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CONTRIBUTIVE RESEARCH IN COMPOUND SEMICONDUCTOR MATERIAL AND RELATED DEVICES

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The objective of this program was to provide the Electronic Device Branch (AFWAL/AADR) with the support needed to perform state-of-the-art electronic device research. In the process of managing and performing on the project, UES has provided a wide variety of scientific and engineering talent who worked in-house for the Avionics Laboratory. These personnel worked on many different types of research programs from gas phase microwave driven lasers, CVD and MOCVD of electronic materials to Electronic Device Technology for new devices. The fields of research included MBE and theoretical research in this novel growth technique. Much of the work was slanted towards the rapidly developing technology of GaAs and the general thrust of the research that these tasks started has remained constant. This work was started because the Avionics Laboratory saw a chance to advance the knowledge and level of the current device technology by working in the compound semiconductor field. UES is pleased to have had the opportunity to perform on this program and is looking forward to future efforts with the Avionics Laboratory.

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1.0 INTRODUCTION

Under the Contributive Research Contract of AFWAL/AADR, Universal Energy Systems, Inc. (UES) was required to investigate, define, and predict the basic physical and engineering phenomena concerning the development of new electronic devices. UES performed basic research in the physical and engineering sciences to accomplish this mission.

In consonance with the broad scope of Avionics Laboratory and their need for specialists to conduct short-term investigations or present seminars on specific subjects, UES researchers and consultants addressed a multitude of technical disciplines under this effort. The work consisted of a wide range of individual tasks involving theoretical studies, analytical studies, seminars, diagnostic and measurement techniques, and the evaluation of new ideas, systems, devices and concepts.

A description of the work performed is presented in this report. The scope and objectives of each individual task are reported. The technical reports, publications, and presentations for each task have been delivered to the government initiator of the tasks. The descriptions presented herein are very brief. Details of research undertaken, results achieved, and possible new avenues of research have been presented in the informal task reports presented to the government technical area monitor for each task.

2.0 AADR TASKS

2.1 Task 001 - Chemical Vapor Deposition Growth of Insulator and GaAlAs Epitaxial Layers

UES has examined the concentrations of the residual impurities in GaAs layers grown on substrates of various orientations. The identification of donor impurities has been accomplished by magneto photoluminescence spectroscopy (MPS) utilizing the two electron transitions of excitons bound to neutral donors. The shallow acceptors are also identified. It was found that contrary to previous belief while higher concentrations of impurities are incorporated on the polar As faces, i.e., 311B, the ratios of the various chemical species are not drastically different from those incorporated on the gallium faces. These results have been obtained with the $Ga/H_2/AsCl_3$ technique under conditions suitable for the growth of high purity GaAs on the 211A orientation.

2.1.1 Task 001A - MOCVD Growth of Semiconductors

The attractiveness of the formation of nitride layers on gallium arsenide stems from the inherent advantages of metal insulator semiconductor field effect transistor (MISFET) devices over metal epitaxial semiconductor field effect transistor (MESFET) devices. There are many factors on which MISFETs emerge superior. Six of the primary factors are listed below.

1. MISFETs are planar structures making them preferable for fine line definition.

2. MISFETs are normally off thus requiring no stand by power (unlike Depletion Mode Metal Semiconductor Field-Effect Transistor (D-MESFETs) which in addition require level shifters in logic circuits to avoid bandwidth reduction due to capacitive loading of succeeding stages gate capacitance.)

3. MISFETs are operable from depletion to enhancement mode and therefore can handle larger voltage swings reducing overall propagation delay. In contrast, Enhancement Mode Metal

Semiconductor Field-Effect Transistor (E-MESFETs) are limited to approximately 0.5v at the onset of conduction.

4. Based on a smaller gate parasitic capacitance, MISFETs are amenable to better small signal microwave performance.

5. Higher transconductance and electron speeds are possible with MISFETs since these operate at lower fields.

6. MISFETs are fabricated on bulk material rendering epitaxial layers unnecessary.

The growth of silicon nitride on gallium arsenide in an epitaxial reactor was in conjunction with a complementary approach of plasma enhanced chemical vapor deposition (CVD). The epireactor system was designed and constructed in two stages. Initially, attempts were made to revitalize an existing system. The irrepairable state of some components, discovered in due course of time, necessitated a second stage wherein the entire system was rebuilt.

The metalorganic chemical vapor deposition (MOCVD) system was designed to be able to separately grow epitaxial GaAs layers on bulk GaAs using the metalorganic trimethyl gallium (TMG) and arsine. Hydrogen is the carrier gas for this subsystem. It also includes the facility to grow silicon and germanium nitrides using silane and germane, respectively, in conjunction with ammonia and nitrogen as a carrier gas. The growth of a nitride layer on freshly grown in-situ GaAs eliminates the exposure of the active layer to oxygen and reduces the hazards of interface states resulting from an oxide layer. The system underwent substantial modifications during the course of the project. The in-situ etch capability was changed to utilize a high purity mixture of hydrochloric acid (HCl) in hydrogen rather than arsenic trichloride.

Baffle configurations were changed. The quartz tube geometry and the outlet sealing methods underwent transformations. Toward the end, the infrared pyrometer temperature measurement technique was redesigned to use a thermocouple (Pt - Pt13% Rh) detector as a second temperature measurement. Finally, the geometric effects of the graphite susceptor block, heated with radio frequency (rf) power, were experimentally evaluated.

2.2 Task 002 - Evaluation of Insulator/Semiconductor Structures

For MISFET applications, a suitable insulator with low surface state density, high breakdown strength, low leakage current, extended bias temperature stressing stability, uniformity across the wafer and adequate adherence to the GaAs surface was required. Different methods for formation of an insulating layer on GaAs have been used in the past including thermal, anodic, and plasma oxidation. The low temperature deposition method was preferred for GaAs due to comparatively high vapor pressure of arsenic at higher temperatures which caused nonstoichiometric composition of gallium and arsenic at the surface unless arsenic overpressure was used during the heating cycle. Our preliminary results on anodic aluminum oxide, metalorganic CVD and plasma enhanced CVD silicon nitride and sputtered germanium nitride films on gallium arsenide have been presented.

The growth of aluminum oxide on gallium arsenide was carried out under a constant current condition in an electrolyte consisting of ammonium pentaborate and ethylene glycol. Prior to aluminum deposition, wafers were etched in NaOH: H_2O_2: H_2O :: 1 : 2 : 100 which gave an etch rate of about 3000 Å/min.

The silicon nitride films were grown in an rf plasma deposition system at 25 watts at 325°C in nitrogen and silane plasma. Metalorganic CVD silicon nitride films were obtained from Amitabh Srivastava and germaniun nitride samples were sputtered by Yu Chung.

Wafers were solvent cleaned (boiled for 5 minutes each in trichloroethylene, acetone, and methanol). Gold-germanium was evaporated on the back side of the wafers and alloyed at 425°C for 2 minutes in forming gas. The aluminum dots were evaporated through a mechanical mask to form MOS devices. All the measurements were taken at room temperature. For the capacitance-voltage (C-V) characterization, an HP-4061A system was used.

