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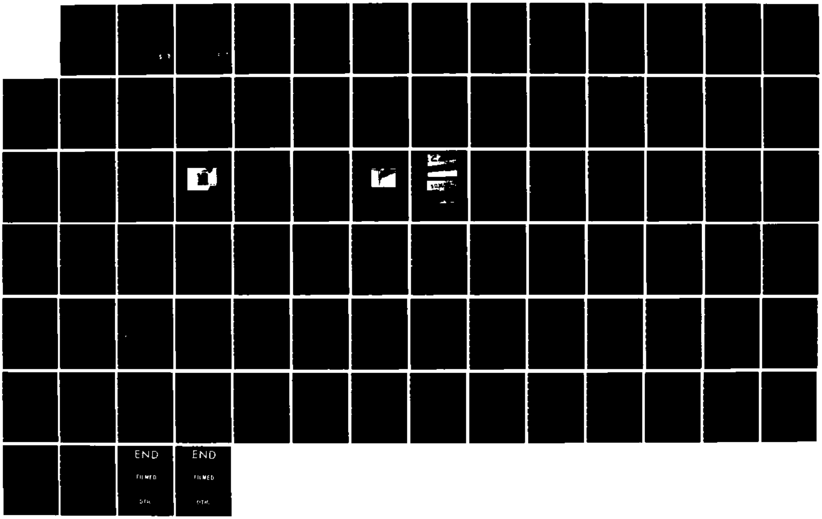

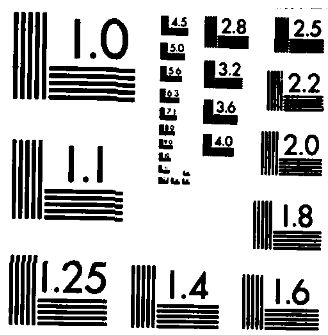

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THREE YEAR FINAL REPORT

MICROWAVE SEMICONDUCTOR RESEARCH -
MATERIALS, DEVICES AND CIRCUITS
AND
GALLIUM ARSENIDE BALLISTIC ELECTRON TRANSISTORS

May 1, 1981 - April 30, 1984
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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

A154 698

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY: Unclassified	3. DISTRIBUTION/AVAILABILITY OF REPORT: Unclassified/Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Cornell University School of Elec. Engin. — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code): Ithaca, NY 14853	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Office of Scientific Research — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F49620-81-C-0082
8c. ADDRESS (City, State and ZIP Code): Building 410, Bolling Air Force Base Washington, DC 20332	10. SOURCE OF FUNDING NOS.

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

11. TITLE (Include Security Classification) MICROWAVE SEMICONDUCTOR RESEARCH - MATERIALS, DEVICES AND CIRCUITS

12. PERSONAL AUTHOR(S) L.F. Eastman, D.W. Woodard, G.W. Wicks, J. Ballantyne, C.L. Tang, H.J. Carlin, W.H. Ku, G.J. Wolga

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
3 Year Final Report	FROM 5/1/81 TO 4/30/84	April 1985	78

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	

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

This program covers the growth and assessment of Gallium Arsenide, and related compounds and alloys, for use in microwave, millimeter, and optical devices. It also covers the processing of the material into devices, and the testing of the devices. Both molecular beam epitaxy (MBE) and organo-metallic vapor phase epitaxy (OMVPE) are used for growth. Materials assessment is included. Short modulation doped heterojunction transistors, as well as ballistic electron vertical FETs and heterojunction bipolar transistors, are covered. The following is a list of tasks pursued:

Task 1 Growth and characterization of GaAs for high performance microwave devices.

Task 2 Investigation of microwave field-effect transistor performance limits set by layer composition and contact geometry.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
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DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

Task 3 Use of MBE tailored profiles for GaAs power FET's for improved performance,

Task 4 MBE multiple GaAs-$Al_xGa_{(1-x)}As$ heterojunctions for confinement of electrons for improved FET performance,

Task 5 High speed receivers for optical communications,

Task 6 Dynamic and spectral characteristics of semiconductor laser materials and structures,

Task 7 Carrier dynamics in compound semiconductors studied with picosecond optical excitation,

Task 8 Advanced design techniques for microwave GaAs FET amplifiers,

Task 9 Wide band circuits and systems, and

Task 10 (Ballistic task) Gallium arsenide ballistic electron transistors.

WORK STATEMENT

TASK 1	Grow and characterize GaAs for high performance microwave devices.
TASK 2	Determine the effect of design and processing on GaAs power FET performance limitations.
TASK 3	Use MBE tailored profiles for improved GaAs power FET performance.
TASK 4	Investigate MBE multiple GaAs $Al_xGa_{1-x}As$ heterojunctions for confinement of electrons.
TASK 5	Develop high speed receivers for optical communication using optical field effect transistors and large area epitaxial photoconductive detectors.
TASK 6	Model and construct components and subsystems which can be useful as transmitters in optical communication systems.
TASK 7	Develop advanced design techniques for microwave GaAs FET amplifiers.
TASK 8	Improve direct method of broad band circuit design.
TASK 9	Use optical excitation to study carrier dynamics in compound semiconductors.
TASK 10	Study ballistic electron effects in transistors for high frequency operation.

JSEP

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TASK 1 GROWTH AND CHARACTERIZATION OF GaAs FOR HIGH PERFORMANCE MICROWAVE DEVICES

L.F. Eastman and D.W. Woodard

OBJECTIVE

The overall program objective is to develop an improved understanding of the role of the substrate and the growth parameters on the quality of device structures on GaAs and related materials grown by Organometallic Vapor Phase Epitaxy (OMVPE).

APPROACH

The approach to improve device quality materials grown by OMVPE centers around a fast feedback loop from data obtained from various characterization techniques and the actual growth parameters used during the deposition of epitaxial films. During this investigation an optimized process for various device structures of interest will be obtained using characterization data from low temperature photoluminescence (PL), deep level transient spectroscopy (DLTS), Hall and CV measurements, and other appropriate techniques. For example, a detailed understanding of the effects of the growth parameters on the optical and electronic properties of a GaAs/AlGaAs heterostructure will result in improved performance of some of the electron devices fabricated in other tasks in the JSEP program.

PROGRESS

During the first year of this reporting period, the technique of conductance DLTS was automated and made more sensitive. Sophisticated analysis routines (modified Boxcar, Fast Fourier Transform and Method of Moments), were developed and applied to the DLTS data in order to identify deep levels in GaAs MESFETs. Many levels found have never been reported. Conductance DLTS theory was developed to enable the calculation of trap densities thus obtaining trap density profiles in the active region of the FETs. The conductance DLTS experiment was also extended to temperatures as low as $15^{O}K$ to observe traps with smaller activation energies than previously possible. Electron traps and hole traps with energies less than 50 meV were observed for the first time in GaAs. Some of these levels can possibly be identified by comparison of the DLTS and photoluminescence data.

MESFETs fabricated from ion-implanted, MBE, VPE and LPE material were analyzed by obtaining trap profiles to enable determination of the effects of deep levels present on the device's performance. Looping, dc drift and light sensitivity of the I-V characteristics were correlated with large densities of deep levels located at the surface and at the active region - buffer layer (or substrate) interface. Trap populations were shown to be deleterious to power applications of the devices by causing premature breakdown through impact ionization processes. It was seen that buffer layers, while decreasing the density of traps coming from the substrate, were not sufficiently opaque to eliminate them. By knowing the locations and energies of the traps in the channel, the contribution of specific deep levels to microwave performance has been calculated. Traps with energies between .07 and .2 eV contribute to the minimum excess noise figure between 1 and 80 GHz. Deeper traps, depending on their emission rates, can affect the performance of the devices down to the dc characteristics.

Electron and hole traps introduced as a result of Si_3N_4 surface passivation have been identified and profiled. Nitride capping and annealing of ion implanted material was found to introduce various low energy surface traps. The effects of these traps on microwave performance were calculated.

By the start of the second year of this reporting period Cornell had successfully designed and constructed a variable pressure OMVPE reactor for the growth of epitaxial III-V compound semiconductors. Since then the research effort at Cornell has centered around the OMVPE growth and characterization of GaAs, AlGaAs and their heterostructures, and recently, also InP and GaInP.

This effort has led to the obtainment of high purity n-type GaAs (μ_n at 77 K in excess of 93,000 cm^2/v-s) an optimized As/Ga ratio of 72 and a substrate temperature of 650^{o}C. In addition, the effects of in-situ substrate etching and arsine cracking on high purity GaAs were determined during this study. Low temperature photoluminescence data showing fine exciton structure at GaAs's band edge has been correlated with the growth parameters including substrate temperature and the As/Ga ratio. In addition, DLTS measurements indicate the dominant residual deep center, the electron trap EL2, decreases with lower As/Ga ratios. The traps concentration has been reduced to less than $10^{13}cm^{-3}$ at As/Ga ratios less than 30. Finally, the behavior of the electron mobility, the carrier concentration and the photoluminescence efficiency for undoped GaAs films with the primary growth parameters has been determined. For example, under suitable growth conditions, thick (around 10 microns) semi-insulation GaAs layers may be reproducably obtained and incorporated buffer layers on semi-insulating substrates for a variety of device structures.

The results obtained early in this program have continually improved as the sources purity has been refined. For example, with recently acquired trimethylgallium (TMG) we have optimized the GaAs undoped films at a lower As/Ga ratio (about 50) with LN_2 mobilities of 130,000 cm^2/v-s. It is believed that the improved TMG source has resulted in lower residual acceptor incorporation which receives a lower As/Ga ratio for the growth of optimized high purity n-type films.

The growth of AlGaAs films has been investigated over the full range of alloy compositions with several As/(Ga+Al) ratios and over a temperature range from 550-800^oC. It was observed that the optical properties of these films were severely degraded due to the incorporation of oxygen from the growth ambient. In an effort to reduce oxygen contamination, a new oxygen gettering scheme was applied to the arsine gas, the suspected source of the contamination. The radiative yield of the $Al_{0.25}Ga_{0.75}As$ was improved by a factor of 5 as a result of the removal of moisture from the arsine gas. The use of this oxygen gettering system has resulted in narrow linewidths (less than 5 meV) in low temperature photoluminescence spectra of $Al_{.26}Ga_{.24}As$ film grown at relatively low temperatures (around 700^oC). These linewidths have been compared with theoretical predictions by Schubert et al. ("Alloy broadening in photoluminescence spectra of $Al_xGa_{1-x}As$", Physical Review B, Vol. 30, No. 2, p. 813, July 1984) and found to be in excellent agreement over the entire range of compositions corresponding to direct bandgap alloys. These calculated linewidths consider broadening from random Ga and Al distributions on the group III sublattice while no impurity related broadening effects are considered. Hence, even when ultra high purity films of AlGaAs are obtained, linewidths of low temperature PL will not be improved over the films presently grown.

The residual shallow impurities in AlGaAs films are at least two orders of magnitude greater than that of GaAs. It appears that the aluminum source, trimethyaluminum, needs further improvements in its purification to improve the AlGaAs quality. Improvement in the purity of OMVPE grown AlGaAs will have a direct impact on device structures incorporating AlGaAs semi-insulating buffers and selectively doped heterojunctions.

The heterojunction abruptness in GaAs/AlGaAs structures is critical to several device applications including modulation doped FET's and quantum well lasers. A series of layers have been grown over a broad range of substrate temperature incorporating quantum well heterostructures as thin as 40 Å. It was observed that narrow quantum wells did not yield photoluminescence at the higher growth temperatures, apparently due to a substantial graded interface region between the GaAs and AlGaAs layers. Attempts to improve the heterojunction interface abruptness by stopping the growth at the heterojunction interface are currently underway.

The GaAs and AlGaAs films have been doped n-type using both hydrogen selenide and silane dopant sources, and p-type with the dopant source diethylzinc. It was observed that the selenium doping produces the longest minority carrier diffusion lengths as opposed to the silicon doping with silane. In addition, lower compensation has been obtained with selenium doping. The dopant memory effect commonly observed with the hydrogen selenide source was avoided by baking the reactor plumbing and reactor cell between growth experiments.

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or AlGaAs buffer.

Two new features have been incorporated into modulation doped structures. The spacer layer between the doped AlGaAs and the two dimensional electron gas, which has traditionally consisted of undoped AlGaAs, has been made of undoped AlAs. This has produced a structure which is more stable to annealing, and also allowed higher mobilities with narrow spacers and high electron concentrations. Secondly, atomic plane doping was used to dope the AlGaAs. This has produced electron mobilities as high as 120,000 cm^2/v-sec at 77K. Atomic plane doping should allow the gate of the FET to be located much closer to the two dimensional electron gas, enabling higher transconductances.

DEGREES

1. W-I Wang, Ph.D., Janaury 1982
"Molecular Beam Epitaxial GaAs-$Al_xGa_{1-x}As$ Heterostructures for Microwave Applications"
2. C.F. Codella, Ph.D., May 1984
"Characterization and Numerical Analysis of the Modulation Doped Heterojunction MESFET"

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of the modulation doped structure to maintain its high electron mobility during annealing was found to depend on the spacer layer thickness and the sheet concentration of electrons in the two dimensional electron gas. Apparently the electric field in the spacer layer causes the donors to drift during the anneal from the AlGaAs into the spacer layer toward the two dimensional electron gas, which causes a degradation in electron mobility. This effect is lessened by reducing the sheet concentration, thereby lowering the electric field, or by widening the spacer layer, thereby increasing the distance that the donors must move before degraded electron mobility occurs. These two effects are demonstrated in the following data on modulation doped samples annealed at 800°C for 15 minutes (a typical annealing cycle for activating silicon implants into GaAs):

	μ_{77} before anneal	μ_{77} after anneal
$n_s = 5 \times 10^{11} cm^{-2}$ spacer - 100 Å	100,000 cm^2/v-sec	90,000 cm^2/v-sec
$n_s = 1.2 \times 10^{12} cm^{-2}$ spacer - 75 Å	62,000 cm^2/v-sec	2,300 cm^2/v-sec

3. Modulation Doped Single Quantum Wells

Enhanced mobilities have been achieved in modulation doped single quantum wells. Single quantum wells 120 Å wide were grown on 0.5 micron $Al_{.3}Ga_{.7}As$ buffer layers. On top of the quantum well was an undoped AlGaAs spacer layer and a doped AlGaAs layer. At sheet electron concentrations of $5 \times 10^{11} cm^{-2}$, room temperature mobilities of 7000 cm^2/v-sec and 77 K mobilities of 7800 cm^2/v-sec were obtained. This structure is applicable to high speed logic and medium power FET's. It has the advantages of high electron mobility and reduced saturation velocity in the AlGaAs buffer.

3rd Year

The use of a superlattice buffer layer in place of an AlGaAs or GaAs buffer has resulted in higher quality GaAs grown on top of the buffer. DLTS and photoluminescence have demonstrated that there is reduced EL2, Fe and C in GaAs on a superlattice when compared to a similar layer on a GaAs in the AlGaAs to drift toward the GaAs-AlGaAs junction. When the donors reach the GaAs, the junction interdiffuses which drastically reduces the mobility of the structure. A heavily doped p-type layer added to the top of the structure inhibits the movement of the silicon donors by reversing the field in the AlGaAs layer. This allows the structures to retain their high mobility after anneals of 800^oC for 10 minutes or longer.

Problems in the reproducability of the barrier heights of planar doped barriers (PDB's) were traced to impurity outdiffusion from substrates. Substrate pre-baking at T > 700^oC in H_2 was found to solve the problems allowing the growth of PDB layers with high yield (about 90%) and good reproducability.

2nd Year

1. GaAs/AlGaAs Superlattice Buffers for FET's

Photoluminescence (PL), secondary ion mass spectrometry (SIMS), deep level transient spectroscopy (DLTS) and microwave FET performance have consistently demonstrated the superiority of GaAs/AlGaAs superlattice buffers over conventional GaAs or AlGaAs buffers. The interfaces of the superlattice have demonstrated the ability to getter impurities and defects such as ion and the deep level EL2. The following data was obtained at 10 GHz on FET's fabricated on MBE grown material (no data is given to AlGaAs buffers since they exhibited extremely poor microwave performance):

buffer layer	superlattice buffer (270Å $Al_{.45}Ga_{.55}As$/30Å GaAs,x100)	GaAs buffer 3 microns
saturated output power (watts/mm)	.71	.63
power added efficiency	.31	.27

2. Annealing Characteristics of Modulation Doped Structures

In order to construct short gate, ion implanted self aligned modulation doped FET's, the high electron mobilities in such structures must not be seriously degraded upon annealing. Previous to this work, little success had been achieved in this area. In this work, the ability

TASK 4 MBE MULTIPLE GaAs - $Al_xGa_{1-x}As$ HETEROJUNCTIONS FOR CONFINEMENT OF ELECTRONS FOR IMPROVED FET PERFORMANCE

L.F. Eastman, C.E.C. Wood and G.W. Wicks

OBJECTIVE

1st Year

Two heterojunction structures for FET's were in this year: the modulation doped structure and planar doped barriers.

2nd and 3rd Years

The objective is to utilize the GaAs-AlGaAs heterojunction for improved FET structures.

APPROACH

1st Year

Layers were grown by MBE and characterized primarily by Hall measurements.

2nd Year

FET's were fabricated on MBE grown layers with different types of buffer layers. The FET's were characterized at 10 GHz.

Modulation doped structures were grown by MBE and annealed under various conditions. The structures were characterized by Hall measurements.

