(2)

Final Report

Evaluation of Heterojunction Interfaces Using Electron Beam Electroreflectance

Prepared by:

Michael H. Herman, Ph.D.

CHARLES EVANS & ASSOCIATES
301 Chesapeake Drive
Redwood City, CA 94063
(415) 369-4567

Reporting Period:
September 21, 1988 - March 24, 1989

Sponsored by:

Defense Advanced Research Projects Agency (DOD)
Defense Small Business Innovation Research Program

Evaluation of Heterojunction Interfaces Using Electron Beam Electroreflectance

ARPA Order No.5916, Amdt 9
Issued by US Army Missile Command Under
Contract #DAAH01-88-C-0873

Prepared by:

Principal Investigator: Michael H. Herman

Effective Date of Contract: September 21, 1988
Contract Expiration Date: March 24, 1989

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS: NONE

2a. SECURITY CLASSIFICATION AUTHORITY: NA

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE: NA

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S):

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: CHARLES EVANS & ASSOCIATES

6b. OFFICE SYMBOL (If applicable): 8T252

7a. NAME OF MONITORING ORGANIZATION: DARPA/AMSMI-RD-DP-TT

6c. ADDRESS (City, State, and ZIP Code): 301 Chesapeake Drive, Redwood City, CA 94063

7b. ADDRESS (City, State, and ZIP Code): Bldg 7770 Room 107, Redstone Arsenal, AL 35898-5244

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: DARPA/SBIR

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: DAAH01-88-C-0873

8c. ADDRESS (City, State, and ZIP Code): 1400 Wilson Avenue, Arlington, VA 22209

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): Evaluation of Heterojunction Interfaces Using Electron Beam Electroreflectance (Unclassified)

12. PERSONAL AUTHOR(S): Herman, Michael H.

13a. TYPE OF REPORT: Final Technical

13b. TIME COVERED: FROM 89FEB02 TO 89MAR24

14. DATE OF REPORT (Year, Month, Day): May 18, 1989

15. PAGE COUNT: 34

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): electroreflectance; heterojunction; interface semiconductor; HEMT, MODFET

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

We have completed the Phase I study of heterojunction III-V layers using EBER. In the case of single films, we have shown that the direct band gap of $Al_xGa_{1-x}As$ composition from the entire range x=0 to 1 is detectable. We have determined the excitonic energy levels of a wide range of AlGaAs/GaAs single quantum wells. The observed levels have been identified with respect to the simple rectangular barrier model, resulting in very good agreement with published work. In HEMT studies, our EBER studies strongly suggest the presence of 2DEG states at the heterojunction interface, as reported by earlier researchers. In addition, we have found direct evidence of superlattice buffer layers in HEMTs, which has not been previously reported. Furthermore, we have utilized the Franz-Keldysh oscillations originating in the heavily doped AlGaAs film to estimate the built-in electric fields in HEMT samples. Although we have not yet succeeded in correlating the 2DEG density nor carrier mobility to features of EBER spectra, we have demonstrated that poor quality HEMT material can be detected.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL:

22b. TELEPHONE (Include Area Code):

22c. OFFICE SYMBOL:

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE: UNCLASSIFIED

Beyond our original intent, our studies have encompassed fundamental investigations of the mechanism of EBER, the presence of excitons in crystals and structured samples. We have also measured the EBER spectra of strained-layer pseudomorphic QW and HEMT structures. Additionally, we have data which shows that carrier type can be determined optically from the phase of the EBER features.

I. SUMMARY

We have completed the Phase I study of heterojunction III-V layers using EBER. In the case of single films, we have shown that the direct band gap of $Al_xGa_{1-x}As$ composition from the entire range $x = 0$ to 1 is detectable. We have determined the excitonic energy levels of a wide range of AlGaAs/GaAs single quantum wells. The observed levels have been identified with respect to the simple rectangular barrier model, resulting in very good agreement with published work. In HEMT studies, our EBER results strongly suggest the presence of 2DEG states at the heterojunction interface, as reported by earlier researchers. In addition, we have found direct evidence of superlattice buffer layers in HEMTs, which has not been previously reported. Furthermore, we have utilized the Franz-Keldysh oscillations originating in the heavily doped AlGaAs film to estimate the built-in electric fields in HEMT samples. Although we have not yet succeeded in correlating the 2DEG density nor carrier mobility to features of EBER spectra, we have demonstrated that poor quality HEMT material can be detected.

Beyond our original intent, our studies have encompassed fundamental investigations of the mechanism of EBER, the presence of excitons in crystals and structured samples. We have also measured the EBER spectra of strained-layer pseudomorphic QW and HEMT structures. Additionally, we have data which shows that carrier type can be determined optically from the phase of the EBER features.

TABLE OF CONTENTS

FIGURES

II. INTRODUCTION AND OBJECTIVE

The objective of our Phase I research was to determine the usefulness of Electron Beam Electroreflectance (EBER) for the characterization and understanding of heterostructures. We intended in Phase I to show the feasibility of the technique for this purpose, and to examine the potential for more advanced studies in Phase II.

Our original proposal called for the initial characterization of electronic structure at AlGaAs/GaAs interfaces by EBER. Specifically, we proposed the investigation of quantum well and HEMT structures, to demonstrate the applicability of EBER to analysis of these structures. We intended to examine the electronic levels associated with single quantum wells, used in laser devices, and single heterojunction interfaces, characteristic of HEMT devices. Our objective was to observe and parametrize additional spectral features of these interfaces, using EBER.

III. PROGRESS AGAINST THE WORK PLAN

In this section, we review the progress made against our original research plans.

A. OBTAIN SAMPLES OF BOTH SINGLE HETEROJUNCTION INTERFACE AND SQW SAMPLES. STATUS: DONE.

(a) SQW samples: We have obtained SQW AlGaAs/GaAs/AlGaAs samples with $x = 0.3$ for the barrier layers and with a well width range of 10, 25, 50, and 100Å. Additionally, we have obtained GaAs/InGaAs/GaAs SQW samples of several well widths and In content. For further studies, we have acquired both InAs/GaAs and AlGaAs/GaAs superlattices.

(b) Single Heterojunction samples (part 1): We have obtained samples of AlGaAs/GaAs structure with a variety of AlGaAs x value and generally low doping. The samples have been grown by both MBE and by MOCVD techniques. These samples play the role of control for comparison to the HEMT-type of structures described in (c) below.

(c) Single Heterojunction samples (part 2): We have obtained HEMT samples with "standard" AlGaAs/GaAs structure with a variety of AlGaAs x value and high doping. Although they are not specifically single heterojunction structures, we also have obtained advanced HEMT samples with InGaAs QW layers between the AlGaAs and GaAs, to preliminarily extend the HEMT study.

B. MEASURE SPECTRA FROM SINGLE HETEROJUNCTION INTERFACES. STATUS: DONE.

We have measured EBER spectra from more than 8 single heterojunction AlGaAs/GaAs HEMT structures, based upon thin N^+-doped $Al_xGa_{1-x}As$ layer on undoped (100) GaAs. We have also studied such structures with a short period AlGaAs/GaAs superlattice underlying the HEMT structure. We have also experimentally obtained spectra using variations in electron beam current density and sample temperature, from 80K to 300K. The data are discussed below in the Results section.

C. QUANTIFY OBSERVATIONS FROM SINGLE HETEROJUNCTION INTERFACES. STATUS: DONE.

We have, to the extent possible, parametrized the observed signals from 2DEG transitions. These signals have been found to be most clear in cases where the sample composition has been simplest. We do observe additional oscillations from HEMT samples in which Hall measurements indicate the presence of a 2D electron gas. These additional features are absent in cases where the AlGaAs is lightly doped, and no 2DEG is observed by Hall measurements. The data obtained so far are discussed below in the Results section.

D. MEASURE SQW SAMPLES. STATUS: DONE.

We have measured several single quantum well (SQW), similar experiments were performed. The quantum wells are formed of a thin layer of GaAs, 25 to 100Å thick, bounded by relatively thick $Al_xGa_{1-x}As$ barrier layers. Total conduction and valence band well depths, determined by composition of the barrier and well materials, were estimated from E_0 band gap measurements. EBER spectra of quantum wells of various depths and widths were obtained for several temperatures and beam current densities. The data obtained so far are discussed below in the Results section.

E. QUANTIFY OBSERVATIONS FROM SQW SAMPLES. STATUS: DONE.

After obtaining the EBER spectra of various quantum wells, the spectral peaks were fitted to the GFF theory expanded to include excitonic effects. The energy positions of the peaks and their lineshapes were quantified. Our data are discussed below in the Results section.

F. COMPARE TO THEORY. STATUS: DONE.

Once energy levels were determined, they were compared to theoretically allowed transitions between electron states and light and heavy hole sub-bands. The simple 1-D potential well model was used to provide the assignment of quantum numbers to observed transition energies. Estimates of critical parameters such as the well width W and the conduction band offset, Q_c, were made. The data obtained so far are discussed below in the Results section. The results of this work are being condensed into a paper for submission to the Journal of Electronic Materials.

G. DESCRIBE THE RELATIVE MERIT OF THE EBER TECHNIQUE FOR THESE PURPOSES.
STATUS: DONE.

A major goal of the Phase I study is to ascertain the relative merit of EBER for analysis of heterojunction interfaces. A comparison of the results to those of photoreflectance and electrolyte ER (EER) and similar techniques has been performed. A table of comparisons is attached as Appendix 1.