The existing computer programs for the evaluation of GaAs-Insulator interfaces were studied. The high frequency C-V measurement program was modified; this program has the capability of changing the ramp voltage from 10 mv to 500 mv/sec. Programs were also tested and modified to calculate ideality factor and built-in potential. These programs are now working for gallium arsenide and can be used for capacitance-voltage (C-V), conductance-voltage (G-V), and current-voltage (I-V) characterization of metal insulator semiconductor (MIS) devices.

2.3 Task 003 - PED Insulator on GaAs

The purpose of this task was to find suitable techniques for forming a good insulator on GaAs with acceptable dielectric and interface properties for encapsulation and MIS devices. The insulator films studied were Ge by sputtering, carbon films by ion beam and dc sputtering, and Si_3N_4 films by rf sputtering, CVD, and plasma enhanced CVD. At the first stage of this program, great efforts were made to investigate the preparation techniques and characterization of

Si_3N_4 which was deposited by different methods, although other films such as Ge_3N_4 and carbon films were also studied. The optical and electrical measurements were carried out to study the intrinsic properties of gate insulating films. For the interfacial electrical properties, C-V and G-V measurements were performed. However, none of these films have been successful in realizing a true inversion layer at the GaAs surface. Therefore, at the second stage, the processing induced (mostly plasma processing) damage was investigated. For the evaluation of the structural damage, transmission electron microscope (TEM) and Rutherford backscattering (RBS) analyses were carried out. The carrier removal and deep level states after plasma exposure were observed by C-V, Raman, and deep level transient spectroscopy (DLTS) measurements.

2.4 Task 004 - Chemical Vapor Deposition

An $AsCl_3$ vapor phase epitaxial reactor has been constructed which is capable of operation with a variable controlled Ga/As ratio. Layers grown in this reactor have been characterized by photoluminescence, electrical and DLTS measurements. Results to date indicate ring influence of the Ga/As gas phase ratio on <100> and <211A> orientation layers, particularly on deep level incorporation.

This work is principally a progress report on the construction and operation of a novel $AsCl_3$ reactor for controlled gas phase stoichiometry. This is part of an effort to bring together a variety of characterization tools and a more flexible version of the $AsCl_3$ system in order to more broadly characterize the growth method and the characterization tools. The motivation is that, while the $AsCl_3$ epitaxial growth system is the most widely used method for the growth of microwave device material and has produced the highest purity material, relatively little information is available on how variations of Ga/As in the gas phase composition affect the material produced. In most $AsCl_3$ reactors, this ratio is not easily controlled being a function of source efficiency, wall deposit extensiveness, flow rates, etc. If stoichiometry related defects or defect complexes are important in GaAs growth, it might be expected that the GaCl/As ratio in the growth environment is important. A number of features in GaAs which were suspected of being related to stoichiometry, such as the observation of complexes in this laboratory, were the initial motivation of this study. While a study was made over a wide range of Ga/As in the chloride system by Merenda, the previous studies of stoichiometry in GaAs growth, which included a study of defects, have used the hydride or metalorganic CVD growth methods. A roughly analogous study was undertaken in the chloride InP system. None of these studies have had access to as extensive facilities for sample characterization as the present study. In this study, we utilized electronic Hall and C-V measurements, photoluminescence for band edge and deep centers, a unique high resolution photoluminescence technique which has recently been utilized to separate bound exciton radiation from different donors, and DLTS. By the use of all these techniques in conjunction with each other and with a knowledge of the growth conditions on suitable samples, we believe that a more complete picture of the chloride VPE GaAs growth can be built-up and the relation of the different characterization methods further established.

For these studies, a novel $AsCl_3$ type reactor was designed and built. In its basic design, it was like the usual two-bubbler $AsCl_3$ reactor used for MESFET growth. The novel feature was the addition of a third bubbler which feeds a cracking furnace and then a second source chamber. This makes possible the operation of the reactor in a GaCl rich mode in a controllable way.

2.5 Task 005 - Raman Spectroscopy/Characterization of Semiconductors

A strongly anisotropic Raman excitation of the coupled longitudinal optical phonon-plasmon modes in n-GaAs near the $E_0 + \Delta_0$ energy gap was observed. The anisotropy is shown to result from the interference between the deformation potential and electro-optic mechanism and the electron charge density fluctuation mechanism.

A UES scientist also investigated the degradation of GaAs substrates and insulating films by exposure to low pressure plasma. The charge carrier reduction to low pressure plasma due to the creation of compensating defects during the hydrogen plasma treatment of n-GaAs was reported. The increased density of fast surface states and the non-uniform storage of positive trapped charge within the oxide layer was responsible for the degradation of metal oxide semiconductor (MOS) devices exposed to low pressure plasma.

2.6 Task 008 - Ion Implantation

The electrical properties of IR radiation transient annealed Si implanted semi-insulating GaAs were presented for 100 keV ion doses from 3×10^{12} to 3×10^{14} cm^{-2}. For wafers implanted with 3×10^{12} cm^{-2} doses suitable for field effect transistor (FET) channel layers, carrier concentration and drift mobility profiles were determined from C-V and transconductance measurements on fat FET structures. Optimum electrical activation and carrier concentration profiles were obtained for peak pulse temperatures of 930-950°C. Van der Pauw measurements were made on substrates implanted with Si doses $\geq 1 \times 10^{13}$ cm^{-2} to determine sheet carrier concentration and Hall mobility. The peak pulse temperature required to give optimum activation efficiency was found to increase with dose. Another result of the UES study was that undoped substrates were preferable to Cr-doped substrates for low dose device applications.

2.7 Task 009 - Chemistry of Semiconductors

The $Ga/AsCl_3/H_2$ and $In/PCl_3/H_2$ mixtures are frequently used for the growth of epitaxial GaAs and InP, respectively. Because of peculiarities in the chemistry and source conditions for the two systems, a brief description of one will apply equally well to the other. In the $Ga/AsCl_3/H_2$, $AsCl_3$ vapor flows from a bubbler via the hydrogen carrier gas into a hot reactor or cracking furnace where reaction (1) occurs

$$4AsCl_3 + 6H_2 \rightarrow As_4 + 12HCl \tag{1}$$

The gas mixture passes over a silica glass boat containing liquid gallium. Two reactions now occur simultaneously. In one, the HCl reacts with the gallium to form GaCl [(Equation (2))]

$$Ga_{(g)} + HCl_{(g)} \rightarrow GaCl_{(g)} + 1/2H_{2(g)} \tag{2}$$

In the reactor, arsenic dissolves in the gallium. After the gallium is saturated, a film of GaAs is formed. Similarly, a film of InP is formed over liquid indium saturated with phosphorous.

A unique feature of both systems is that the best epilayers were formed under those experimental conditions of temperature control, flow rate and boat length which are conducive to the presence of a uniform film over the entire period of growth. The thermochemical analysis of these $Ga/AsCl_3/H_2$ systems under stable growth conditions was based on the source reaction

$$2GaAs_{(s)} + 2HCl_{(g)} \rightarrow 2GaCl_{(g)} + 1/2As_{4(g)} + H_{2(g)} \qquad (3)$$

and the assumption that the arsenic in the vapor phase is elemental, i.e., $X_{As} = P^{o}_{AsCl_3}$ where X_{As} is the molefraction of arsenic in the vapor phase and $P^{o}_{AsCl_3}$ is the initial partial pressure of $AsCl_3$. The thermochemical analysis of the $In/PCl_3/H_2$ system is based on the corresponding chemical reaction of HCl with In and the concentration of phosphorous in the vapor phase. The purpose of this task was to develop a model for the reserve reactor which would rationalize the stability of the GaAs (and InP) layer. Good agreement was established between the observed and calculated III/V ratio over a wide range of temperature for the loss of arsenic (and P) from the vapor phase.

