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USE OF DEPLETION-EDGE-TRANSLATION FOR HIGH SPEED MODULATION AND SWITCHING OF LIGHTWAVES

by
L.A. Coldren, J.G. Mendoza-Alvarez, T.C. Huang, T.R. Hausken, K.W. Lee and R.H. Yan
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This report covers the period from 1 Aug 86 to 28 Feb 87. This period covers the 13th through the 19th month on this project, and it represents the culmination of the first phase of this work, which focused on the investigation of the basic properties of novel depletion-edge-translation (DET) waveguide phase modulators oriented in the plane of the substrate. Devices based upon this concept have now provided record levels of phase shifting efficiency, and theoretical calculations have indicated a significant potential for still further improvements in this area. The in-plane geometry maximizes the interaction between applied fields and the propagating wave by maximizing the optical energy density, the applied fields and providing the necessary interaction length. In this report we review the progress in three separate areas: 1) theory and design of DET devices; 2) improvements in fabrication technology; and 3) experimental device measurements. Extensive use of materials in the previous report will allow us to focus on the advances made during the

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II. Summary

This report covers the period from 1 August 1986 to 28 February 1987. This period covers the 13th through the 19th month on this project, and it represents the culmination of the first phase of this work, which focused on the investigation of the basic properties of novel depletion-edge-translation (DET) waveguide phase modulators oriented in the plane of the substrate. Devices based upon this concept have now provided record levels of phase shifting efficiency, and theoretical calculations have indicated a significant potential for still further improvements in this area. The in-plane geometry maximizes the interaction between applied fields and the propagating wave by maximizing the optical energy density, the applied fields and providing the necessary interaction length. In this report we review the progress in three separate areas: 1) theory and design of DET devices; 2) improvements in fabrication technology; and 3) experimental device measurements. Extensive use of material in the previous report will allow us to focus on the advances made during the subject period. Future work will focus more on device demonstrations which should support advances in optical computing. Some of these will involve propagation of light normal to the substrate as well as in-plane. Use of the highly concentrated light in the plane to control the surface normal beam is a particularly attractive possibility that will be pursued.

III. Objectives

The general objectives for this project are to demonstrate and evaluate the potential of the depletion-edge-translation concept in the modulation and switching of lightwaves. The initial work has focused on in-plane, waveguided lightwaves and simple double-heterostructures to demonstrate the basics of the concept. Future work will include surface-normal beams and quantum-well active regions for higher performance and direct relevance to certain optical interconnection and computing schemes.

During this specific reporting period, the objectives have been 1) to develop a more complete and rigorous theory for the device, 2) to develop fabrication techniques for more controlled and ideal device structures and 3) to measure the characteristics of a variety of different device structures, including the high-frequency response, to empirically determine the optimum structure and to compare with theoretical predictions.

IV. Progress

Since the general device configuration and measurement apparatus was outlined in the initial progress report, the reader is referred to it for the details[1]. Here we will simply update what progress was made during the reporting period. However, the reader is reminded that the general philosophy behind the success of the DET concept is to 1) use an optical mode of minimum width, 2) provide doping in the active region to create breakdown fields at a few volts applied, and 3) arrange the depletion region and optical mode so that the overlap between them increases with applied reverse bias.

1. Theory and Design

A complete theoretical analysis of the device has been carried out. This analysis starts from first principles, and develops predictions of the device loss and phase shift due to the several effects that are believed to be important. No fitting parameters were found to be necessary. It gives for the first time the relative importance of the various constituent effects. The only possible omissions are due to contributions related to the lateral waveguiding, which is not considered in the theory. Effects due to the more dominent transverse waveguiding are central to the results reported. In the last report the properties of the device were estimated using approximate expressions. Here the results are exact.

Figure 1 gives the normalized phase shift as a function of wavelength for the device longitudinal cross section shown. The points represent data taken previously[2]. As shown four different effects add to provide the net effect for the TE mode: a first order and a higher order field effect and a first order and a higher order carrier effect. The higher order effects are associated with the dispersion due to absorption edge movement. The index change is calculated from the absorption change using a Kramers-Kronig transform. For the TM mode the first order field effect, LEO, does not contribute because of symmetry. The agreement between theory and experiment is quite good, indicating that the record level of phase shift represented by the data is believable, and that the constituent physical contributions are probably those considered. Also, it is clear that larger phase shifts are possible for wavelengths nearer the bandgap. However, losses associated with the absorption edge movement become important for wavelengths below 1 μm. For less than a 3dB loss change, the wavelength must be greater than 0.98 μm, at which point the normalized phase shift is 80°/Vmm. It might be expected that still higher effects may be possible by placing the p-n junction in the center of the active region to align the applied field with the peak of the optical field. This will be the subject of further study, and the results will be given in the next report.