3rd Year

Work has continued on two fronts: use of AlGaAs/GaAs superlattice buffers for FET's, and improvement in the modulation doped FET structure.

PROGRESS

1st Year

μ_{77} figures for modulation doped structures are routinely in excess of 100,000 cm^2/v-sec.

Annealing of modulation doped structures, necessary to achieve ion implanted self aligned FET's, was investigated. It was found that the electric field which is built into the structure causes the silicon donors

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"The Application of III-V Semiconductor Heterojunction Structures Grown by Molecular Beam Epitaxy to Microwave Devices"
4. S. Palmateer, M.S., August 1982
"The Chemical and Electrical Incorporation of Maganese in Gallium Arsenide Grown by Molecular Beam Epitaxy: and an Analysis of Impurity Out-diffusion from Cr-Doped Semi-Insulating GaAs During MBE Growth"
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"Specific Interface Resistance Measurements of Abrupt Ge/$Al_xGa_{1-x}As$ Heterojunctions"

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1. "Characterisation of Al/AlInAs/GaInAs Heterostructures", D.V. Morgan, H. Ohno, C.E.C. Wood, W.J. Schaff, K. Board and L.F. Eastman, IEE Proc., 128, PT. I (4) 141-143 (Aug. 1981).
2. "Carrier Compensating Effects at Interrupted M.B.E. Interfaces", N.J. Kawai, C.E.C. Wood, W. Schaff and L.F. Eastman, Third Workshop on MBE, Santa Barbara, CA (Sept. 10-11, 1981).
3. "Magnesium and Calcium Doping from Dissociative Captive Sources or 'Now You See It, Now You Don't'", C.E.C. Wood, D. DeSimone and K. Singer, Third Workshop on MBE, Santa Barbara, CA (Sept. 10-11, 1981).
4. "Doping Limits in MBE GaAs", D. DeSimone, G. Wicks and C.E.C. Wood, Third Workshop on MBE, Santa Barbara, CA (Sept. 10-11, 1981).
5. Summary Abstract: "Surface and Interface Proximity Effect on Quantum Well Electron Mobilities in Modulation Doped GaAs/$Al_xGa_{1-x}As$ Heterostructures", W.I. Wang, N. Dandekar, C.E.C. Wood and L.F. Eastman, J. Vac. Sci. Technol., 19 (3) 576-577 (Sept./Oct. 1981).
6. "The Effect of Growth Conditions of Si Incorporation in MBE GaAs", Y.G. Chai, R. Chow and C.E.C. Wood, Appl. Phys. Lett., 39 (10) 800-803 (Nov. 1981).
7. "Ion Beam Analysis of Molecular Beam Epitaxy InAlAs/InGaAs Layer Structures", D.V. Morgan, H. Ohno, C.E.C. Wood, L.F. Eastman and J.D. Berry, J. Elec. Chem., 128 (11) 2419-2424 (Nov. 1981).

(110) surfaces giving p-type films above 550°C and n-type films below 550°C.

Carrier depletion in n-type MBE films was found to be 2-8 x $10^{11}cm^{-2}$ at interrupted growth interfaces when the layer was exposed to air or atmospheric pressure of nitrogen. No depletion was observed at interfaces which were maintained in an As_4 overpressure while the growth was stopped.

Finally, MBE GaAs layers which were capped with Si_3N_4 and annealed at 700°C were found to have enhanced defect exciton and carbon acceptor features in their photoluminescence and enhanced EL2 levels as seen by DLTS. No such enhancement was observed in layers which were annealed without a cap in arsenic overpressure.

3rd Year

Substrate annealing and repolishing prior to MBE growth was found to reduce impurity outdiffusion from the substrate into the epitaxial layer. Non-annealed substrates resulted in growths with Mn buildups at the epi-substrate interface (detected by SIMS), a carrier concentration which varied over an order of magnitude from the top surface of the epitaxial layer to the substrate interface (detected by CV) and enhanced Mn and Cu acceptors (detected by PL). Growth on pre-annealed substrates resulted in epitaxial material with no detectable MN or Cu and flat (± 10%) carrier profiles. Single quantum wells also were shown to be affected by substrate treatment. Single quantum wells of 160 Å width exhibited PL linewidths of 1 meV and 4 meV PL linewidths when grown on pre-annealed and non-annealed substrates, respectively.

The arsenic to gallium flux ratio was also found to effect impurity incorporation into MBE grown films. High arsenic fluxes were found to cause surface accumulation of C, S and Mn.

DEGREES

1. D. DeSimone, Ph.D., January 1982
   "Mn and Mg as P-Type Dopants in GaAs Grown by MBE"
2. J. Ballingall, Ph.D., August 1982
   "Conduction Band Discontinuity Measurements and Crystal Growth Characterization of the Abrupt Ge-GaAs Heterojunction"

PROGRESS

1st Year

Following the success in our laboratory by Stall et al. of achieving extremely low contact resistances to GaAs ($\rho_c < 10^{-7}$ Ω-cm^2), an MBE grown Ge layer, a similar approach for contacts to AlGaAs was investigated. The abrupt Ge-AlGaAs heterojunction was found to have a high specific interface resistance.

For AlAs mole fractions between 14% and 37% interface resistances were between 0.08 and 8 Ω cm^2. These results indicate that the abrupt Ge-AlGaAs interface is not a low resistance ohmic contact to AlGaAs. However, by grading the AlGaAs to GaAs then depositing Ge, contact resistances to AlGaAs on the order of those to GaAs may be achieved.

GaAs layers, grown by MBE on superlattice buffer layers have been characterized by photoluminescence (PL) and found to be superior to those grown on AlGaAs or GaAs buffers. The superlattice buffer simultaneously alleviates the major problem of the GaAs buffer: the outdiffusion of impurities from the substrate, and that of AlGaAs buffers: structural problems which propagate into the subsequently grown GaAs.

2nd Year

Subjecting substrates to a bake and repolish cycle prior to epitaxy was conclusively shown to reduce impurity and defect outdiffusion from substrate to epitaxial layer. Secondary ion mass spectroscopy (SIMS) studies on MBE layers showed Mn accumulation at the substrate interface and Mn and Cr outdiffusion on unbaked substrates. These effects were not detected in layers grown on baked substrates. Deep level transient spectroscopy (DLTS) showed a reduction by a factor of 2 to 3 in the density of deep levels in MBE layers grown on baked substrates. Planar doped barriers (PDB's) grown on unbaked substrates exhibited barrier heights 10-20% lower than theoretically expected and poor uniformity. PDB's on baked substrates gave the expected barrier heights and excellent wafer uniformity. Finally, substrate baking plus precise control of arsenic to gallium ratio during MBE growth allowed the growth of single quantum wells with the narrowest photoluminescence linewidths yet reported, 0.7 meV.

In other areas, silicon was found to be weakly amphoteric on (100) surfaces of GaAs in MBE giving n-type films, but strongly amphoteric on

TASK 3 USE OF MBE TAILORED PROFILES FOR GaAs POWER FET's FOR IMPROVED PERFORMANCE

L.F. Eastman, C.E.C. Wood and G.W. Wicks

OBJECTIVE

1st Year

The possibility of low resistance contacts to AlGaAs by growing Ge epitaxially was studied. Also, superlattice buffers were investigated.

2nd and 3rd Years

A study of the behavior impurities and defects in MBE growth and their influence on electrical and optical properties of epitaxial films.

APPROACH

1st Year

Structures were grown by MBE and evaluated.

2nd Year

The majority of the effort of the past year of this project has been directed at substrate effects on MBE layers. Substrates were cleaved into two pieces, one of which was heated at $750^{o}C$ in H_2 for 24 hours then repolished. MBE layers were grown simultaneously on both pieces and characterized.

Other areas which were investigated were Si incorporation into different orientations of GaAs during MBE growth, effects of interrupted growth on MBE films and annealing of MBE GaAs.

3rd Year

The effects of substrates and group V to group III flux ratios on the quality and purity of MBE grown material was investigated. Pairs of layers were grown where a single parameter, e.g. substrate treatment or flux ratio, was varied. The layers were characterized primarily by secondary ion mass spectroscopy (SIMS) low temperature photoluminescence (PL), and capacitance-voltage (CV) profiling.

2. "Superlattice Buffers for GaAs Power MESFETs Grown by MBE", W.J. Schaff, L.F. Eastman, B. Van Rees and B. Liles, 5th MBE Workshop, Atlanta, GA (Oct. 6-7, 1983); J. Vac. Sci. Tech., B2 (2) 265-268 (Apr.-June 1984).

in multi finger devices. For the multi finger devices, there is a fairly clear monatonic decrease of breakdown voltage as I_{DSS} increases. Thus, for a 0 3 micron device with I_{DSS} = 110 ma/mm, the gate-drain breakdown was 22 V. For the same gate length and I_{DSS} = 270 ma/mm, the breakdown is 8 volts. The difference between single and multi finger devices is believed to be due to a difference in the source pad area. The single gate finger devices had a large source pad for probing or bonding while for the multi finger devices, the source pad area was kept small to minimize airbridging distances. The larger source pad served to terminate some of the gate field lines reducing the field between gate and drain. That this effect in multi finger devices was discovered by observing the pattern of light emission near the onset of breakdown. In multi finger devices, the light is first observed near the gate fingers most remote from the source bonding pads, so the lower breakdown of these devices is due to that area.

Consistent with the results of the earlier period, the breakdown voltage was found to increase with gate length. However, a new result of the present period is that when comparisons are made at the same I_{DSS}, devices with a gate recess are found to have lower breakdowns at pinch-off. At full channel current, however, a recess equal to the surface depletion avoids a current constriction in the gate-drain region of the channel and improves breakdown. Such a recess is thus still considered a desired design feature.

DEGREES

1. J. Tenedorio, Ph.D., May 1982
   "Automated Microwave Measurements of GaAs MESFET's"
2. J. Tenedorio, Ph.D., May 1982
   "The Materials Properties and Microwave Performance of the Gallium Arsenide MESFET"

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1. "The Large Signal Performance of GaAs MESFETS Fabricated from Material Grown by Molecular Beam Epitaxy", W.J. Schaff, L.F. Eastman, B. Van Rees and B. Liles, Late Paper, Proc. Ninth Biennial High Speed Semiconductor Devices and Circuits Conf., Cornell University, Ithaca, NY, pp. 226-233 (Aug. 15-17, 1983).

TASK 2 THE EFFECT OF DESIGN AND PROCESSING ON GaAs POWER FET PERFORMANCE LIMITATIONS

L.F. Eastman and D.W. Woodard

OBJECTIVE

The objective of this task is to investigate experimentally and analytically the performance limits of GaAs microwave power FET devices.

APPROACH

The approach taken has been to explore structural and materials related determinants of the breakdown voltage and output conductance. These determinents have included the surface notch configuration, electrode spacing, layer thickness and doping, source or type of epitaxial material, and buffer layer thickness, resistivity, and deep level occupancy.

PROGRESS

During the first year experimental and theoretical work showing an approximately linear dependence of breakdown voltage on gate length down to 0.8 microns was reported. During the second year those studies were extended down to 0.4 microns and power limitations improved by current flowing in the substrate were investigated. In an effort to control substrate current, a buffer layer consisting of an AlGaAs-GaAs superlattice was employed. For this attempt, parameters of the buffer layer were not sufficiently optimized to effect a reduction in the current. However, device performance for the first time on an AlGaAs buffer was comparable to the results with GaAs buffers. This suggests that the superlattice approach significantly improved the properties of the final AlGaAs layer under the GaAs active layer.

During the third year, gate lengths of 0.25 microns were achieved, and breakdown of pinch-off was studied with particular attention to its dependence on the zero gate-bias saturation current, I_{DSS}, and also on the depth of the gate recess. Results from both single and multi-gate finger devices were also compared. For single gate finger devices there is a very large scatter in breakdown voltage with values generally larger than

15. "Enhanced Mobilities in Single Quantum Well Structures on $Al_{.30}Ga_{.70}As$ Buffers Grown by MBE", P.A. Maki, G.W. Wicks and L.F. Eastman, Proc. Ninth Biennial High Speed Semiconductor Devices and Circuits Conf., Cornell University, Ithaca, NY, pp. 209-217 (Aug. 15-17, 1983).

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17. "As_2 Ambient Activation and Alloyed Ohmic Studies of Si^+ Ion Implanted $GaAs/Al_{0.3}Ga_{0.7}As$ Modulation Doped Structures", S. Mukherjee, P. Zwicknagl, H. Lee, A. LePore and L.F. Eastman, WOCSEMMAD, San Francisco, CA (Feb. 20-21, 1984).

TASK 5 HIGH SPEED RECEIVERS FOR OPTICAL COMMUNICATIONS

J. Ballantyne and D.K. Wagner

OBJECTIVE

The objectives of this program are to develop large area photoconductive detectors which are suitable for monolithic integration with preamplifiers, and to develop MOCVD growth techniques of materials suitable for monolithic optoelectronic subsystems. Included in these objectives are the analysis of fast photoconductive detectors so that the details of their operation at high frequencies are understood. This includes the development of suitable circuit models to describe their operation and the development of design strategies which allow prediction of properties such as speed, gain and noise of large area photoconductors monolithically integrated with preamplifiers. Prototype photo detectors and monolithically integrated receivers are fabricated and performance evaluated and compared with predictions.

APPROACH

In order to accomplish the above objectives, various geometry detectors, transistors and diodes were fabricated in LPE and MOCVD GaAs epilayers, as well as in MOCVD GaAs/AlGaAs heterostructures. The devices and layers were characterized by I-V, C-V, and transmission line measurements (as appropriate) to determine quiescent and low frequency characteristics. The high speed testing was accomplished with the aid of a picosecond mode-locked dye laser. The optical pulsewidth that impinges on the detector (3 ps) is short enough to be considered an impulse, and the output response of the detector is therefore the transfer function of the detector or detector/amplifier combination. From this measurement and knowledge of the width and power in the optical pulse, gain and speed of the detector circuit at high speeds is determined.

Analytical models of interdigitated large area photoconductive detectors have been constructed and evaluated. Computer simulation is used to predict characteristics of individual devices and of device amplifier combinations.

Techniques for the MOCVD growth of GaAs/AlGaAs and InP/InGaAs heterostructures are being developed. Grown structures are evaluated by electrical and optical measurements on the layers and by measuring the performance of devices fabricated in the grown layers.

PROGRESS

A GaAs MESFET amplifier was integrated with four different types of fast photoconductive detectors of the OPFET geometry. Fabrication processes were developed which yield successful integration of the different photodetectors with the GaAs MESFET amplifiers.

The four different photoconductive detectors integrated were all of the OPFET geometry. They include small OPFETs with and without notches, and interdigitated OPFETs with and without notches. The areal response of the interdigitated detectors taken with a scanning laser microscope is relatively uniform, showing they behave as expected and are suitable for receiving light from optical fibers. Gain for the interdigitated OPFET detectors was measured at about 14 (low frequency). High-speed testing of the discrete detectors was done with a suitable modification of existing commercial SMA end launchers. (cf. Figure 1) Results showed the slower detectors without notches had response speeds on the order of 200 ps, and the faster notched detectors had response times of about 100 ps.

Standard MESFET's have been successfully integrated and quite reliably fabricated with 1 micron length gates, gate widths of 50-250 microns, and transconductances of 80-90 ms/mm. The processing sequence for themonolithic circuit consists of four steps.

First, moats are etched around transistor and detector areas using a 3:1:1 methanol $:H_2O_2:H_3PO_4$ etch for electrical isolation. A more conventional mesa etch was not used due to technical problems in fabricating larger clear areas in masks by e-beam lithography. The moat etch is highly successful in isolating the components, however. Ohmic contacts consisting of layers of about 500 A of AuGeNi, 500 A Ag, 1500 A Au are then thermally evaporated onto the substrate and annealed at $600^{\circ}C$ for 90 s. This second step, which in addition to the normal optical photolithography also includes a liftoff of excess metallization in acetone, provides ohmic contacts and virtually all of the required metallization. The third step consists of defining uniform 1 micron gates using a projection mask aligner, etching self-aligned notches in the transistors to lower quiescent currents, evaporating about 1000 A of Au

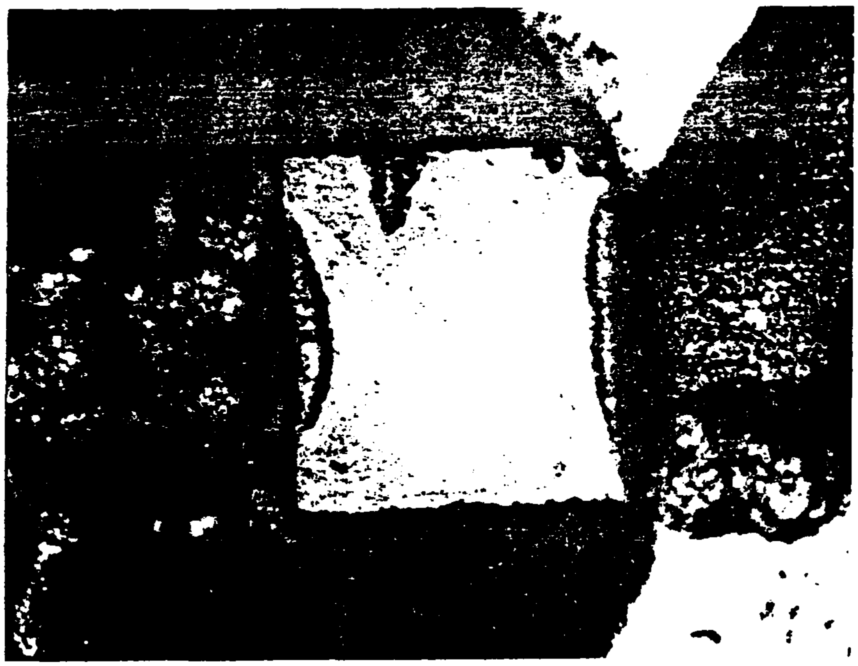

Fig.1 Low-inductance mount of photoconductive detector on back of SMA converter. Detector is in center of clip between triangular contact pads. Pads are connected to center conductor (left) and outside conductor (right) of SMA connecter with conducting epoxy (mottled areas overlapping pads). Chip sits over teflon insulator (dark ring) of connector.

for the Schottky barrier gates, and performing a liftoff of the excess gate metallization. The last step is a notch etch (if desired) performed on the photoconductive detectors.

