33 ps optical switching of symmetric self-electro-optic effect devices

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We report significant improvement in the optical switching times of symmetric self-electro-optic effect devices due to enhanced tunneling by using a 35 Å barrier versus the previous 60 Å barrier thick multiple quantum well GaAs/$Al_xGa_{(1-x)}As$ devices. Also, the voltage required for bistability was reduced from 10 V in the thick barrier devices to 3 V in the thin barrier devices with no apparent degradation in the contrast ratio.

Symmetric self-electro-optic effect devices (S-SEEDs)[1] are optical bistable logic gates that operate in a dual rail geometry with two optical input beams. The gate consists of two reverse-biased multiple quantum well (MQW) *p-i-n* diodes placed in series and often grown on top of a mirror structure (Fig. 1). The state of the device is defined as a logic 1 or 0, depending on which diode in the pair is highly reflecting. The change in reflectivity of each diode modulator[2] is due to the quantum-confined Stark effect (QCSE),[3] where increases in the electric field across the intrinsic MQW region of the diode causes a shift in the exciton wavelength (850 nm at zero field) and thus a reduction in the absorption coefficient at the bistable wavelength. The switching speed of an S-SEED is limited by the slower of either the charging time of the capacitance to reach the required voltage across the diodes, or the vertical transport time which includes the carrier emission time of the carriers from the bottom of the quantum wells plus the transport time perpendicular to the layers. The charging time is limited by the photocurrent source, which is proportional to the optical power, or by the series resistance in the RC time constant. This maximum photocurrent in turn is limited by either the maximum available power or by saturation of the absorption. As will be shown, vertical transport dominates the switching time of the 60 Å barrier samples. For 35 Å barrier samples, vertical transport and the RC time constant are important.

Recent research on MQW modulators has shown that tunneling escape times decrease with decreasing barrier thickness and increasing electric field.[4-8] Prompted by this research, S-SEEDs have been fabricated with 35 Å barriers using the same mask set and processing techniques as the previous 60 Å devices.[9] The molecular beam epitaxially grown structure consists of 100 Å quantum wells of GaAs with $Al_xGa_{1-x}As$ ($x = 0.3$) barriers of either 35 or 60 Å repeated 60 times.[9] The total thickness of the intrinsic region in the diodes is the sum of the MQW region plus 700 Å. In this letter we describe switching speed measurements that show that the 35 Å devices are indeed faster by an order of magnitude.

The S-SEED is driven with alternate 2 ps mode-locked (ML) optical pulses as shown in Fig. 1. The sequence of pulses shown will toggle the S-SEED between the complementary high and low states on each mesa. Five optical beams are needed. All ML pulses are derived from the same synchronously pumped Stryl 9 dye laser. A schematic of the optical setup is shown in Fig. 2 where *P*3 is derived from the ML source and delayed by 6 ns. The remainder is further split into a weak probe Pr and *P*4. The probe is then delayed by 6 ns, scannable over 1 ns, and then made collinear with *P*4. Two equal strength continuous wave (cw) laser beams *P*1 and *P*2, from a dye laser, can hold the bistable state.[1] In practice, it was not necessary to have the cw beams present for operation of the device in this experiment except to prove the switching was complete and for direct monitoring of the mesa reflectivity of the photodiode. Charge leakage times are far in excess of 12 ns and so the state is effectively held without the cw beams. The presence of the cw beams, *P*1 and *P*2, also does not affect the switching transition time. The beams are placed on the

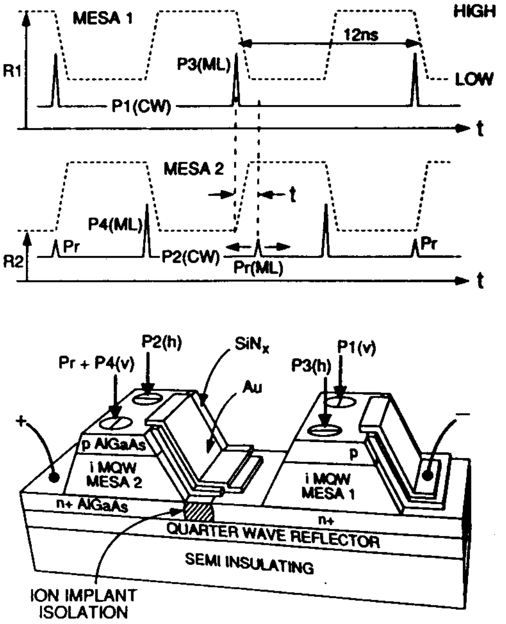

FIG. 1. Timing sequence for toggle of S-SEED. The dotted curve shows the high and low reflection state. The mesa shown has 60 MQWs of 100 Å well width.

