Interleaved-Contact Electroabsorption Modulator Using Doping-Selective Electrodes with 25°C to 95°C Operating Range

K. W. Goossen, J. E. Cunningham, W. Y. Jan, and D. A. B. Miller

Abstract—**We demonstrate a multiple-quantum-well (MQW) modulator with multiple stacked p-i(MQW)-n-i(MQW)-p-regions. Electrodes are deposited such that all the n-layers are connected to one contact and all the p-layers to the other. This allows high fields to be produced in the i-regions with relatively low voltages, since the i-regions may be made thin while retaining large optical interaction because they are stacked. Because of large Stark shifts in the MQW's at high fields, we obtain a large usable wavelength range which translates into a large operating temperature range. For a 0 to 6 V swing we achieve > 22% reflectivity change from 25°C to 95°C, or alternatively over a wavelength range of 15 nm at 25°C.**

As the number and bandwidth requirements of connections to integrated circuit chips approach thousands and hundreds of megahertz, respectively (which is occurring now), the capability of standard electrical chip input/output becomes strained. For this reason optical input/output to chips is being explored by a number of groups [1]. To accommodate this large number of optical channels requires two-dimensional arrays of "surface-normal" optical devices. A possible solution for optical output devices is to place surface-normal lasers on the chip. However, operation of such a large array is currently undemonstrated and would be problematic due to thermal and device-yield considerations. Alternatively we could use modulators. In modulator systems an off-chip laser would be split into an array of beams that illuminates an array of modulators. The modulators would be switched by the on-chip electronics to imprint information on the reflected beams. Multiple quantum well (MQW) modulators are attractive because they can produce large enough absorption changes in surface-normal devices with good yields, low intrinsic power dissipation and apparently good reliability. Since the modulators are p-i-n type devices they are also efficient input detectors. 64 × 64 arrays of operational modulators have been demonstrated [2]. Reliable modulators have also been demonstrated on silicon [3].

A problem with such modulators, however, is their narrow usable wavelength range, which results in a small operating temperature range, since semiconductor bandgaps depend on temperature. There are two types of operation, termed λ_0 (where the operating wavelength is set at the exciton wavelength), and λ_1 (where the operating wavelength is set longer than the exciton wavelength). For λ_0, the optical bandwidth is set by the exciton width, a few nm. For λ_1, the optical bandwidth is set by how far the exciton shifts due to the quantum-confined Stark effect [4]. The exciton can shift up to 30 nm without significant broadening, but this requires fields greater than 20 V/μm [5]. Since for reasonable reflectivity changes the i-region must be about 1 μm thick, this results in prohibitively large voltage requirements. Furthermore such high voltages (V) would result in large heat dissipation ($P = V \cdot I_P$) from the photocurrent (I_P).

Here we present a solution to this problem. This i-region may be made thinner, reducing voltage requirements, if several diodes are stacked (a n-i-p-i $\cdots$). The optical path length, and so the reflectivity change, may be made large by increasing the number of i-regions. This results in a higher capacitance, which leads to systems designers' choice of tradeoffs between voltage, temperature and wavelength operating range, and capacitance. Here we present the capability of making this tradeoff. Our device yields a reflectivity change > 22% from 25°C to 95°C, or alternatively over a 15 nm wavelength range at 25°C, for a 0–6 V swing. There are five i-regions in the example device here, each about a third the thickness of usual p-i-n modulators, resulting in 15 times the capacitance of usual devices. The capacitance of this device is therefore expected to be about 2 fF/μm^2, or about 200 fF for a typical 10 × 10 μm modulator. Such a capacitance is still easy to drive electronically and is much less than the capacitances of conventional electrical bond pads and interconnections.

The schematic of our device is shown in Fig. 1. An intrinsic mirror consisting of 14.5 periods of 722 Å AlAs/602 Å $Al_{0.07}Ga_{0.93}As$ is grown atop an intrinsic GaAs substrate. Then a 500 Å n^+ $Al_{0.07}Ga_{0.93}As$ contact layer is grown, followed by a 700 Å n^- $Al_{0.07}Ga_{0.93}As$ layer. Throughout the design +doping refers to 2×10^{18} cm^{-3} and −doping refers to 5×10^{17} cm^{-3}. This is followed by

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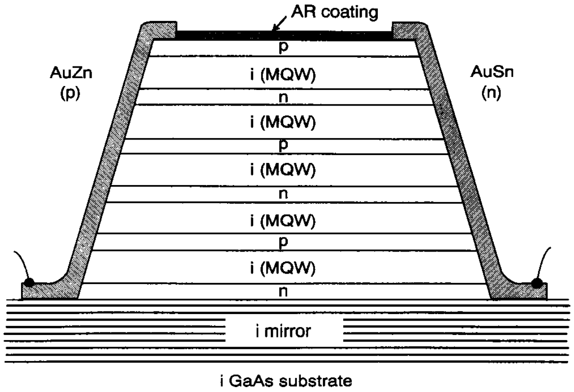