IV. DIRECT RESULTS OF PHASE I RESEARCH.

A. INVESTIGATIONS OF $AL_xGA_{1-x}AS$ DIRECT BAND GAP FROM $x = 0$ TO 1.

Our investigations of $Al_xGa_{1-x}As$ has shown that the direct band gap of the entire range of composition from $x = 0$ to 1 is detectable. The EBER data from both low and high-x $Al_xGa_{1-x}As$ films, grown by MBE, are shown in the attached Figures 1 and 2. They show that clear features can be observed and fitted to lineshapes for the evaluation of band gap energies E_0, $E_0+\Delta_0$, E_1, and $E_1+\Delta_1$. The formulae of both Casey and Panish[1], and of the more recent Kuech[2], et al are used for estimation of the Al content of the films. Unfortunately, these two formulae do not agree closely at middle ranges of x value, so we currently employ both expressions as estimates of Al content from band gap.

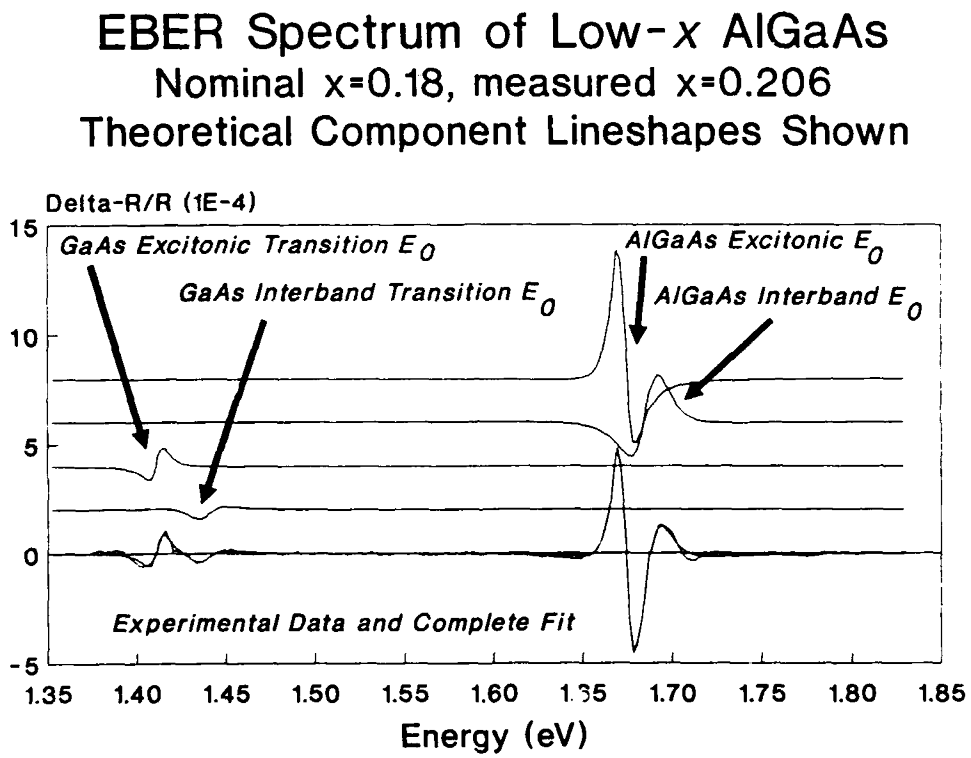


Figure 1: EBER spectrum of low-x $Al_xGa_{1-x}As$.

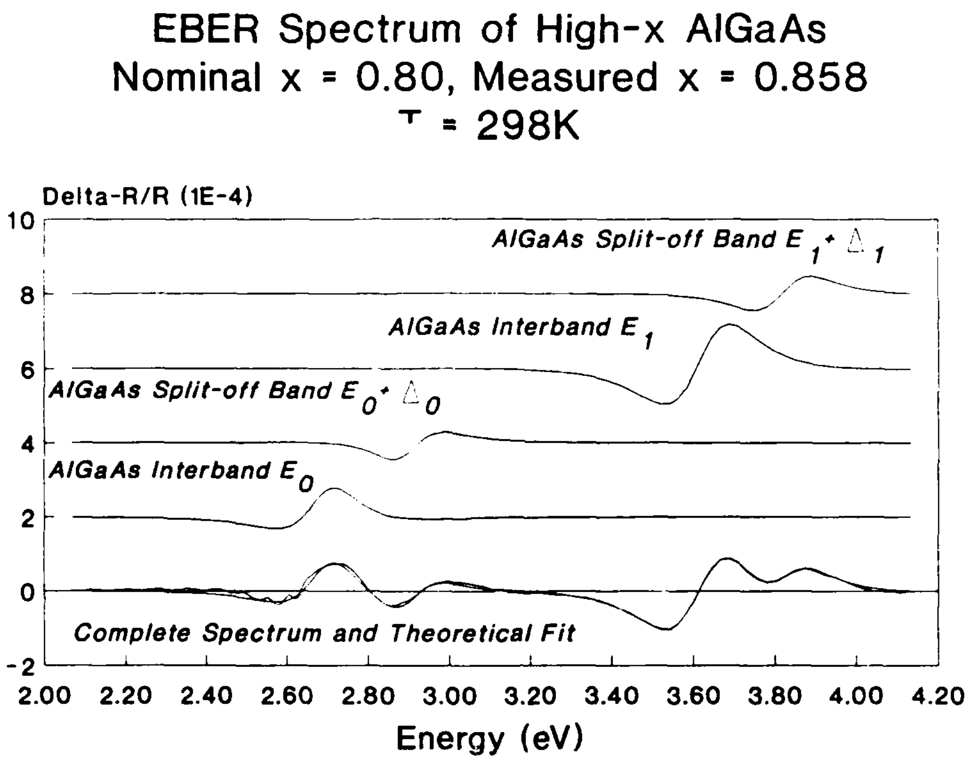


Figure 2: EBER spectrum of high-x $Al_xGa_{1-x}As$.

B. QUANTUM WELL STUDIES (ALGAAS/GAAS/ALGAAS).

One of the main objectives of the Phase I proposal was to investigate multiple heterojunction samples, specifically quantum wells (QWs). We have completed this section of the study, by using EBER to determine optical transition energies in AlGaAs/GaAs samples from 10Å to 100Å. We have developed software, based on the rectangular barrier model, for the analysis of these samples, and have successfully fitted the data to the theory.

1. **Rectangular Barrier Model.**

The model appears schematically in Figure 3. It shows the designations for conduction band (C), and valence band light (L) and heavy (H) hole states. We observe very similar unbound (unconfined, resonant) states as reported by earlier researchers[3]. Additional unconfined transitions are incorporated with two simple above-band gap states labelled CT and VB. Resulting transition energies are non-linear functions of the well depth, band offset parameter Q_c, and the well width, and of course the choices of effective mass values. It is known that the observed transitions are really excitonic and lie somewhat below the interband levels predicted by the theory[4]. Therefore, to minimize the discrepancies induced by the (unknown) exciton binding energies, we have minimized the energy differences between the C1H1 level and the other transitions. We also know that this method has a weakness, as the Stark effect[5] on the lowest (C1H1) level results in a lowering of that energy, but the higher transitions are shifted to higher energy.

2. **Comparison of EBER results to model.**

In spite of these arguments, we obtain very close agreement between the predicted and observed spectral features in these wells. Our results appear in Figures 4, 5, and 6. The predicted Q_c parameters agree well with those of other researchers. We find that Q_c lies between 0.57 and 0.65, within the 0.60 ± 0.05 range suggested by Glembocki et al[6]. Our estimates of well width lie generally within 10% of the nominal values. A paper describing these results have been submitted to the Journal of Electronic Materials for publication[7].

3. **Superlattice studies.**

Further, we have studied multiple, interacting QWs (superlattices) of AlGaAs/GaAs, and have found precise agreement between our studies and those of earlier researchers using photoreflectance (PR). The spectrum of a superlattice, provided kindly by Dr. Robert Sacks of United Technologies, appears in Figure 7.

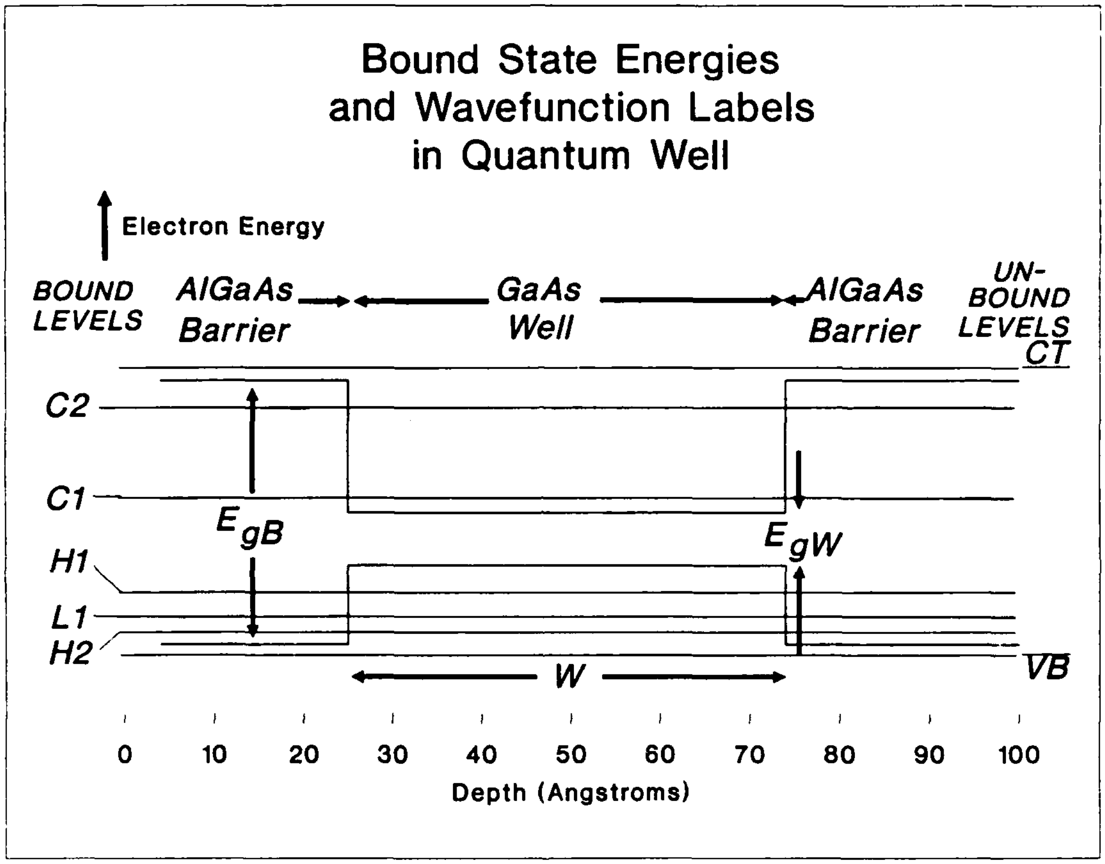


Figure 3: The QW model, based on the rectangular barrier model.

