FINAL REPORT
QUANTUM WELL OPTICAL WAVEGUIDE MODULATORS
N00014-91-J-1662

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A. Introduction - The original proposal

The purpose of this project was to examine several different quantum well waveguide modulator designs with the goal of developing a quantum well waveguide optical modulator suitable for integration into III-V opto-electronic integrated circuits.

One potential design was based on the large dipole matrix element, relatively sharp absorption spectrum, and potentially large carrier-optic effect of intersubband transitions in the conduction band of quantum wells. We proposed to develop a complete theoretical model for the change in χ_1, χ_2, and χ_3 (and thus α and n) as a function of the change in carrier concentration.

The second potential design was based on the large quantum-confined Stark effect for conduction to valence band transitions in coupled symmetric quantum wells. We proposed to construct a waveguide structure using coupled symmetric MBE-grown multiple quantum wells as the active layers.

The third potential design was based on the potentially large carrier-optic effect for conduction to valence band transitions in single and coupled quantum wells. We proposed to develop a complete theoretical model of the change in χ_1, χ_2, and χ_3 (and thus α and n) as a function of the change in carrier concentration for conduction to valence transitions including the band-mixing effects in the valence band.

A summary of the originally proposed work is as follows:

	Conduction band	Valence band	Band-to-band
Energy band location	proposed	proposed	proposed
Stark effect	proposed	proposed	proposed
Calculation of χ_1, χ_2, and χ_3	proposed	proposed	proposed
Inclusion of band mixing	Not necessary	proposed	proposed
Waveguide Stark shift			proposed

B. Work completed during the course of the project

In the computational area, we have developed and tested the basic conduction and valence band parts of the computation model. The conduction part of the model includes the Stark effect and the Fermi level carrier effects. The valence part of the model includes the Stark effect, the Fermi level carrier effects, and valence band mixing effects.

Development of this model resulted in papers [1], [2] and [8] and in presentation [9]. The process of developing this model produced some interesting new computational techniques for accurately solving quantum well problems [3, 5]. In the course of testing the model, we observed that the band-gap ratio determined from experimental measurements depends significantly on the choice of the analysis Hamiltonian [4]. We also observed that the connection matrix technique may not be accurate for AlGaAs/GaAs quantum well systems [7].

Once the basic conduction band part of the model was complete, we began to examine the behavior of conduction band states as a function of carrier density. (This part of the effort was done in collaboration with Leung Tsang) We discovered that carrier-carrier interactions are of extreme importance and thus incorporated the direct and exchange carrier interactions into our conduction band model. Interestingly enough, the direct interaction shifts the intersubband transition energy down in energy -- while the exchange interaction shifts it up. Thus, the direct interaction alone yields both an incorrect magnitude and incorrect sign for the change. We discovered that these commonly neglected carrier-carrier effects are extremely significant and may explain the reduction in wavelength observed experimentally in intersubband quantum well samples. These fascinating results are summarized in paper [6] and presentation [10].

We (in collaboration with Leung Tsang) are in the process of developing the analytic formalism for χ_1, χ_2 and χ_3 for the band to band transitions. Based on the published work in the field, we had originally expected this formalism to be relatively straightforward. However, during our initial analysis, we discovered that the majority of existing published work is not valid for optical modulators. Thus, the analytic and computational problem has turned out to be much more difficult than originally anticipated. This is a very rich and exciting problem which we expect to be the foundation of a significant amount of future work.

We have reviewed the possibility of including carrier-carrier effects in the valence band. Inclusion of such effects might explain a number of anomolous experimental results. However, the calculation is quite extensive, and we have elected to delay work in this area until the χ_1, χ_2 and χ_3 analysis is completed.

In the experimental area, we grew several simple structures with different quantum well depths and different doping densities. We used FTIR to measure the absorption of this quantum well material in an effort to compare with papers [1,2] and presentation [1]. We had a number of experimental difficulties, ranging from transitions moving in energy to transitions vanishing and reappearing randomly. Our increasing sophistication in mounting and polishing the samples has resulted in some improvements -- unfortunately, the data is still not reproducible enough for publication. However, this work is still in progress and will be published should the experimental results become trustworthy.

Additionally, we have grown several simple photodetector structures. We are currently in the process of fabricating these structures into photodetector devices. When complete, we will measure the spectral response of the photocurrent as a function of applied voltage and compare these results with our theoretical predictions using the model. We anticipate publication of these results by Summer 1993.