For the integrated receivers a ceramic carrier was made which incorporated 50 ohm microstrip transmission lines. The GaAs wafers were cleaved or alternatively sawed up (with a higher yield) to obtain individual circuits.

Although individual photoconductors and transistors performed well, significant problems were encountered in the biasing of the amplifier, overall circuit yield, and longer than expected decay times when excited by picosecond optical pulses. Bypassing circuit nodes effectively at GHz frequencies and the reliability of a large number of ultrasonically bonded wires required for the circuit (9) were also problems. Together, these problems prevented high speed testing of the complete receiver.

Many of the above are processing or design flaws, not fundamental problems. Several are interconnected. The level shifting biasing scheme attempted was thought to be the simplest. However, it necessitated the large number of ultrasonic bonds, as well as having the initial power transients cause severe circuit trauma before the different bias voltages to the stages stabilized. This often caused the forward biasing of the MESFET gates, damaging the transistors.

Our solution is a redesign that uses at the most a positive and negative supply and includes either Schottky diode strings to perform the necessary DC voltage level shifts internally, or a differential amplifier scheme with zero DC offset from input to output stage. The feasibility of differential amplifier schemes in particular and self-biasing schemes in general depends on the uniformity and quality of the epitaxial layers the circuits are fabricated in. The characteristics of the transistors for differential pairs have to be very closely matched. Otherwise, the zero DC offset property is not obtained. The current layer quality indicates that a self-biasing scheme with level shifting diodes is the most practical, unless more uniform layers can be obtained from the MOCVD system or other sources. With any self-biasing scheme, there are less circuit nodes to bypass. Also, improved capacitors have been obtained for the circuit bypassing. They are smaller in physical size and have higher self-resonant frequencies and better loss tangents, thus the bypassing problem should be alleviated.

Difficulties with circuit yield are now less important due to an improved photolithography system being used and better quality layers being used for processing.

The most potentially serious problem is the long decay time observed in optical measurements. Although the risetime of the detectors to an optical impulse (3 ps FWHM) is fast in all cases (less than 100 ps), the response has a long tail. (cf. Figure 2) This decay may be caused either by circuit effects (bonding wire inductance, device capacitance, bias tee insertion loss, etc.) or excess minority carriers being trapped in the semi-insulating substrate.

A GaAs/AlGaAs heterostructure was grown on the MOCVD system. The undoped AlGaAs layer acts as a barrier to prevent the excess minority carriers (holes), which determine the decay characteristics of the device, from entering the substrate and becoming trapped. The AlGaAs has a larger band gap (1.9 eV) than the GaAs (1.43 eV), creating the barrier. As a further precaution, a thicker layer of GaAs was grown (.6 micron) than had been used in previous work (.3 micron). Since the absorption coefficient in GaAs is .25 micron at the wavelength used in our tests, about 90% of the light is absorbed in the epilayer.

Various interdigitated photoconductors were fabricated ranging in size from 5x5 to 400x400 microns. (cf. Figure 3) All but the smallest devices are suitable for direct coupling of optical fibers to the surface. I-V measurements are consistent with previous detector characteristics if changes in active device area are noted. The largest devices (400x400) were not successful because of material inhomogeneties.

A problem with all larger area arrays is the relatively large amount of current needed (up to 100 mA). This also leads to undesirable heating effects in the devices. Work is in progress on a normally off detector which would have a low quiescent current. Such a device would eliminate both of the above undesirable effects. Preliminary results show photoconductive detectors can be made with total power dissipation on the order of 0.4 W/ , three orders of magnitude smaller than previous OPFETs. This power dissipation is low enough to make the devices attractive for applications demanding arrays.

Optical impulse measurements showed a long tail still present in the

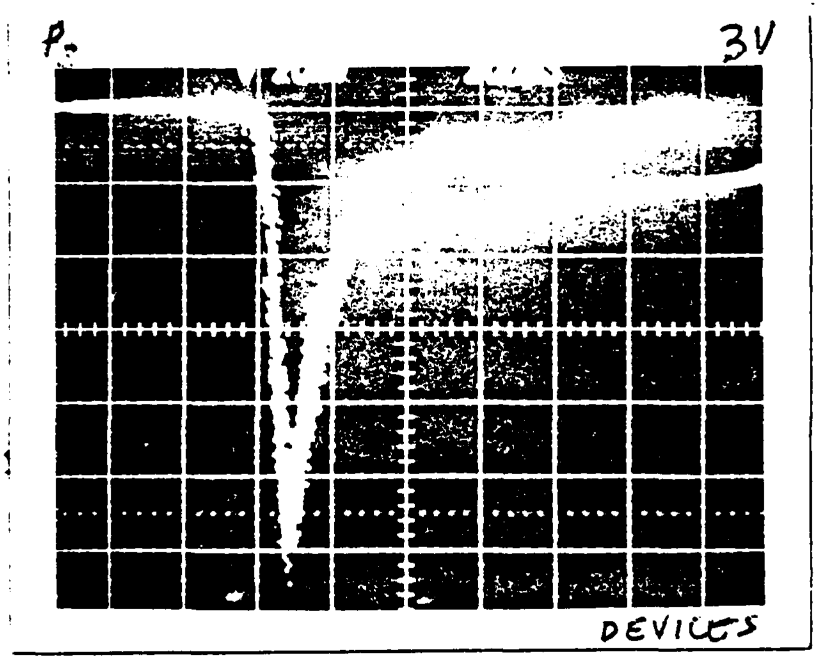

Fig.2 Photoresponse of 12x2μm detector. Note long tail
Scales are 200 ps/div and 20mv/div

3a

3b

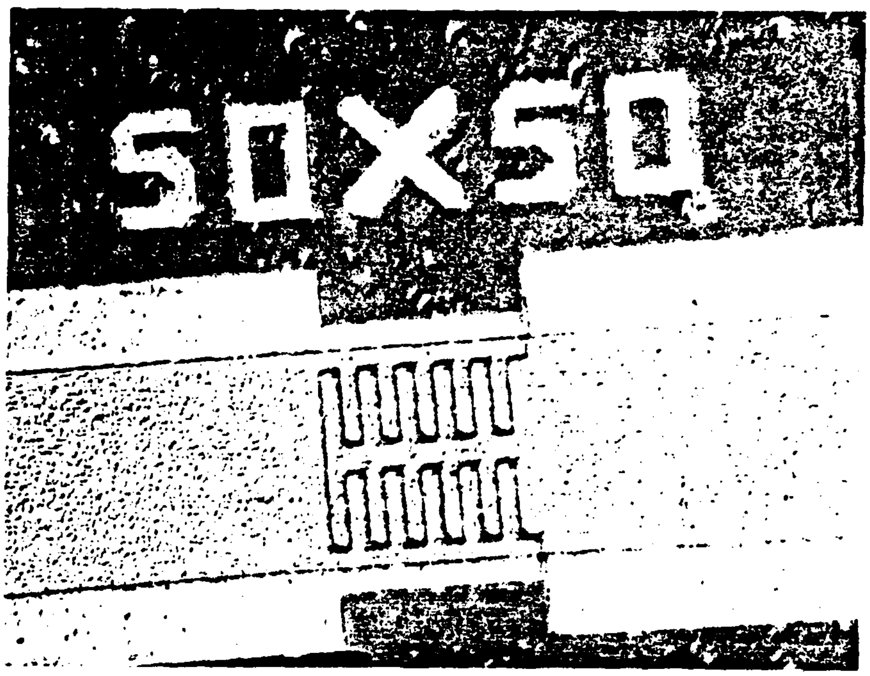

Fig.3 a) Photograph of 12x2μ photoconductive detector.
b) Photograph of newest design for 50x50μ detector.

new detectors made on heterostructure layers, although reduced from previous levels by a factor of 30%. The device decay was exponential. Previously, the decays were more anomalous. The continuing long decays may be due to surface recombination effects, or continued hole trapping at the lower interface. Improved layer structures are being designed to study the problem. The pulse response shape has been found to depend on the device bias and the illumination levels employed in the tests, as well as device active area. These effects are being studied to determine the optimum size and operating conditions. The fastest responses have a FWHM of 100 ps at 3 V bias at .1 mw incident power (25x25 micron device).

To gain insight into the problem of a tail on impulse response, an exact analysis was performed on a simple detector model and yielded the result that the risetime should be almost instantaneous and the falltime should be exponential with a time constant equal to the product of the load resistance and internal device capacitance (T=RLOAD*CDEV) if reasonable approximations are made.

Since the measured risetime of the devices is 50-80 ps in all cases regardless of the device area, the speed of the external bias circuit, transmission line, and sampling oscilloscope were checked with a fast electrical signal and were found to contribute about 40-50 ps to the response. The remaining difference in risetime (30-40 ps) can be accounted for if instead of using a lumped capacitance in the device model, a distributed capacitance and resistance is used instead, which is a more physically accurate model.

The static capacitance of the structure was estimated through conformal mapping and the load resistance is known exactly; however, the measured falltime (about 200-350 ps) was greater than the calculated value (10-30 ps). As noted previously, the largest part of this tail is due to trapping of minority carriers in the semi-insulating substrate. A new heterostructure layer graded in both doping and bandgap to aid the photogenerated carriers to the surface has been grown and has been used to fabricate the latest set of devices. (cf. Figure 4).

In the course of this work it was discovered that the resistance of the ohmic contact regions actually dominated the resistance used in the decay time calculation. For example, for the smallest devices, the contact resistance was measured to be 200 ohms while the load resistance

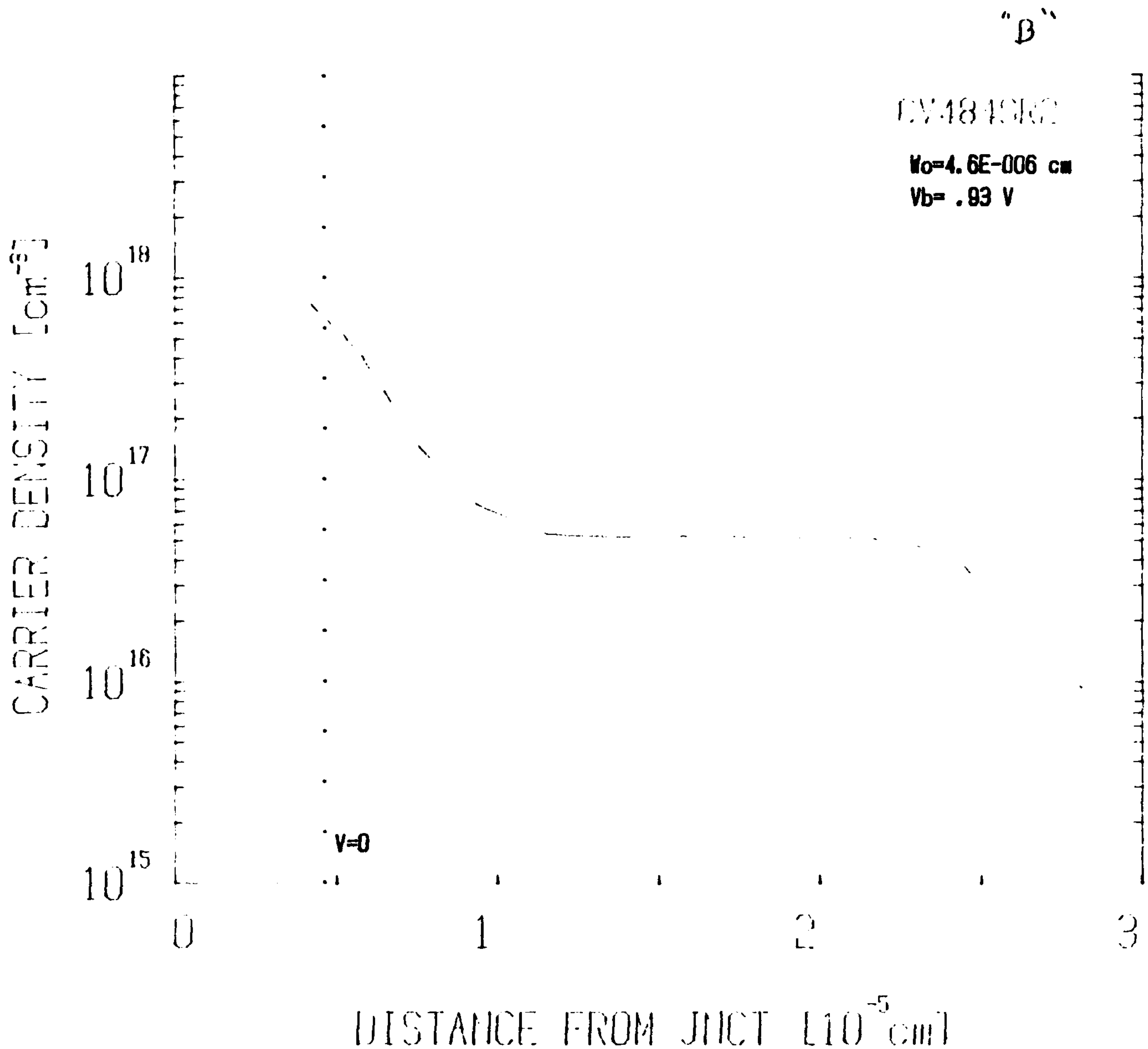

Fig.4 Capacitance-voltage doping-thickness profile of newest heterostructure layer. Note heavily doped cap, 1500A constant doped active region, and tailored doping into AlGaAs. AlGaAs bandgap is also graded.

is 50 ohms. Therefore, when this is taken into account, the theoretical falltime is T=(RLOAD+RCNTACT)*CDEV and gives a value of (50-130 ps). From this, it is clear that although trapping is important, the non negligible contact resistance contributes a significant part. Work on the contact system used in these detectors has improved the contact resistivity from about 2 x 10^{-5}ohms-sq. cm. to 2 x 10^{-6}ohms-sq. cm. This improvement was accomplished by using a different evaporator which operates at a lower pressure, is cleaner, and by including a heavily doped cap layer on new layer growths.

As a result of the ohmic contact work, a formula was derived to optimize the area and contact resistance product used for the large area interdigitated detectors. This is an important result since these competing factors trade off between gain and speed. The optimum contact width is shown in Figure 5.

An MOCVD system for the growth of uniform and large-area thin layers of III-V compounds was completed during the period. The system has been used to grow state-of-the-art layers of GaAs, AlGaAs, and InP. Mobilities exceeding 90,000 cm^2/V sec at 77^oK are measured in layers of GaAs grown on the system, with total impurity levels well below $10^{15}cm^{-3}$ reproducibly achieved. High quality layers of AlGaAs are also grown on this system by the incorporation of a unique Ga/Sn/Al bubbler to remove unwanted O_2 from the source gas flows.

The photoluminescence spectra obtained on the AlGaAs material is the best in the published literature. In and P sources have been installed in the machine and layers of InP and GaInAs have been successfully grown. The InP is the best reported by MOCVD, with nitrogen mobilities exceeding 80,000 cm^2/V sec and a sharp photoluminescence spectra riveled only by the best published result by halide vapor epi.

The GaInAs/InP is good, but much work and characterization remains to be done on this materials system. Materials grown in this machine are now being used in all of our other opto-electronics programs. Quantum wells, and sophisticated structures like that in Figure 4 are routinely grown. Both N and P type layers can be produced in the system, and the unique system design which allows in situ cleaning has allowed growth of layers with no perceptible memory effect from one run to the next.