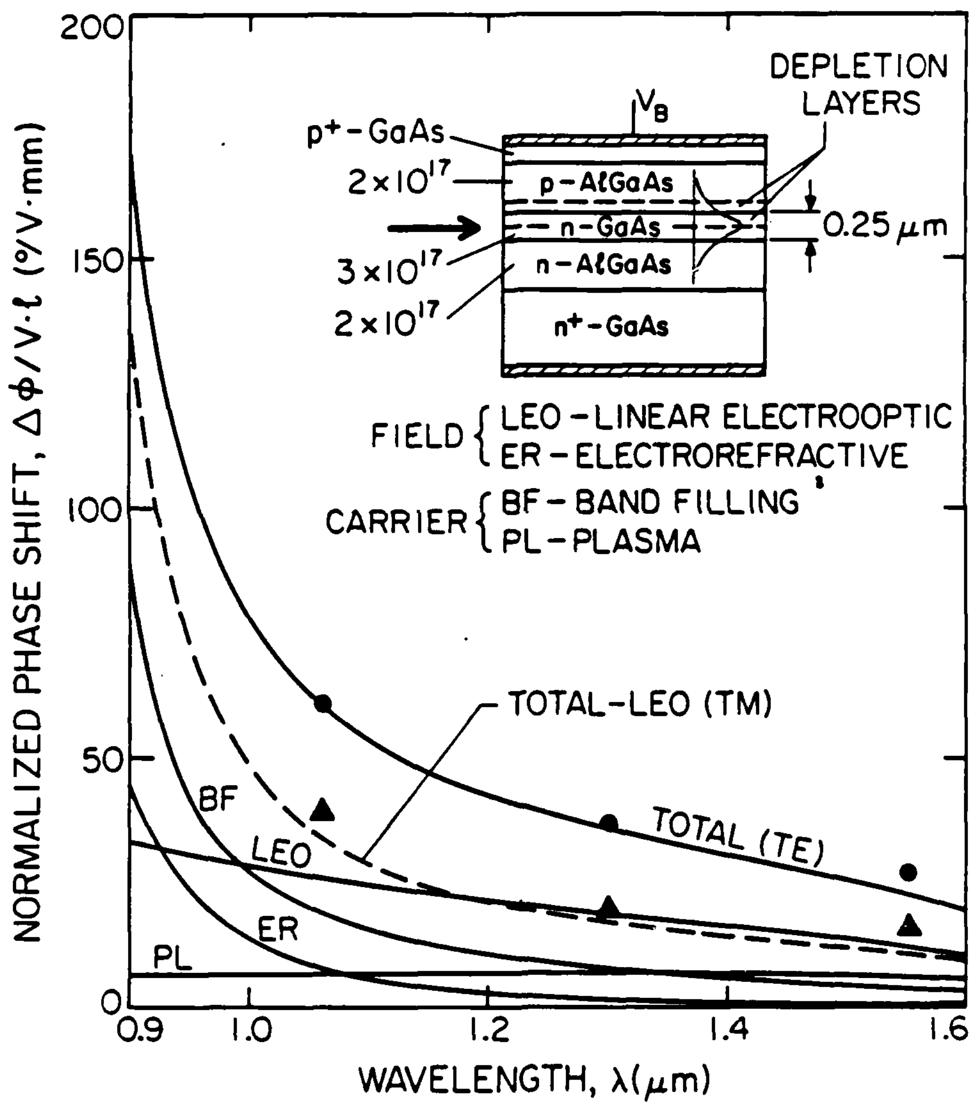

Figure 1. Theoretical normalized phase shift versus wavelength for the four physical effects listed. Round and triangular data points represent experimental TE and TM measurements, respectively. Inset shows longitudinal cross section.

Figure 2 gives the phase shift versus applied voltage for the configuration indicated in Fig. 1. The phase shift versus applied voltage results show that a nearly linear response is expected even though the constituent effects are nonlinear. This again is in good agreement with experiment.