For the band-to-band carrier optic effect modulators, we have grown several simple p-i-n and n-i-n optical modulator structures with different quantum well depths and different carrier densities. We have constructed a waveguide measurement station that can measure the character of the electromagnetic mode as a function of applied voltage. We have fabricated, mounted, and are in the process of testing several of the n-i-n devices. As one might expect, there are a number of processing and packaging issues involved in the fabrication of a complete optical modulator device. As such, we do not expect reproducible experimental results from these devices until Fall 1993.

A summary of the progress as of May 1, 1993.

	Conduction band	Valence band	Band-to-band
Energy band location	Complete	Complete	Complete
Stark effect	Complete	Complete	Complete
Calculation of χ_1, χ_2, and χ_3	Complete	In progress	In progress
Inclusion of band mixing	Not necessary	Complete	In progress
Direct and exchange interaction	Complete	Future	Future
Waveguide Stark shift			In progress
FTIR of intersubband	In progress	Future	
Photodetector measurement			In progress
Optical modulator measurement			In progress/Future

C. Specific Accomplishments:

Both an analytical formulation and a numerical implementation which calculate the refractive index and absorption changes as a function of temperature and carrier concentration for intersubband transitions in quantum well samples [1,2,8,9].

Inclusion of the direct and exchange interaction for carrier-carrier effects in the conduction band [6,10]

An explanation that the reduction in wavelength commonly observed in intersubband quantum well samples is due to the extra carriers that are added to increase the observed optical absorption. [6,10]

Comparison of finite-element and finite-difference techniques for the accurate solution of AlGaAs/GaAs quantum well problems [3,5].

Identification of the correlation between the measured band-gap ratio (i.e. 60:40, 70:30) and the choice of the effective mass Hamiltonian [4].

A new analytical and numerical approach to Ando's interface matching conditions [7].

D. Publications

[1.] K.J. Kuhn, G. Iyengar and S. Yee, "Free carrier induced changes in the absorption and refractive index for intersubband optical transitions in $Al_xGa_{1-x}As$ /$GaAs/Al_xGa_{1-x}As$ quantum wells ", Journal of Applied Physics, Vol. 70, No. 9, November 1, 1991, pp. 5010-5017.

[2.] G. Iyengar, K.J. Kuhn, and S. Yee, "Free carrier induced changes in the absorption and refractive index for intersubband optical transitions in $Al_xGa_{1-x}As$ /$GaAs/Al_xGa_{1-x}As$ quantum wells ", Institute of Physics Conference Series No. 120, 431 (1991)

[3.] T.L. Li and K.J. Kuhn, "Effects of mass discontinuity on the numerical solutions to quantum wells using the effective mass equation", submitted to the Journal of Computational Physics, August 13, 1991. JCP reorganized the editorial office and transferred the manuscript on October 21, 1991. We received the first reviews on October 7, 1992 (one year later!) and mailed the corrected manuscript back on November 19, 1992. We sent a letter of inquiry to JCP on March 19, 1993.

[4.] T.L. Li and K.J. Kuhn, "Band-offset ratio dependence on the effective mass Hamiltonian based on a modified profile of the GaAs/AlGaAs quantum well. Accepted Physical Review, anticipated publication date May 15, 1993.

[5.] T.L. Li and K.J. Kuhn, "Finite element solution to quantum wells by irreducible formulations", submitted to IEEE Journal of Quantum Electronics on March 17, 1993.

[6.] A. Sengers, L. Tsang and K. Kuhn, "Optical properties due to intersubband transitions in n-type quantum wells including the effects of the exchange interaction", submitted to Physical Review B, April 3, 1993.

[7.] T.L. Li and K. J. Kuhn, "An examination of the validity of the connection matrix approach to semiconductor heterojunction", submitted to Physical Review B on April 14, 1993.

[8.] G. Iyengar, K.J. Kuhn, and S. Yee, "Temperature effects on free carrier induced changes in the absorption and refractive index for intersubband optical transitions in $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ quantum wells ", in progress.

(B) Presentations

[9.] G. Iyengar, K.J. Kuhn, and S. Yee, "Free carrier induced changes in the absorption and refractive index for intersubband optical transitions in $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ quantum wells ", 18th International Symposium on Gallium Arsenide and Related Compounds, Seattle, WA, September 1991.

[10.] A. Sengers, G. Iyengar, L. Tsang and K. Kuhn, "Optical Properties due to Intersubband Transitions in n-type Quantum Wells Including the Effects of the Exchange Interaction", 1993 March meeting of the American Physical Society, Seattle, WA 22-26 March 1993.