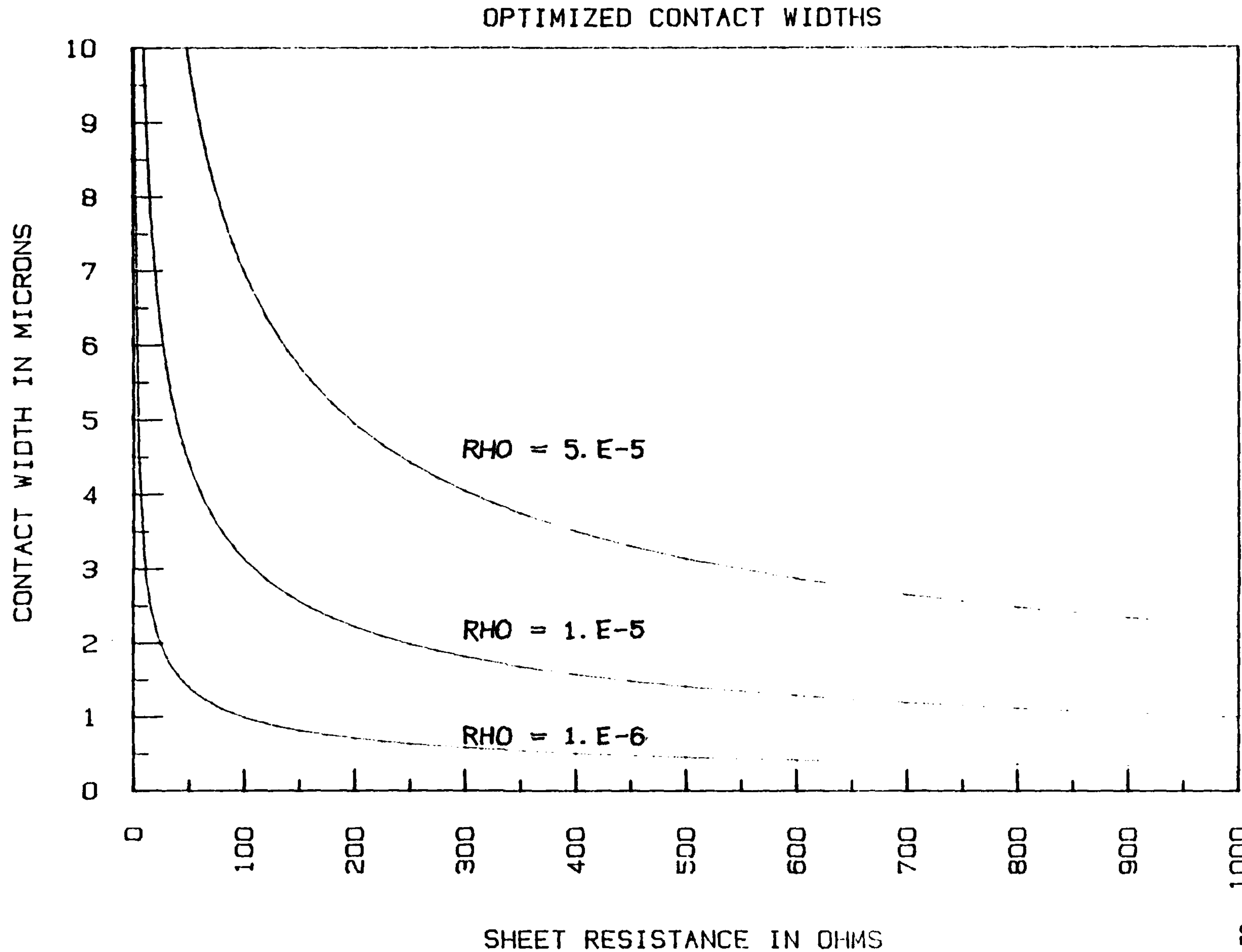

Fig.5 Optimized contact (finger) width as a function of layer sheet resistance and contact resistivity (RHO). This width minimizes the product of contact area and resistance, which is inversely related to the gain-bandwidth product.

PERSONNEL

J.M. Ballantyne, D.K. Wagner, S. Wojtczuk, K. Chan, A. von Lehmen, C. Harding and L.D. Zhu.

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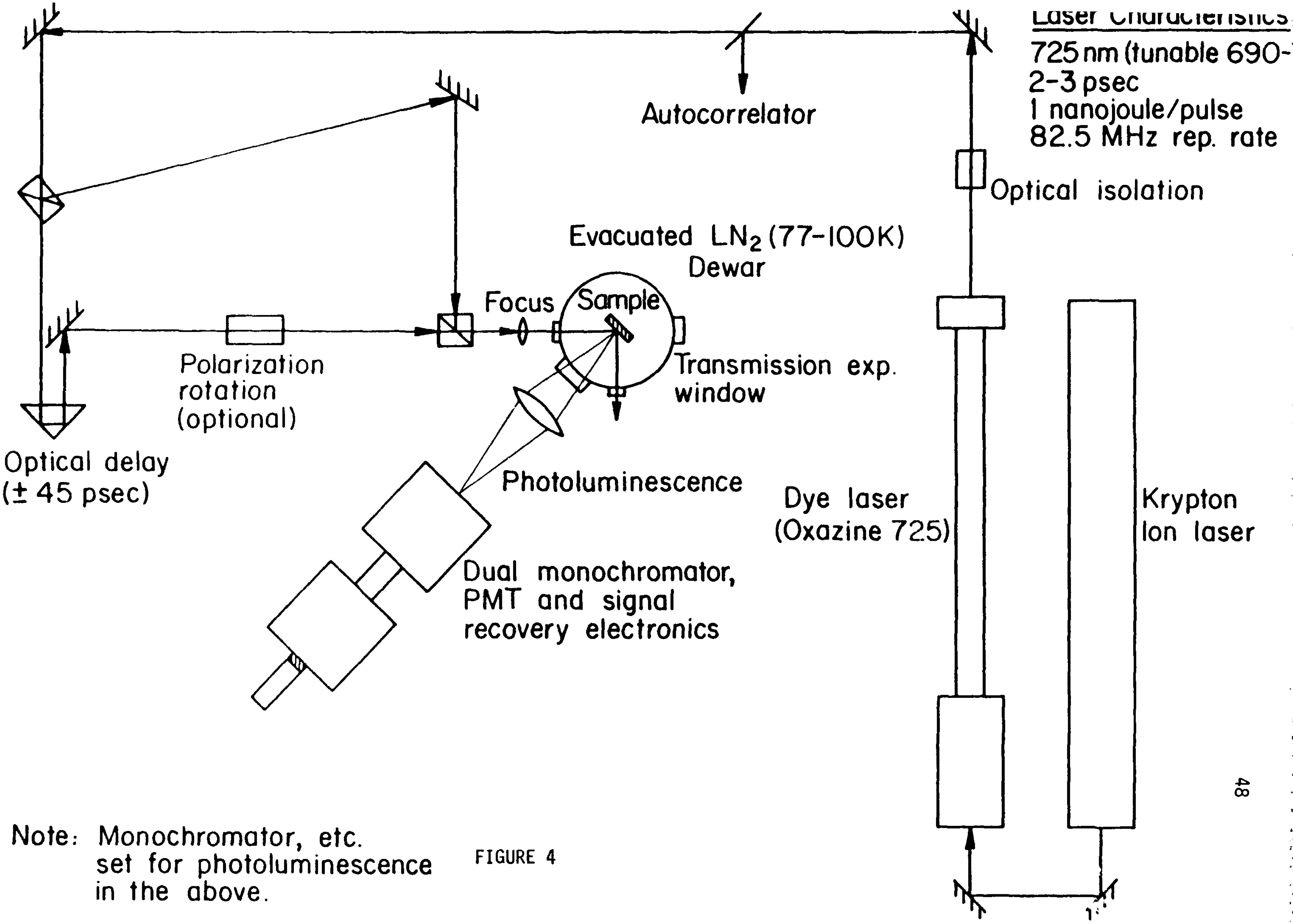
20. "Monolithic Waveguide Polarization Modulator", B. Kushner and J. Ballantyne, Proc. of the Fifteenth NSF Grantee-User Meeting on Optical Communications Systems, MIT, 110-117, June 1-3, 1983.



Note: Monochromator, etc. set for photoluminescence in the above.

FIGURE 4

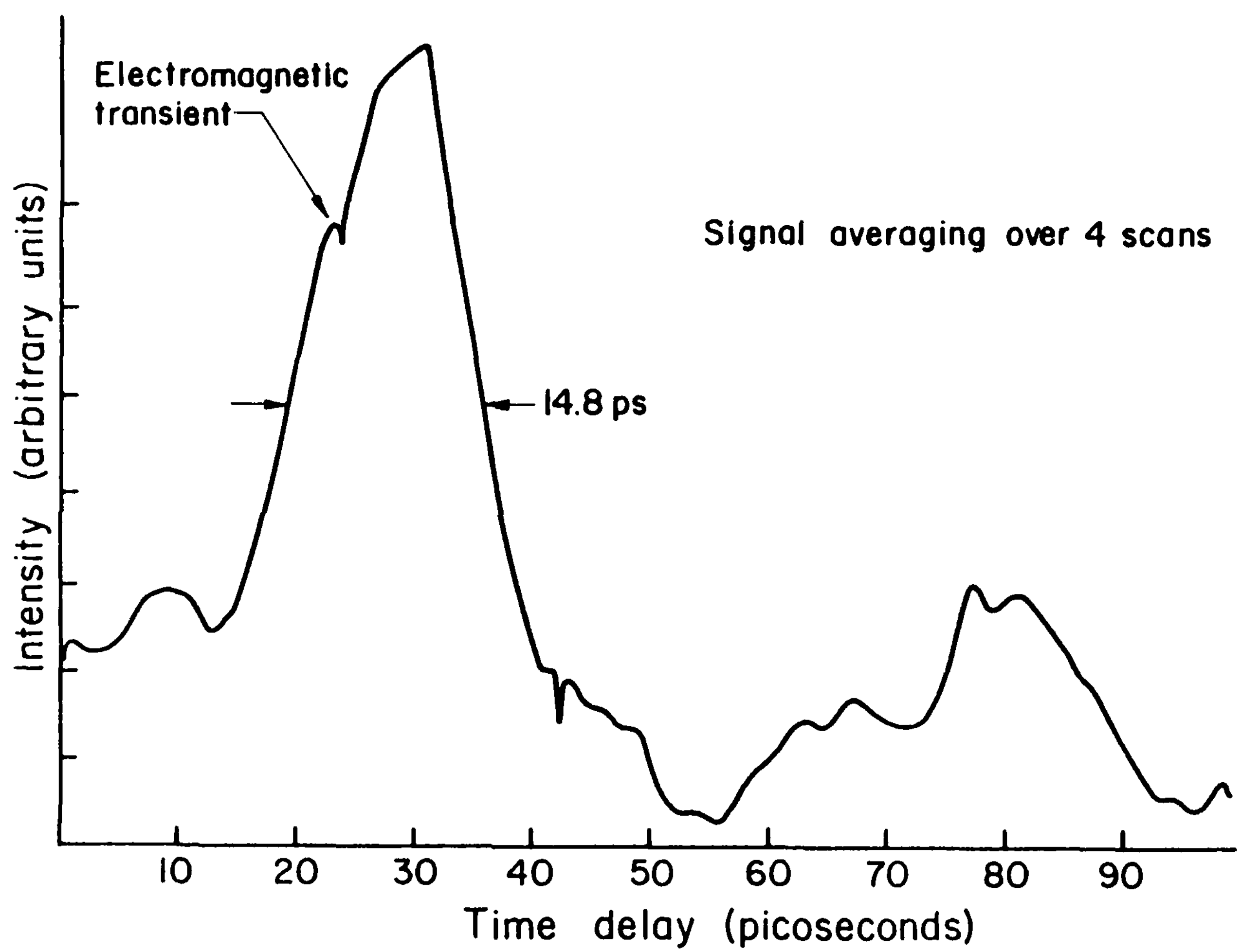

Electromagnetic transient
Signal averaging over 4 scans
14.8 ps
Intensity (arbitrary units)
10
20
30
40
50
60
70
80
90
Time delay (picoseconds)

FIGURE 3

to that obtained from photoluminescence studies. However, here the lifetimes of the actual charge carriers are being measured. Although only slight changes were observed, it is believed that excitation using shorter pulses would reveal the thermalization of carriers within the conduction band. Other (C.V. Shank, R.L. Fork, R.F. Leheny and Jagdeep Shah, Phys. Rev. Lett., 42 (2) (Jan. 1979)) have shown through photoluminescence studies that intraband relaxation occurs on the time side of a few tenths of picoseconds. By varying the wavelength of subpicosecond pulses the relaxation from different regions of the conduction band could be characterized. Also the effects of intervalley scattering could be observed.

Second, a fast electromagnetic transient was observed. These short electromagnetic pulses appear as a prepulse on each autocorrelation trace (Figure 3). The origin of this transient is not clear. However, it may be due to the rapid induced polarization within the bulk plasma. Again shorter pulses would reveal more about the origin and usefulness of these extremely short (less than 1 psec) electromagnetic pulses.

Relaxation of Hot Electrons in GaAs

Fundamental work on the properties of hot electron relaxation is nearing completion. The laboratory is fully operational in the production and use of picosecond laser pulses in a "pump/probe" anaysis. Using these pulses, data collection demonstrates various properties of hot electron relaxation.

Refer to Figure 4. A picosecond pulse train (2-3 picosecond FWHM and 1 nanojoule/pulse) with a repetition rate of 82.5 mhz is generated by a synchronously mode locked, tunable, oxazine dye laser. After chopping, the pulse train is split into two pulse trains of equal intensity and a time delay is introduced into one of the split pulse trains. The two pulses are then recombined and focused onto a sample mounted in a cryostatic chamber maintained at LN_2 temperatures. The laser light pumps the sample at a 45^o incidence angle and the resulting luminescence is collected normal to the sample. The collection apparatus consists of a collection lens, double--1/4 meter monochromator in conjunction with a PMT, phase sensitive detector and display electronics.

When the two pulse trains arrive at the sample with zero relative

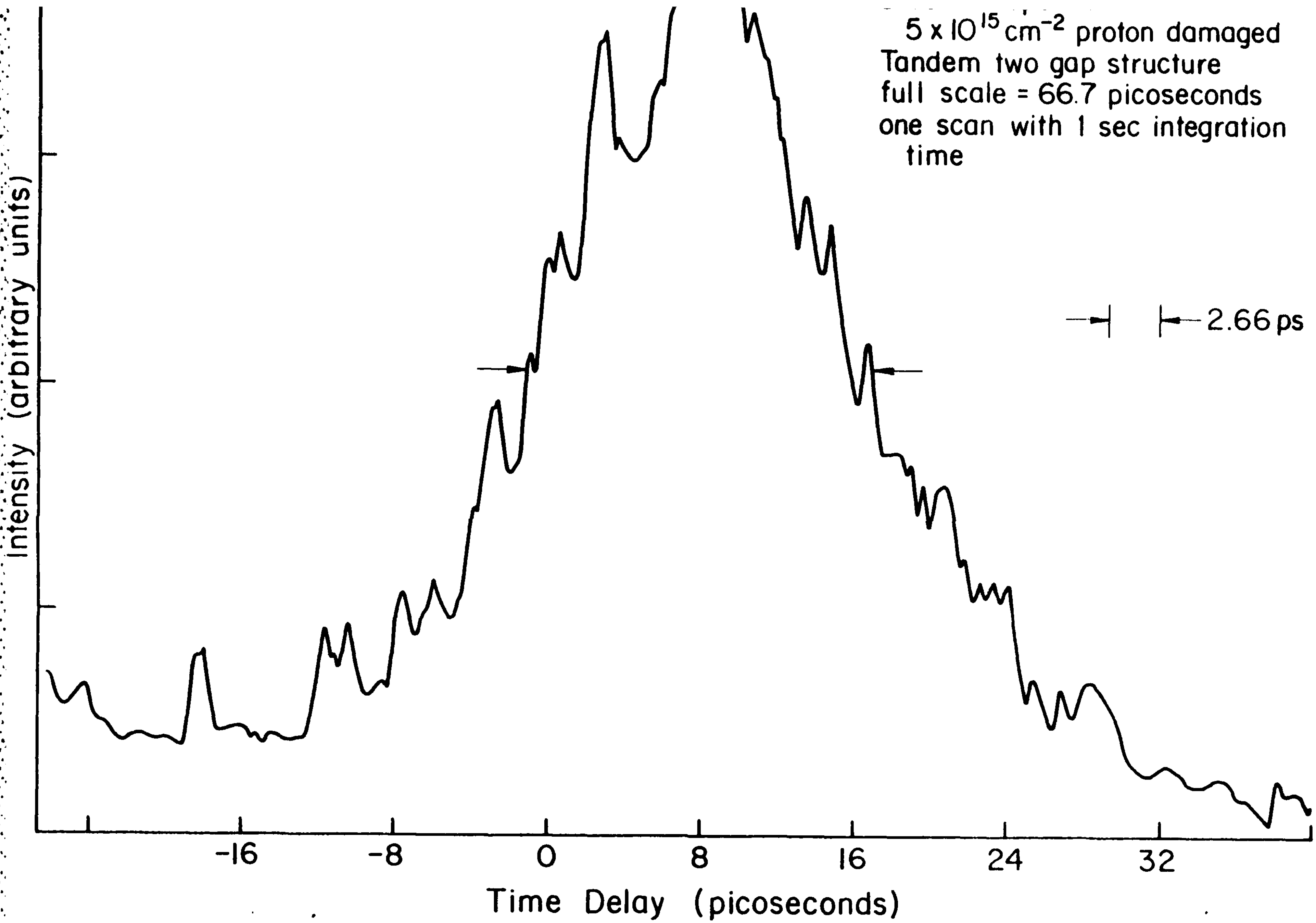

$5 \times 10^{15}\,cm^{-2}$ proton damaged
Tandem two gap structure
full scale = 66.7 picoseconds
one scan with 1 sec integration time
2.66 ps
Intensity (arbitrary units)
-16
-8
0
8
16
24
32
Time Delay (picoseconds)