An anomaly occurs at low temperatures where a bulge in the Ga/Cl ratio was observed. The anomaly suggests that the extent of reaction (1) decreases rapidly below 700°C and that the increase in the Ga/Cl ratio in the vicinity of 575-675°C is due to the reaction of $AsCl_3$ itself with GaAs [(Equation (4))]

$$3\ GaAs_{(s)} + AsCl_3 = 3\ GaCl_{(g)} + As_{4(g)} \qquad (4)$$

The second part to this research was to confirm the above suggestion by simulating the Ga/Cl ratio as a temperature curve from 450-1000°C.

2.8 Task 012 - Theoretical Modeling of Epitaxial Semiconductor Crystal Growth

This project was undertaken to develop an understanding of the molecular beam epitaxy (MBE) technique and through this understanding control the quality of the structures grown. A Monte Carlo program which had been developed earlier was appropriately modified to study several problems in lattice-matched growth of heterostructures. In addition, a new formalism was developed to attack the problem of non-lattice matched epitaxy. The method used was based on continuous space Monte Carlo and was developed for understanding dislocation formation in simple model systems. We will briefly describe the three main areas that were addressed during the period of this funding.

2.8.1 Alloy Clustering In InAlAs

$In_{0.52}Al_{0.48}As$ lattice matched to InP is an important material which is used as a barrier region for both optical devices and modulation doped field effect transistors. The optical and transport properties are thus of great value. An important structural parameter characterizing an alloy is the extent of alloy clustering present in the alloy. Alloy clustering can seriously affect both the optical and transport properties of an alloy and therefore must be controlled. InAlAs grown under MBE conditions is expected to be immiscible from purely thermodynamic considerations. However, since MBE is not an equilibrium growth technique, one can expect to produce a miscible alloy. To study the effect of growth conditions on the alloy quality, a series of computer experiments were carried out.

This effort was to understand the physics of semiconductor heterostructures. Three main areas of research were explored to develop theoretical models for understanding a variety of novel observations: (1) theoretical studies to understand the growth of heterostructures by MBE, (2) understand the effect of structural imperfections (e.g., interface roughness, alloy clustering) in quantum wells on photoluminescence lineshapes, and (3) develop models to understand high field transport.

2.9 Task 015 - Ion Implantation Studies

Since extremely high transconductance is possible with high electron mobility transistor (HEMT) devices, the source resistance and hence the ohmic contact resistance becomes an important factor in reaching the maximum obtainable performance of the devices. Unfortunately, the formation of ohmic contacts to AlGaAs surfaces has been problematic because the contacts generally exhibit high, nonuniform, and nonreproducible resistance. Therefore, n^+-GaAs cap layers are sometimes grown onto the AlGaAs for easier contact formation. In any case, it is necessary to dope degenerately the semiconductor immediately beneath the ohmic contact in order to obtain minimum contact resistance, and one of the methods of obtaining this n^+ layer is by ion implantation technique.

In this work, we have studied the electrical properties of Si-implanted GaAs using the Hall-effect/sheet-resistivity measurements in order to obtain useful information in the ohmic contact formation of HEMT devices. Also, in order to better understand the electrical behavior of the Si implants in GaAs, we have carried out a comparative study of secondary ion mass spectrometry (SIMS) atomic profiles and electrical carrier profiles.

It has been found that the annealing behavior of sheet carrier concentrations is highly dependent upon ion dose and annealing temperature.

It has also been found that the electrical carrier profiles follow very closely the SIMS atomic profiles for low dose implanted samples.

Therefore, the electrical activation efficiencies are generally high for the Si-implanted GaAs.

One of the important reasons for pursuing HEMT device research is to learn how to take advantage of its extremely high electron mobility for use in high speed digital signal processing and high frequency microwave systems. However, this advantage cannot be achieved unless high quality electrical isolation between devices can be guaranteed. One of the methods of producing isolation strips between the active devices is by ion implantation using ions such as protons and oxygen. The physical principle involved in device isolation by the ion-implantation technique is based on the production of ion-bombardment induced damage in the irradiated zones. This technique will have an advantage in fabricating truly monolithic device structures by eliminating mesa etching and thus providing planar structures.

In this work, we have studied the electrical properties of Si-implanted GaAs after bombarding with oxygen ions.

Although we do not understand the exact nature of defects or compensating centers created by the ion bombardment, we can successfully produce high-resistivity layers by oxygen implantation into conducting GaAs layers.

2.10 Task 020 - A MOCVD Growth System

MBE was used to produce a variety of semiconductor heterostructures for materials studies and novel device applications.

Resonant (double-barrier) tunneling diode structures were produced and gave rise to the best reported device characteristics. Peak-to-valley current (PVC) ratios as high as 3.6 and 21.7 were found from a structure which utilized AlAs/GaAs superlattice barriers at 300 K and 77 K, respectively. In an alloy barrier structure with x = 0.42, PVC ratios of 3.9 and 14.3 were observed at 300 K and 77 K, respectively. These excellent results are thought to be in part due to a "two-step" spacer layer incorporated in the doped regions of the devices.

Inversion base transistor (IBT) structures were produced and gave rise to world record device results. Current gains greater than 25 and 100 were observed at 300 K and 77 K, respectively.

AlAs/GaAs and AlGaAs/GaAs superlattice structures were grown and studied by variable angle of incidence spectroscopic ellipsometry (VASE). Confined particle states near the fundamental band gap were observed by VASE for the first time. The results were used to determine the quality of the interfaces present in the superlattice structures.

The growth and vacuum sublimation of GaAs on AlAs was studied at temperatures near 700°C by the technique of reflective high energy electron diffraction (RHEED). The temporal behavior of the crystal surface symmetry was studied as a function of arsenic overpressure and substrate temperature, both during growth and upon growth interruption. The results suggest that the incorporation coefficient of Ga is a strong function of the local Al concentration; this dependence was found to be stronger than that predicted by current theoretical models. RHEED oscillation measurements of the growth rate of AlGaAs as a function of substrate temperature gave rise to results which support these conclusions. The activation energy associated with the desorption of Ga from an AlGaAs surface was calculated as a function of the local Al concentration for the first time.

Many other materials and device studies were performed on MBE grown heterostructures based on the (Al,Ga) As system. Techniques used in these studies include VASE, RHEED, photoluminescence spectroscopy, photoreflectance spectroscopy, Raman spectroscopy, transmission electron diffraction, C-V profiling, Hall effect measurements, infrared absorption, and Auger electron spectroscopy.

2.11 Task 021 - Raman Semiconductor Characterization

The surface characteristics of several substrates of interest in the electronic device field were investigated. A Varian Auger electron spectrometer was installed in a new vacuum system and repaired and cleaned to make it operational. The channeltron device was repaired and electron energy spectra were collected for a variety of sample materials.