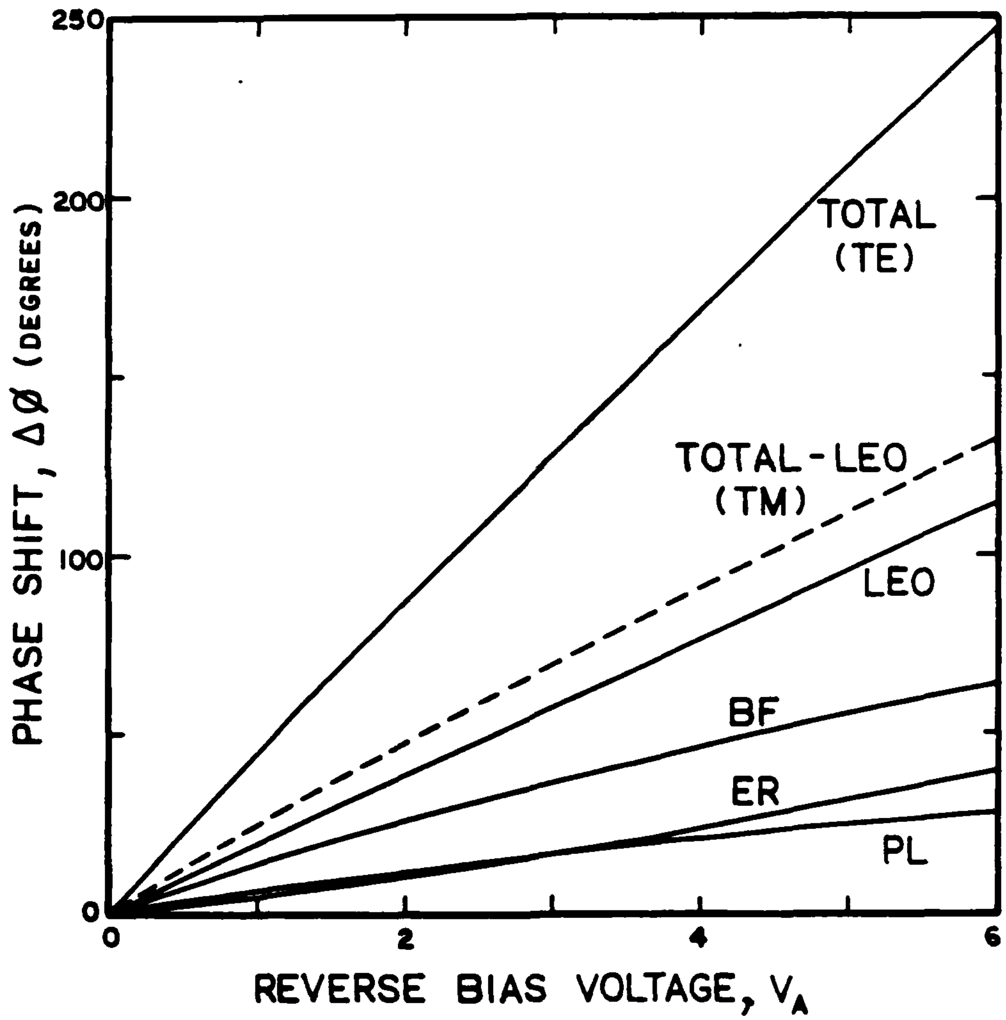

Figure 2. Theoretical phase shift vs. applied voltage. Sum of all effects gives expected result for TE mode.

The dependence on carrier density is shown in Fig. 3. The dependence on doping results primarily from the change in depletion width for the given voltage change and the change in the bandfilling contribution. The optimum doping depends upon wavelength, but, as can be seen, levels around 10^{17} cm^{-3} are best for the geometry considered.