FIGURE 2

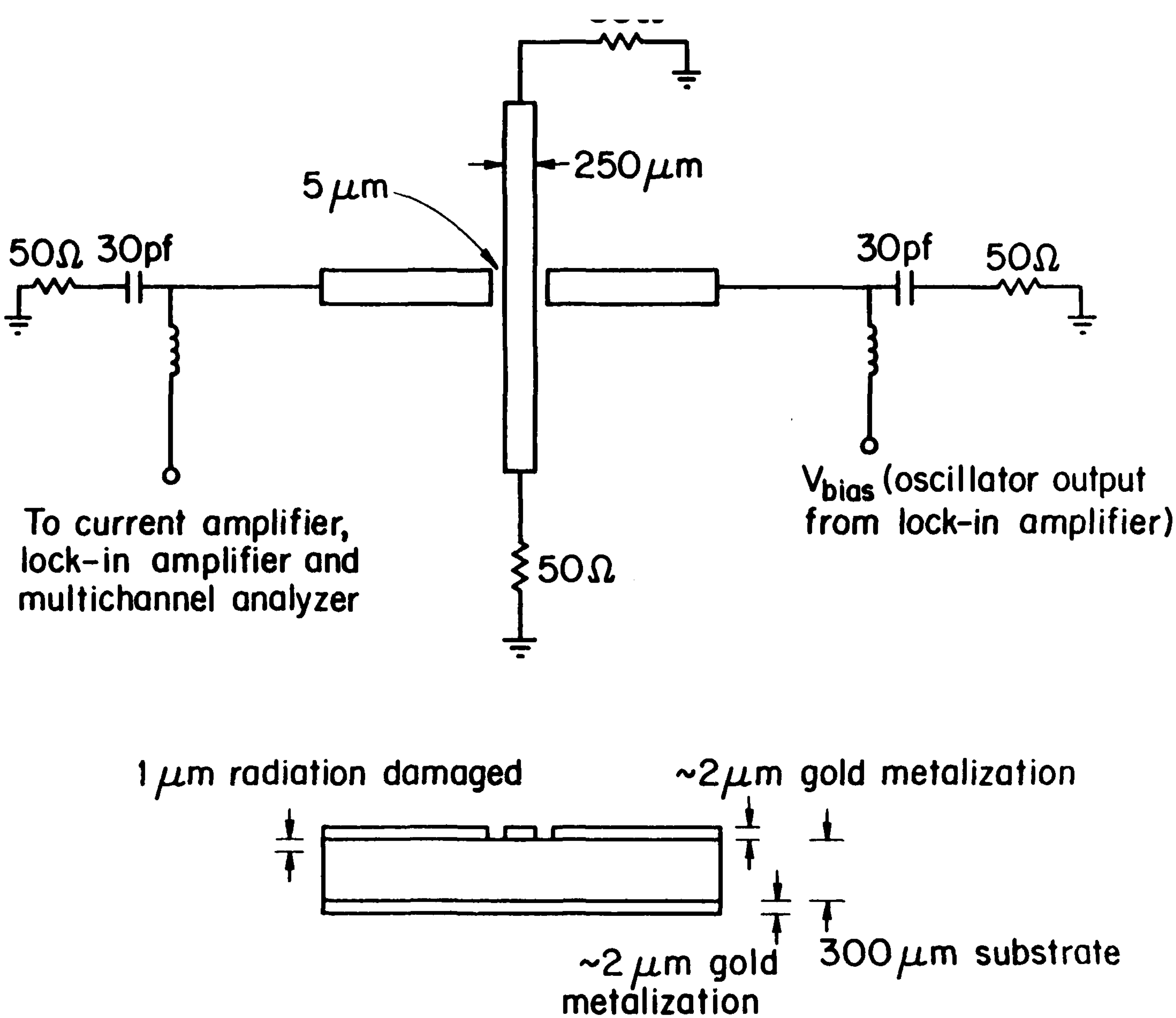

50Ω 30pf
5 μm
250 μm
30pf
50Ω
To current amplifier, lock-in amplifier and multichannel analyzer
50Ω
V_bias (oscillator output from lock-in amplifier)
1 μm radiation damaged
~2 μm gold metalization
~2 μm gold metalization
300 μm substrate

FIGURE 1

produce a 5 mv signal into a 50 ohm load.

InP

This early investigation involved semi-insulating iron doped InP samples which were not radiation damaged. These devices had excellent sensitivity. However the response time was always longer than 100 psec. Although it is possible to decrease the carrier lifetime by radiation damage, higher performance was expected with ion implanted GaAs.

Gallium Arsenide

The irradiated GaAs photoconductors produced the fastest electrical pulses and were the most sensitive. Two types of GaAs substrates were tested. The high resistivity chromium doped substrates provided the best results in contrast to the undoped lower resistivity substrates which had unacceptable dark current due to the extremely low dark resistance (10 KΩ). The dark current is typically 250 nano amps for the chromium doped substrates with a 5 volt bias applied to a 5 micron active region (20 MΩ dark resistance). The best switches fabricated had response times of less than 10 psec and an on-resistance of about 10 K-ohm. The peak current is of the order of 1 mA and is limited primarily by breakdown and arcing across the 5 micron gap.

In order to measure recombination lifetimes that were faster than about 25 psec (sampling scope limit) an electronic autocorrelation was done. Two photoconductors were fabricated on opposite sides of a microwave transmission line (Figure 1). The first photoconductor injected carriers into the transmission line and the second sampled the electrical pulse at later times. By adjusting the time delay between injection and sampling the auto correlation of the detector response was obtained (Figure 2). It is this technique which allows the measurement of transmission line dispersion and device testing.

Two important observations were made. First, the carrier relaxation of the induced bulk plasma was dependent upon the energy of the incident photons. Since the charge carriers are excited to different regions of the conduction band when photon energy is varied it is possible that the relaxation from those regions was observed. This data obtained is similar

Thus a major goal was to decrease carrier lifetime while maintaining lattice integrity.

APPROACH

The investigation involved three types of substrate material:

1) Silicon on Sapphire (S.O.S.)
2) Indium Phosphide (InP), and
3) Gallium Arsenide (GaAs)

Both the InP and GaAs have high mobility and therefore should have high sensitivity. S.O.S. is an excellent material due to its inherent low capacitance and ruggedness.

The simplest microwave circuit fabricated consisted of a single microstrip transmission line with a gap (3 to 40 micron) in the conductor. The switch was activated by creating a bulk plasma within the gap with high intensity laser pulses. The source of short pulses was a tunable (680-730 nm) dye laser which produced 100 mw average power and 1 nj in a 2 psec pulse.

By varying the radiation damage to otherwise identically prepared substrates and measuring the electrical response to a 2 picosecond laser pulse the effects of the implanted traps was determined. Increasing the trap density produced a decrease in carrier lifetime and hence faster switches. However, with increasing speed came decreased sensitivity. The effects of annealing the substrates after radiation damage to restore the high mobility were investigated.

PROGRESS

Improvement of several of the important switch parameters was accomplished, primarily the speed and sensitivity of the devices we made. This work is described below.

Silicon on Sapphire

Although the S.O.S. photoconductors were not the fastest nor the most sensitive, they were the easiest to fabricate. The lifetime of the undamaged silicon was greater than 1 ns and decreased to nearly 10 ps after O^+ ion implantation of $5 \times 10^{15} cm^{-2}$ at 100 kev. The lower mobility of the silicon necessitated the use of a high bias voltage (65 volts) to

TASK 7 CARRIER DYNAMICS IN COMPOUND SEMICONDUCTORS STUDIED WITH PICOSECOND OPTICAL EXCITATION

G.J. Wolga

The use of high speed photoconductors for fast optical detection and testing of fast solid state microwave devices has been the subject of many recent papers.[1-3] The ability to generate picosecond and subpicosecond laser pulses has created a need to measure these short pulses and a desire to create similarly short electrical pulses. As an optical detector the high speed photoconductor is a convenient and simple device to monitor moderately fast (greater than 10 ps) optical pulses. Conversely, when used with fast optical pulses (less than 1 ps) the relaxation characteristics of the photoexcited carriers can be investigated. High speed solid state devices can be evaluated by using the photoconductors as electrical pulse generators and sampling gates. Thus, advances in speed and sensitivity of the photoconductors will allow precision testing of solid state devices.

1. D.H. Auston, A.M. Johnson, P.R. Smith and J.C. Bean, Appl. Phys. Lett., 37 (4) (Aug. 1980).
2. T.F. Deutsh, F.J. Leonberger and A.J. Foyt, Appl. Phys. Lett., 41 (5) (Sept. 1982).
3. P.R. Smith, D.H. Auston and W.M. Augustgniak, Appl. Phys. Lett., 39 (9) (Nov. 1983).

OBJECTIVE

The purpose of the investigation was to develop high speed (picosecond response time) photoconductive semiconductor switches and incorporate them into a wide bandwidth microwave circuit. These fast switches were then to be used to investigate carrier relaxation and to test high speed microwave circuits.

The carrier recombination lifetime, which determines switch speed was altered by irradiating the semiconductor substrate with ions. The implanted ions behave as traps and their presence reduces carrier lifetime. At sufficiently high ion density the crystal lattice appears amorphous and the mobility and hence sensitivity are greatly reduced.

4. "Femtosecond lasers and applications", C.L. Tang, Invited talk, Am. Phys. Soc./AAPT Annual Joint Meeting, San Antonio, TX, January 3, 1984.
5. "Femtosecond relaxation in molecules and semiconductors", C.L. Tang, Invited seminar, Department of Physics, University of Toronto, Toronto, Canada, March 21, 1984.
6. "Femtosecond studies of the intraband relaxation in semiconductors and molecules", C.L. Tang, D.J. Erskine, and A.J. Taylor, Invited talk, 4th Topical Meeting on Ultrafast Phenomena, Monterey, CA, June 15, 1984.
7. "Femtosecond relaxation in GaAs and related materials and structures", D.J. Erskine, A.J. Taylor, and C.L. Tang, 13th International Quantum Electronics Conference, Anaheim, CA, June 18-22, 1984.
8. "Picosecond relaxation of hot carriers in GaAs and AlGaAs/GaAs quantum wells", Z.Y. Xu and C.L. Tang, 13th International Quantum Electronics Conference, Anaheim, CA, June 18-22, 1984.

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1. "Stimulated emission of GaAs-AlGaAs multiple quantum well structures grown by metalorganic chemical vapor deposition", Z.Y. Xu, V.G. Kreismanis, and C.L. Tang, Appl. Phys. Lett., Vol. 44, 136-138 (January 1984).
2. "Equal-pulse correlation technique for measuring femtosecond excited state relaxation times", A.J. Taylor, D.J. Erskine, and C.L. Tang, Appl. Phys. Lett., Vol. 43, 989-991 (Dec. 1983).
3. "Femtosecond studies of intraband relaxation in GaAs, AlGaAs, and GaAs/AlGaAs multiple quantum well structures", D.J. Erskine, A.J. Taylor, and C.L. Tang, Appl. Phys. Lett. (July 1984).
4. "Dynamic Burstein-Moss shift in GaAs and GaAs/AlGaAs multiple quantum well structures", D.J. Erskine, A.J. Taylor, and C.L. Tang, submitted for publication in Appl. Phys. Lett.
5. "Picosecond relaxation of hot carriers in highly photoexcited bulk GaAs and GaAs-AlGaAs multiple quantum wells", Z.Y. Xu and C.L. Tang, Appl. Phys. Lett., Vol. 44, 692-694 (April 1984).
6. "Femtosecond vibrational relaxation of large organic molecules", A.J. Taylor, D.J. Erskine, and C.L. Tang, Chem. Phys. Lett., Vol. 103, 430 (1984).
7. "Femtosecond study of the recovery dynamics of malachite green in solution", D.J. Erskine, A.J. Taylor, and C.L. Tang, J. Chem. Phys. (May 1984).
8. "Second harmonic generation of various sugars in powder form", M.J. Rosker and C.L. Tang, J. Quant. Elect., Vol. QE-20, 334 (April 1984).
9. "Urea optical parametric oscillator", W.D. Donaldson and C.L. Tang, Appl. Phys. Lett., Vol. 44, 25-27 (January 1984).

PROCEEDINGS, CONFERENCE PAPERS, INVITED TALKS

1. "Femtosecond relaxation of hot carriers in semiconductors", C.L. Tang, A.J. Taylor, and D.J. Erskine, Invited talk, Gordon Conference on Nonlinear Optics and Lasers, Wolfboro, NH, August 1983.
2. Invited panelist, Laser Hardened Materials Concepts Workshop, Wright-Patterson Field, Dayton, OH, C.L. Tang, September 27-29, 1983.
3. "Femtosecond optics", C.L. Tang, Invited seminar, 3M Company Science Center, Minneapolis-St. Paul, MN, November 1983.

technique and the corresponding advantages of the new technique are illustrated with numerical results on semiconductors and oprganic dye molecules substantiating the results are shown.

III. Femtosecond studies of intraband relaxation in GaAs, AlGaAs, and GaAs/AlGaAs multiple quantum well structures (Ref. 3). Femtosecond intraband relaxation dynamics of hot carriers in highly excited states of GaAs, AlGaAs, AlGaAs/GaAs multiple quantum well (MQW) structures are studied at room temperature using the equal pulse correlation technique. Initial carrier lifetimes of 35, 60 and 50 femtoseconds are measured for GaAs, $Al_{0.32}Ga_{0.68}As$, and MQW structures for excitation with 2.02 eV photons at low carrier densities, and are in reasonable agreement with calculated scattering rates. The carrier-density dependence of these lifetimes is measured for densities in the range of 1.5×10^{17} to $5 \times 10^{19} cm^{-3}$.

IV. Dynamic Burstein-Moss shift in GaAs and GaAs/AlGaAs multiple quantum well structures (Ref. 4). Time resolved studies of the dynamic Burstein-Moss shift of the absorption edge following intense photoexcitation are reported for room temperature samples of GaAs/AlGaAs multiple quantum well structures. Band-filling times, which correspond to the redistribution of electrons from an energy of 0.5 eV above the bottom of the conduction band to an energy of 0.15 eV, are found to be 1.7 to 1.3 pico-seconds for GaAs in the density range of 0.5 to $2 \times 10^{19} cm^{-3}$ and 1 pico-second for a MQW structure at a carrier density of $2 \times 10^{19} cm^{-3}$. An approximate rate equation model is presented which agrees reasonably well with experimental results.

V. Picosecond relaxation of hot carriers in highly photoexcited GaAs and GaAs-AlGaAs multiple quantum wells (Ref. 5). The relaxation rate of hot carriers following pico-second photoexcitation in GaAs-AlGaAs multiple quantum well structures is found to be significantly slower than the corresponding rate for bulk GaAs under high excitations. This is confirmed by a detailed comparison of the hot luminescence tails for the two cases using picosecond pulsed and cw photoexcitation.

TASK 6 DYNAMICS AND SPECTRAL CHARACTERISTICS OF SEMICONDUCTOR LASER MATERIALS AND STRUCTURES

C.L. Tang

OBJECTIVE

The objectives of this project are (1) to study the ultrafast dynamics of highly excited free carriers in III-V and II-VI compound semiconductors and related quantum well structures and (2) to study the spectral characteristics and the origin of the spontaneous and stimulated emissions of GaAs/AlGaAs quantum well structures.

APPROACH

The basic approach to study the ultrafast dynamics of free carriers in semiconductors is to use the femtosecond and picosecond lasers developed in our laboratory to photoexcite electrons in a given energy range in the conduction band and then measure the relaxation of these carriers from these excited states. To study the spectral characteristics of quantum well structures, our approach is to optically pump these structures using various tunable laser sources developed in our laboratory and then analyze the induced photoluminescence.

PROGRESS

I. Stimulated emission of GaAs-AlGaAs multiple quantum well structures grown by metalorganic chemical vapor deposition (Ref. 1). Well correlated stimulated and spontaneous emission peaks corresponding to electronic transitions from the n = 1 and 2 sub-bands of the conduction band to the corresponding states in the valence band of GaAs-$Al_{0.6}Ga_{0.4}As$ multiple quantum well structure grown by metalorganic chemical vapor deposition were observed. No evidence of phonon-assisted transitions was seen in any of our samples.

II. Equal pulse correlation technique for measuring femtosecond excited state relaxaation times (Ref. 2). A new technique for measuring extremely fast excited state relaxation times, on the order of or less than the laser pulse width in the femtosecond time domain, in the presence of a longer relaxation time is described. The difficulties involved in using the conventional pump-and-probe

31. "Microfabrication for Guided Wave Optics", G.J. Sonek and J.M. Ballantyne, Engineering Cornell Quarterly, 18, 33, 1984.

32. "Picosecond Optical Measurement of Circuit Effects on Carrier Sweepout in GaAs Schottky Diodes", A. von Lehmen and J.M. Ballantyne, Appl. Phys. Lett.

21. "Studies of High Speed Photodetectors in III-V Compounds", A. von Lehmen, S. Wojtczuk, D.K. Wagner and J.M. Ballantyne, paper presented at SPIE's 27th Annual Technical Symposium, August 21-26, 1983, San Diego, CA; Proc. of SPIE - The International Society for Optical Engineering, Picosecond Optoelectronics, 439, 182-184, 1983, G. Mourou, Ed.

22. "Influence of Surface Corrugations on Surface Electromagnetic Waves", E.S. Koteles, Y.J. Chen, G.J. Sonek, and J.M. Ballantyne, presented at the Sur La Dynamique des Interfaces, Lille, France, 12-16 September 1983; published in the special issue of Journal de Physique, C5, 213, April 1984.

23. "A Two-Dimensional Electrooptic Polarization Modulator for Integrated Optics", B. Kushner, D.K. Wagner and J.M. Ballantyne, Proc. SPIE Technical Symposium, Integrated Optics III, 408, 140-144, 1983.

24. "Recent Progress in Microstructures for Electronics", J.M. Ballantyne, Invited seminar at SUNY/Buffalo, November 9, 1983.