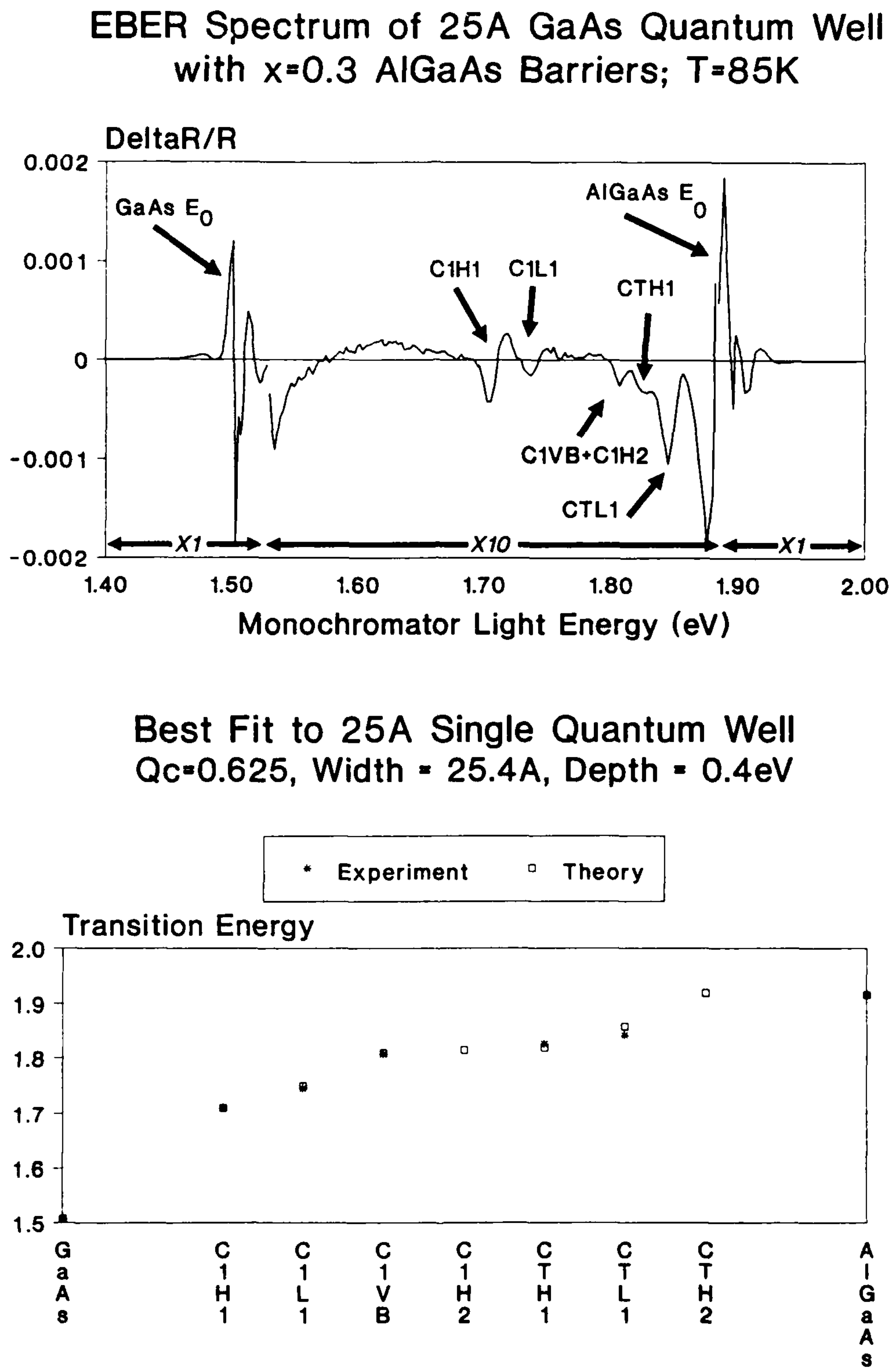
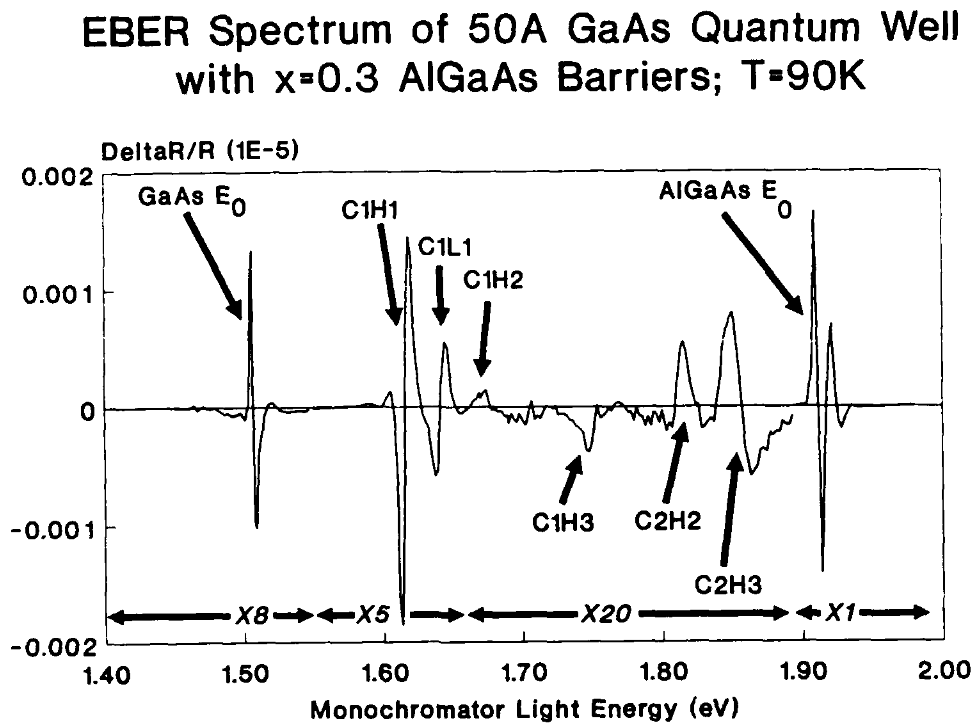


Figure 4: The EBER spectrum of a 25Å QW, with peaks identified from the model of Figure 1.



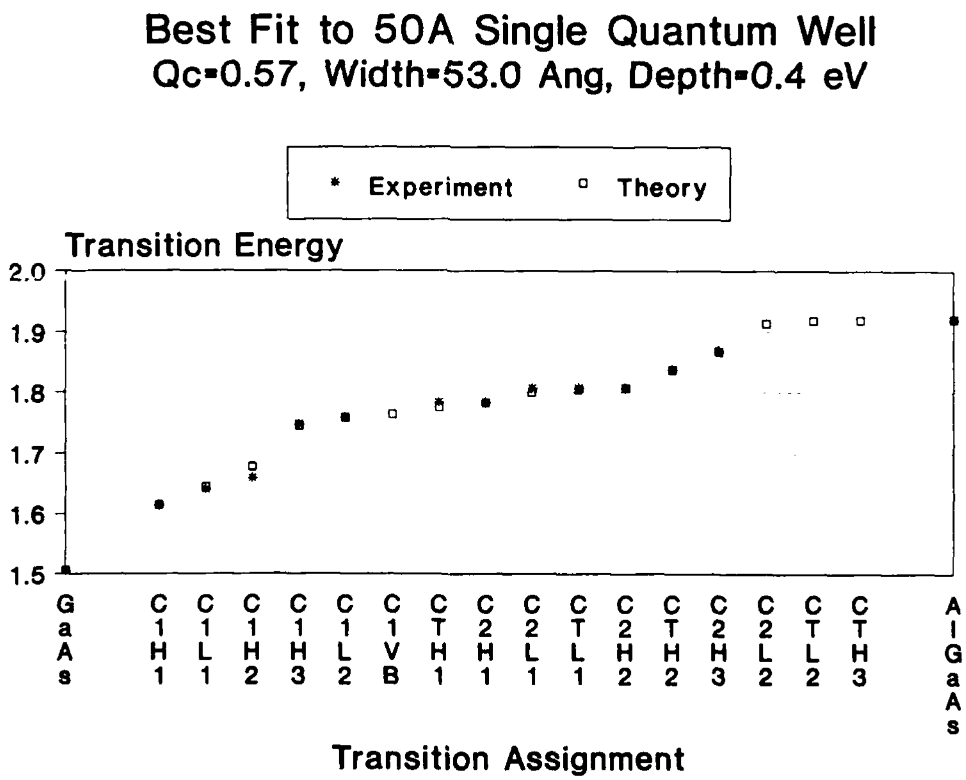


Figure 5: The EBER spectrum of a 50Å QW, with peaks identified from the model of Figure 1.