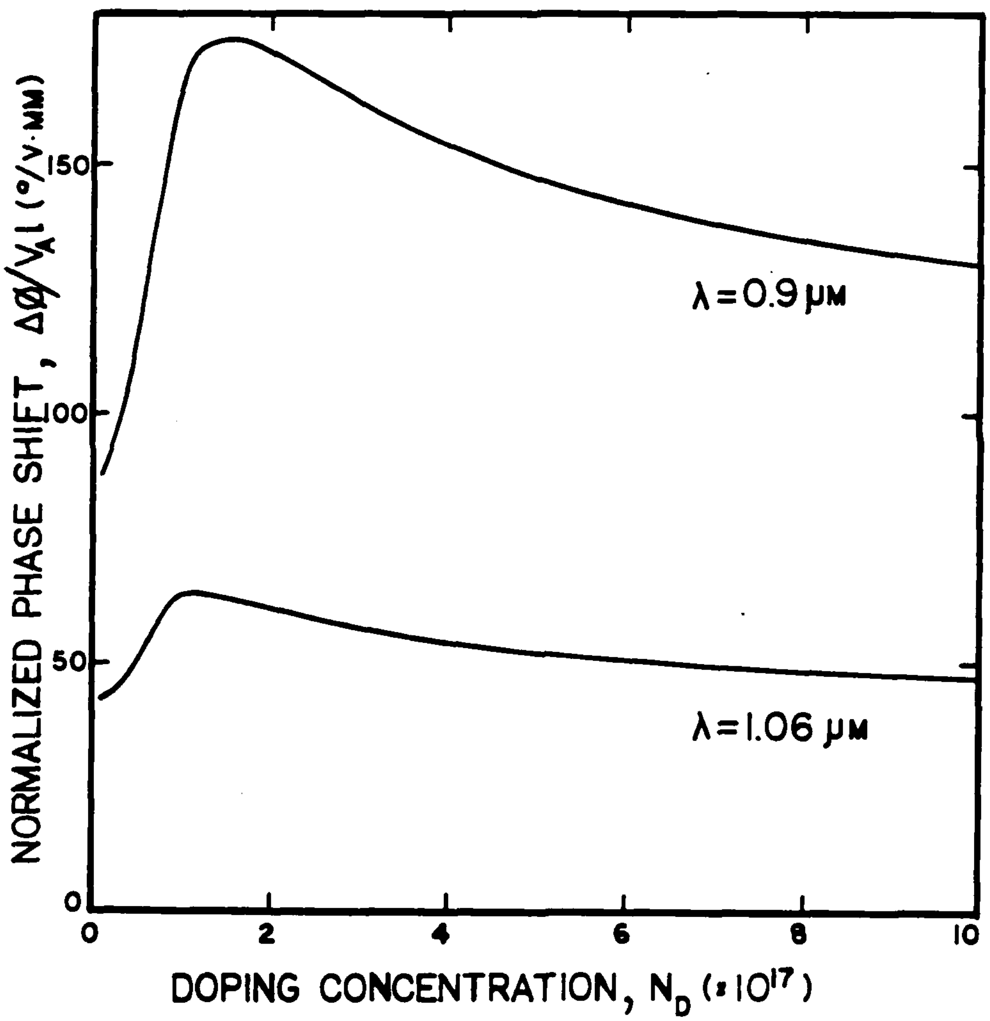

Figure 3. Normalized phase shift vs. doping concentration for several wavelengths.

The good agreement between theory and experiment shown in Fig. 1 above and the large magnitude of the observed phase shift shows that the basic DET configuration is both well understood and good. It should be reemphasized that the DET concept is a general philosophy for a desirable waveguide/bias structure, not a detailed recipe for the materials used in a particular device structure. In fact, considerable improvement should be possible by including more complex active layers within this structure. For example, we are presently experimenting with quantum-well structures that are known to exhibit large absorption edge shifts with voltage. The electro-refractive term with such active layers should increase significantly. Also, we are suggesting that still larger effects should be possible, if carriers are first added to these quantum-wells to quench the excitons and then these same carriers are removed to restore the excitons again. The fields used to remove the carriers will also shift the absorption edge even more to longer wavelengths, and the existence of the carriers before the removing field is applied will shift the starting absorption edge more to shorter wavelengths. Figure 4 crudely illustrates these changes in the absorption edge. The net shift in absorption from carrier filled quantum-wells (no excitons plus bandfilling) to carrier depleted quantum-wells (excitons plus field) is several times larger than what we presently use in the simple double-heterostructure. Thus, the associated index change in the low absorption region should be much larger (~1-2% vs. 0.3-0.5%), and when combined with the DET structure, the resulting phase shift should also be several times larger than the present values.