25. "Growth and Characterization of Epitaxial GaAs on Ge/Si Substrates", R.M. Fletcher, D.K. Wagner, and J.M. Ballantyne, presented at the Materials Research Society Conference, Boston, MA, November 1983; Proc. Mat. Res. Soc. Symp., V, 25, 417-422, 1984.

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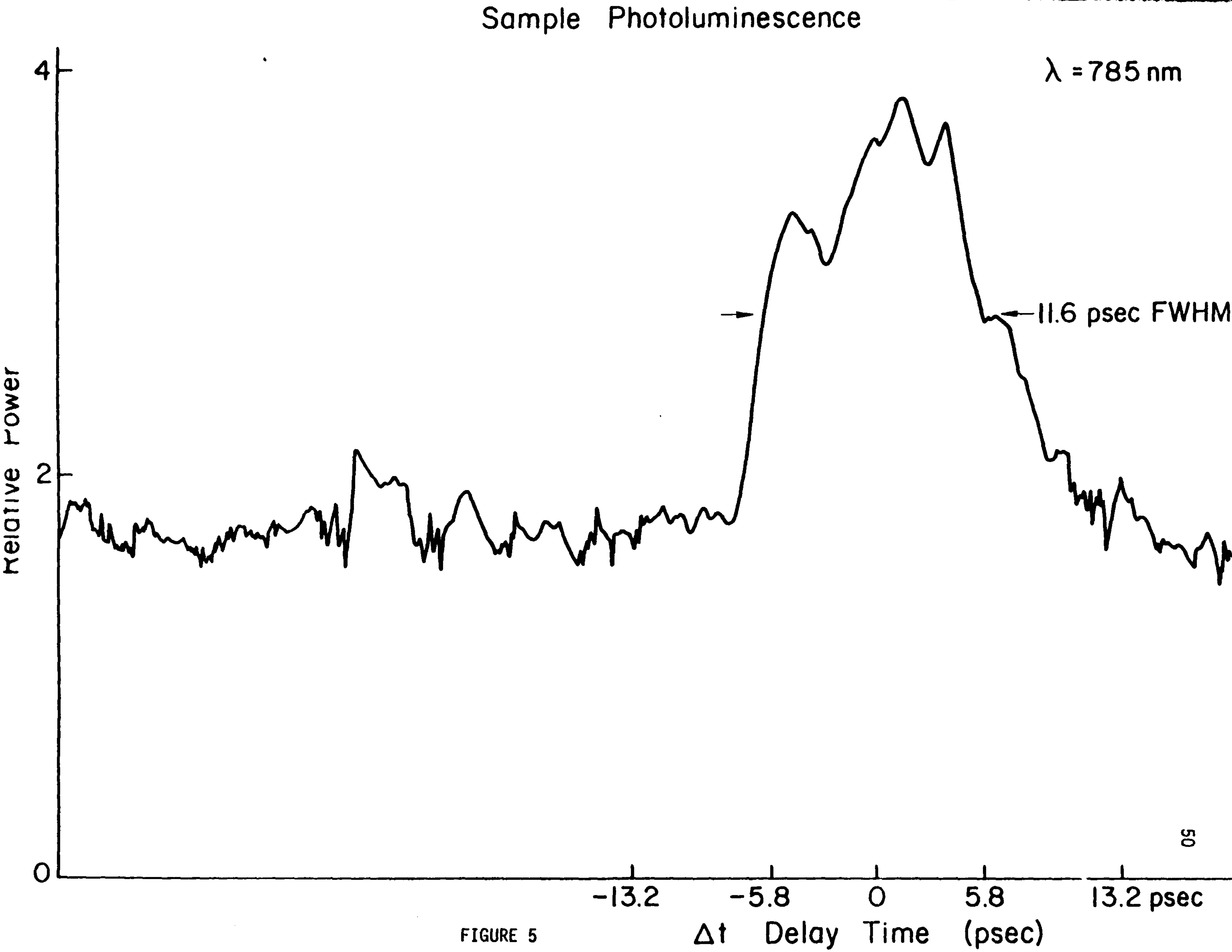
29. "Why We are Inferior to the Japanese", J.M. Ballantyne, Critical Thinking, Ed. Anne Bradstreet Grinols, Cornell University Press, pp. 48-54, 1984.

30. "GaAs Light Emitting Diodes Fabricated on Ge-Coated Si Substrates", R.M. Fletcher, D.K. Wagner, and J.M. Ballantyne, Appl. Phys. Lett., 44, 967, May 1984.

time delay ($\Delta t=0$) there is a distribution of hot electrons and holes created proportional to $f_e f_h$ the product of electron and hole state occupation probabilities. These electrons and holes decay with a familiar luminescence proportional to $f_e f_h$. The situation is different if the two pulses arrive with Δt greater than the relaxation time of hot electrons and holes since each pulse interacts with a relaxed population. If this is the case, each pulse will create half as many electrons and holes as the one large pulse ($\Delta t=0$) did. One pulse of half energy results in one fourth the luminescence ($1/2f_e 1/2f_h=1/4f_e f_h$). The pair of delayed pulses together (Δt greater than the relaxation time) create 1/2 the average luminescence of the superimposed pulses. See Figure 5, which shows a peak average power ($\Delta t=0$) to D.C. value (Δt relaxation time) of two to one. This experiment, therefore, permits a determination of a relaxation time by measuring the time delay required for the average luminescence at the wavelength being monitored to drop from a peak value to a D.C. value of 1/2 the peak value.

Figure 6 is a collection of data like that of Figure 2 but signal averaged and showing data at various luminescence wavelengths. The average power of luminescence depends on the wavelength being investigated. Noted from this plot are the number of decay times obtained if one measures time delay between peak average luminescence and D.C. luminescence. This spread of the relaxation time is a result of a statistical averaging of all inherent relaxation times as the hot electrons and holes relax to the states from which luminescence is observed. The farther the luminescence is probed from excitation the larger the complexity of the decay process becomes apparent and hence a larger overall relaxation time is recorded.

Due to the small average luminescence power relative to the larger laser "pump/probe" power scattered into the collection optics a measurement of luminescence at $E=E_{pump}$ is not directly possible. However, a good estimate of the overall relaxation time inherent in the sample being monitored can be made. As shown in Figure 7, a collection of relaxation times obtained through plots of the type shown in Figure 2 are plotted. Subsequently, an extrapolation towards luminescence at the excitation wavelength of observed relaxation times is constructed from this plot. The extrapolation of Figure 4 shows a relaxation time of 7 ± 1



Sample Photoluminescence
λ = 785 nm
11.6 psec FWHM
Relative Power
4
2
0
−13.2
−5.8
0
5.8
13.2 psec
Δt Delay Time (psec)

FIGURE 5

Photoluminescence Power vs Δt

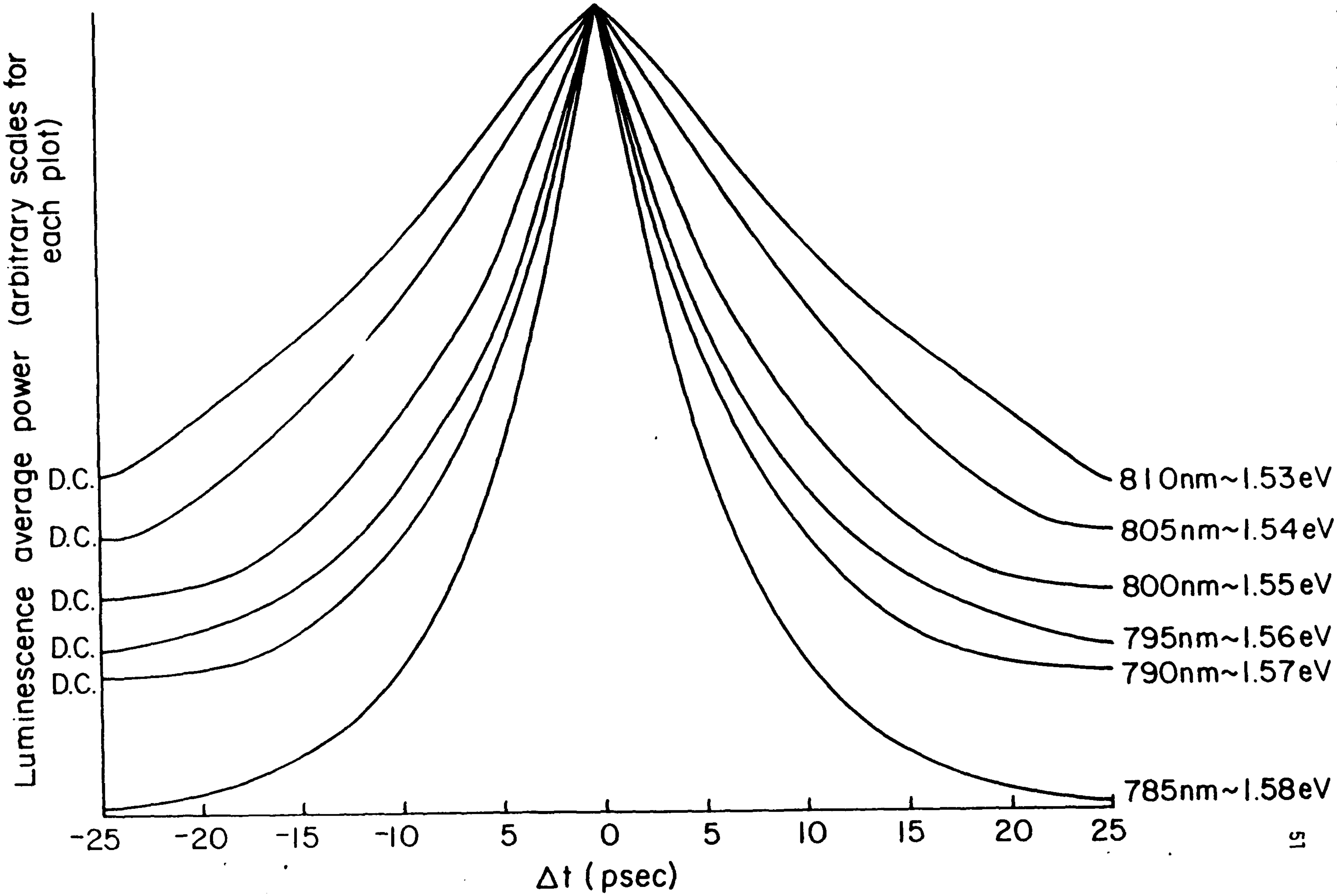
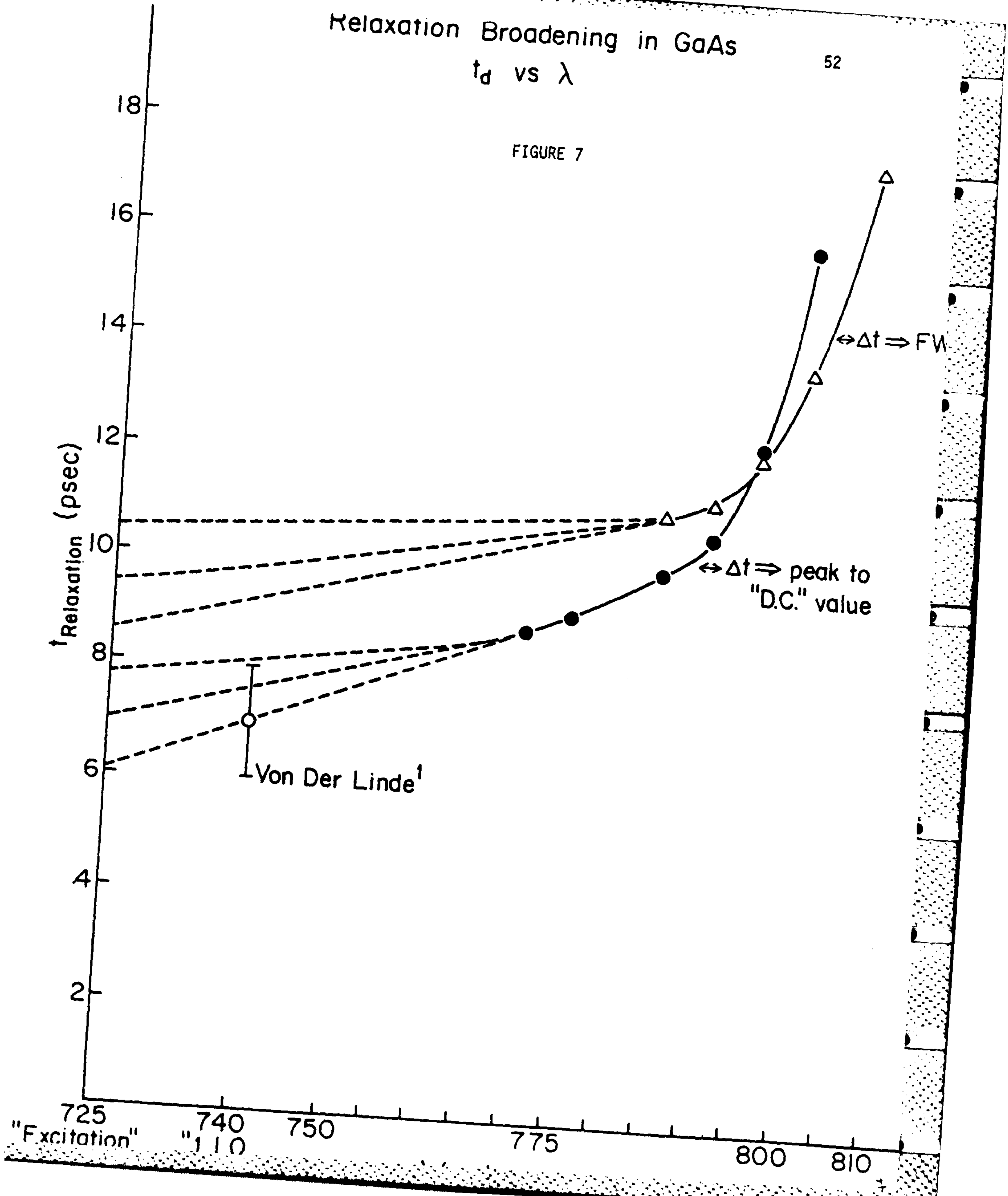


FIGURE 6



Relaxation Broadening in GaAs
t_d vs λ
FIGURE 7
$t_{Relaxation}$ (psec)
18
16
14
12
10
8
6
4
2
↔Δt ⇒ FW
↔Δt ⇒ peak to "D.C." value
Von Der Linde[1]
725
740
750
775
800
810
"Excitation"

psec. Figure 4 also contains an extrapolation of FWHMs obtained from plots like that of Figure 5. Assuming an exponential relaxation mechanisms (.725 correlation factor), a relaxation time of (.725) (FWHM extrapolation) = 6.9±.7 psec is obtained.

In a paper by Von der Linde, et al. (D. Von der Linde, J. Kuhl and H. Klingenberg, Phys. Rev. Lett., 23, 1505 (1980), a modified excite and probe experiment on GaAs utilizes Raman scattering to measure a relaxation time. The experiment measures the intensity of Stokes shifted light (1 LO phonon from excitation) as a function of relative time delay between two pulse trains scattered off a sample. As shown in Figure 7, the results of the Von der Linde experiment (7±1 psec) fall well within the results extrapolated above.

The data described above used a "pump/probe" wavelength of 725 nm. Current effort is directed at the collection of data at other "pump/probe" energies. There is interest in extending the measurement of luminescence to shorter wavelengths to confirm the extrapolation of Figure 4, as well as to pump at shorter wavelengths to permit electron excitation/scattering into the upper conduction band valley. The latter experiment may reveal differences in the measured carrier relaxation and is relevant to the design of devices utilizing hot electrons injected at a heterojunction where limitations on the electron energy may be required.

CURRENT AND FUTURE EFFORTS

The possibility of ballistic electron transport in gallium arsenide has been predicted by numerous researchers. However to date there has been no direct, conclusive experimental evidence to verify this. Monte Carlo simulations suggest that ballistic electron transport will occur over crystal dimensions of nearly 1 micron. These simulations show the velociy distribution remains well defined with a velocity centered at 5-8 x 10^7cm/sec for an initial injection energy of 210 meV. A direct measurement of the electron velocity will determine if ballistic electron transport does occur and how the crystal parameters (dimension, temperature, impurities) affect the velocity distribution.

We propose to measure the electron velocity by Thomson scattering of photons by the electrons within the crystalline material of an active device. The Doppler shift of the scattered photons is directly related to the component of the electron velocity parallel to the direction of observation. Thus the goal of the experiment is to collect the elastically scattered photons and determine the Doppler shift and hence their velocity distribution.

1. Jeffrey Yuh-Fong Tang and Karl Hess, IEEE Transactions on Electron Devices, Vol. ED-12, No. 29, Dec. 1982.

The experimental apparatus consists of a tunable dye laser, a spectral filter, a detector and photon counting system, and a specially designed electron launcher.

