

# An Interdigitated Stacked p-i-n Multiple-Quantum-Well Modulator

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**Abstract**—We demonstrate low-voltage operation of a strained InGaAs–GaAs interdigitated hetero n-i-p-i modulator (or stacked SEED) that is grown and fabricated using a shadow-mask growth technique for making the metal contacts to the n- and p-layers separately. An absorption change of  $6 \times 10^3 \text{ cm}^{-1}$  with an applied bias as low as  $\sim 1 \text{ V}$  is observed in an unoptimized structure. Optical switching of the unbiased structure is also demonstrated.

## I. INTRODUCTION

**S**IMPLE p-i-n structures with multiple quantum wells in the intrinsic regions [p-i(MQW)-n] are of interest for possible applications in optical communications, interconnects, and image displays [1]–[3]. Such devices can be either electronically modulated or optically switched (e.g., the self-electrooptic effect devices or SEED's [1]). When operated in the electrooptic mode, such structures modulate the incident light through a shift of the exciton with applied field (i.e., the quantum confined Stark-effect, QCSE [4]). To obtain a satisfactory on-off ratio (typically 3:1) in current GaAs p-i(MQW)-n modulators, it is necessary for the excitons in a substantial number of wells (typically  $>100$ ) to experience a relatively large change in the perpendicular field (in the range of  $100 \text{ kV/cm}$ ). This currently dictates a rather large operating voltage (typically,  $10\text{--}20 \text{ V}$ ). However, to be fully compatible with existing silicon CMOS electronic technology, a lower operating voltage is preferred ( $<3 \text{ V}$ ).

One approach to lowering the operating voltage would be to fabricate interdigitated stacks of several mini-SEED's optically connected in series and electrically connected in parallel. These "stacked SEED's" would have narrower intrinsic regions between electrodes and, thus, would require a lower applied voltage to achieve a given field across the wells. This narrower intrinsic region would, however, also dictate fewer wells per intrinsic region, but the stacking of the p-i(MQW)-n structures would allow one to achieve the same optical thickness (i.e., same total number of wells). An extreme example of such a structure would be an interdigitated hetero n-i-p-i. One would expect, however, the optimum structure

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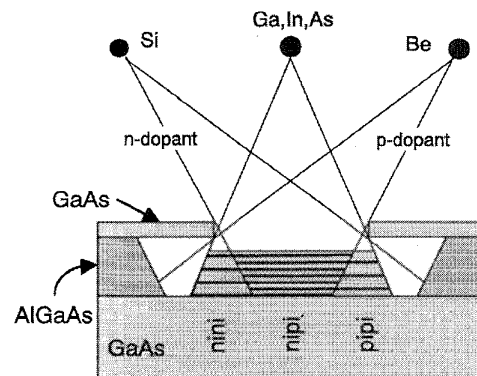


Fig. 1. Schematic of the shadow mask and interdigitated growth.

to lie between a SEED and an interdigitated hetero n-i-p-i. That is, the optimum structure (from the point of view of maintaining a low switching voltage and a good contrast ratio) would be an interdigitated structure with a few n-i-p-i periods and a large number of wells per period (but fewer than in current SEED's). As proof-of-principle, in this paper, we demonstrate the growth and operation of an unoptimized stacked SEED modulator that exhibits an absorption change of  $6 \times 10^3 \text{ cm}^{-1}$  with an applied bias as low as  $\sim 1 \text{ V}$ . Optical switching of the unbiased structure is also demonstrated.

Our interdigitated stacked p-i(MQW)-n device was fabricated by the shadow-mask molecular-beam epitaxy (MBE) regrowth technique [5]–[7], which has been used previously to fabricate interdigitated doping superlattices [5]–[10], hetero-n-i-p-i band-filling modulators [11], and voltage-tunable Bragg reflectors [12]. This technique is described elsewhere [5]–[7], but for purposes of discussing the details of our own work, it is shown schematically in Fig. 1. Our shadow masks were formed by starting with a  $0.75\text{-}\mu\text{m}$ -thick layer of GaAs and a  $3\text{-}\mu\text{m}$ -thick layer of  $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$  grown by MBE on a GaAs substrate. Conventional photolithographic techniques were then used to etch an opening in the top GaAs layer and to selectively remove the AlGaAs to leave a GaAs overhang of  $\sim 3.5 \mu\text{m}$  as shown in Fig. 1. The patterned wafer was then brought back into the MBE system, and with the n- and p-dopant sources located at opposite sides of the MBE carousel, a InGaAs–GaAs hetero-n-i-p-i structure was grown, as indicated in Fig. 1. The intrinsic layers were grown while the wafer was rotating, so that they would have gentle slopes at the edges of the active regions. During doping, the wafer was held stationary at positions

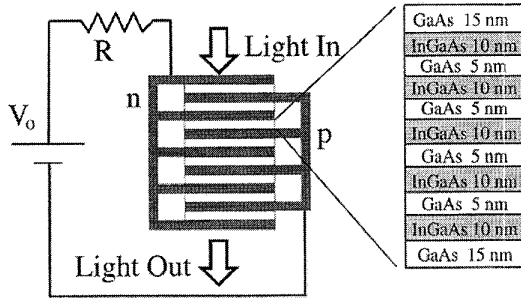


Fig. 2. Schematic of interdigitated stacked p-i(MQW)-n modulator.