2.12 Task 022 - Molecular Beam Epitaxy/Auger

This task involved upgrading a MBE system, Varian model 360. MBE is an ultra high vacuum (UHV) deposition system used for the single crystal epitaxial growth of semiconductor materials. Prior to this upgrade the MBE 360 was capable of growing only one-inch-diameter semiconductor materials. Only one of these samples could be processed from atmosphere to UHV per day.

To upgrade the system capabilities, two major equipment additions were installed. A six sample wafer loading system was added to the existing air lock mechanism on the MBE 360. This wafer loading system allows for the loading of six 2-inch wafers at one time in a UHV station. This will increase sample throughput and decrease operation time. The wafer loading system has incorporated a heatable wafer station so a substrate can be outgassed in UHV prior to loading into the growth chamber. This allows for continued growth chamber cleanliness.

The other upgrade installation is a new sample manipulator that allows continuous rotation of the substrate to increase deposition uniformity across the 2-inch growing surface. Another very important feature of the rotating substrate holder is it allows the operator an easy way of aligning the correct crystalline planes to use. RHEED allows for the in-situ determination of exact growth parameters, such as correct arsenic to gallium ratio in the growth of GaAs. RHEED also gives important surface information while the material is growing on a monolayer scale.

Before the new upgrades were added, the MBE 360 was completely dismanteled and cleaned after seven years of GaAs deposition. This improved system cleanliness and material quality.

2.13 Task 025 - Theory of Semiconductor Devices

The contract effort was largely directed to creation of a model and its implementation in FORTRAN code that will describe the tunneling of electrons in III-V heterojunction compounds. The starting point was a version of a single-barrier tunneling program written by Joel Schulman of Hughes Research Laboratories, and is an extension of great deal of theoretical work (starting in the late seventies and continuing to the present day) in using a transfer-matrix approach coupled with tight-binding calculation of the electronic wave functions within the heterojunction devices. Early papers describe the basics of the tight-binding formalism and apply it to the case of a single interface between similar compounds. Later papers use the formalism and apply it to parameterized band structure calculations of III-V compounds. In addition, several papers apply the reduced Hamiltonian method to the calculation of tunneling currents and represent the direct forebears of the effort here.

2.14 Task 026 - Semiconductor Research

This task developed new state-of-the-art processes to be implemented in GaAs and/or AlGaAs device technologies. Test vehicles to demonstrate and/or optimize these advanced processes, and photomasks were designed and fabricated. Analysis of the data was tested and performed to provide feedback for the optimization of these fabrication processes. A UES scientist provided guidance, leadership and encouraged clean room discipline required for successful processing of advanced integrated circuits.

3.0 AADM TASKS

3.1 Task 006 - Rough Surface Cathode Emission Investigation

The objective of this program was to improve thermionic cathodes by developing an improved qualitative understanding of surface cathode emission and to apply this knowledge to existing cathodes. Work under this program included investigations to match theoretical and experimental current-voltage curves for the full range of cathode operation with special interest on the high current density Schottky range where conventional theory breaks down. Active oxide-type cathodes consistently exhibit a "Schottky temperature" (obtained from the ratio $\log J/V^{1/2}$; J = current, V = cathode-to-anode voltage) significantly different from the cathode temperature. Theoretically, these two temperatures should be equal. During this program, a new theory, proposed by the principal investigator, was investigated to explain this discrepancy.

The theory addressed the analytical model and experimental measurements of the deviations of oxide-type cathodes (especially Ni matrix cathodes) from the ideal theoretical picture for the planar metallic emitters [Langmuir-Schottky (LS) model]. The two main deviations investigated were: (1) Schottky temperature different from cathode temperature, (2) Excessive "rounding of the knee." A semi-quantitative theory titled the "Rough Surface Model" (RSM) was developed by the principal investigator. The RSM explains both of the previously unexplained deviations from the LS model by "semi-microscopic" surface roughness of the thermionic cathodes. The RSM was investigated by correlating cathode test characteristic curves with theoretical curves. In conducting a quantitative comparison of the LS Model with the experimental results from the thermionic cathodes, it was found necessary to compare the theoretical second derivative, $d^2j/dV^2 = j''(V)$, of the LS Model with the experimental results for the thermionic cathodes obtained by means of a second derivative machine for obtaining $j''(V)$, (because the j(V)'s are much too featureless) and to use a movable anode tube, in order to find the fundamentally significant dependence of the different functions, especially $j(V)$, $j'(V)$, $j''(V)$, on the cathode-anode distance D. The results of this theory have lead to a better understanding of oxide-type cathodes.

Experimental investigation were conducted at the Microwave Technology Branch, Electronics Technology Division, Avionics Laboratory (AFWAL/AADM).

3.2 Task 007 - GaAs MESFET Burnout Investigations

This report describes an effort by Dr. James J. Whalen a UES consultant.

Low noise GaAs MESFETs have been developed for use as rf amplifier stages in microwave receivers. One important application for these RF amplifier stages will be in transmit-receive (T-R) radar systems which share a common antenna. T-R radar systems usually have protection devices (such as T-R cells) to limit the microwave power incident upon the GaAs MESFET. Since the protection devices cannot respond instantaneously, there is a time duration of 1 to 10 nanoseconds (ns) during which the protection device cannot limit the microwave power incident upon the GaAs MESFET. During this short duration of time, the MESFET may be burned out. When limiting occurs (e.g., after 10 ns), there is still leakage of the order of 100 mW through the limiter which can cause GaAs MESFET degradation or burnout. There were also some applications in which it may be desired to omit a limiter in order to reduce weight, cost, or the degradation in system noise figure caused by the limiter insertion loss which may be in the range 0.2 to 0.8 dB. The reliability of such radar systems will depend upon the burnout properties of the GaAs MESFET. Information on this subject is still rather sparse. For this reason, an experimental investigation has been carried out to obtain X-band microsecond pulse, millisecond pulse, and CW burnout data for GaAs MESFETs. This investigation was a continuation of an investigation initiated to obtain ns pulse burnout data.

3.3 Task 010 - Physical Concept in RF Power Generation

A useful method for matching input and output impedances of GaAs MESFETs to source and load impedances on 50 ohm microstrip lines was presented. The matching networks described are moveable square metallized ceramic chips that are placed on the main microstrip conductors which connect the source and load to the MESFET. These metallized ceramic chips (METCHIPs) have dimensions which make them wider than the main microstrip conductor. A model of these transformers was developed which characterizes them as sections of movable low impedance transmission lines.

The range of impedances that can be matched by a single METCHIP transformer was illustrated by developing a Smith chart plotting techniques for representing the impedances produced by single METCHIPs terminated in 50 ohms. From this, the limitations of single METCHIP matching were shown.

To extend the range of METCHIP matching, dual METCHIP transformers were considered. These transformers consist of two movable sections of low impedance line on the main 50 ohm microstrip conductor. A basic model was developed for the dual METCHIP transformer using transmission line theory to determine impedances throughout the transformer network. The basic model was then modified to include corrections for nonzero conductor thickness, dispersion, and parasitics associated with the step changes in width at the edges of the METCHIPs.

A Smith chart plotting technique which employs a least squares circle fit was presented to illustrate the range of dual METCHIP matching. This plotting technique was used to provide a method for obtaining the separation of the dual METCHIP transformer for a specific matching requirement.