It is crucial that the incident photons do not induce band to band transitions since this would introduce electrons with different initial kinetic energy into the conduction band. Hence the photons should be of wavelength greater than 870 nm. The source of the light is to be a tunable dye laser with center frequency of 900 nm and a spectral width of a few gigahertz. A bandwidth of one gigahertz corresponds to a line width of about .1 Å at 900 nm. This sets the ultimate spectral resolution of the measurement which, in turn, determines the velocity resolution. A linewidth of .1 Å will allow the velocity to be resolved to within 10^5cm/sec. However other considerations such as total signal power and the spectral resolution of the spectral filter will change this to about 10^6cm/sec.

$$\Delta_{\text{scattered}} = \frac{v_e}{c}\,\nu_{\text{incident}} \text{ for } 180^0 \text{ backscattering}$$

The Doppler shift is expected to be small $\left(\frac{\text{electron velocity}}{\text{photon velocity}} = \frac{10^7\ \text{cm/sec}}{10^{10}\ \text{cm/sec}} = 10^{-3}\right)$. At 900 nm this is a 9 Å shift. Thus the shift is expected to be betweeen 10 Å → 70 Å since the velocity is expected to be between 2 x 10^7cm/sec → 8 x 10^7cm/sec.

The Doppler shift will be determined by filtering the collected scattered light with a five pass scanning Fabry-Perot etalon. The parameters of the multipass etalon are determined by the required resolution and contrast. The contrast is the ratio of signal throughput during maximum transmission to the signal throughput when the signal is not in the passband of the filter. The parameters can be evaluated by calculating the expected signal strength and expected noise strength.

The expected number of collected Doppler shifted photons per incident photon is given by

$$n \frac{d\sigma}{d\Omega} \Delta\Omega \ell N \quad .$$

where n is the number of carriers $\frac{d\sigma}{d\Omega}$ is the differential scattering cross section, $\Delta\Omega$ is the collection solid angle ℓ is the interaction length, and N is the number of incident photons.

The differential cross section is given by the classical electron cross section modified by the effective mass of the electron in the GaAs crystal lattice

$$\frac{d\sigma}{d\Omega} = \left(\frac{e}{4\pi\tau_o} c^2 m^2\right)^2 = r_e^{\,2} \left(\frac{M_o^{\,2}}{M_e^{*\,2}}\right) \; ; \; M^*_e = .062\ M_o$$

$$= 2.0 \times 10^{-23} cm^2/STR$$

The launcher is being designed to have an active region of .5 micron with a carrier density of $10^{16} cm^{-3}$.

Thus the total number of Doppler shifted scattered photons is

$$R_s = 10^{16} cm^{-3}\ (.5 \times 10^{-4} cm)\ (2 \times 10^{-23} cm^2/STR) \times \Delta\Omega$$

$$= 10^{-11} \ \frac{\text{scattered photons}}{\text{incident photon - STR}}$$

The number of collected unscattered photons is estimated from measurements made with polished GaAs substrates to be 10^{-4} of the pump power (in 1 STERADIAN). Thus the unfiltered signal to noise is

$$\frac{1 \times 10^{-11}}{1 \times 10^{-4}} = 10^{-7}$$

which requires a contrast of 10^9 to yield a S/N of 100.

For 1/2 watt input (5×10^{18} photons/sec) the total number of signal photons is

$$\text{number signal photons} = 2 \times 10^7$$

Hence the total system efficiency must be greater than 10^{-3}-10^{-4} to insure that more than 100 counted photons/sec are expected. The 5 pass etalon is designed for contrast = 10^9; transmission efficiency = 10%.

An additional signal enhancing technique which will be employed is low frequency (1 hz) modulation of the electron injection with synchronous photon counting. Photons counted when the device is off will be subtracted from the number counted when the device is on thus removing the background from the signal.

By incorporating each of these features, the expected S/N is greater than 100. The scanning etalon will have a free spectral range of ~ 30 cm^{-1} and a finesse of 40. This determines the resolution which is 1 Å. A 1 Å resolution corresponds to a velocity resolution of 10^6cm/sec. The accuracy of the absolute velocity measurement is expected to be of this same order (10^6cm/sec) and will depend on the accuracy of distinguishing the peaks of both the unshifted laser line and the Doppler shifted signal.

The launcher is being designed to contain an optical window through which the incident photons enter the crystal and the scattered photons are collected. The general features of the device are depicted in Figure 8.

The lowest layer is the n^+ GaAs substrate under which an ohmic contact is evaporated. On top of the substrate an AlGaAs layer is grown followed by the ballistic transport region of GaAs. The AlGaAs is proportioned so that a bandgap difference of 200 mev exists between the GaAs and AlGaAs layers.

Following the GaAs layer is an ohmic contact consisting of an n^+ GaAs layer which is transparent to the 900 nm pump beam, and a metalization layer. The 100 micron optical window is then etched in the metal layer.

The direct measurement of the electron velocity by Doppler shifted Thompson scattering will be an invaluable tool to be used in characterizing electron velocity profiles in semiconductor device structures. Since the technique is inherently nonintrusive it can be used

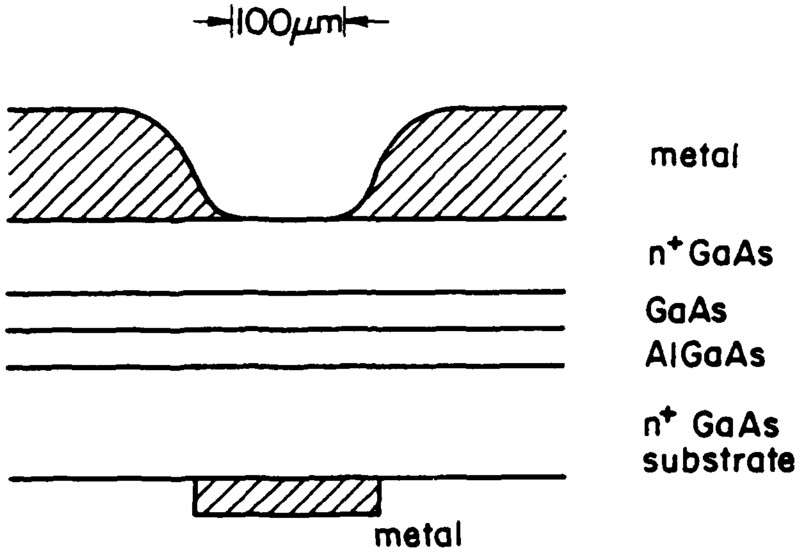


FIGURE 8

whenever optical access to the region of interest is available. Devices or device structures can be evaluated and the results used to confirm the design.

TASK 8 ADVANCED DESIGN TECHNIQUES FOR MICROWAVE GaAs FET AMPLIFIERS

W.H. Ku

OBJECTIVE

The primary objectives of this continuing research program are to derive fundamental device/circuit performance limitations for GaAs metal-semiconductor FETs (MESFETs) and to develop advanced and integrated analytical and computer-aided design (CAD) techniques for the synthesis and design of GaAs MESFET amplifiers, mixers and VCO's leading to monolithic microwave integrated circuits (MMICs) and subsystems. A secondary objective of this research program is to fabricate prototype GaAs MESFET amplifiers and circuits in microstrip and monolithic realizations using state-of-the-art submicron gate-length MESFETs to verify the integrated design approach developed in the main portion of this 6.1 JSEP program.

It is anticipated that, because of the fundamental nature of this proposed research, the results obtained should have a direct and significant impact on various DOD programs involving ultra-wideband GaAs MESFET amplifiers and MMICs which are directed to ECM and EW system applications and monolithic transceiver modules for phased array applications.

APPROACH

Tremendous progress has been made over the past several years in low-noise and power GaAs MESFET devices and integrated circuits. Low-noise GaAs MESFETs with submicron gate lengths using optical and e-beam lithography have been reported which can operate at frequencies up to 60 GHz. Power GaAs FETs are capable of output powers of hundreds of milliwatts at Ku- and Ka-bands. More significantly, recent advances in monolithic integration of GaAs integrated circuits (ICs) have stimulated great interest in the applications of GaAs ICs for both analog and digital systems.

It is expected that with the advent of monolithic realizations, the complexity of the device and circuit design for GaAs ICs will increase significantly. Techniques common to the design of silicon ICs must be developed for GaAs ICs. We have developed an integrated approach involving both analytical and computer-aided design and synthesis techniques for the design of monolithic GaAs ICs. New and innovative circuit designs including feedback and distributed amplifiers have been studied. Nonlinear circuit analysis programs are being developed for the analysis and design of monolithic GaAs MESFET devices and circuits. An integral part of our technical approach is to verify our designs by the design and actual fabrication of prototype monolithic GaAs MESFET circuits.

PROGRESS

Significant progress on this unit of the research program was made on the successful design and fabrication of state-of-the-art submicron gate-length GaAs MESFETs and broadband monolithic medium-power GaAs MESFET amplifiers. In addition, new analytical and computer-aided design techniques have been developed for monolithic GaAs MESFET feedback amplifiers, distributed amplifiers and mixers. A new computer-aided synthesis technique applicable to odd-order lumped and distributed matching networks has also been successfully developed. This work has resulted in a number of publications, conference presentations and two patent disclosures.[1-13]

Results we have obtained on sub-half-micron GaAs MESFETs are comparable to the best achieved in any laboratory and our successful fabrication of monolithic medium-power amplifiers is a first in any university. Progress of our research is summarized in the following subsections.

a) Design and Fabrication of Submicron Gate-Length GaAs MESFETs

Fabrication technology for extremely-short gate length GaAs single- and dual-gate MESFETs has been developed to minimize parasitic resistances. Based on the developed technology, a DC transconductance of 360 mS/mm gate width was observed in a GaAs FET. Three optical lithographic techniques have also been developed to produce state-of-the-art sub-quarter-micron gate structures. 0.2 micron long Cr/Au gates with thickness of 0.9 micron have been successfully fabricated by using the first technique, which we call the pile-up masking technique.[7] These gate structures are superior to the state-of-the-art gates fabricated by electron beam.

Gate lengths were further minimized to 0.1 micron with an aspect ratio (gate thickness/gate length) of approximately 20 by employing the second gate technique which we call the gate-wall technique.[4,5] Using this high aspect-ratio gate structure, GaAs MESFETs have been fabricated with gate lengths as short as 0.1 micron and widths as wide as 300 micron. Electrical properties of GaAs FETs with long and ultra-short gate lengths fabricated by this technique were experimentally compared for the first time.[6] The gate length effect on the FET transconductance, pinchoff voltage, drain current, output conductance and knee voltage were evaluated.

A new fabrication technique has been developed to generate sub-half-micron T-shaped (or mushroom) gates in GaAs MESFETs.[10] The technique uses a single-level resist and an angle evaporation process. (A patent disclosure on this new technique has been filed). By using this technique, T-shaped gates with lengths as short as 0.2 micron near the Schottky interface have been fabricated. Measured gate resistance from this structure was 6.1 ohm/mm gate width which is the lowest value ever reported for gates of equal length. GaAs single- and dual-gate MESFETs with 0.3 micron long T-shaped gates have been fabricated. At 18 GHz, maximum available gain of 9.5 dB in the single-gate FET and maximum stable gain of 19.5 dB in the dual-gate device have been measured.[10]

b) Design and Fabrication of Broadband GaAs Monolithic Microwave Power Amplifiers

A broadband 6-12 GHz medium-power GaAs monolithic power amplifier has been successfully designed, fabricated and tested based on the work of this research unit. This represents the first successful MMIC realization of GaAs MESFET amplifiers in any university of the U.S. and abroad. We obtained 165 mW of output power with 5 dB of power gain across the octave frequency band of 6-12 GHz. The submicron GaAs FET used has 600 micron total gate periphery and was fabricated using the angle evaporation technique described previously. A combined computer-aided synthesis and large-signal dynamic characterization technique was used in the design of the broadband monolithic power amplifier.

c) Computer-Aided Synthesis for MMICs

Computer-aided synthesis of lumped and distributed element even-order

)lifier matching networks developed by Ku and Petersen has been extended include odd-order networks.[12] The gain-bandwidth performance of ıeral odd-order networks as well as that of several specific odd-order pologies have been evaluated explicitly. Tables of circuit element lues for a number of lumped and distributed element topologies for rrow and wide bandwidths have been obtained. These results provide neral design information for monolithic microwave GaAs MESFET amplifiers d represent a further advance in the computer-aided design and synthesis monolithic microwave integrated circuits (MMICs). Results are esented in a Ph.D. dissertation by Air Force Captain Jerry Dijak, titled "Computer-Aided Synthesis and Design of Monolithic Microwave GaAs SFET Amplifiers". A paper describing our LUMSYN program has been blished[13] and the program is ready for distribution through a Cornell cense agreement.

Design of Monolithic GaAs MESFET Distributed Amplifiers

We have recently developed a new and general design theory for ınolithic GaAs MESFET distributed amplifiers. Preliminary results of ıis design theory have been presented recently[12] and a more complete ıper was presented at the IEEE/Cornell Conference on High Speed ›miconductor Devices and Circuits in August 1983.[14] Monolithic istributed GaAs FET amplifiers have been reported in the literature but ıe designs are based on a number of simplifying assumptions which ›strict their general applicability. The design theory we have developed ; more general and is applicable to both lumped and distributed gate and ·ain matching elements. Based on measured 0.5 micron and 0.25 micron ıAs MESFET characteristics, the predicted distributed amplifier responses :tend from 2 GHz to 26 GHz and 40 GHz, respectively.

Computer-Aided Simulation and Design of Microwave MESFET Mixers

We have developed a nonlinear MESFET circuit modeling and analysis ›mputer program based on state variables formulation and fast convergent ime-domain analysis. This new computer program has been used for the ›mputer-aided simulation and design of microwave GaAs MESFET mixers. ixers considered include single ended single- and dual-gate FET mixers ıd balanced mixers. This program fills a void in the area of computer-

"The Limits of Electron Ballistic Motion in Compound Semiconductor Transistors", L.F. Eastman, 1981 Int. Symp. on Gallium Arsenide and Related Cpds, Tokyo, Japan (Sept. 20-23, 1981); Inst. Phys. Conf. Ser., 63 (6) 245-250 (1982).

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. "Measurement of the J-V Characteristics of a GaAs Submicron n^{+}=n^{-}-n^{+} Diode", M.A. Hollis, L.F. Eastman and C.E.C. Wood, Electronics Lett., 18 (13) 570-572 (June 1982).

epend on minimization of parasitic resistances and capacitances, but hould eventually exceed 200 GHz.

EGREES

. A.S. Brown, M.S., May 1984
"The Growth of $Ga_{.47}In_{.53}As$ Planar-Doped Barrier Devices by Molecular Beam Epitaxy"

:. R. Sadler, Ph.D., January 1984
"Fabrication and Performance of Submicron GaAs MESFET Digital Circuits by Self-Aligned Ion Implantation"

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2. "GaAs Planar Doped Barrier Transistors", R.J. Malik, M.A. Hollis, L.F. Eastman, D.W. Woodard, C.E.C. Wood and T.R. AuCoin, DRC, Santa Barbara, CA (June 22-24, 1981).
3. "Experimental Studies of Ballistic Transport in Semiconductors", L.F. Eastman, Third Inter. Conf. on Hot Carriers in Semiconductors, Montpellier, France (July 1981); J. de Physique, Col. C7, Sup. °10, Tome 42, C7-263-C7-269 (Oct. 1981).
4. "Limits of Ballistic Electron Motion in Compound Semiconductors", L.F. Eastman, Proc. 8th Biennial Conf. on Active Microwave Semiconductor Devices and Circuits, Cornell University, Ithaca, NY (Aug. 11-13, 1981); 65-74 (1982).
5. "GaAs Planar-Doped Barrier Transistors Grown by Molecular Beam Epitaxy", R.J. Malik, M.A. Hollis, L.F. Eastman, D.W. Woodard, C.E.C. Wood and T.R. AuCoin, Proc. 8th Biennial Conf. on Active Microwave Semiconductor Devices and Circuits, Cornell University, Ithaca, NY (Aug. 11-13, 1981); 87-96 (1982).
6. "Planar Doped Barrier Transistors in GaAs Grown by Molecular Beam Epitaxy", R.J. Malik, M.A. Hollis, L.F. Eastman, D.W. Woodard, C.E.C. Wood and T.R. AuCoin, Third Workshop on MBE, Santa Barbara, CA (Sept. 10-11, 1981).

The third transistor is the vertical FET with ballistic electron ıjection. Up to about .36 V injection energy can be used before ıbstantial transfer to the GaAs upper valley occurs. Only .18 V otential step would normally occur if $Al_{.235}Ga_{.765}As$ N^+ material were used o launch ballistic electrons into N GaAs material. In order to raise his injection energy, a doping dipole should be added to have an dditional about .18 V potential step. This could either be built into he N GaAs drift material or into the N^+ AlGaAs launcher material, or can traddle the heterojunction. The dipole is formed by having the electrons irst encounter a thin layer of acceptors, followed by a thin layer of xtra donors. The acceptor and donor densities would be high, equal to or reater than the doping in the N^+ $Al_{.235}Ga_{.765}As$. The electrons flowing ill have a density well under this value and will thus not create any erious space charge self-limitation in current flow.

If there is no launching potential step, as discussed earlier, the lectrons have only about 4 x 10^7cm/s maximum value average velocity. his value can be reached for 1 x $10^{17}/cm^3$ doping only if the total athode-anode drift space is held at or below .3 micron. Less doping llows a longer drift space such as .32 micron with 6 x $10^{16}/cm^3$ doping or 36 micron with 2 x $10^{16}/cm^3$ doping. For about 4 x 10^7cm/s average lectron velocity, these .30, .32 and .36 micron lengths, with 1 x $0^{17}/cm^3$, 6 x $10^{16}/cm^3$ and 2 x $10^{16}/cm^3$ doping yield current density alues of 6.4 x $10^{15}A/cm^2$, 3.8 x $10^5A/cm^2$ and 1.3 x $10^5A/cm^2$ respectively. ll these designs are marginal, when the associated lithography and yield re considered in light of today's technology. Also, space-charge limited urrent injection could yield lowered output resistance for such short tructures. Longer structures were tried, as discussed previously.