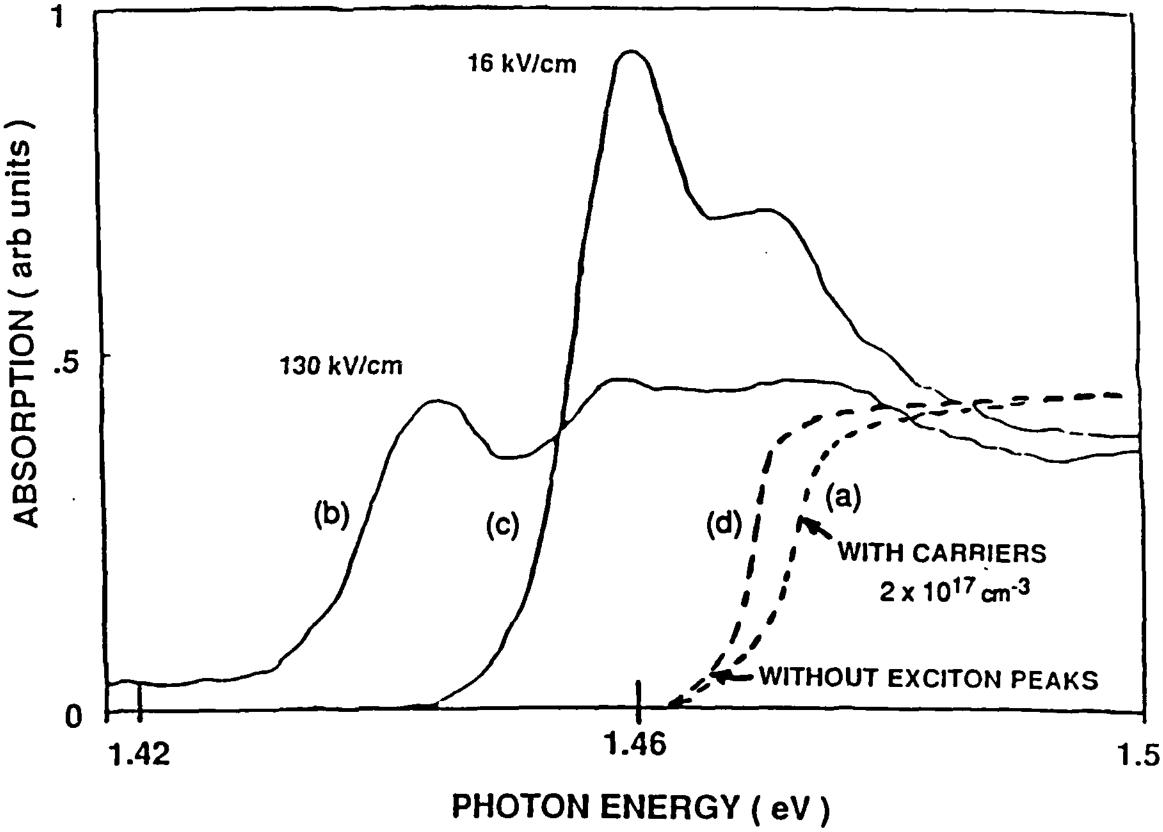

Figure 4. Schematic transmission coefficient vs. energy for a quantum-well structure with (a) carriers added and (b) carriers depleted by an electric field. [(c) is for no carriers and no field, (d) is for no excitons and no carriers]

2. Fabrication Technology

a. Ridge waveguide phase modulator

The two major advances in this area have been 1) the development of reliable etching procedures for several ridge waveguide configurations and 2) the development of a polyimide spacer layer process that allows larger contact pads without any increase in capacitance.

Table I gives the etches used and a summary of the results.

Etch	Selectivity	Mask	Characteristics
1. $HBr{:}Br{:}H_20$	non-selective	photoresist	Smooth sides; large undercut; U-shaped groove
2. Br:Methanol	non-selective	oxide	moderately smooth; (111) wall faces; no undercut for $[\bar{1}10]$
3. HF	selective	oxide/GaAs	large undercut & rough; stops at x=0.3
4. $KI{:}I_2{:}H_20$	selective	oxide	rough walls; stops at x=0
5. RIE/Cl_2	non-selective	resist or metal	vertical walls; no undercut; complex

Table I.

Figure 5 gives schematics of fabrication processes and photos of actual devices. These include the polyimide step prior to the final contact metalization to reduce device capacitance and allow a slightly larger bonding pad. The ployimide was a photosensitive variety which behaves like a conventional negative photoresist. Typical thicknesses of the polyimide layers are ~1-2 μm. We are presently using evaporated 50 μm wide contact stripes to keep the end-to-end resistance below 5 Ω. However, this width is much larger than needed for bonding, and it will affect the speed of future devices. Thus, we are investigating the use of smaller contact lines and electroplating to thicken the metalization for minimal resistance.