In order to provide a method for designing dual METCHIP transformers on 50 ohm microstrip, a program for a hand-held, Texas Instruments model TI-59 programmable calculator was developed. This program calculates the parameters needed to establish the modified model of the dual METCHIP transformer under consideration. It then uses the model to calculate impedances at key points throughout the dual METCHIP transformer. The TI-59 calculator program listing was given.

Experimental results on input impedances produced by single METCHIP transformers terminated in 50 ohms were presented. These results are compared to the computed results produced by the TI-59 program. A good correlation exists between the calculations and the experimental measurements.

As a microstrip matching transformer design aid, computed input impedance results for dual 100 mil wide METCHIP transformers operated at frequencies from 2 to 12 GHz were illustrated in Smith chart form.

3.4 Task 023 - Gallium Arsenide Materials/Device Analysis and Correlation

This program considers GaAs material and device parameters. The objective was to correlate GaAs material and device data resulting from the joint AAD/MLP GaAs Program with the goal of relating key microwave and digital GaAs device and circuit performance parameters to GaAs material parameters.

To meet the program objective, data generated by AFWAL/MLP low-pressure and high-pressure liquid-encapsulated Czochralski growth program and by four AFWAL/AAD devices fabrication programs were reviewed for accuracy.

3.5 Task 028 - Radomes

The work covered two different technical areas. One was cross-pole electronic countermeasures (ECM), the other was airborne missile radomes.

The work on cross-pole ECM in this task began with a written overview of the subject. Then the background for a detailed analysis of typical scenarios was developed, using reasonable approximations for some of the more complicated functions involved. Some of the Georgia Tech reports on the subject were reviewed for direction and some pattern calculations were made for typical antennas.

The work on airborne radomes involved two missile radome contracts, one with Texas Instruments and one with Raytheon Missile Systems Division. There were several telephone conversations with personnel from both companies. In addition, one visit was made to each company. Each company had various difficulties in carrying out the terms of its contract with the Air Force. There were electrical, structural, thermal and materials problems. The problems and progress on the contracts were reviewed and suggestions were made to solve the problems.

4.0 AADO TASKS

4.1 Task 018 - Microwave Excited Gas Discharge Laser Study

The density of a plasma generated in a TM_{010}/2.45 GHz microwave cavity has been measured from the shift of the TM_{110} mode excited at a higher frequency. Since the design was aimed at obtaining optimum power coupling, the cavity is imperfect from the viewpoint of the density measurement. A technique based on the dipole resonance behavior of cavity modes with nonzero axial mode number has been utilized to calibrate the observed TM_{110} mode frequency shift, which is found to differ considerably from the ideal cavity formula. A new theoretical formula, taking account for the particular form of cavity imperfection used in the experiment, has been derived and verified. It is shown that the cavity shift method also is conveniently applicable to pulsed microwave discharges.

4.2 Task 024 - Calculation of the Optical and Transport Properties of Semiconductor Multilayer Studies

Under this contract, a study of the electronic and optical properties of rectangular GaAs-$Al_xGa_{1-x}As$ quantum wells in electric fields has been completed. A multiband effective mass theory in this study incorporates the important effects of valence subband mixing to study exciton binding energies, transition energies, and oscillator strengths, as well as the total absorption coefficient as a function of the applied electric field. The valence band structure in quantum wells is rather complicated. Because of the mixing of the heavy and light hole bulk states in the quantum well, the valence subband structure is highly nonparabolic even at wavevectors very close to the zone center (within 1% of the Brillouin zone center along directions parallel to the interface). Valence band mixing has nontrivial and interesting effects on the optical properties and accounts for the large strengths observed in the so-called forbidden excitonic transitions. The multiband effective mass method produces results for the top of the valence band in wide gap semiconductor quantum wells such that are almost identical to state-of-the-art tight-binding calculations and has the advantage that it can be easily applied to situations other than rectangular quantum wells such as graded gap structures and wells in electric fields.

5.0 VHSIC TASKS

5.1 Task 014 - VHSIC Training Manager Technical Consultant

In April 1986, the Environmental Research Institute of Michigan (ERIM) received a renewal contract from the AFWAL/AAD VHSIC program office entitled VHSIC Training Manager and Technical Consultant. This task was a continuation of a contract first initiated in December 1983.

5.1.1 Subtask 14A - VHSIC Training Manager and Technical Consultant

The first effort of this subtask was to provide support for the VHSIC Technology Insertion Regional Workshops. As part of this subtask, ERIM attended the status reviews held by the six VHSIC Phase I contractors, as well as other reviews and workshops which were important to the VHSIC program. The information presented at these reviews and workshops was analyzed and used to update presentation material for the VHSIC Technology Insertion Regional Workshops. Technical areas analyzed included the Integrated Design Automation System (IDAS) program, VHSIC hardware description language (VHDL), process technology, system and chip design, chip architecture, packaging, and computer-aided design (CAD). In addition, initial planning of a VHSIC tutorial course continued.

5.1.2 Subtask 14B - VHSIC Video Tape Presentation

Efforts on this subtask included the planning, development and production of a video tape describing the VHSIC program. This presentation was to explain the VHSIC technology, describe the VHSIC program, and illustrate the uses of VHSIC technology. It was to be targeted at the senior officers of the three services. A length of approximately 15 minutes was required.

Both tasks were successfully completed. The efforts on Subtask 14A contributed significantly to the VHSIC Workshops held in 1986 and have been a major factor in the organization and design of the VHSIC seminars being planned for 1987. Subtask 14B resulted in a video tape draft entitled "VHSIC, the Answer" which was delivered in February 1987. The final length of this draft was 19 minutes 10 seconds.

5.2 Task 016 - VHSIC/IDAS Consultants

UES provided analysis and consultation services for the VHSIC program. The technical consulting team was formed from UES employees, industry, and academic institutions.

The UES consulting team provided support, planning, coordination and implementation related to IDAS - 1,2,3.

The consulting team worked in an advisory capacity to the government engineers. They did not take part in the VHSIC meetings. This support was provided on a short-time/short-term schedule.

5.3 Task 017 - VHDL Simulator Program

The primary objective of the VHDL Simulator program was to produce an efficient simulator capable of handling designs of the size expected in the VHSIC program. Typically, these designs contain 50 K to 100 K (or more) gates and require 10 K to 20 K test patterns to verify. Using existing simulator software, problems of this size would require from 24 to 120 hours of execution time on large minicomputers or mainframe computers.

The simulator will be used to analyze digital system descriptions written in the VHDL language. These descriptions include the gate (or logic) level of abstraction up through the system level of design. The idea was to mimic, in software, all test equipment available at a normal engineering workbench.

VHDL User's Manual, Volume I-Tutorial and User's Guide, 30 July 1984

VHDL User's Manual, Volume II-Usage Scenarios, 30 July 1984

VHDL User's Manual, Volume III-Benchmarks 30 July 1984

VHDL Language Reference Manual Version 5.0, 30 July 1984

VHDL Language Requirements, 30 July 1984

VHDL Analyzer Program Specification, 30 July 1984

VHDL Simulator Program Specification, 30 July 1984

VHDL Profiler Program Specification, 30 July 1984

VHDL Design Library Specification, 30 July 1984

VHDL Support Environment System Specification, 30 July 1984

These documents were reviewed for technical accuracy and their substantive merits. The documents were also reviewed for utility and accuracy.