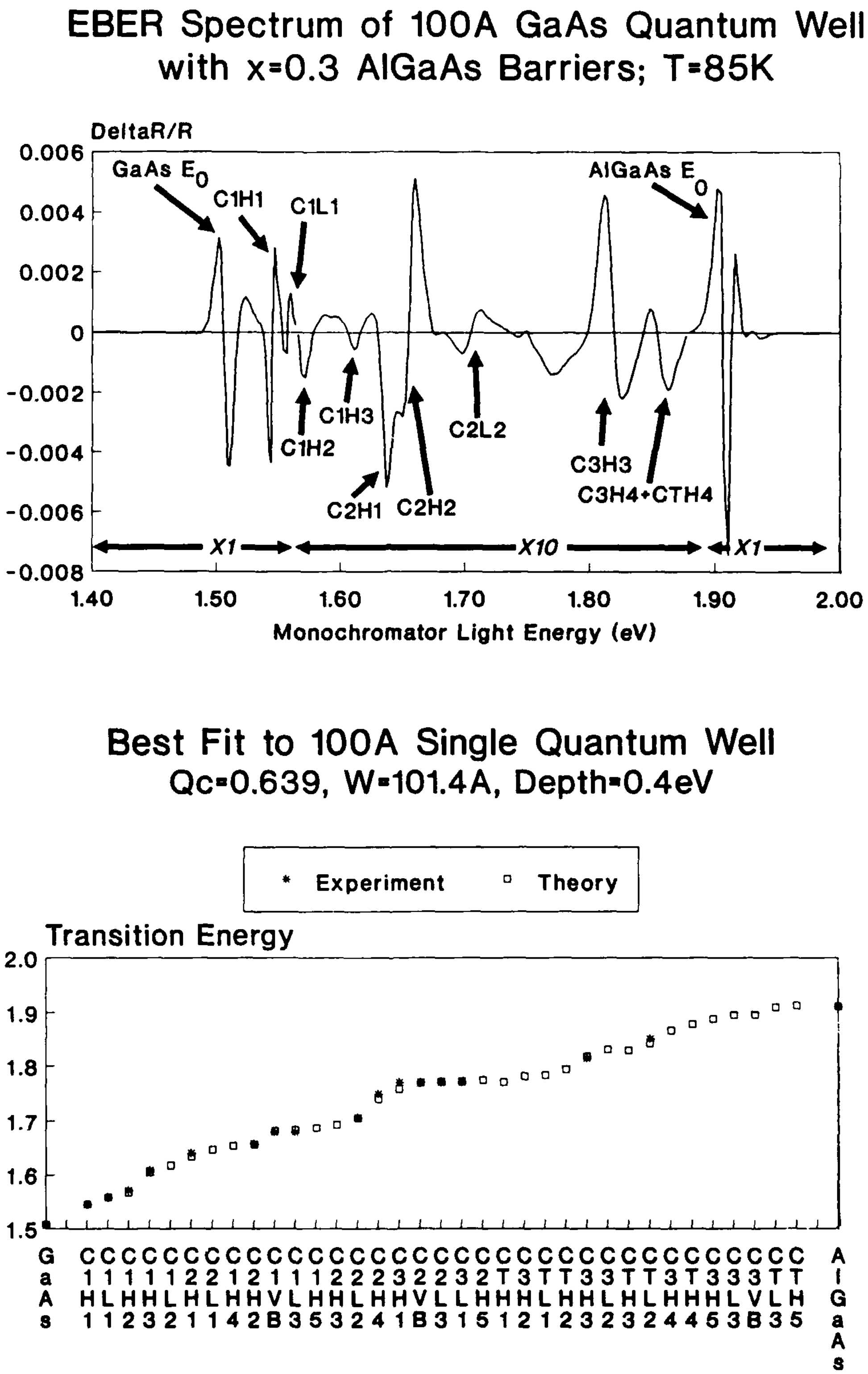


Figure 6: The EBER spectrum of a 100Å QW, with peaks identified from the model of Figure 1.

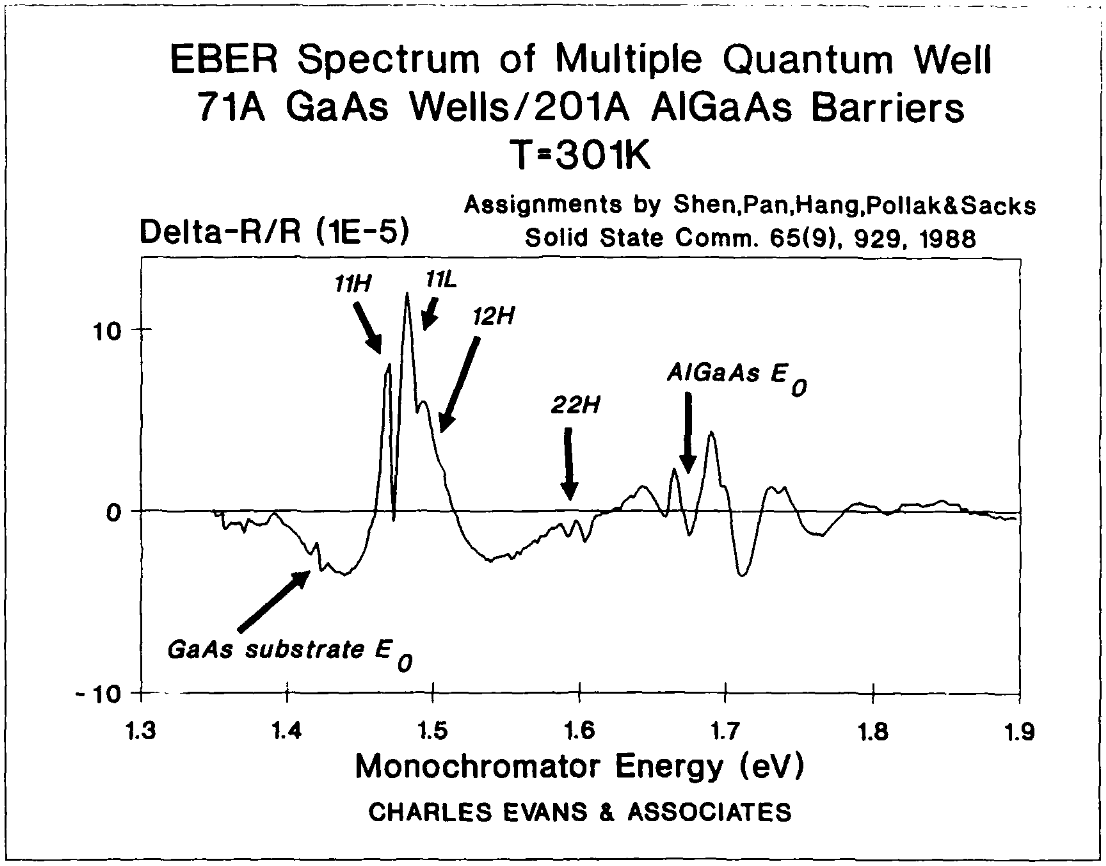


Figure 7: Superlattice of AlGaAs/GaAs (71Å Well/201Å Barrier).

C. HEMT STUDIES (ALGAAS/GAAS).

Applying our technique to the industrially important issue of HEMT qualification, we have studied "standard" AlGaAs/GaAs MODFET structures included in the Phase I plan. The energy band diagram for this structure is shown in Figure 9. Additionally, there often is used a superlattice (SL) buffer of thin AlGaAs and GaAs layers to provide better confinement of the 2DEG, and to isolate the HEMT from the substrate.

1. Signals originating from the GaAs epitaxial film.

As shown in Figure 10, the EBER spectra of these structures possess many spectral features, covering a wide energy range. Lowest in energy is a strong feature which we believe is an excitonic state associated with the substrate and epitaxial GaAs lying below the AlGaAs film. This feature is much stronger than observed from simple bulk GaAs at room temperature, but is typical of observed signals in epitaxial GaAs capped by AlGaAs films. It may be the case that some carrier confinement effects or impurity binding of excitons causes an increase in exciton Rydberg. We note that verbal discussions with researchers versed in photoluminescence (PL) indicate that large exciton signals are observed from single heterojunction interfaces, typically.

2. Signals originating from the AlGaAs film.

At about the energy expected from the Al content of the AlGaAs film, we observe large oscillatory EBER features. These features we believe to be Franz-Keldysh oscillations arising from the high electric field in the doped AlGaAs film. These oscillations can be used to estimate the magnitude of built-in electric fields in the HEMT structure. As Figure 11 shows, this analysis can be useful in the case of the HEMT.

From a search of the literature and verbal discussions with experts in ER, we understand that the band gap energy of the AlGaAs is uncertain under these conditions. Even so, we have been able to place reasonable bounds on the AlGaAs E_0 band gap energy from the spectra. Another issue which we have investigated is the effect of AlGaAs doping on the E_0 band gap -- the Burstein shift effect. We have discussed this situation with Professor P. M. Raccah of the University of Illinois at Chicago, and he has reported finding this effect in InP EER spectra. Therefore, we have composed simple software to estimate the corrected E_0 band gap in the case where the AlGaAs doping is known.