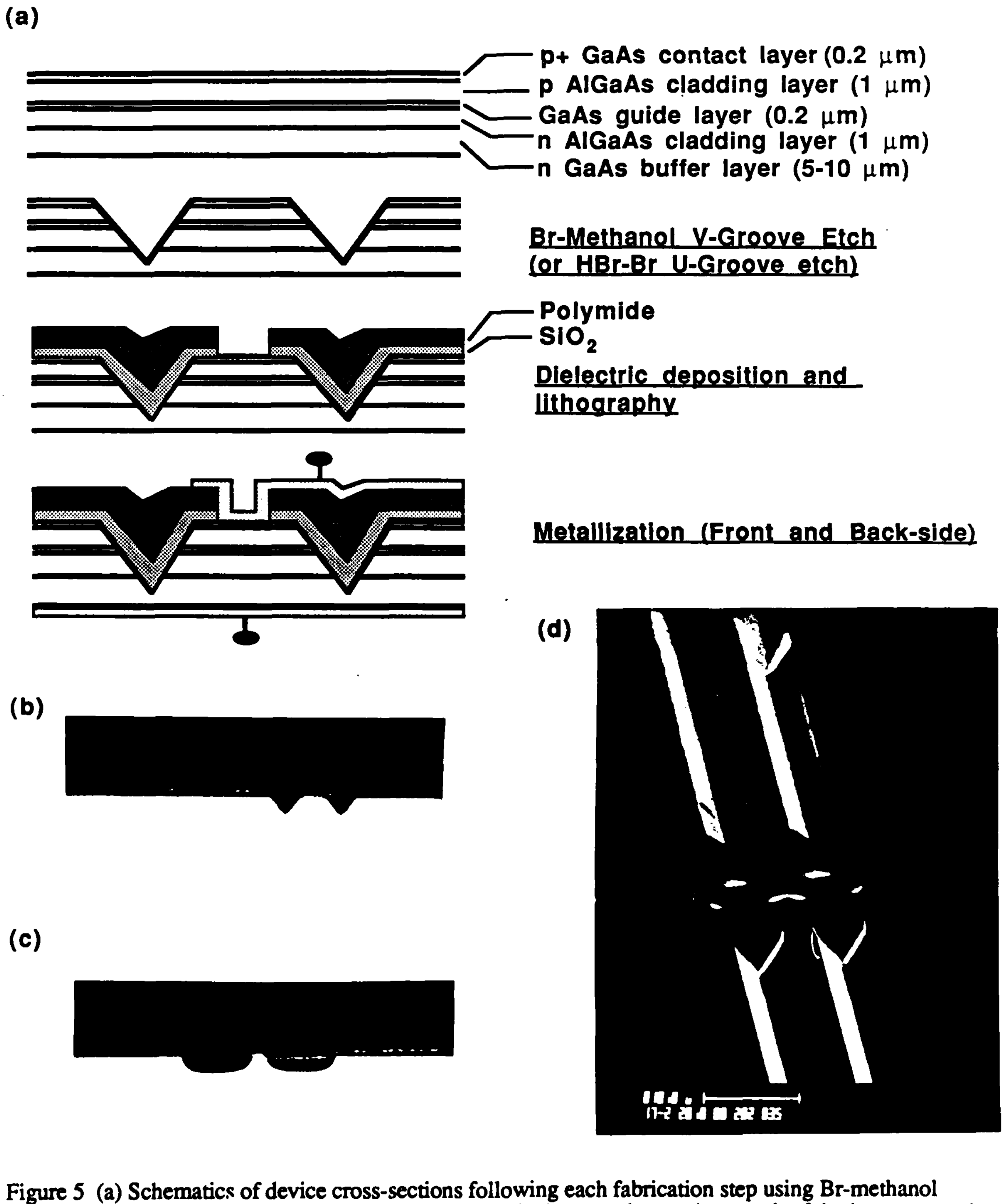

Figure 5 (a) Schematics of device cross-sections following each fabrication step using Br-methanol V-groove etch, (b) Photo-micrographs of a fabricated device, (c) photo-micrograph of device processed with alternate HBr-Br U-groove etch, and (d) SEM micrograph of top profile view showing groove quality.

b. Reflection switches

One of the important reasons for investigating large index changes is for use in optical switching. We have proposed several switching geometries that use the concept of total-internal-reflection at an impedance discontinuity. If an impedance discontinuity is inserted at the intersection of two crossing waveguides, the energy can be deflected from one guide to the other[3,4]. To make this device a switch, the impedance discontinuity must be controllable so that it can be added or removed.

Two concepts are being pursued. Figure 6 shows both schematically.

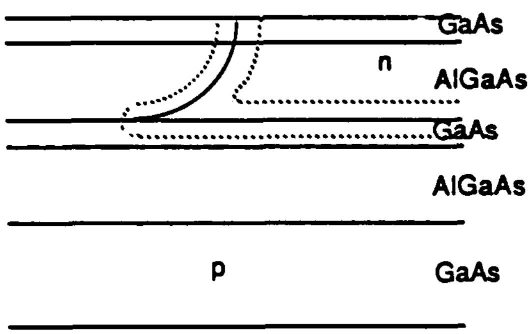

Fig 6 (a)

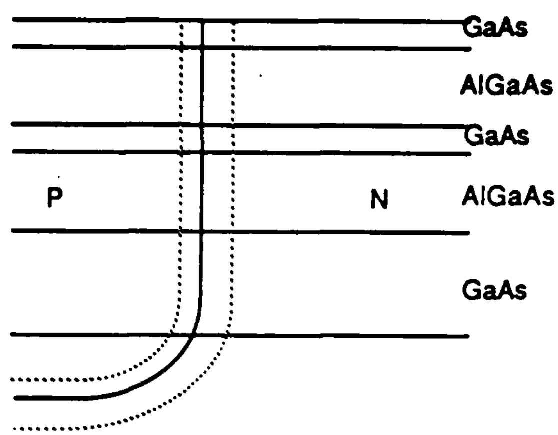

Fig 6 (b)

Figure 6. Cross sections of switchable impedance discontinuities in optical waveguides. (a)-depletion edge lowered into the guide for variable reflection; (b)-interference of the reflections from the two depletion edges varied as width varied.

In Fig 6a, the necessary impedance discontinuity is provided by lowering the depletion edge of a p-n junction into a waveguide. If the incident beam is near the critical angle for the largest index change (maximum reverse bias), the magnitude of the reflection will change by a large amount as the depletion edge is lowered (reverse bias is increased). In Fig. 6b, the reflection is effectively turned on and off by changing the width of a depletion region that is normal to the plane of the waveguide. If the depletion region is an odd multiple of quarter-wavelengths, the reflections from both depletion edges will add; if this region is an even multiple of quarter-wavelengths, the reflections cancel and the wave is transmitted. Since the impedance discontinuity in both cases is relatively small, total reflection will only occur for relatively small angles. However, the angle of wave deflection calculated for our levels of index discontinuity ($\Theta \sim 4$-$10°$) are much larger than for previous devices of this kind.