6.0 CONCLUSIONS

Project 730 was active during the period of 1981 to 1987. During that time UES supplied scientific and technical talent for a variety of research projects at the Avionics Laboratory, Wright-Patterson AFB, Ohio. Because of the wide range of talent required and the short response times involved, a special type of organization was tailored to handle this work. UES has grown into a R&D business that has a wide range of capabilities to bring to bear on a particular problem. This type of organization has been developed in order to respond to the quick response needs of the Avionics Laboratory.

A glance at the wide range of technical topics discussed in this report demonstrates the breadth of technical expertise required. No small business can hope to keep all the required technical talent needed to perform on such a contract. The best that can be achieved is to have a flexible and responsive organization that can quickly fill needed customer requirements.

The fact that UES chose this approach and performed the work with the Avionics Laboratory, is an indication of the capability of UES in this area.

BIBLIOGRAPHY

Bajaj, K.K.; Sanders, G.D.; Greene, R.L. "Excitons in Semiconductor Quantum-Well Structures." Proc. NATO Advanced Workshop on Band Structure Engineering in Semiconductor Microstructures, (April 1988).

Bajaj, K.K.; Reynolds D.C.; Litton, C.W.; Yu, P.W.; Klem, J.; Huang, D.; Sanders G.D.; Morkoc, H. "Determination of Transition Energies and Oscillator Strengths in GaAs-AlGaAs Multiple Quantum Wells Using Photovoltage Induced Photocurrent Spectroscopy." Phys. Rev. B35 (1987):9250.

Bajaj, K.K.; Reynolds, C.W.; Litton C.W.; Singh, J.; Masselink, W.T.; Fischer, R.; Morkoc H. "High-Resolution Photoluminescence Studies of GaAs-GaAlAs Multi-Quantum-Well Structures Grown by Molecular Beam Epitaxy." Solid State Electronics 29 (1986):215.

Bajaj, K.K.; Reynolds D.C.; Litton, C.W.; Singh, J.; Yu, P.W.; Henderson, T.; Peng C.K.; Morkoc, H. "Photovoltaic Spectra of Undoped GaAs-GaAlAs Multiple Quantum Well Structures Correlation with Photoluminescence." Solid State Communications 58 (1986):37.

Bajaj, K.K.; Reynolds D.C.; Litton, C.W.; Singh, J.; Yu, P.W.; Henderson, T.; Pearah, P.; Morkoc, H. "Low-Temperature Photoluminescence in GaAlAs Grown by Molecular Beam Epitaxy." Journal Applied Physics 58 (1985):1643.

Bajaj, K.K.; Reynolds D.C.; Litton, C.W.; Yu, P.W.; Singh, J.; Masselink, W.T.; Fisher, R.; Morkoc, H. "Determination of Interfacial Quality of GaAs-GaAlAs Multi-Quantum-Well Structures Using Photoluminescence Spectroscopy." Appl. Phys. Lett. 46 (1985):51.

Bhattacharya, R.S.; Rai, A.K.; Yeo, Y.K.; Pronko, P.P. "Sulphur Implantation in GaAs." Ion Beam Modification of Materials Conference. Grenoble, France (September 6-10, 1982).

Becker, R.J; Luehrumann, P.F.; Langer, D.W. "Raman Scattering from Phonon-plasmon Modes in $Ga_{1-x}Al_xAs$." Applied Phys. Lett. Vol. 47 (1985):513-515.

Chaudhuri, S.; Bajaj, K.K. "Energy Levels of a Hydrogenic Donor in GaAs-GaAlAs Quantum Well Structures in a Magnetic Field." Solid State Communications 52 (1984):967.

Chaudhuri, S.; Bajaj, K.K. "Effect of Non-Parabolocity on the Energy Levels of Hydrogenic Donors in GaAs-GaAlAs Quantum Well Structures." Phys. Rev. B29 (1984):1803.

Chen, C.Y. "Anisotropic Raman Excitation of the Coupled Longitudinal-optical-phonon-plasmon Modes in n-GaAs Near the $E_0 + \Delta_0$ Energy Gap." Physical Review B Vol. 27, No. 2 (January 15, 1983): 1436-1439.

Chung, Y.; Langer, D.W.; Becker R.; Look D. "Modification of Surface Characteristics in GaAs with Dry Processing." IEEE Vol. ED-32, No. 1 (January 1985):40-44.

Chung, Y.; Rai, A.K.; Bhattacharya, R.S.; Langer, D.W.; Park, Y.S.; "Electrical and Structural Changes in GaAs by Hydrogen and Helium Plasma Exposure." Solid State Electronics, (June 1984).

Chung, Y.; Banks, B.; Khan, Azim A.; Woollam J.A. "Interfacial Electrical Properties of Ion-Beam Sputter Deposited Amorphous Carbon on Silicon." IEEE Vol. DEL-4, No. 5 (May 1983):34-37.

Chung, Y.; Chen, C.Y.; Langer, D.W.; Park, Y.W. "The Effect of Low Pressure Plasma on GaAs Substrates and SiO_2 Films." 10th International Conference of Physics and Chemistry, (May 25, 1983).

Chung, Y.; Chen, C.Y.; Langer, D.W.; Park, Y.S. "The Effect of Low Pressure Plasma on Si-SiO_2 Structures and GaAs Substrates." J. Vac. Sci. Technol., Vol. B1 (1983):799-802.

Chung, Y.; Khan, A. Azim; Mathine, David; Woollam, John A. "Optical Properties of 'Diamondlike' Carbon Films: An Ellipsometric Study." Physical Review B Vol. 28, No. 12 (December 15, 1983):42-48.

Chung, Y.; Langer, D.W.; Singh, H.P.; Woollam, J.A. "Surface States at the GaAs-Germanium Nitride Interface." Thin Solid Films 103 (1983):193-199.

Colter, P.C.; Reynolds, D.C.; Litton, C.W.; Smith, E.B. "The Spectroscopic Identification of Residual Impurities in GaAs Grown an Polar Crystal Orientations." Abstract American Physical Society Meeting, Detroit, MI, 26-30 March 1988.

Colter, P.C.; Look, D.C.; Reynolds, D.C. "Low Compensation Vapor Phase Epitaxial Gallium Arsenide." Appl. Phys. Lett. Vol. 43 (1983):282-284.

Colter, P.C.; Reynolds, D.C.; Litton, C.W.; Smith, E.B. "Identification of the Tellurium Donor at the Residual Level in GaAs." Solid State Communications Vol. 45, No. 4 (May 19, 1982):375-377.

Colter, P.C.; Reynolds, D.C.; Litton, C.W.; Look, D.C.; Li, S.S.; Wang, W.L. "Novel Ga/$AsCl_3$/H_2 Reactor for Controlling Stoichiometry in the Growth of Vapor Phase Epitaxy (VPE) GaAs." Proceedings of SPIE Vol. 323 (January 26-27, 1982):28-35, Los Angeles, CA.

Dudley, S.; Bajaj, K.K.; Singh, J. "Asymmetric Interface Roughness in Semiconductors Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. B5 (1987):712.

Eng-Kie Souw, "Plasma Density Measurement in an Imperfect Microwave Cavity," Journal of Applied Physics (1986).