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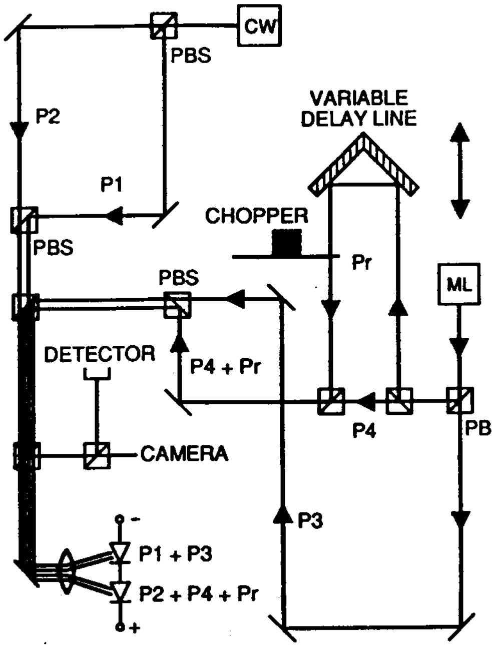

FIG. 2. Schematic of the pump-probe switching measurement setup showing the formation of the optical pulse sequence needed in Fig. 1.

mesas with horizontal (h) and vertical (v) polarizations as shown in Fig. 1. The photocarriers produced by absorption change the field and voltage across each diode and cause a change in reflectivity.

The state of the optical latch during switching can be determined in two ways. The simplest is to monitor the reflected beam strength of the cw beam *P2*(h), with Pr blocked with a fast photodetector. We used an avalanche photodiode (APD) with full width half maximum (FWHM) of 230 ps. The optical change of state of diode 2 from low to high, induced by pulse *P3* on the other diode, is observed on a sampling oscilloscope. Previously,[10] for S-SEEDs with 60 Å barriers and 13×14 μ mesas, the switching energy was measured as 3.6 pJ and the 10–90% switching time δt as 860 ps at 22 V. Using the above technique, new measurements yielded switching times, plotted in Fig. 4, consistent with the previous measurement. With the thinner 35 Å barrier we measured a switching energy of 4±1 pJ at 6 V and switching times less than 230 ps, the detector response time.

To measure switching times less than the detector response time, the pump-probe technique was used for which the cw beams were not required. The probe time delay relative to the time of arrival of the pump pulse *P3* on diode 1 is slowly scanned with a computer-controlled translation stage from slightly before to afterward up to 900 ps. The reflected probe (diode 2) strength is monitored and the switching transition is presented in Fig. 3 for various voltages. A computer fit of a single exponential is shown in Fig. 3. The switching transition time $\delta t = 2.2\tau$ is plotted in Fig. 4 for the 35 Å barriers.

The probe experiment requires a weak pulse so as not to oppose the transition from the low to high state. The detector for the reflected probe Pr must not, however, be swamped by any of the other beams so the reflected beams are imaged on an intermediate image plane where a variable aperture is placed to eliminate *P3* and *P1*. This apertured image of mesa 2 is then re-imaged onto the detector with some energy split to a camera. Within the aperture which includes mesa 2, a knife edge plus a polarizer in front of the detector rejects *P2*. In our experimental setup there is no efficient way that Pr could be polarized opposite *P4*. We tried to align the system such that the pull down pulse *P4* and the probe pulse on mesa 2 were not overlapped, but usually some leakage of pump power was present in the aperture overlapping the probe beam. Consequently to separate Pr and *P4* it is necessary to chop the probe. The switching transition times (Fig. 4) show a factor of 10 reduction in switching times between the 60 and 35 Å barrier samples. Previously[8] sweep out times (when converted to the δt measurement) at similar applied voltages ranged from 77 to 715 ps for the 60 Å and 14 to 286 ps for the 35 Å samples.