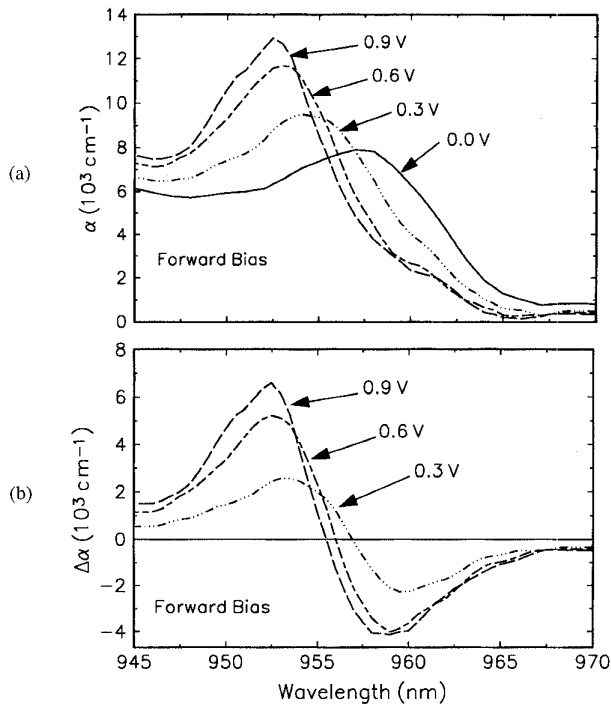


Fig. 3. Electrooptic response of the interdigitated stacked p-i(MQW)-n modulator under forward bias conditions: (a) the absorption and (b) the differential absorption spectra.

where the overhang shadow effects were optimum. In this way, an n-i-n-i structure was formed on one side of the active n-i-p-i region due to the p-shadow, while on the other side, a p-i-p-i structure was grown due to the n-shadow. Once the regrowth was complete, the sample was removed from the chamber, and the GaAs overhangs and the AlGaAs layer were removed with a selective etch. The remaining isolated active-areas were approximately  $1 \text{ mm} \times 0.25 \text{ mm}$ . Finally, AuGe(50 nm)–Ni(20 nm)–Au(100 nm) metal contacts were deposited along the 1-mm-long edge for the n-layers and AuZn(50 nm)–Ni(10 nm)–Pt(35 nm)–Au(60 nm) contacts for the p-layers, and the sample was wire bonded to facilitate electrical and electrooptical measurements.

As shown schematically in Fig. 2, the final modulator consists of four periods of an interdigitated n-i-p-i structure with five 10-nm-thick  $\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$  wells separated by 5-nm-thick barriers per intrinsic region. The doping densities

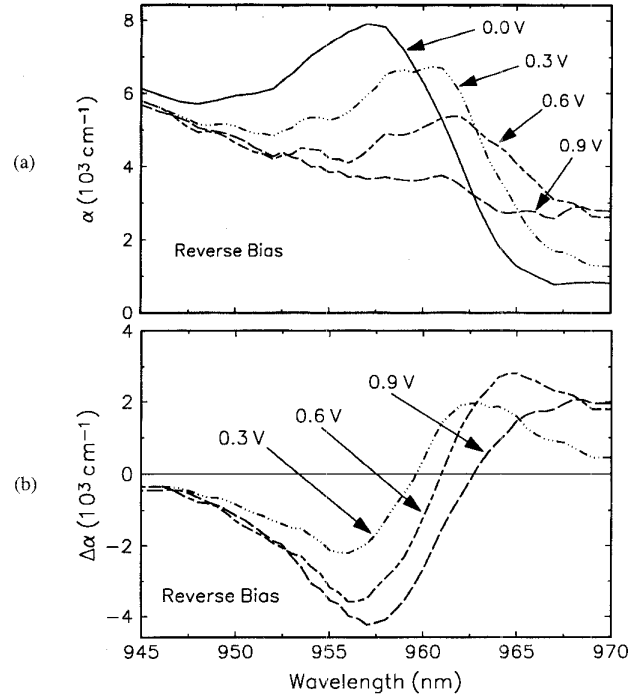


Fig. 4. Electrooptic response of the interdigitated stacked p-i(MQW)-n modulator under reverse bias conditions: (a) the absorption and (b) the differential absorption spectra.

and thicknesses of the n- and p-layers are nominally  $6 \times 10^{18} \text{ cm}^{-3}$  and 20 nm, respectively. The measured [13] current-voltage curves showed good rectification with low leakage current, e.g., less than  $5 \mu\text{A}$  at 0.5 V (forward bias) and at  $-4.0 \text{ V}$  (reverse bias).