When there is a potential step for launching ballistic electrons, the verage electron velocity is as high as 8 x 10^7cm/s across a short drift pace ($\leq$ .5-.75 micron for ion density at or below about 3 x $10^{16}/cm^3$). n a moderate electric field of 2,000 V/cm or so, the energy of the lectron is kept nearly constant, and the small-angle scattering of the allistic electrons by polar optical phonons limits the distance over hich the high average electron velocity can be maintained. The transit ime of about .75 psec for such a .6 micron long device allows an ntrinsic f_T value exceeding 200 GHz. The f_{max} values possible will using high doping or thickness in the base was not possible without lowering the momentum sharply. This in turn would sharply lower the current gain for an adequate collector barrier, needed to stop thermionic electron emission from the base into the collector. This approach was thus considered less likely to yield high performance than the ballistic electron heterojunction bipolar transistor, or the ballistic electron injection vertical FET.

The ballistic electron heterojunction bipolar transistor was studied with $Al_xGa_{1-x}As$ emitters having x = .20-.25 in order to have shallow donors. Doping up to 4 x $10^{17}/cm^3$ has been used in the emitter. The base had acceptors of 5 x $10^{18}/cm^3$ in most cases and ranged up to 2000 Å in thickness. Values of the current unity gain frequency (f_T) have ranged up to 16 GHz and the power unity gain (f_{max}) frequency up to about 13 GHz. Static current gain values ranged from 20-200, being traded off inversely for f_T. This trade off was made by tapering the aluminum content over about 100 Å at the heterojunction. More abrupt heterojunctions gave higher f_T, but lower current gain. It was also found to be necessary to stop the heavy base doping 100 Å or more away from the heterojunction in order to prevent the acceptors from drifting into the AlGaAs and lowering the current gain. The build-in electric field was the driving force for this drift. In the devices of higher f_T, first order measurements showed that the transit time for electrons across the base was nearly negligible, being 10-20 times less than for the diffusion typical of such bipolar transistors without the ballistic electron launch condition. The key problem in obtaining high f_{max} was the base resistance. It in turn was high due to the high specific contact resistance to the p-type base material. This specific contact resistance was 10^{-3} to 10^{-4} Ω-cm^2 rather than the 10^{-6} Ω-cm^2 required for good operation. Because of the short base contact fingers, the base resistance was nearly 1000 times the value desired. Thus, with effort, this device should be capable of operating at high speed and high frequency. A program was proposed to WPAFB, and was accepted for technical content, but Cornell could not accept new, strict conditions on information transfer that were imposed by the A.F. Systems Command. The program is proceeding on a very limited effort basis with industrial support. Projected limits, after considerable effort, should reach f_T = 100 GHz.

such transistor was the planar doped barrier transistor. It used the planar-doped barrier to launch and retrieve the ballistic electrons, with an N^+ base region, having no drift field, between the two barriers for bias application. The second such transistor was the heterojunction bipolar transistor, which could have a drift field built into its base by having a gradient of aluminum across the base. This bipolar transistor has AlGaAs for its emitter and has either GaAs or AlGaAs with a low, tapered Al fraction, and has a GaAs collector. The third transistor is a vertical MESFET with the AlGaAs/GaAs heterojunction for launching ballistic electrons into the low-field, drift region. These transistors will be discussed in more detail below.

One other electron device being studied at Cornell is the electron ballistic injection and exchange transferred electron device (BIXTED). In this device, the electrons are injected at a fairly high energy, just below the upper valley energy, yielding high average velocity, when the bias voltage is low. At much higher bias, the electrons are forced to transfer to the upper valley a short distance from the launch point, yielding low average velocity. Instead of the usual Gunn device with 2 micron length, a BIXTED for 100 GHz would be about .75 micron long, and would have higher operating efficiency. The rise in operating efficiency is due to a higher peak velocity to valley velocity ratio, the elimination of the 1 micron lossy "dead space" for heating electrons, and the shorter recovery time each cycle due to the spatial removal of hot electrons. This device is being pursued with a small grant from industry.

The first of the transistors, the planar doped barrier version, was pursued for about one year on a DARPA subcontract from General Electric. After succeeding in obtaining reproducible planar doped barriers with .20-.25 eV and higher barrier heights, transistors were made and constructed. The electron momentum loss through the N^+ base was determined for ballistic electrons injected with about .25 V energy. The momentum was halved by passing through 1200 Å base thickness with $7 \times 10^{17}/cm^3$ donor and electron density. Coupled plasmon -1.0 phonons were determined to be approximately the main scattering mechanism, and momentum loss was found to be proportional to the doping times thickness product. Power gain values of about 6 db at 77^oK, and unity current gain frequency values of over 20 GHz were obtained. It was clear that low sheet resistivity by

AlGaAs buffer layer is needed. This could be done with an inverted modulation doped structure, or with the modulation-doped quantum well recently initiated at Cornell.

Vertical FET devices, .5 micron long between source and drain N^+ contacts were tested also. Gradual acceleration, mixed with collisions, occurred during electron drift. One had $7 \times 10^{15}/cm^3$ doping and the other had $5 \times 10^{16}/cm^3$ doping in the active region. Based on an analysis of the I(V) curves, including the voltage drop across the source resistance and the built-in Schottky barrier voltage, average electron velocity values were determined. These were about 3.5×10^7cm/s for the $7 \times 10^{15}/cm^3$ doping, and 2.3×10^7cm/s for the $5 \times 10^{16}/cm^3$ doping. These values did not quite reach the limiting values of $\geq 4 \times 10^7$cm/s because they were longer than the .4 micron required for such near ballistic devices, and because they had moderate doping. Without even more doping, and shorter drift distance to obtain higher velocity, the g_m values and current density values would be too low for high frequency operations. Again, if modulation-doped FET's were made $\leq$ .4 micron, they would have high electron density without ions to cause collisons. Thus high performance would be expected, if the high energy electrons can be confined.

Ballistic Injection of Electrons in Transistors

When electrons are injected into a GaAs drift region with high velocity, and the electron energy is maintained with a moderate electric field, then the electron average velocity during transit is about double that for gradual acceleration. Because mean free path length is larger, and the scatter angle is lower for such energetic injected electrons, a longer drift distance is possible. For lightly doped ($<< 10^{17}/cm^3$) drift regions it can range from .5-.75 micron depending on the injection energy. This energy must remain below the .36 eV energy of electron transfer to upper valleys in GaAs. It takes about .1 psec or about .1 micron distance for transfer. Such transfers completely redirect the electron momentum, increase the electron mass, and thus yield very low average electron velocity.

Three different transistor configurations were conceived at Cornell to make use of this injection of ballistic electrons with high energy. One were made using self-aligned, ion-implanted ohmic contacts. The maximum density of the ions in the channel was 9 x $10^{16}/cm^3$ for all the devices tested. Mask lengths of down to .50 micron were used, yielding about .40 micron separation of source and drain when the side scattering of the implanted ions was considered. In order not to cause excessive device capacitance, the implanted contacts were placed .1 micron from the gate metal on each side, using a T-shaped cross section for the gate metal.

During the course of this work, using normally-off logic transistors, several interesting results occurred. First, a new world record switching speed of 15 ps at room temperature was achieved for .75 micron separation of source-drain implants corresponding to .55 micron gate length. Next, it was shown that shorter structures with the same periphery were slower, yielding 16.7 ps for a structure with .50 micron source-drain and .30 micron gate length. All devices had a nominal 10 micron periphery and the same interconnecting circuit. The periphery was kept small, to lower the power required. While the device g_m was rising as the length was shortened, the output conductance was rising faster. The high output conductance robbed away output current from the g_m, charging the interstage capacitance more slowly. The output conductance due to space charge limited current flow in the fringing electric field in the source-drain region was rising approximately as the square of the reciprocal of the effective electric length of the device. It reached .025 Ω mm or 40 Ω mm output impedance for .50 micron source-drain separation. Of course a larger periphery FET could switch the interstage capacitance faster, but would require more power. In future logic devices, this would have to be partially cured by symmetry in vertical FET devices, or by having an AlGaAs buffer layer under the GaAs active layer. The same conclusions apply to obtaining high frequency transistors.

The electron velocity did not rise in these short GaAs doped-channel MESFET's at room temperature. Earlier at Toshiba, epitaxial .25 micron gate MESFETS yielded 2.0 x 10^7cm/s average electron velocity, and recently at G.E. a .25 micron gate MESFET with about .35 micron effective source-drain spacing yielded 2.1 x 10^7cm/s average electron velocity, both at 300^oK.

In order to get near ballistic electron velocity and a much lower output conductance, a .5 micron long undoped active channel layer with the doping level. Thus the distance over which near ballistic electrons can be maintained with high average velocity is shorter with $1 \times 10^{17}/cm^3$ doping than with pure GaAs.

An initial test of our idea of ballistic electrons was briefly made with an early DARPA contract. It consisted of testing I(V) of thin GaAs layers with $2 \times 10^{15}/cm^3$ calibrated doping density. Since this doping density was 50 times lower than that required for equal frequency of ion and phonon scattering, it was safe to neglect the ion scattering. Since the limiting peak ballistic electron group velocity is about 9.5×10^7cm/s in the [100] crystal direction in GaAs, gradual acceleration across these layers would yield half this value for the average electron velocity in the ballistic limit. It was expected that near ballistic electron velocity could be obtained for .40 micron separation of N^+ contacts. At .50 eV bias, 25,000 A/cm^2 were obtained at both 300°K and 77°K. The average electron velocity was calculated, after accounting for space charge injection of electrons. Approximately 4×10^7cm/s was calculated from these data. Some time later a detailed Monte Carlo theory done in France obtained about 3.7×10^7cm/s for a simulation of this device. Another experimental device at Cornell with the same doping had .24 micron length and yielded 40,000 A/cm^2 at .40 eV bias at 300°K, 77°K, and at 8°K. Just over 4×10^7cm/s was calculated from these data. Monte Carlo calculations in Japan yielded about 4.2×10^7cm/s average velocity for a .25 micron long device, and a Bell Laboratory experiment using two short optical pulses yielded about 4.4×10^7cm/s for .22 micron drift distance. The conclusion then was that, if doping was $<< 1 \times 10^{17}/cm^2$, electron velocity was within 20% of the ballistic limit if the devices were equal to .40 micron length or less. The independence of the current of temperature changes also gave clear evidence of near ballistic electron dynamics, nearly free from the crystal phonon activity. It could also be concluded that for $1 \times 10^{17}/cm^3$ doping, structures would need to be .20 micron length or so to obtain near ballistic velocity. Monte Carlo results on .25 micron structures with $7 \times 10^{16}/cm^3$ doping did show the near ballistic results, for example.

<u>Short GaAs MESFET</u>

In order to test for elevated electron velocity, short FET devices

TASK 10 GALLIUM ARSENIDE BALLISTIC ELECTRON TRANSISTORS

L.F. Eastman, C.E.C. Wood, D.W. Woodard and G.W. Wicks

OBJECTIVE, APPROACH AND PROGRESS

Introduction

During the past three years this task has been devoted to the fundamental study of ballistic electrons in GaAs and their use in transistors for high frequency operation. Electron velocity above the 1.2 x 10^7cm/s in GaAs MESFET's was sought for improved transistor frequency response. This report covers the fundamental limits of fast, ballistic electrons, the experiments done to show these limits, and some of the initial transistor results.

Fundamental Physical Effects

Electrons in pure GaAs have long mean free path lengths when they have about .3 eV energy. The collisions are predominantly with polar optical phonons, the mean free path is about .22 micron at 77^{o}K, and is .18 micron at room temperature. The collision frequency rises only slightly with reduced energy, yielding mean free paths of .08-.10 micron in the energy range of about .075-.10 eV. The scattering during such collisions is mainly forward, with an average angle of about 15^o for the .3 eV electrons, and rising to near 30^o or more for the electrons with less than .1 eV energy. The low angle of deviation from the original direction of mome tum allows a few collisions to happen before the momentum angle has become random. Thus by making up the .036 eV energy, lost in launching each polar optical phonon, with an electric field of about 2,000 v/cm, the direction and magnitude of the momentum can be nearly maintained for a few mean free path lengths. If the electron energy is raised above .36 eV, electrons transferred to upper valleys in the [111] direction become massive, and slow down. In the limit, no energy is lost, and the electron has a desired kinetic energy equal to the potential drop yielding that kinetic energy. In this limit the electron has been termed "ballistic", and near this limit, "near ballistic".

At 1 x 10^{17}/cm^3 donor density, the mobility of GaAs is half that of pure material, at 300^{o}K. This means that there is effectively an equal frequency of collision with ions as with polar optical phonons at this

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2. "a) Physical Realizability, b) Gain-Bandwidth Theory, c) Circuit Models for Dielectric Wave Guide", H. Carlin, 1982 Electrotechnical Systems Institute of Turin, Turin, Italy (Jan. 1982).
3. "Matching Applied to Microwave FET's", H. Carlin, RCA Labs, Princeton, NJ (March 1982).
4. "New Methods of Broadbanding", H. Carlin, Tokyo Inst. of Tech., Tokyo, Japan (May 1982).
5. Series of lectures on "Modern Developments in Network Theory", H. Carlin, Tianjin University, China (June 1982).
6. "That Perennial Problem of Broadband Matching", H. Carlin, IEEE St. Louis Section Meet., Washington University of St. Louis (Oct. 1982).
7. "The Ancient Modern Art of Broadband Matching", H. Carlin, IEEE Boston Section Meet., MIT Lincoln Labs (Jan. 1983).
8. Series of lectures on "New Directions in Gain-Bandwidth Theory", H. Carlin, University College, Dublin, Ireland (June 1983).

has recently been discovered and is now being prepared for publication.

These results are fundamental in character and have been published in highly regarded, refereed technical journals. The results have been frequently cited in the literature and used in industry. For example, RCA under the guidance of Ph.D. student Siddik Yarman (who had been partially supported by JSEP) now has prepared extensive programs for FET amplifier design based on our "Real Frequency Method".

The principle investigator has been invited to give many talks on these results as listed below, including invited lectures in Europe and Japan and China. The highly successful IEEE-MTT Workshop (May 1983 MTT Symposium) attracted wide representation from industry and was originally initiated by interest in our "Real Frequency Method".

As another example of the impact of this research, it should be noted that just recently a new book was published entitled "Circuit Design Using Personal Computers" by T.R. Cuthbert, J. Wiley, 1983. It has a full section (pp. 218-227) devoted to "Carlin's Broadband-Matching Method".

NOTE: This research has been terminated as of May 1985.

DEGREES

1. H. Zumda (May 1982) "Simplified Dispersion Analysis of Multi-Step and Graded Index Dielectric Slab Waveguide", MS.
2. B.S. Yarman (Jan. 1982) "Broadband Matching a Complex Generator to a Complex Load", Ph.D.
3. J. Hantgan (Jan. 1981) "Single and Coupled Transmission Line Models of Open Dielectric Waveguides", Ph.D.

Anticipated:

1. H. Zumuda, Ph.D., August 1984.
2. C. Near, M.S., August 1984.

REFERRED PUBLICATIONS

1. "On Optimum Broadband Matching", with P. Amstutz, IEEE Trans., CAS-28, No. 5, May 1981, pp. 401-405.
2. "Broadband Matching", with P. Amstutz, Ann. Telecommunications, 36 (5-6) 281-294 (May-June 1981).

TASK 9 WIDEBAND CIRCUITS AND SYSTEMS

H.J. Carlin

OBJECTIVE, APPROACH AND PROGRESS

This task has been concerned with fundamental engineering research or the application to the analysis and design of wideband systems.

Two topics have been emphasized.

1. Broadband circuit design in view of fundamental gain-bandwidth limitations on all physical systems.
2. Equivalent circuit methods for predicting dispersion in dielectric (optical) waveguide.

The former topic has resulted in many papers and presentations. The latter topic is now being summarized in a Ph.D. dissertation and a graph is being prepared for publication.

There have been significant and recognized research accomplishments in gain bandwidth circuit theory and design:

1. We have shown that the procedures of hitherto widely accepted gain bandwidth theory inevitably lead to sub-optimal equalizer circuit realizations.
2. A new approach to gain bandwidth design "The Real Frequency Method" has been developed and applied to the many practical cases which are not accessible to classic methods. Furthermore the resulting equalizer circuits designed by the "Real Frequency Method" are both simpler to build and superior in performance to those of the conventional theory.
3. An entirely new and simpler solution of the theoretical gain bandwidth problem associated with interstage amplifier design has been found. This makes the so-called "Double Matching Problem" (equalizer loaded by parasitics at both input and output) more tractable for design purposes.
4. We have extended the "Real Frequency Method" to the design of optimum multi-stage FET amplifiers. This is a design generalization made possible by our solution of the double matching problem.
5. A new and basic theorem are the physical impossibility of realizing flat gain to arbitrary tolerance in equalizer design

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6. "Experimental Comparison in the Electrical Performance of Long and Ultrashort Gate Length GaAs MESFET's", P.C. Chao, W.H. Ku and J. Nulman, IEEE Electron Device Letters, Vol. EDL-3, pp. 187-190, August 1982.
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aided design of microwave mixers using GaAs MESFETs.

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