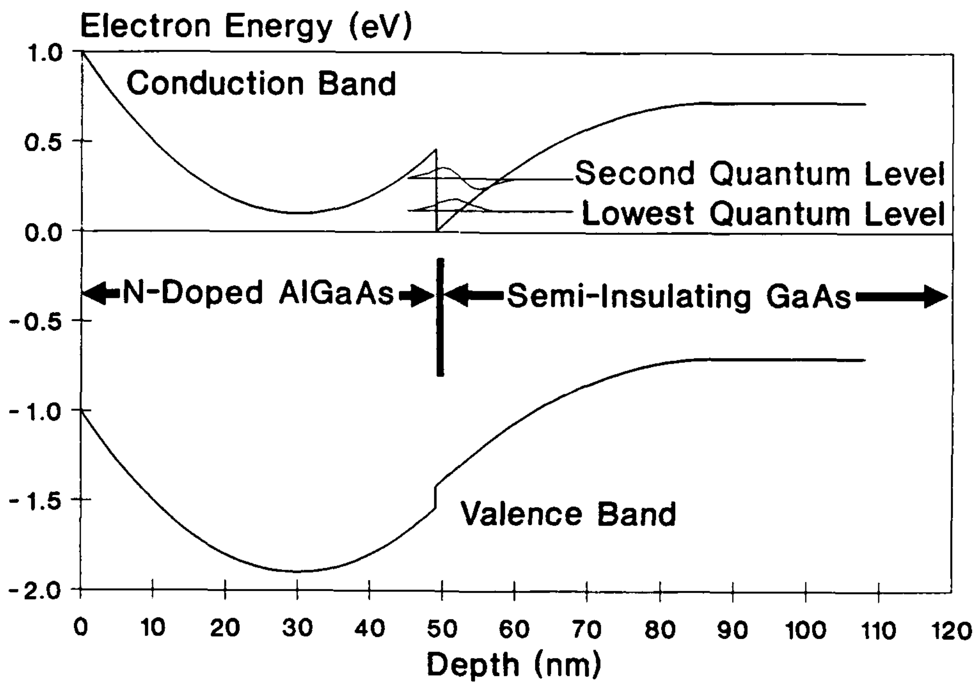


Figure 8: Energy band diagram of an AlGaAs/GaAs HEMT.

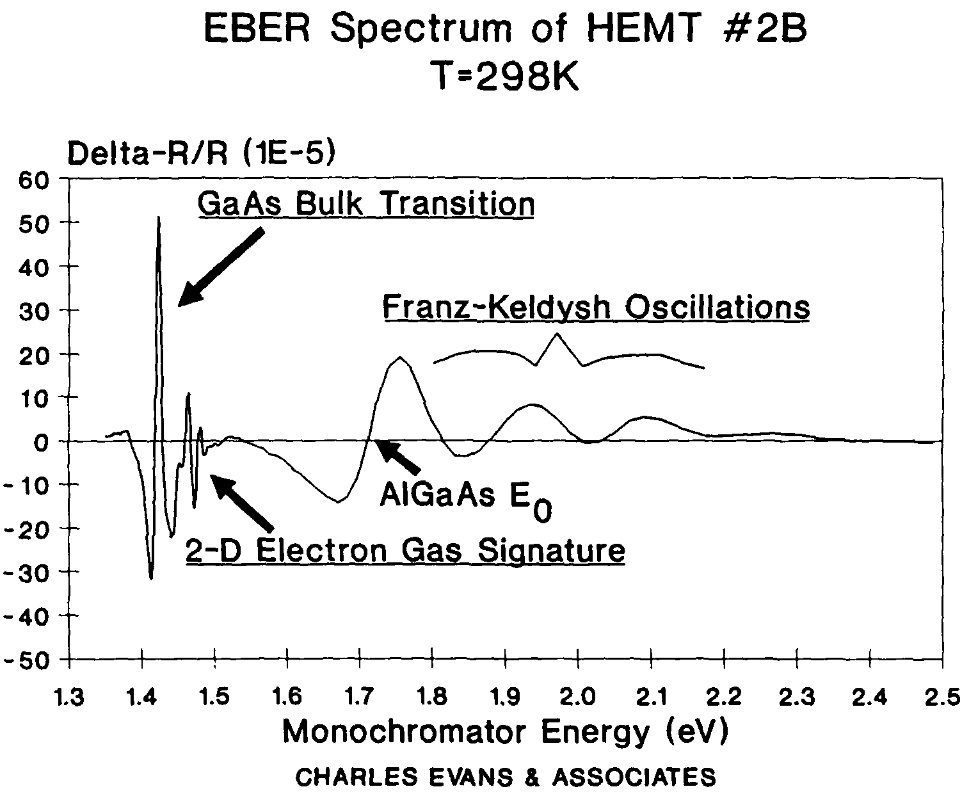


Figure 9: EBER spectrum of a typical AlGaAs/GaAs HEMT.

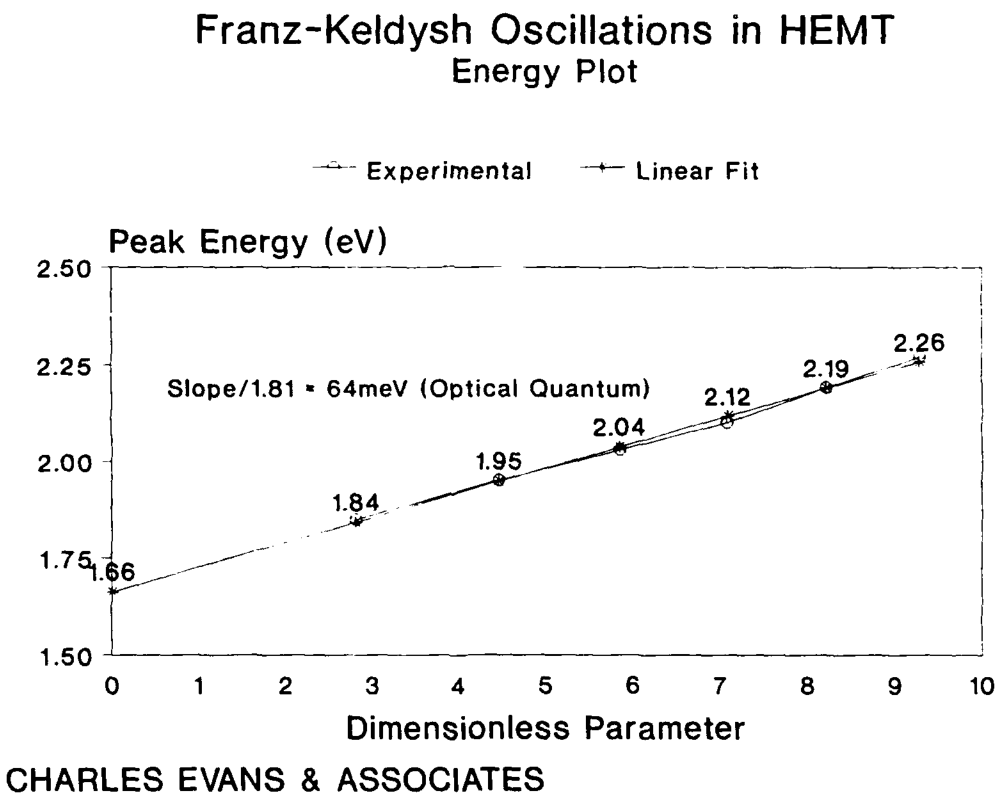


Figure 10: Franz-Keldysh oscillations observed from the EBER spectrum of an AlGaAs/GaAs HEMT.

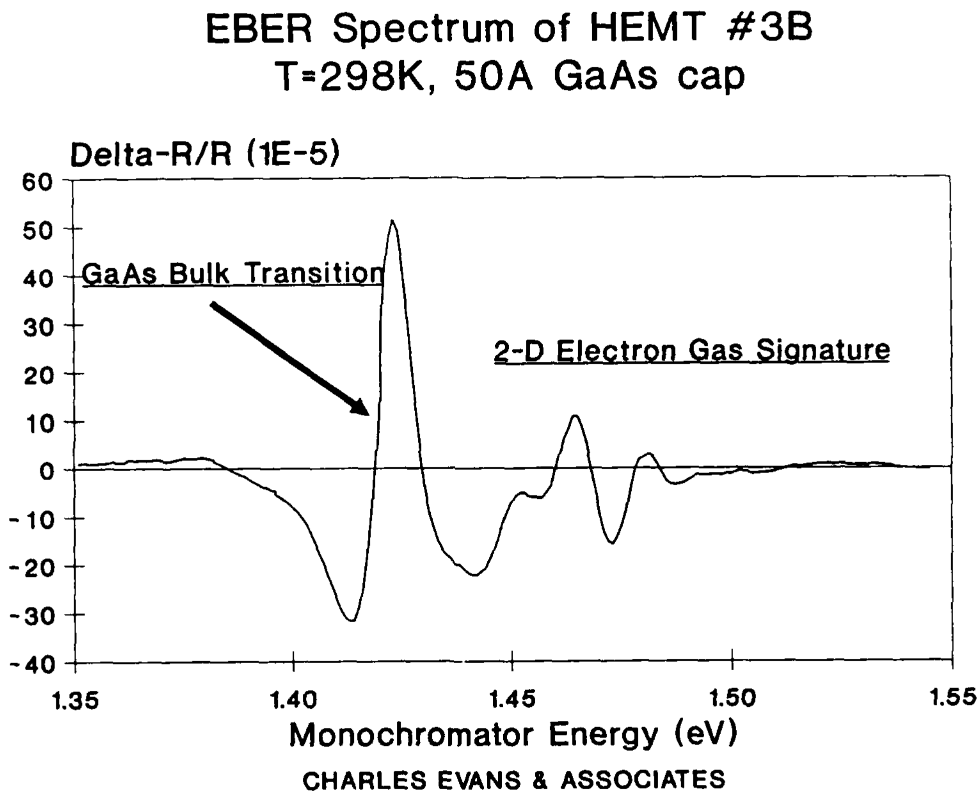


Figure 11: EBER spectra of the 2DEG signals in AlGaAs/GaAs HEMT.