Evans, K.R.; Stutz, C.E.; Jones, R.L. "A Novel RHEED Study of the Growth of GaAs on AlAs at High Substrate Temperatures," Midwest MBE Workshop, Eden Prairie, Minnesota, (October 7, 1986).

Ezis, A. "IR Radiation Transient Annealing of Silicon Implanted Si Gallium Arsenide." Published in Proceedings of Symposium A: Energy beam-solid Ineractions and Transient Thermal Processing. Editors J.C.C. Fan and N.M. Johnson, Annual Meetings of MRS, Boston, Vol.23 (November 14-17, 1983):681-686.

Huang, C.I.; Paulus, M.J.; Bozada, C.A.; Dudley, S.C.; Evans, K.R.; Stutz, C.E.; Jones, R.L.; Cheney, M.E. "AlGaAs/GaAs Double Barrier Diodes With High Peak to Valley Current Ratio." Applied Physics Letters. 51, No. 2 pp. 121-123.

Langer, D.W.; Schuermeyer, F.L.; Johnson, R.L.; Singh, H.P.; Litton, C.W.; Hartnagel, H.L. "Chemical Reactions of Oxide Lagers on GaAs." J. Vac. Sci. Technol. 17 (September/October 1980):964-966.

Look, D.C.; Blakemore, J.S.; Kah-nee-ta. "The Effect of Mobility Profiles on Implanted GaAs MESFET Performance," published in the Proceedings of the Third Conference on Semi-Insulating III-V Materials, held in Warm Springs, Oregon, April 24-26, 1984, with D.C. Look, S. Chaudhuri and M. Maloney, p. 397.

Look, D.C.; Chaudhuri, V.S.; Moloney, M; Ezis, A. "The Effect of Mobility Profiles on Implanted GaAs MESFET Performance." Published in the Proceedings of the Third Conference on Semi-Insulating III-V Materials, Editors D.C. Look and J.S. Blakemore, (April 24-26, 1984):397.

Look, D.C.; Colter, P.C. "Electrical Properties of Low Compensation GaAs" Physical Review B (April 14, 1983):1151-1153.

Reynolds, C.W.; Bajaj, K.K.; Litton C.W.; Yu, P.W.; Singh, J.; Pearah, W.T.; Masselink, W.T.; Morkoc, H. "Optical Properties of $Al_xGa_{1-x}As$ Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. B4(2) (1986):556.

Reynolds D.C.; Bajaj, K.K.; Litton, C.W.; Yu, P.W.; Klem, J.; Peng C.K.; Morkoc, H.; Singh, J. "Excitonic Photoluminescence Linewidths in AlGaAs Grown by Molecular Beam Epitaxy." Appl. Phys. Lett. 48 (1986):727.

Reynolds D.C.; Bajaj, K.K.; Litton, C.W.; Yu, P.W.; Pearah, P.; Klem, J.; Morkoc, H.; Singh, J. "High Resolution Reflection and Emission Spectra of GaAs/AlGaAs Multi-Quantum Well Structures." Phys. Rev. B33 (1986):5931.

Reynolds, D.C.; Bajaj, K.K.; Litton, C.W.; Yu, P.W.; Singh, J.; Masselink, W.T.; Fischer, R.; Morkoc, H. "Determination of Interfacial Quality of GaAs-GaAlAs Multi-Quantum-Well Structures Using Photoluminescence Spectroscopy," Appl. Phys. Lett. 46 (1985):51.

Reynolds, D.C.; Bajaj, K.K.; Litton, C.W.; Singh, J.; Yu, P.W.; Henderson, T.; Pearah, P.; Morkoc, H. "Low-Temperature Photoluminescence in GaAlAs Grown by Molecular Beam Epitaxy," J. Appl. Phys. 58 (1985):1643.

Sanders, G.D; Evans, K.R.; Yu, P.W.; Reynolds, D.C.; Bajaj, K.K.; Stutz, C.E.; Jones, R.L. "Determination of Exciton Transition Energies and Oscillator Stengths of Undoped GaAs-AlGaAs Quantum Well Structures Determined by Photocurrent Spectroscopy." J. Vac. Sci. Technol. B6 (1988):649.

Sanders, G.; Bajaj, K.K. "Theory of Electroabsorption in Semiconductor Quantum Well Structures." Proceedings of the 18th International Conference on the Physics of Semiconductors. 11-15 August, 1986, Stockholm, Sweden, Editor: Olof Engstrom (World Scientific, Singapore, 1987):529.

Sanders, G.D.; Bajaj, K.K. "Electronic Properties and Optical Absorption Spectra of GaAs-AlGaAs Quantum Wells in Applied Electric Field." Phys. Rev. B35 (1987):2308.

Sanders, G.D.; Bajaj, K.K. "Theory of Electroabsorption in Asymmetric Graded Gap Quantum Wells." J.Vac. Sci. Technol. B5 (1987):1295.

Sanders, G.D.; Yu, P.W.; Reynolds, D.C.; Bajaj, K.K.; Litton, C.W.; Klem, J.; Huang, D.; Morkoc, H. "Determination of Transition Energies and Oscillator Strengths in GaAs-AlGaAs Multiple Quantum Wells Using Photovoltage Induced Photocurrent Spectroscopy." Phys. Rev. B35 9250(1987).

Sanders, G.D.; Bajaj, K.K. "Electronic Properties and Optical Absorption Spectra in Graded Gap Quantum Wells." Phys. Rev. B36 (1987):4849.

Sanders, G.D.; Bajaj, K.K. "Electronic Properties and Optical Absorption Spectra of GaAs-AlGaAs Quantum Wells in Applied Electric Field." Phys. Rev. B35 (1987):2308.

Singh, J.; Dudley, S.; Bajaj, K.K. "Asymmetric Interface Roughness in Semiconductors Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. B5 (1987):712.

Singh, J.; Bajaj, K.K.; Dudley, S. "Formation of Misfit and Threading Dislocations in MBE Grown Strained Layer Epitaxy - Role of Growth Modes." J. Vac. Sci. Technol. B5 (1987):1167.

Singh, J.; Bajaj, K.K.; Dudley, S. "Formation of Misfit and Threading Dislocations in MBE Grown Strained Layer Epitaxy - Role of Growth Modes." J. Vac. Sci. Technol. B5 (1987):1167.

Singh, J.; Bajaj, K.K. "A Quantum Mechanical Theory of Line Widths of Localized Radiative Transitions in Semiconductor Alloys." Appl. Phys. Lett. 48 (1986):1077.

Singh, J.; Bajaj, K.K. "Role of Computer Simulations in the Development of Heterostructure Fabrication Technology Using Molecular Beam Epitaxy." Superlattices and Microstructures 2 (1986):185.

Singh, J.; Bajaj, K.K.; Dudley, S. "A Study of Novel Growth Approaches to Influence the Growth Mechanism and Interface Quality in Heterostructures Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. B4 (1986):878.

Singh, J.; Davies, B.; Bajaj, K.K.; Dudley, S. "Theoretical Studies of Alloy Clustering and Interface Roughness in InAs, GaAs and AlAs based Heterostructures Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. B4(2) (1986):558.

