Bistable self-electro-optic operation of strained $In_{0.1}Ga_{0.9}As/GaAs$ asymmetric Fabry–Perot modulators

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We report bistable operation of a strained-layer InGaAs/GaAs asymmetric Fabry–Perot optical modulator configured as a self-electro-optic effect device (SEED) operating in reflection mode. Bistable loops are observed from 949 to 962 nm with switching powers down to submicrowatt levels. The contrast ratio between on and off states is as large as 5:1 (7 dB) and the device will hold in either state indefinitely. A 600-μm-diam device has a switching time of 20 μs for 2.1 fJ μm^{-2} switching energy. Large optical latch arrays are envisaged using this device.

The asymmetric Fabry–Perot modulator (AFPM) is able to offer a large on-off ratio for a thin absorbing region, since at the matched condition the overall reflection is very small as the reflections from the front and rear mirrors are of similar magnitude and in antiphase.[1] A change in the absorption inside the cavity alters the apparent reflection from the rear mirror and effects modulation. This change is the result of the quantum-confined Stark effect (QCSE). In this letter we are concerned with devices based on the strained InGaAs/GaAs system,[2] which operate at long wavelengths where GaAs is transparent. Such AFPMs operating in the normally-on[3] and normally-off[4] modes have been reported. Here we report the first bistability observed in these structures operating as self-electro-optic effect devices (SEEDs).

The device studied here was grown by molecular beam epitaxy on an n^+-GaAs substrate; the back mirror is an n-type 1/4 wave Bragg stack comprising 15.5 pairs of AlAs/GaAs, whilst the front mirror is the air-semiconductor interface formed at the p^+-GaAs capping layer. Between the two, the absorbing region is a 29-period 150-Å GaAs/150-Å $In_{0.1}Ga_{0.9}As$ strained-layer multiple quantum well (MQW), which is nominally undoped. The device was fabricated from a section of the wafer where the MQW exciton and the Fabry–Perot cavity mode are coincident. It is a 600-μm-diam etched mesa with an annular front contact giving a 400-μm-diam window; the other contact is to the substrate.

Photoreflectance curves for 0 and 4 V reverse bias are shown in Fig. 1. At the minima (952 nm) the reflectance changes from 3.8% (0 V) to 29.8% (4 V). This is 8.9 dB modulation for 5.2 dB insertion loss. Little extra modulation is obtained by a further increase in bias. These are an improvement on figures reported previously for a device from a different part of this wafer.[3] Figure 2 shows the variation in responsivity (photocurrent per unit incident power) versus bias (reverse) measured at a wavelength near the exciton peak (955 nm). Also shown in a load line for a resistive-SEED (R-SEED) configuration.[5,6] The slope of the line is $(RP)^{-1}$, where R is the resistance in series with the modulator P is the incident optical power. V_b is the bias across the R-SEED (see inset to Fig. 2). The intercept of the two lines gives the operating point. As the power is increased from (a) the operating point shifts towards (c) where a triple intersection is evident. There are two stable (●) and one unstable solution (○), thereby giving rise to bistable operation. Photocurrent is related to the absorption and hence to the device reflectance, so bistable behavior in the incident/reflected power response is expected.

Figure 3 shows a series of plots of input versus output power taken at a number of wavelengths. The device was reverse biased at 14 V with a 1 MΩ series resistance. Illumination provided by a tunable Ti-sapphire ring laser was modulated by an acousto-optic modulator. Input and output powers were monitored using silicon photodiodes which were fed to the X and Y inputs of an oscilloscope. Bistable loops were seen from 949 nm to at least 962 nm. At longer wavelengths the up and down switching powers diverge more. The optimum on-off ratio was at 952 nm where a 5:1 (7 dB) change is observed. When operated in the bistable region the device held in either state indefinitely, unless laser noise exceeded one of the switching thresholds.

Figure 4 shows the effects of bias voltage at 953 nm (1 MΩ load). A bistable loop is seen at voltages above 8 V. The loop size is increased with higher bias voltages, as expected from Fig. 2. The reverse breadkdown voltage is 26 V, so a suitable operating voltage is 15 V. For this bias the switching thresholds at 953 nm with 1 MΩ load are at 28.5 and 25 μW. Under the same conditions, but with a 100 kΩ load, the shape of the input/output curve is unchanged but merely scaled, switching now occurring at 285 and 250 μW. The constant RP product for these two loads suggests that the device has an internal resistance much less than 100 kΩ. For larger R the switching power is reduced still further: with an 11 MΩ load switching was observed at around 3 and 5 μW; for a 100 MΩ load switching was seen below 0.5 μW; however, in this case it becomes very slow and is obscured by noise.