3. **Signals originating from the 2DEG.**

Most importantly, between the GaAs E_0 excitonic feature and the AlGaAs E_0 and Franz-Keldysh oscillations, we find characteristic features which we attribute to transitions between the valence band Bloch states and those of the 2DEG quantized states, as suggested by Glembocki and Shanabrook in PR studies[8]. These additional features are present at all temperatures measured, from 90K to 400K, with slight changes in characteristic. We have found that these spectral features are oscillatory, but are not the typical Franz-Keldysh oscillations one may expect. We do not believe that these features arise primarily from excitonic transitions, as argued by Bottka, et al[9], due to the extremely high electric fields present at the heterojunction interface, and the fact that these oscillations appear to be very independent of temperature -- two conditions seem incommensurate with excitonic states. However, currently we have not enough experimental evidence to completely support or reject the theoretical excitonic vs. interband argument. Although we have extended the Generalized Functional Form (GFF)[10] for fitting transitions to include excitonic effects, we can generally find several theoretical models which exactly match our data. We have also quantified the changes induced by current density and sample temperature variations, and find them to be small. This is an area which will require further investigations in a Phase II study. We anticipate publishing our results on HEMTs in the next few months.

Further, we have preliminarily examined HEMT structures isolated from the substrate by AlGaAs/GaAs superlattices. From collaborations with Bell Laboratories researchers, we have found clear evidence of transitions from the superlattice (SL) buffer states. The SL is used to electrically isolate the HEMT from the substrate, to provide immunity from substrate potential fluctuations, and is very difficult to characterize by alternate methods. We have been able to detect clear differences between samples grown a different times, showing that optical analysis of these structures may provide the means for non-destructive production analysis.

V. ANCILLARY RESULTS OF PHASE I RESEARCH.

A. INVESTIGATIONS INTO THE MECHANISM OF EBER.

We have studied the mechanism of EBER to experimentally elucidate the modulation origin. From our experiments, we have determined that surface charging by electrons satisfactorily explains the observed signal $\Delta R/R$ strength dependence upon electron beam voltage and current. Our data contradicts earlier speculation that the electron beam merely excites electron-hole pairs, and therefore reproduces PR. In fact, the unipolar modulation of EBER provides both the means to increase non-contact signals, due to the square-law dependence of the signal on modulation surface electric field, and to detect the carrier type of the material.

B. DETECTION OF CARRIER TYPE WITH EBER.

As a consequence of the unipolar modulation mechanism, we have observed the phase changes in EBER signals which arise from P-type and N-type semiconductors such as GaAs and InP. We have actually demonstrated carrier type inversion in "high resistivity" GaAs crystals between 90K and 300K, as shown in Figure 13. We conclude that we can detect the carrier type of these crystals, non-destructively and non-contact, as others have shown in the past with the contact techniques of electrolyte ER (EER) and surface barrier ER (SBER). This is a capability which is impossible with the alternative non-contact technique of PR. Further, we have been able to detect a 2f modulation signal from P-type InP, which clearly elucidates the EBER mechanism as surface charging by electrons.

C. FREE AND BOUND EXCITONS OBSERVED IN GAAS.

Following observations of sub-band gap spectral features, we have probed into both free and bound excitonic transition determinations in bulk and epi films, and found evidence for impurity-to-band transitions as well. These investigations underlie the study of heterojunction structures, for we anticipate that spectral features from alternative mechanisms must be understood. Therefore, we have opened up the possibility for impurity and defect analysis using EBER. We have presented evidence of these alternate mechanisms during the March American Physical Society Meeting in St. Louis.

D. STRAINED LAYER QUANTUM WELL STUDIES (GAAS/INGAAS/GAAS).

We have extended our studies from the well-understood regime of AlGaAs/GaAs heterojunctions to the more current and difficult regime of the strained-layer system InGaAs/GaAs and InGaAs/AlGaAs. Through our research with EBER, we have successfully found energy transitions in such QW structures, and have successfully fitted the observed spectra to excitonic models. A typical spectrum appears in Figure 8. We anticipate significant future work in this area, but we require special IR detectors, gratings, and order-sorting filters for our system to extend operation to 0.7eV. In the theoretical area, we still require research to model the strained layer system so that the energy levels may be determined from physical parameters such as the strain, the well thickness, the In content, and the band offset parameter. We are presently collaborating with Professor B. Streetman and Dr. A. Dodabalapur at the University of Texas at Austin in the application of EBER to pseudomorphic HEMTs[11].

E. BIBLIOGRAPHY.

Lastly, we have continued to build a complete annotated bibliography of ER and related papers, for a comprehensive reference in the field. To date, we have over 200 technical papers which have been reviewed.

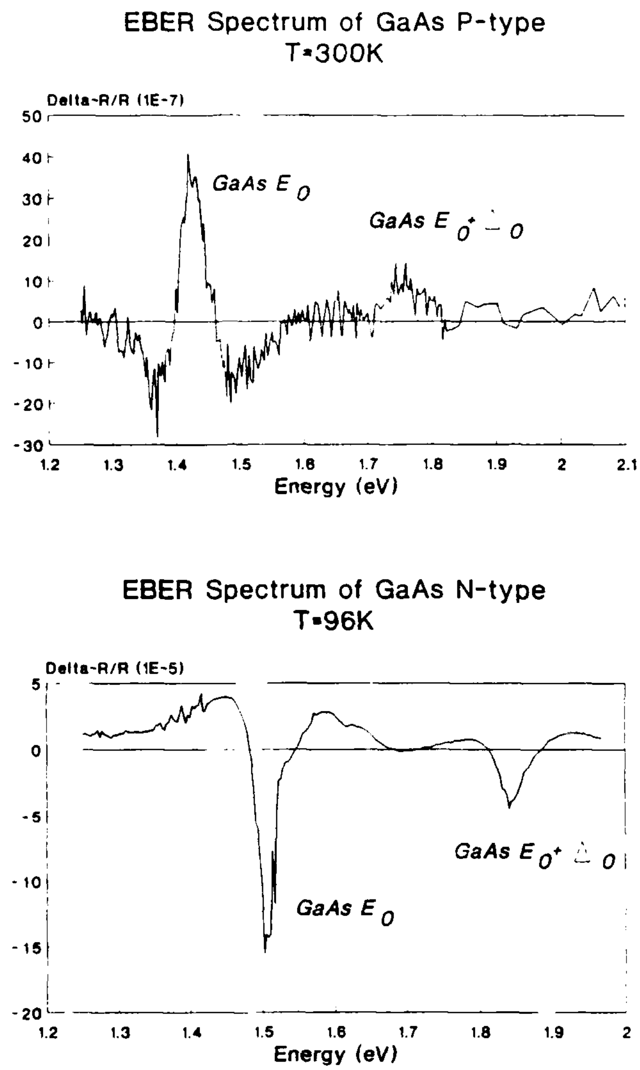


Figure 12: EBER spectra of GaAs at 300K and 90K. Note the phase inversion of the signal, which arises from change in carrier type, from P-type at 300K to N-type at 90K.