Fig. 1. Schematic of our modulator. A $p^+(n^+)$ region forms under the AuZn(AuSn) electrodes, forming selective contacts to the p(n) layers. Each MQW consists of twenty 95 Å GaAs wells separated by 50 Å $Al_{0.4}Ga_{0.6}As$ barriers. Each doped region consists of a 200 Å heavier-doped layer clad by 200 Å lighter-doped layers.

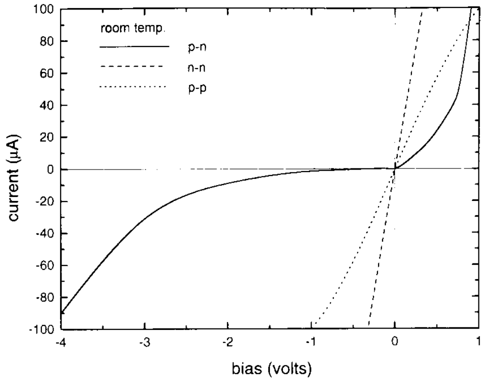

Fig. 2. Current voltage characteristics of a mesa (two types of electrode were made per mesa).

a 20 period intrinsic MQW with 95 Å GaAs wells and 50 Å $Al_{0.4}Ga_{0.6}As$ barriers, and then a $Al_{0.4}Ga_{0.6}As$ p region consisting of a central 200 Å p^+ layer clad on either side by 200 Å p^- layers. Next an identical i-MQW as before is grown, followed by an n-region identical to the preceding p-region except for its opposite doping, and so on until five i-MQW's are grown as shown. The final p layer consists of 200 Å p^- $Al_{0.4}Ga_{0.6}As$ followed by 200 Å p^+ $Al_{0.4}Ga_{0.6}As$, and finally a 50 Å p^+ GaAs cap.1

The contacting scheme has been previously illustrated by us for a surface-normal refractive modulator, which also requires high fields [6]. 200 × 200 μm mesas were etched down to the mirror. The etch used was 64:20:16 H_2O:H_2O_2:H_3PO_4. This results in sloping sidewalls as illustrated in Fig. 1. Then AuZn and AuSn electrodes were deposited along the sidewalls as shown, and annealed at 420°C. for 1 min. Since Zn is a p-type dopant in AlGaAs, a p^+ region is formed under the AuZn contact, resulting in an ohmic contact with all the p-layers and a rectifying contact with the n-layers. Similarly, a n^+ region is formed under the AuSn contact, resulting in ohmic contacts with all the n layers and rectifying contacts with the p-layers. Finally, a SiO_x antireflection coating was deposited as shown.

Two types of each contact were deposited per mesa, so that p-p, n-n and p-n conduction could be measured. This is shown in Fig. 2. The n-n conduction is ohmic with about 3 kΩ resistance. The n-contacts were approximately on diagonally opposing corners of the mesa, with the p-contacts on the other corners. Assuming the conductivity of a layer is given by $G = ne\mu t$ where t is the thickness (ignoring current spreading), and assuming a mobility $\mu = 1000\ cm^2/Vs$, we calculate at total resistance of 0.33 kΩ. Current crowding could increase this by a factor of 4 at most (since the contact pad was 50 μm wide), leaving a factor of 2 discrepancy. This could be accounted for by a number of factors. The most likely is that the actual doping is lower than the design since doping activation tends to be lower in high Al content AlGaAs. We believe that all the layers are contacted because as we will show all the oscillator strength of the exciton shows a shift with bias. The p-p resistance is higher (about 8500 kΩ), probably due to a lower mobility. However, slightly less than ohmic behavior is shown, indicating some problem with the contact. Since the electrodes here were 50 μm wide, if one scales to a typical 10 × 10 μm mesa, for the present structure there would be about 20 kΩ per p contact. Assuming the 200 fF calculated earlier for that size device, one obtains a time constant of 4 ns. This is borderline for anticipated chip-to-chip interconnects, indicating that changes in the structure (e.g., higher doping) will need to be made.

The p-n conduction shows clear diode behavior, albeit with some leakage under reverse bias. This could be either due to tunneling current through the i-region, or, more likely, tunneling current from the p^+, (n^+) regions under the electrodes to the $n^+(p^+)$ contact layers. Under forward bias there is a kink near 0.8 V. Probably for > 0.8 V the conduction is dominated by normal diode current but for < 0.8 V is dominated by some type of leakage.