To date we have been studying diffusion techniques to fabricate the desired device structures. For more control, ion implantation will also be investigated. In any event, it is necessary to create a lateral p-n junction for either of the schemes suggested in Fig. 6. In case 6a, p-type AlGaAs lower cladding and GaAs active layers are covered by n-type AlGaAs upper cladding and GaAs contact layers in the initial epi-growth. Then, a p-type dopant (zinc in our case) is diffused from the surface to reach the active layer. This procedure leaves an n-type top region which has a cusp near the active region as shown in Fig. 6a. The cusp shape provides for an abrupt impedance discontinuity, which is preferable to the more gradual one that results after diffusing a rounded p-type region into an all n-type layer structure. For the case of Fig. 6b, a p-type dopant is diffused through all n-type epi-layers to the semi-insulating substrate, so that a nearly vertical junction at the active layer results. Of course, inverse structures where an n-type dopant is diffused are also possible.

Both structures have been fabricated with approximately the correct junction profile. However, most device measurements have not been successful due to a very large level of propagation loss in the diffused regions. Also, in cases where a significant amount of diffusion occurs through the active layer [case 6b], we have observed a large amount of impurity induced mixing of the AlGaAs and GaAs layers, so that the waveguide is changed or even destroyed. This later problem should be solvable by ion implantation and/or more careful diffusion techniques. The first problem is presumably due to a very high doping level (>>10^{18} cm^{-3}), which leads to free carrier absorption. This problem, again, should be solvable using ion implantation and/or more careful diffusion techniques. We are presently exploring a separate drive-in diffusion, which should give a lower doping at the diffusion front. It should also be realized that the implanted or diffused regions in a practical device configuration will only extend a few tens of microns in the direction of more propagation at a maximum. Thus, a reasonably high incremental loss is tolerable.

The same optical switching concepts as outlined in Fig. 6 can be applied for a surface-normal optical beam. In this way arrays of switchable mirrors or transmissive modulators can be constructed. Here, the device construction may also be simpler, since the p-n junctions and critical layer thicknesses for multiple layers are in the vertical direction, and they can easily be grown-in during MBE growth. To demonstrate the concept of variable reflection using the interference between reflections from alternate sides of a p-n junction (like Fig. 6b), a simple experiment with one p-n junction parallel to the surface was performed. Figure 7 shows the experimental configuration and the measured reflectivity change from the surface of a GaAs wafer with a modulated p-n junction grown-in parallel to the surface. Here the angle of incidence is 45° so the reflection is weak as expected. If a more grazing angle or a multilayer structure is used, the reflection change can approach unity.