Plots shown in Figs. 3 and 4 are for low-frequency behavior. As the modulation speed of the laser increases

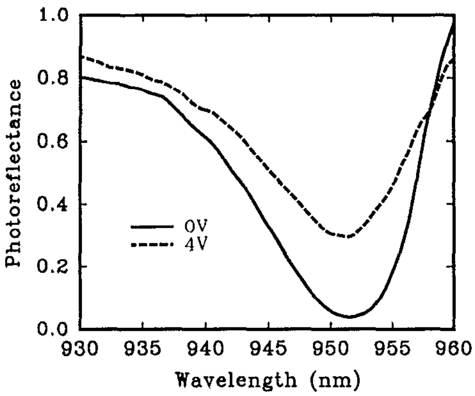

FIG. 1. Photoreflectance as a function of wavelength for strained AFPM device, at 0 and 4 V reverse bias.

above 50 Hz the bistable loop is seen to widen since the switching occurs in a finite time. At low frequencies both the switch-up and switch-down take approximately 80 μs. With increasing scan speed the switching time is decreased, taking just 20 μs at 1 kHz where it is thought to be limited by the circuit's *RC* time constant. The switching energy in that case is approximately 600 pJ. This demonstrates critical slowing down,[7] i.e., when the incident power is at the switching threshold, the switching is very slow; only an increase in power beyond this level will allow the device to switch quickly.

In conclusion, we have demonstrated the first optical bistability in a strained AFPM. The optical switching energy for a 600 μm device is 600 pJ or 2.1 fJ μm^{-2}. Operating at 952 nm, a 5:1 contrast ratio between on and off states is obtained: better matching of the absorber should improve this further (a well-matched AlAs/GaAs symmetric SEED achieves 130:1 on:off ratio[6]). With refinements to the front mirror, lower insertion loss is expected. The switching time for a 30 μW threshold is 20 μs: switching is observed at submicrowatt powers but with reduction of switching speed. Large arrays of devices 10 μm in diameter are envisaged and these are expected to switch with an energy of 166 fJ in 5 ns at 30 μW optical power (if *RC* time constant is limiting). It should be possible to incorporate the R-SEED resistance in the back mirror by a reduction in its doping.

Bistable devices have potential applications in optical computing: they can be used to implement optical NAND functions or *SR* and *D*-type latches. Electrically resettable latches are also possible. Such a spatial memory array is necessary for highly parallel neural and vector processing optical architectures. These devices are compatible with

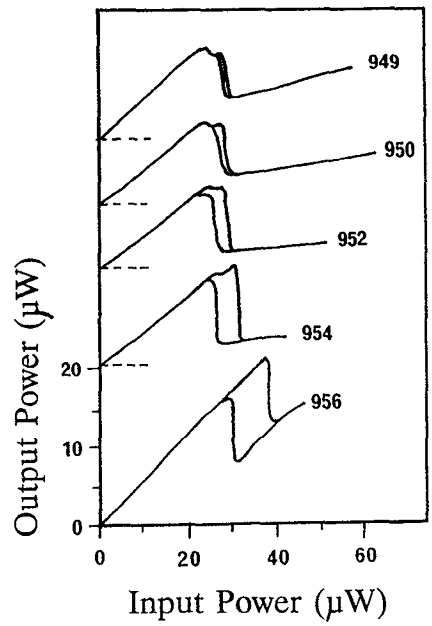

FIG. 3. Power in vs power out for R-SEED (14 V bias, 1 MΩ load). Bistable loops are demonstrated at a number of wavelengths (in nm)

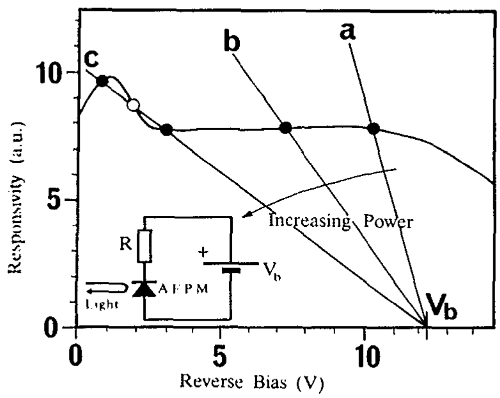

FIG. 2. Responsivity (photocurrent per unit optical power) at 955 nm as a function of reverse bias voltage for AFPM. Also shown are load lines for R-SEED configuration: stable (●) and unstable (○) operating points. Line (c) shows bistable operation. Slope of line is $(RP)^{-1}$. Inset: Circuit diagram for R-SEED.

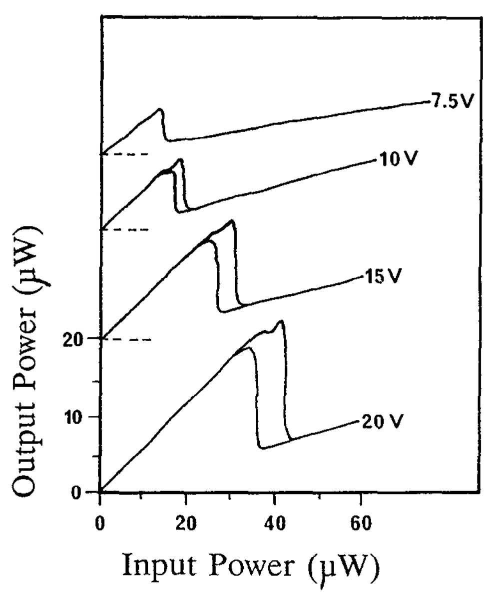

FIG. 4. Power in vs power out for R-Seed operating 953 nm, 1 MΩ load; showing effect of bias voltage on the shape of the bistable loop.

surface-emitting lasers and other novel optoelectronic devices produced in the InGaAs/AlGaAs system.

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