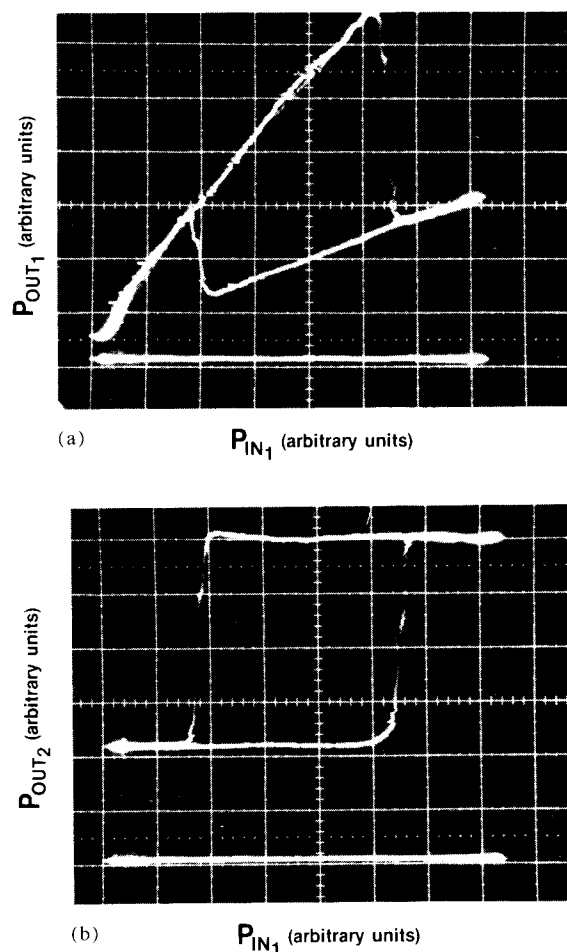


FIG. 3. Optical input/output characteristics of the S-SEED measured at a supply voltage of 15 V at 856 nm with average input power levels of  $\sim 20\text{ }\mu\text{W}$ . (a) Optical power exciting first diode ( $P_{\text{OUT}1}$ ) vs optical power incident on first diode ( $P_{\text{IN}1}$ ) with the optical power incident on second diode ( $P_{\text{IN}2}$ ) held constant. (b) Optical power exciting second diode ( $P_{\text{OUT}2}$ ) vs  $P_{\text{IN}1}$  with  $P_{\text{IN}2}$  held constant. Optical transmission levels are  $\sim 41\%$  and  $14\%$  for the two states shown in the figure.

mercially available AlGaAs semiconductor diode laser. To measure bistability and switching speed, the light emitted from the laser was split into two paths using a polarization beamsplitter. The optical power in one side was varied using an acousto-optic modulator. The two beams are combined using another polarization beamsplitter and focused through a  $5\times$  microscope objective onto the device. The spot size of the optical beams was varied from  $\sim 7$  to  $50\text{ }\mu\text{m}$  in diameter as measured using a television camera looking at the light transmitted through the device. The relative intensity of the light in each path was adjusted by rotating a half-wave plate to vary the polarization of the light incident on the first beamsplitter.

The device showed bistability at 856 nm for supply voltages greater than 3 V, and showed bistability from 845 to 862 nm at 15 V. The transmission ( $P_{\text{out}}/P_{\text{in}}$ ) of the quantum well diodes at 856 nm in the two states was 31% and 14% at 5 V (2.2:1 contrast ratio), increasing to 41% and 14% (2.9:1 contrast ratio) at 15 V. The devices had greater than a 2:1 contrast ratio from 855.5 to 857 nm at 5 V and from 854.7 to 857.7 at 15 V. All of the above measurements were made with optical input intensities below  $100\text{ }\mu\text{W}$ . The fastest switching time measured was 40 ns when the modulation frequency of the acousto-optic modulator was 1 MHz, increasing to 60 ns for a 100 kHz sine wave input. This speed was limited by the maximum optical power available rather than any intrinsic limit of the device. For this measurement, the supply voltage was 10 V, the spot sizes were  $50\text{ }\mu\text{m}$  in diameter, and the average optical input power levels into each *p-i-n* diode were 8 mW at 866 nm. The wavelength was adjusted for optimum contrast ratio at these power levels, and the shift in wavelength from the optimum at low-power levels was probably due to local heating of the device. The speed-power product for a 1 MHz sine wave input corresponds to a minimum optical switching energy of 640 pJ. Since the usable device area is  $40\,000\text{ }\mu\text{m}^2$ , the minimum optical switching energy density is  $16\text{ fJ}/\mu\text{m}^2$ . This agrees with the calculated energy required to charge and discharge the capacitance of the device. Additionally, the switching energy per unit area could be reduced by a factor of 2 by growing the material on a semi-insulating substrate and eliminating the two isolation diodes, one of which needs to be charged with the photocurrent. We tested that, and just as in the D-SEED,<sup>7</sup> as we reduce the power, the switching speed and power scale inversely over several decades, resulting in a constant switching energy. We also observed that, for small spot sizes only, a degradation in contrast ratio was seen at power levels greater than 1 mW. We believe this is related to saturation of the quantum well material.

Since bistability was observed at optical input intensities varying from less than 10 nW to greater than 8 mW, we can have a large effective signal gain. We have demonstrated this by using the output of one device to drive another with greater than 10 dB of loss between the devices. Of course, switching at low powers takes proportionately longer, so

that gain is obtained at the expense of switching speed. Another way of expressing this is to say that the device has a constant gain-bandwidth product, just like many other amplifiers. Note that this time-sequential gain mechanism gives some input-output isolation, an important attribute for a logic device. If the two incident signal levels are roughly equal, a small reflection of one of the outputs back onto the device will not switch the state of the device because of the wide bistable loop, independent of the intensity of the inputs. The reflection of a large signal never coincides in time with the application of a small signal that is used to switch the device; hence we have a device with a large gain that is insensitive to reflections back onto the device. This isolation is a classic attribute of a good "three-terminal" device such as a transistor, where fluctuations in the load are not themselves amplified by the gain of the device, but is not shared by "two-terminal" devices such as tunnel diodes or conventional optically bistable devices.

In conclusion, we have demonstrated an integrated symmetric self-electro-optic effect device that consists of two quantum well *p-i-n* diodes electrically connected in series. The device acts as a bistable optical memory element with individual set (*S*) and reset (*R*) capabilities and complementary outputs (optical *S-R* latch), and can also function as a logic amplifier because it shows time-sequential gain. In contrast to conventional bistable devices, it is insensitive to optical power supply fluctuations, does not require critical biasing, and possesses significant input/output isolation when used as an amplifier. These attributes, characteristic of a "three-terminal" rather than a "two-terminal" device, make it an attractive device for optical processing systems.

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