Singh, J.; Dudley, S.; Davies, R.; Bajaj, K.K. "Role of Kinetics and Thermodynamics in Alloy Clustering and Surface Quality in InAlAs Grown by Molecular Beam Epitaxy: Consequences for Optical and Transport Properties," J. Appl. Phys. 60 (1986):3167.

Singh, J.; Bajaj, K.K. "Role of Thin Multi-Quantum Wells in Controlling Intrinsic Interface Quality in MBE Grown Heterostructures." Appl. Phys. Lett. 47 (1985):594.

Singh, J.; Bajaj, K.K. "Impurity Scattering Effects on Electron Transport in Short GaAs Channels." J. Appl. Phys. 57 (March 15, 1985):2048-2050.

Singh, J.; Bajaj, K.K. "Role of Resonant Laser Enhanced Surface Kinetics in the Low Substrate Temperature Molecular Beam Epitaxial Growth of Compound Semiconductors." Appl. Phys. Lett. 46 (March 15, 1985):577-579.

Singh, J.; Bajaj, K.K. "Role of Interface Roughness and Alloy Disorder in Photoluminescence in Quantum-Well Structures." Appl. Phys. Lett. 57 (June 15, 1985):5433-5437.

Singh, J.; Bajaj, K.K. "Theoretical Studies of the Intrinsic Quality of GaAs/AlGaAs Interfaces Grown by MBE: Role of Kinetic Processes." J. Vac. Sci. Technol. B3 (1985):520.

Singh, J.; Bajaj, K.K.; Reynolds D.C.; Litton, C.W.; Yu, P.W.; Masselink, W.T.; Fisher, R.; Morkoc, H. "Determination of Microscopic Structural Quality of MBE Grown GaAs/GaAlAs Interface by High Resolution Photoluminescence Spectroscopy." Journal Vac. Sci. Technol. B3(4) (1985):1061.

Singh, J.; Bajaj, K.K. "A Model for High Field Transport in Alloys: Application to InGaAs," J. Appl. Phys. 57 (1985):322.

Singh, J.; Bajaj, K.K. "Theoretical Studies of the Intrinsic Quality of GaAs/AlGaAs Interfaces Grown by MBE: Role of Kinetic Processes," J. Vac. Sci. Technol. B3 (1985):520.

Singh, J.; Bajaj, K.K. "Role of Thin Multi-Quantum Wells in Controlling Intrinsic Interface Quality in MBE Grown Heterostructures," Appl. Phys. Lett. 47 (1985):594.

Singh, J.; Bajaj, K.K. "Role of Arsenic Sources (As_2, As_4) in Controlling the Quality of GaAs Grown by MBE - Theoretical Studies," J. Vac. Sci. Technol. B2 (1984):276.

Singh, J.; Bajaj, K.K.; Chaudhuri, S. "Theory of Photoluminescence Line Shape due to Interfacial Quality in Quantum Well Structures." Appl. Phys. Lett. 44 (April 15, 1984):805-807.

Singh, J.; Bajaj, K.K. "Theory of Excitonic Photoluminescence Linewidth in Semiconductor Alloys." Appl. Phys. Lett. 44 (June 1, 1984):1075-1077.

Singh, J.; Bajaj, K.K. "Theoretical Investigations of the Nature of the Normal and inverted GaAs-GaAlAs Structures Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. 2 (July-September 1984):576-581.

Souw, Eng-Kie "Plasma Density Measurement in an Imperfect Microwave Cavity." Journal of Applied Physics (1986).

Theis, W.M.; Sanders, G.D.; Leak, C.E.; Bajaj, K.K.; Morkoc, H. "Excitonic Transitions in GaAs/GaAlAs Quantum Wells Observed by Photoreflectance Spectroscopy: Comparison with a First Principles Theory." Phys. Rev. B37 (1988):3042.

Whalen, James J.; Kemerley, Robert T.; Rastefano, Elisee "X-Band Burnout Characteristics of GaAs MESFET's." IEEE Transactions on Microwave Theory and Techniques Vol. MTT-30, No.12 (December 1982):2206-2211.

Yeo, Y.K.; Ezis, A.; Kim, Y.Y.; Ehret, J.E.; Park, Y.S.; Langer, D. "Correlation of Electrical Carrier and Atomic Profiles of Si Implant in GaAs." Presented at the Annual Meeting of the APS, Detroit, MI, March also published Bull. Am. Phys. Soc., Vol. 29, (1984):389.

Yeo, Y.K. "CW Incoherent Light Annealing of Ion-Implanted Si for VLSI Application." Extended Abstracts Vol. 83-2, (October 9-14, 1983).

Yeo, Y.K. "Electrical Properties of Low-Dose Si Implants in GaAs." Bull. Am. Phys. Soc. Vol. 28 (1983):370.

Yeo, Y.K.; Kim, Y.Y.; Hengehold, R.L.; Park, Y.S.; Ezis, A. "Substrate-Dependent Electrical Properties of Low-Dose Si Implants in GaAs." Materials Research Society and Proceedings. (14-17 November 1983).

Yu, P.W.; Sanders, G.D.; Evans, K.R.; Reynolds, D.C.; Bajaj, K.K.; Stutz, C.E.; Jones, R.L. "Effect of Electric Field on the Exciton Transition Energies and Oscillator Strengths of Undoped GaAs-AlGaAs Quantum Well Structures Determined by Photocurrent Spectroscopy," J. Vac. Sci. Technol. B6(2) (1988):649.

Yu, P.W.; Sanders, G.D; Evans, K.R.; Reynolds, D.C.; Bajaj, K.K.; Stutz, C.E.; Jones, R.L. "Determination of Exciton Transition Energies and Oscillator Stengths in AlGaAs-GaAs Multiple Quantum Well Structures in an Electric Field Using Photocurrent Spectroscopy." Superlattices and Microstructures 4 (1988):281.

Yu, P.W.; Reynolds, D.C.; Bajaj, K.K.; Litton, C.W.; Singh, J.; Peng, C.K.; Henderson, T.; Morkoc, H. "Photovoltaic Spectra of Undoped GaAs-GaAlAs Multiple Quantum Well Structures Correlation With Photoluminescence," Solid State Commun. 58 (1986):37.

Yu, P.W.; Reynolds D.C.; Bajaj, K.K.; Litton, C.W.; Singh, J.; Peng C.K.; Henderson T.; Morkoc, H. "A Comparative study of Photovoltaic and Photoluminescence Spectra of Undoped GaAs-AlGaAs Multiple Quantum Well Structures Grown by Molecular Beam Epitaxy." J. Vac. Sci. Technol. B4(2) (1986):554.

Yu, P.W.; Sanders, G.D.; Evans, K.R.; Reynolds, D.C.; Bajaj, K.K.; Stutz, C.E.; Jones, R.L. "Electric Field Dependence of Exciton Transition Energies in GaAs-$Al_xGa_{1-x}As$ Quantum Wells Studied by Photocurrent Spectroscopy." Phys. Rev. B (in press).

Yu, P.W.; Chaudhuri, S.; Reynolds, D.C.; Bajaj, K.K.; Litton, C.W.; Masselink, W.T.; Fischer, R.; Morkoc, H. "Temperature Dependence of Sharp Line Photoluminescence in GaAs-GaAlAs Multiple Quantum Well Structures," Solid State Comm. 54 (1985):159.

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