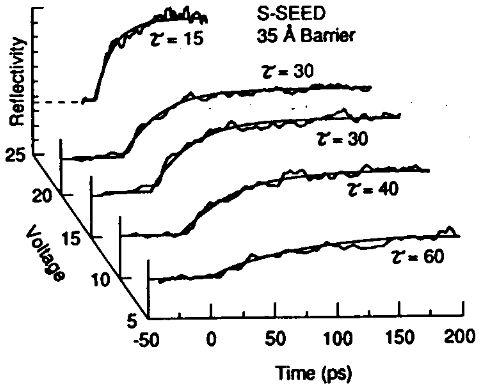

FIG. 3. Reflected probe signal at various voltages showing the switching transient on the thin barrier MQW. τ is the exponential fitting parameter.

To understand the factors limiting the switching time consider the following. The capacitances of the thick and thin barrier samples are similar, and estimated to be 0.023 pF for each diode. The maximum charging time, without the series resistance *R*, is the pulse length of 2 ps, which is

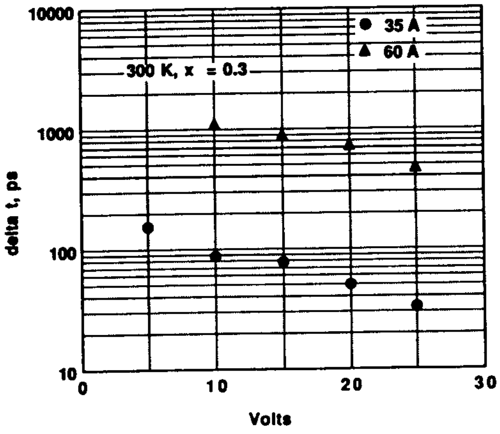

FIG. 4. Switching time $\delta t = 2.2\tau$ is plotted vs the applied voltage for the 35 Å barrier. δt for the 60 Å barrier device was directly measured using a fast detector.

small compared with the observed 33 ps minimum so this is not a limiting factor. Measurements of the sheet and contact resistance on similarly grown samples indicate that the total series resistance R could be as high as 400 Ω (dominated by the resistance of the p-doped material). Since the two diode capacitances are in series, the effective capacitance for the time constant for charge redistribution is one-half of the single diode capacitance. Consequently, the effective RC time constant τ could be 5 ps, which when multiplied by 2.2 yields 11 ps for the effect of RC on the switching time δt. The other factor to consider is the sweep out times. The previously reported measurements[8] were made at constant field, whereas during the switching transition from low to high, the voltage across the diode changed from a low forward bias voltage to a reverse bias that exceeded the supply voltage by an amount equal to the forward bias voltage of the other diode. Consequently, the field varied from a low value up to approximately the field applied in the sweep out measurements. The vertical transport component of the switching time is thus an average of the sweep out times over a varying electric field and thus must be in excess of the 14 ps minimum measured.[8] The observed switching time of 33 ps at high voltages seems reasonable. We conclude that the 60 Å barrier devices are limited by vertical transport, whereas the 35 Å barrier devices are probably limited by a combination of vertical transport and the RC time constant.

There are other added benefits of using thinner barriers. Previous thick barrier devices required up to 10 V to obtain bistable characteristics for the 13×14 μm mesas but only 2 V for larger (100×100 μm) mesas. The reason for this is thought to be that for the small devices, carriers recombine at the walls at low voltages before they can be swept out as photocurrent;[11] thus the exciton peak in photocurrent is greatly diminished. However, for thin barrier devices, the carriers are swept out faster, thus even the small (13×14) mesa devices show bistability at 3 V. The measured contrast ratio was 3.5:1 at 5 V and 5:1 at 15 V. We also observed that the degradation in contrast ratio with increased power is lessened in thin barrier SEEDs due to decreased saturation when compared with thick barrier SEEDs. This was also the case with modulators[8] where the improved saturation characteristics were first observed.

In conclusion, we have measured switching times as low as 33 ps in symmetric self-electro-optic effect devices with thin (35 Å) barriers, using a pump-probe technique. The voltage required for bistability was reduced from 10 V in the 60 Å barrier to 3 V in the 35 Å barrier devices. The 33 ps switching time indicates the possibility of a 10 GHz gain bandwidth channel.

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