The electrooptical response of this prototype is shown in Fig. 3 for several forward-bias voltages at room temperature. The measurements were performed by tuning the wavelength of 1-ps pulses from a modelocked dye laser across the excitonic features for each bias voltage. Notice that as the net field (i.e., the difference between the built-in and applied fields) across the wells is reduced that the exciton feature increases in amplitude, narrows, and shifts to the blue, as expected. Also notice that a change in absorption coefficient of  $\sim 6 \times 10^3 \text{ cm}^{-1}$  is obtained for a forward bias of  $<1 \text{ V}$ , corresponding to  $\sim 100 \text{ kV/cm}$  swing in the field. The corresponding electroresponse under reverse bias is shown in Fig. 4. In this case, the exciton shifts to the red, broadens, and decreases in amplitude, as expected. In fact, the excitonic feature is difficult to resolve for reverse bias voltages  $>1 \text{ V}$ .

All optical switching of this stacked SEED under short-circuit conditions is illustrated in Fig. 5. These measurements were performed using a standard pump-probe geometry and two synchronized, independently tunable dye lasers. For the measurements shown in Fig. 5, the pump was tuned to a fixed wavelength (925 nm) just above the band edge, and the probe was tuned across the excitonic feature. The delay between pump and probe was also fixed and was chosen to ensure that the optically generated carriers had escaped the wells,

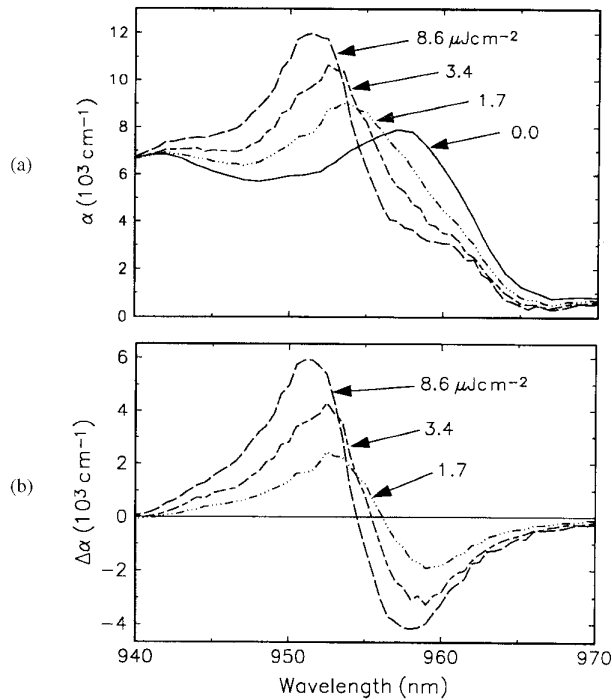


Fig. 5. The probe (a) absorption and (b) differential absorption spectra for selected pump fluences.

but that negligible recombination had occurred. Under these conditions, a fluence of  $<10 \mu\text{J}/\text{cm}^2$  produces a change in absorption coefficient of  $\sim 6 \times 10^3 \text{ cm}^{-1}$ .

The results shown in Figs. 3–5 are indicative of good contacts and strong quantum confinement, and they demonstrate that such structures can be operated at voltages as low as  $\sim 1$  V. Of course, this prototype is unoptimized. It was designed to demonstrate low-voltage operation and the ability to produce interdigitated structures with reliable contacts with minimum growth. A more realistic prototype would incorporate more n-i-p-i periods (i.e., a larger total number of wells) and would perhaps incorporate an underlying Bragg mirror for multiple-pass operation. For example, the absorption change of  $\sim 6 \times 10^3 \text{ cm}^{-1}$  measured here suggests that a double-pass device containing 100 wells would exhibit a contrast ratio  $>3:1$  while operating at  $\sim 1$  V. The reduced operating voltage for our stacked SEED does not come without penalty. For example, it is well known that as the thickness of the intrinsic regions is reduced the capacitance of the device will increase and the speed will decrease. However, some of this speed may be

recovered by proper design. For example, some of our initial work suggests that carrier recombination at the mesa edges may dictate the minimum ratio of modulator surface area to electrode separation that can be tolerated. Consequently, as the electrode separation is reduced to lower the switching voltage, it should be possible to simultaneously reduce the modulator area, thereby minimizing the loss of speed. There are a number of such tradeoffs that need to be examined and optimized before a practical device can be manufactured.

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