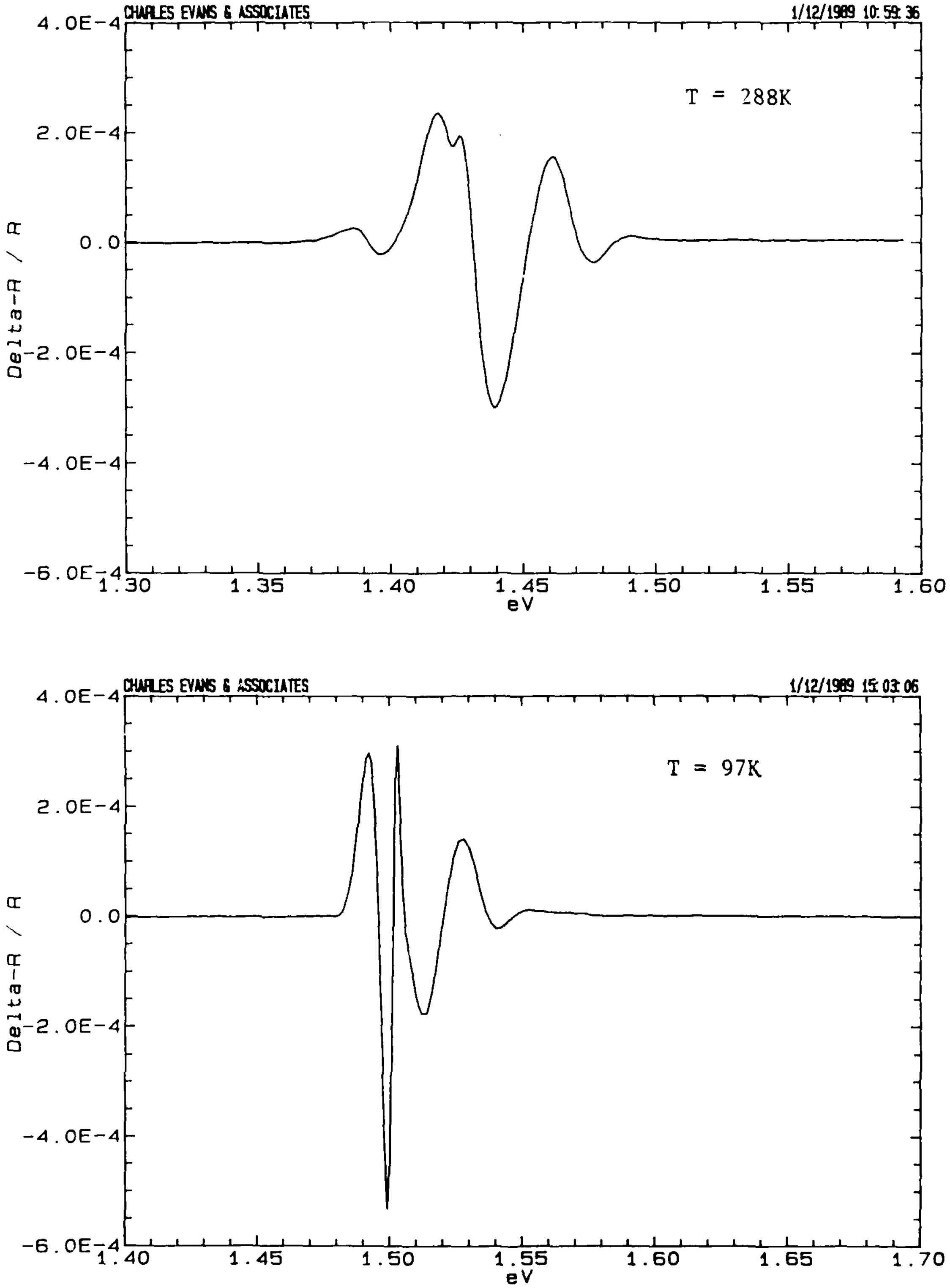
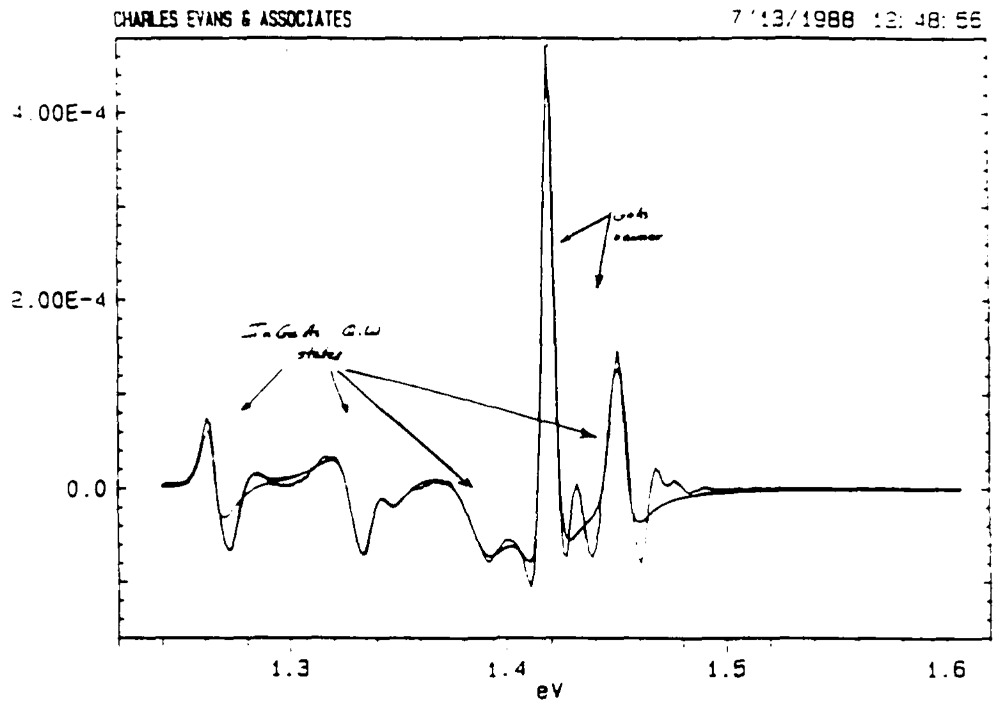


Figure 13. 300K and 90K EBER data from an MBE grown GaAs film, with very low Si doping. We observe a noticeable peak in the 300K data which is clearly increased in magnitude at 90K. This peak is attributed to excitonic interactions.



Id: QW008-162, InGaAs QW, Temp: 301.0 K, 2.190 uA
qw080001 880701.1157 FIT 1

BACKGROUND

B0	B1	B2
3.667E-7 0.638E-7	0.0	0.0

7 LINESHAPES

	Energy	Gamma	Theta	A1	A2	A3	A5	A7
A	1.2635 0.0010	5.9 1.0	4.020 0.431	-4.762E-9 2.137E-9	0.0	0.0	0.0	0.0
B	1.2728 0.0021	13.5 2.1	0.126 0.678	-3.132E-9 4.334E-9	0.0	-1.335E-12 1.045E-12	0.0	0.0
C	1.3317 0.0012	10.7 1.1	2.607 0.240	2.121E-8 5.091E-9	0.0	0.0	0.0	0.0
D	1.3449 0.0033	9.8 3.4	1.784 0.797	6.002E-9 4.054E-9	0.0	0.0	0.0	0.0
E	1.3806 0.0017	18.2 1.7	2.681 0.166	3.895E-8 6.617E-9	0.0	0.0	0.0	0.0
F	1.4190 0.0001	5.0 0.1	3.047 0.035	-2.450E-8 8.653E-10	0.0	0.0	0.0	0.0
G	1.4512 0.0003	6.6 0.3	3.449 0.091	-1.360E-8 1.234E-9	0.0	0.0	0.0	0.0

Figure 14: EBER spectrum of strained layer InGaAs/GaAs quantum well.

VI. PLANS.

A. IMPROVEMENTS IN INSTRUMENTATION AND METHODOLOGY.

From discussions with our collaborators, we anticipate that significant work is required further into the infrared region, which we are currently unequipped to perform. To remedy this situation, we have studied the requirements of new detectors (InGaAs) and monochromator gratings (600 l/mm), with accompanying software changes to facilitate this modification. We anticipate that work in the near-IR (from 0.6 eV to 2 eV) will enable studies of InGaAs films to achieve near IR band gaps required in telecommunications research, Ge/Si superlattices which hold promise of direct-band gap transitions induced by strain, and of EL2 mapping (at 0.74eV in GaAs).

B. IMPROVEMENTS IN SOFTWARE AND MODELS.

We already feel that, in addition to experimental support, certain theoretical modeling efforts must also be undertaken. From the work on superlattices which has been published, we believe that the Bastard envelope-approximation method must be developed in-house. This would provide us with the ability to identify and predict the optical transitions in the superlattices of HEMTs. We are also working to make models of HEMTs for prediction of optical transitions, similarly to those initially done by researchers at the Naval Research Laboratories[12].

C. COLLABORATIONS.

During the Phase I research, we have collaborated with many researchers on evaluation of GaAs and heterojunction samples using EBER. Researchers at Aerospace, Hughes, Varian, Xerox, Hewlett-Packard, AT&T Bell Labs, Stanford University, United Technologies, Spectrum Technology, Intel, ICI, and AMOCO, among others, have submitted samples for analysis. We anticipate joint research with many of these organizations in the future.

VII. CONCLUSION.

We believe that each of the initial goals of the Phase I proposal have been clearly achieved, demonstrating not only the feasibility but also the wide utility of EBER studies of heterostructures. We have observed spectral features which indicate 2D electron gas at the heterojunction interface of AlGaAs/GaAs HEMT samples. Using the EBER, we have successfully studied the AlGaAs signals for estimates of composition over the full range of Al content. We also have calculated the magnitude of built-in electric fields in the AlGaAs layers of HEMTs, using the Franz-Keldysh oscillations present in the EBER spectra. We have determined the existence and the energy levels of underlying superlattice buffer layers, used in the isolation of HEMT structures.

In the case of quantum well samples, we have achieved satisfactory agreement with simple theoretical models. We have measured single quantum wells of the range 25 to 100Å. We observed both allowed and forbidden transitions, and we also find evidence for unconfined states. Our estimates of the conduction band offset parameter are in close agreement with those of earlier researchers.

Following observations of sub-band gap spectral features, we have examined both free and bound excitonic transitions in bulk and epi films, and found evidence for impurity-to-band transitions as well. These investigations underlie the study of heterojunction structures, for we anticipate that spectral features from alternative mechanisms must be understood. Therefore, we have opened up the possibility for impurity and defect analysis using EBER.

In the realm of multiple heterojunction studies, specifically those of quantum well (QW) samples, we have used EBER to determine optical transition energies in AlGaAs/GaAs samples from 10Å to 100Å. We have developed software, based on the rectangular barrier model, for the analysis of these samples, and have successfully fitted the data to the theory. Further, we have studied multiple, interacting QWs (superlattices) of AlGaAs/GaAs, and have found precise agreement between our studies and those of earlier researchers using photoreflectance (PR).

We have extended our studies from the well-understood regime of AlGaAs/GaAs heterojunctions to the more current and difficult regime of the strained-layer system InGaAs/GaAs and InGaAs/AlGaAs. Through our research with EBER, we have successfully found energy transitions in such QW structures, and have successfully fitted the observed spectra to excitonic models. We anticipate significant future work in this area, as many of the fundamental physical parameters of this system have yet to be determined.

Applying our technique to the industrially important issue of HEMT qualification, we have studied both "standard" AlGaAs/GaAs MODFET structures as well as the strained layer AlGaAs/InGaAs/GaAs structure. We find characteristic features above the GaAs band gap, which we attribute to transitions between the valence band Bloch states and those of the 2DEG quantized states, as suggested by Glembocki *et al* in PR studies. For the strained layer systems, we find additional features below the GaAs band gap which we attribute to absorption from the Stark-shifted energy levels of the InGaAs QW.