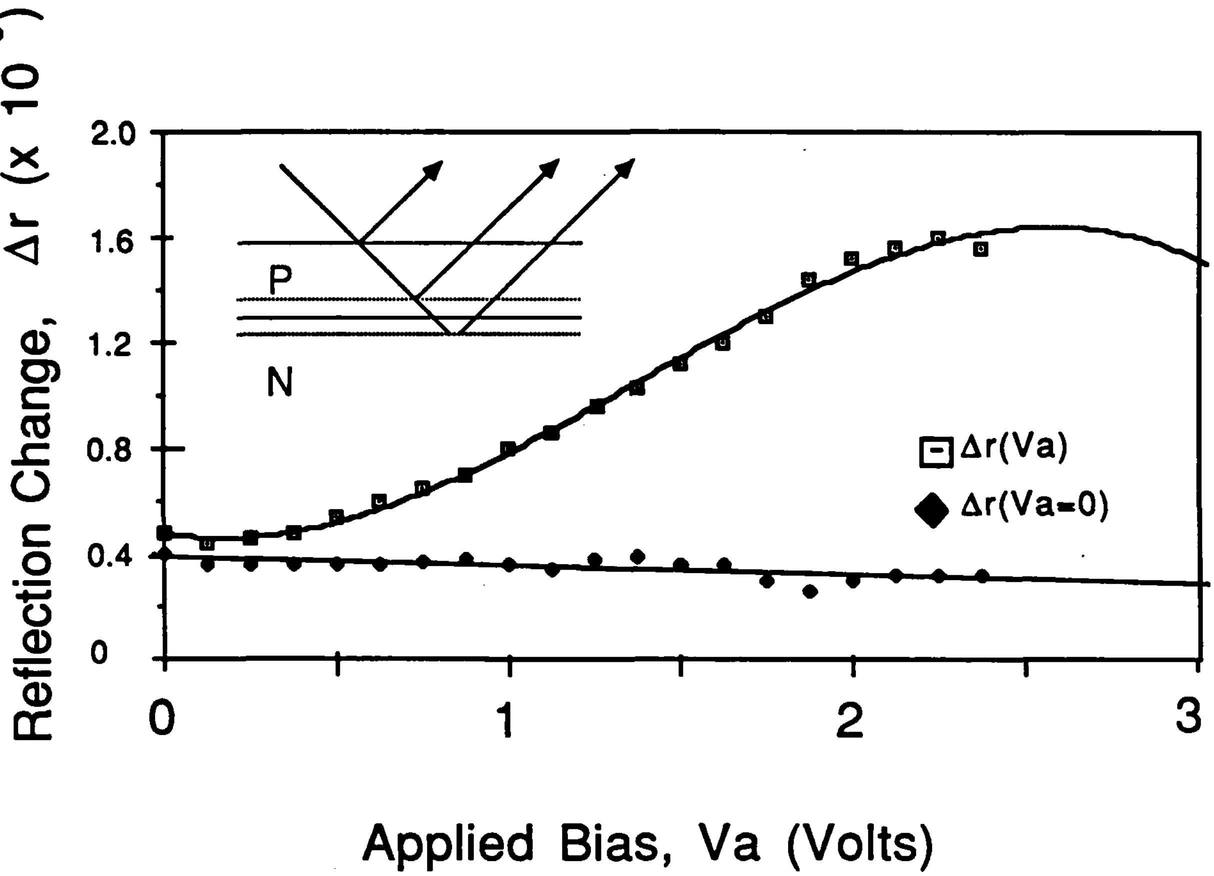

Figure 7. Variable reflection from a modulated p-n junction in GaAs. Inset shows experimental configuration.

3. New Measurements on Waveguide Phase Modulators

Work has continued on the measurement of the efficiency of our waveguided phase modulators. Recent measurements on one LPE grown wafer gave normalized phase shifts ~90-99°/Vmm @ 1.06 μm. It is unclear how such high efficiencies could be obtained since the configuration was very similar to that shown in Fig. 1. However, a small reverse breakdown voltage and relatively large loss changes suggest that the doping may be higher than expected in this sample and that the p-n junction could have diffused to the center of the active region. As mentioned above, a junction at the center should give larger numbers than shown in Fig. 1.

Initial work with quantum-well active regions gave results roughly the same as for simple double-heterostructures. However, it is unclear whether or not excitons exist at room temperature in this MOCVD material, and if so, whether or not they might tune with voltage. We are presently setting up an absorption edge measuring apparatus to measure these as well as our other devices in hopes of correlating the absorption edge movement with the measured index shift.

Most of the measurement effort during this reporting period was directed at measuring the frequency response of these devices and comparing these measurements to expected levels. We have confirmed that the cut-off frequency in this device is due to an RC cut-off, $f_c = (2\pi RC)^{-1}$, where R is the source impedance and C is the device capacitance (if a terminated transmission line of characteristic impedance R interconnects the two). The new structure, which uses a polyimide dielectric layer beneath the contact pad, has given RC cut-off frequencies somewhat less than those calculated from the junction capacitance alone. For a 400 μm long sample this cut-off was measured to be 1.8 GHz. Further improvements in reducing bonding pad capacitance may improve this number and the expected improvements in the efficiency of the device will add proportionately to the cut-off frequency. Nevertheless, it should be realized that these measurements give state-of-the-art values of f_c/V_π, due in part to the very low required voltage to drive these devices ($V_\pi = 4V$ in the above example).

4. References

1. L. A. Coldren et al, "Use of depletion-edge-translation for high speed modulation and switching of lightwaves: year-1", Annual Report of AFOSR Contract #85-0323 for period 8/85-7/86, Dec. 1986.

2. A. Alping et al, "Wavelength dependence of high-performance AlGaAs/GaAs waveguide phase modulators", *Electron. Lett.*, **23**, 93-95 (Jan. 1987).

3. C. Tsai, B. Kim, and F.R. El-Akkari, "Optical channel waveguide switch and coupler using total internal reflection", *IEEE J. Quantum Electron*, **QE**, 513-517 (1978).

4. R.C. Alferness, "Waveguide electro-optic modulators", *IEEE Trans. Microwave Theo. and Tech.*, **MTT-30**, 1121-1137 (1983).

V. Publications

1. A. Alping et al, "Wavelength dependence of high-performance AlGaAs/GaAs waveguide phase modulators", *Electron. Lett.*, 23, 93-95 (Jan. 1987).

VI. Talks

Conference

1. L. A. Coldren et al, "Optical waveguide phase-shifters for high-speed signal processing", *Optical fiber Conference*, Reno, NV, paper TuQ34 (Jan., 1987)

2. L. A. Coldren, "Monolithic Optoelectronics", *Conf. on Electronic Materials*, Am. Defense Preparedness Assoc., Los Angeles, CA (Oct., 1986) INVITED

VII. Personnel

1. Professor Larry A. Coldren, PhD: Principal Investigator. 15% time.
2. Dr. Julio Mendoza-Alvarez, PhD: Visiting Research Engineer. 100% time.
3. Mr. T. R. Hausken, M.S.: Research Assistant. 50% time academic, 100% time summer.
4. Mr. T. C. Huang, M.S.: Research Assistant. 50% time academic, 100% time summer.
5. Mr. K. W. Lee: Research Assistant. 25% time academic, 50% time summer.
6. Mr. R. H. Yan, M.S.: Research Assistant. 25% time academic, 50% time summer.

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