The reflectivity of the sample was measured with a lamp/monochromator. This is shown in Fig. 3 for room temperature. The reflectivity of the mirror extends from 900 nm to shorter wavelengths and is reduced near 848 nm for 0 V by the heavy-hole exciton. The light-hole exciton can be seen near 840 nm. Upon applying a reverse bias of 6 V the heavy-hole exciton shifts more than 20 nm. This shift is consistent with that previously observed for the same fields in p-i-n samples [4]. The reduction in strength of the exciton with field is also consistent with earlier observations. A change in reflectivity $> 20\%$ is obtained over a bandwidth of 20 nm. This change is smaller than anticipated for a structure with 100 QW's. This may be caused by dopant redistribution into the MQW regions, giving rise to variation in the electric field there and broadening of the exciton. Notice that this effect may be exacerbated in this structure since a greater

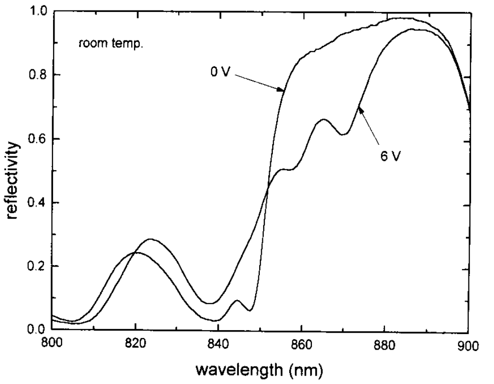

Fig. 3. Reflectivity spectra for sample at 0 and 6 V p-n reverse bias. The heavy-hole exciton shifts from 848 nm at 0 V to 870 nm at 6 V.

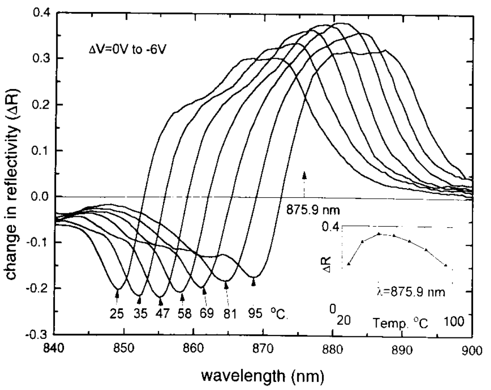

Fig. 4. Change in reflectivity for a 0–6 V swing as a function of wavelength for different temperatures. Approximately 20 nm optical bandwidth is achieved at each temperature. The band edge moves with temperature, causing the shift in the spectra. The inset shows ΔR at a fixed wavelength as a function of temperature. Greater than $22\% \Delta R$ is achieved from 25 to 95°C.

fraction of QW's are near doped regions, necessitating larger spacers between the MQW and the doped regions. Larger changes in reflectivity may be achieved at the same voltage by increasing the number of intrinsic regions, albeit with an increase in capacitance. Even though the maximum contrast is relatively low (about 1.5:1), in a differential-mode system this should be acceptable.

In Fig. 4 we show the change in reflectivity for a 0–6 V swing at different temperatures from 25 to 95°C. The heavy-hole exciton corresponds to the dip in reflectivity for each curve. This shows a clear shift with temperature. The optical bandwidth over which positive ΔR is achieved is determined by the Stark shift of the exciton. This seems to be fairly independent of temperature. The wavelength for which maximum ΔR is achieved at 25 or 95°C is 875.9 nm, shown by the arrow. The insert of Fig. 4 shows ΔR as a function of temperature for this wavelength. Greater than $22\% \Delta R$ is achieved from 25 to 95°C, with a maximum of $37\% \Delta R$ at 47°C.

In conclusion, we have demonstrated an interleaved-contact n-i-p-i electroabsorption modulator. This modulator allows broad operating wavelength or temperature ranges without requiring high voltage drive. It relies on using several thin MQW absorbing regions, each operating at high field with consequent large absorption edge shifts. We have shown $> 22\%$ change in reflectivity for a 0–6 V swing for either a 25 to 95°C temperature range at 875.9 nm or for a 15 nm wavelength range at 25°C. Operating voltage could be reduced by using thinner intrinsic regions. Alternatively, if voltage was kept constant this would result in increased wavelength or temperature range because of larger Stark shifts. Reflectivity change could be increased by using more intrinsic regions. In all cases the tradeoff is higher capacitance and a more complex, thicker structure. It appears that the capacitance of a small device is still low by normal electrical output standards, and we are not near any limit in the thickness of complexity of crystal growth, so the outlook for such further improved designs is promising.

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