Importantly, from collaborations with corporate researchers at Bell Laboratories, we have found clear evidence of transitions from the superlattice (SL) buffer states. The SL is used to electrically isolate the HEMT from the substrate, to provide immunity from substrate potential fluctuations, and is very difficult to characterize by alternate methods. We have been able to detect clear differences between samples grown a different times, showing that optical analysis of these structures may provide the means for non-destructive production analysis.

We have studied the mechanism of EBER to experimentally elucidate the modulation origin. From our experiments, we have determined that surface charging by electrons satisfactorily explains the observed signal $\Delta R/R$ strength dependence upon Electron beam voltage and current. Our data contradicts earlier speculation that the electron beam merely excites electron-hole pairs, and therefore reproduces PR. In fact, the unipolar modulation of EBER provides both the means to increase non-contact signals, due to the square-law dependence of the signal on modulation surface electric field, and to detect the carrier type of the material.

To this end, we have studied the phase changes in EBER signals which arise from P-type and N-type semiconductors such as GaAs and InP. We are, in fact, able to detect carrier type inversion in "high resistivity" GaAs crystals between 90K and 300K. We conclude that we can detect the carrier type of these crystals, non-destructively and non-contact, as others have shown in the past with have the contact techniques of electrolyte ER (EER) and surface barrier ER (SBER). This is a capability which is impossible with the alternative non-contact technique of PR. Further, we have been able to detect a 2f modulation signal from P-type InP, which clearly elucidates the EBER mechanism as surface charging by electrons.

We have collaborated with many other researchers on evaluation of GaAs and heterojunction samples using EBER. Researchers at Aerospace, Varian, Xerox, Hewlett-Packard, AT&T Bell Labs, Stanford University, United Technologies, Spectrum Technology, Intel, ICI, and AMOCO, among others, have submitted samples for analysis.

In response to the needs for rapid analysis of samples, we have redesigned the EBER sample holders to significantly improve throughput. We have eliminated the silver paint originally used, as it proved an unreliable mechanical mounting in UHV, and after repeated thermal cycles often failed. We have instead chosen to hold samples to the same Cu holder using a Cu-Be spring clip. For studies requiring enhance thermal contact, we have additionally used a Cu-Be gasket to hold the samples to the mounting.

Finally, we anticipate that significant work is required further into the infrared region, which we are currently unequipped to perform. To remedy this situation, we have studied the requirements of new detectors (InGaAs) and monochromator gratings (600 l/mm), with accompanying software changes to facilitate this modification. We anticipate study of Ge/Si superlattices, and InGaAs films to achieve near IR band gaps required in telecommunications research.

REFERENCES

1. S. Adachi, "GaAs, AlAs, and $Al_xGa_{1-x}As$: Material parameters for use in research and device applications," J. Appl. Phys. 1985, reprinted in Gallium Arsenide: Key papers in physics; no.1, J. S. Blakemore, ed., p62, American Institute of Physics, 1987. Adachi reviews the work of many researchers, and cites the study by H. C. Casey and M. B. Panish, Heterostructure Lasers (Academic, New York, 1978), Part A.

2. T. F. Kuech, D. J. Wolford, R. Potemski, J. A. Bradley, K. H. Kelleher, D. Yan, J. Paul Farrell, P. M. S. Lesser & F. H. Pollak, "Dependence of the $Al_xGa_{1-x}As$ band edge on alloy composition based on the absolute measurement of x," Appl. Phys. Lett. 51(7), 505-507, 1987.

3. U. K. Reddy, G. Ji, T. Henderson, H. Morkoc & J. N. Schulman, "Investigation of GaAs/(Al,Ga)As multiple quantum wells by photoreflectance," J. Appl. Phys. 62(1), pp145-151, 1987.

4. X. L. Zheng, D. Heiman, B. Lax, F. A. Chambers & K. A. Stair, "Evidence of room-temperature exciton by magnetophotoreflectance in epitaxial GaAs and quantum well structures," Appl. Phys. Lett. 52(12) 984-986, 1988. Proves that PR peaks are excitonic by their Magnetic field dependence. Also see D. C. Reynolds, K. K. Bajaj. C. W. Litton, P. W. Yu, W. T. Masselink, R. Fischer & H. Morkoc, "Sharp-line photoluminescence spectra from GaAs-GaAlAs multiple quantum well structures," Phys. Rev. B29(12) 7038-7041, 1984. x=0.25, MQW of 100, 200, 300, 400Å studied. See excitonic transitions vs. magnetic field changes of 1meV at about 50kGauss (or 0.1meV at 5kGauss), using PL.

5. W. Potz & D. K. Ferry, "Non-rectangular quantum wells as a basis for studying the band offsets at GaAs-AlxGa1-xAs interfaces," Phys. Rev. B32(6) 3863-3867, 1985. Finds that the wells are best approximated by triangular-shaped wells may better fit experimental data.

6. O. J. Glembocki, B. V. Shanabrook, N. Bottka, W. T. Beard, and J. Comas, "Photoreflectance characterization of interband transitions in GaAs/AlGaAs multiple quantum wells and modulation-doped heterojunctions," Appl. Phys. Lett. 46(10), 15 May 1985, 970-2.

7. M. H. Herman, S. E. Buttrill, Jr. and G. L. Francke and F. A. Chambers, "Electron Beam Electroreflectance (EBER) Analysis of Single $Al_xGa_{1-x}As$/GaAs Quantum Wells" submitted to the Journal of Electronic Materials.

8. O. J. Glembocki, B. V. Shanabrook, N. Bottka, W. T. Beard, and J. Comas, "Photoreflectance characterization of interband transitions in GaAs/AlGaAs multiple quantum wells and modulation-doped heterojunctions," Appl. Phys. Lett. 46(10), 15 May 1985, 970-2.

9. Bottka, N., D. K. Gaskill, R. S. Sillmon, R. Henry, and R. Glosser, "Modulation Spectroscopy as a Tool for Electronic Material Characterization," J. Electr. Mater. 17(2), 161-170, 1988.

10. The GFF is described in J. W. Garland & P. M. Raccah, SPIE 659 Materials Technologies for IR Detectors (1986). pp. 32-43.

11. A. Dodabalapur, V. P. Kesan, D. P. Neikirk, B. Streetman, M. H. Herman & I. D. Ward, "Photoluminescence and Electroreflectance Characterization of Modulation-Doped Quantum Wells." to be presented at the Electronic Materials Conference to be held in Cambridge, MA during June 21-23, 1989.

12. E. S. Snow, O. J. Glembocki & B. V. Shanabrook, "Optical absorption profile of a single modulation-doped AlGaAs-GaAs heterojunction," Phys. Rev. **B38**(17), 12483, 1988.

METHODS TO EVALUATE OPTICAL TRANSITIONS IN SOLIDS

Category	Luminescence	Transmission/ Absorption & Mod. Absorption	Reflectance & Mod. Reflectance
Special Realizations	Photo-L.(P.L.) Cathodo-L. Thermo-L. P.L.Excitation (PLE)	Electro-Abs. Piezo-Abs. Thermo-Abs.	PiezoR (PzR) ThermoR (TR) ElectroR (ER): ElectrolyteER (EER) Surface Barrier ER (SBER) TransverseER (TER) Electron Beam ER (EBER,CathodoR) Magneto - ER, Etc. PhotoR (PR) Magneto-PR,
General Character-istics	Shows lowest electronic states only PLE shows higher states also.	Shows all states - broad features in Absorption, sharp in modulated Absorption.	Shows all states - broad features in Reflectance, sharp in modulated Reflectance.
Experimental Temperature Required:	Requires Low Temp (6K) for best results	Any Temp.	Any Temp
Level of Understanding:	Large wealth of applied experience and theory	Large experience simple theory	Large theory well developed, but not simple
Capabilities:	Radiative transitions only, (except PLE). Does not show indirect gap transitions	All radiative & Nonradiative transitions: Shows All transitions	All radiative & Nonradiative transitions: Shows All Transitions
Effects on sample:	Nondestructive	Destructive	Nondestructive
Probed depth:	Variable by choice of excitation wavelength.	Entire sample thickness is probed.	Depth probed depends upon wavelength and absorption properties of sample.

METHODS TO EVALUATE OPTICAL TRANSITIONS IN SOLIDS

Comparison EER to PR to EBER	Electrolyte ER EER	Photo R	Electron Beam ER
Modulation mechanism:	Modulation of Surface Electric field $\propto V_A^2$ in either +V or -V direction (Unipolar)	(Non polar) Annihilation of built-in surface Electric Field, using e^-hole generation (essentially photoconductivity and photocurrent)	Unipolar modulation of surface potential, by adding electrons to surface, (even though e^- hole pairs are also generated)
Experimental Inadequacies/ Problems	Electrolyte can: Etch sample, Contaminate surface, Freeze/boil (T limits)	Scattered laser light looks like sample signal. Non-polar modulation cannot tell carrier type. Weak built-in fields give weak PR signals. Probe beam DC weakens built-in field. Requires surface states recharge each cycle-poorer at low temps.	Cathodo-luminescense modulation frequency looks like sample signal
Strengths/ Advantages	Inexpensive to set up. Know Electric Field! So can get doping, etc. m+ from FK osc.	Appears to be inexpensive to set up in lab - HeNe laser + chopper. Could be done in UHV without any difference.	Excellent S/N! UHV environment. Unipolar modulation can give carrier type.
Remarks	Typically, very noisy spectra. Problem w/ sample etching by . Electrolyte	Very weak signals- in general ~10-100x smaller than EBER	Very strong signals in general. Success in cases where PR and PzR failed.