The Electronics Research Center at The University of Texas at Austin consists of interdisciplinary laboratories in which graduate faculty members, Master's and Ph.D. candidates from numerous academic disciplines conduct research. The disciplines represented in this report include information electronics, solid state electronics, and electromagnetics.

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This report summarizes scientific progress on "Basic Research in Electronics" which has been conducted under the auspices of the DoD Joint Services Electronics Program during the period 01 January - 31 December 1990. Progress on five solid-state, two information electronics, and two electromagnetic projects is described.

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ANNUAL REPORT ON ELECTRONICS RESEARCH

AT THE UNIVERSITY OF TEXAS AT AUSTIN

NO. 42

For the period January 1, 1990 through December 31, 1990

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December 31, 1990

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712-1084

TABLE OF CONTENTS

DIRECTOR'S OVERVIEW

and

SIGNIFICANT ACCOMPLISHMENTS

DIRECTOR'S OVERVIEW

This report covers the twelve-month period January 1, 1990 to December 31, 1990 and reports on work carried out under research contract AFOSR F49620-89-C-0044. The current JSEP program at The University of Texas at Austin is a relatively balanced program with five solid-state, two information electronics, and two electromagnetic research units. Our work in solid-state electronics is centered around MBE growth of multilayer heterostructures, characterization, measurement and simulation of carrier transport effects, and applications to high-speed devices. The information electronics research units share a common theme of measurement science and the development of methods for the extraction of information from signals that would be lost if conventional measurement techniques or algorithms were employed. In the most general sense, the two electromagnetics units deal with wave interactions, the first with interactions with various active and passive devices in guided wave structures, the second with nonlinear wave interactions and the associated nonlinear transfer of energy.

In the following pages we report on two significant accomplishments. The first involves the influence of mirror-quantum well optical coupling on the spontaneous emission of closely spaced quantum wells. The second is concerned with the ability to intergrate information from disparate sensors to arrive at meaningful interpretations of a scene. Of particular significance is the fact that the approach has been demonstrated with actual field test data. As with much of the research carried out under the JSEP program, these two projects are synergistic in that the work reported under significant accomplishments was also supported by other agencies as well.

Finally, we mention that the new building to house microelectronics research at U.T.'s Balcones Research Center is coming along very well. We anticipate moving into this building in mid-1991. New laboratory and office space for approximately 15 faculty and 120 graduate students will be provided. The availablility of this new research space should have a very positive impact on the U.T. JSEP Program.

Edward J. Powers for the
U.T. JSEP faculty participants

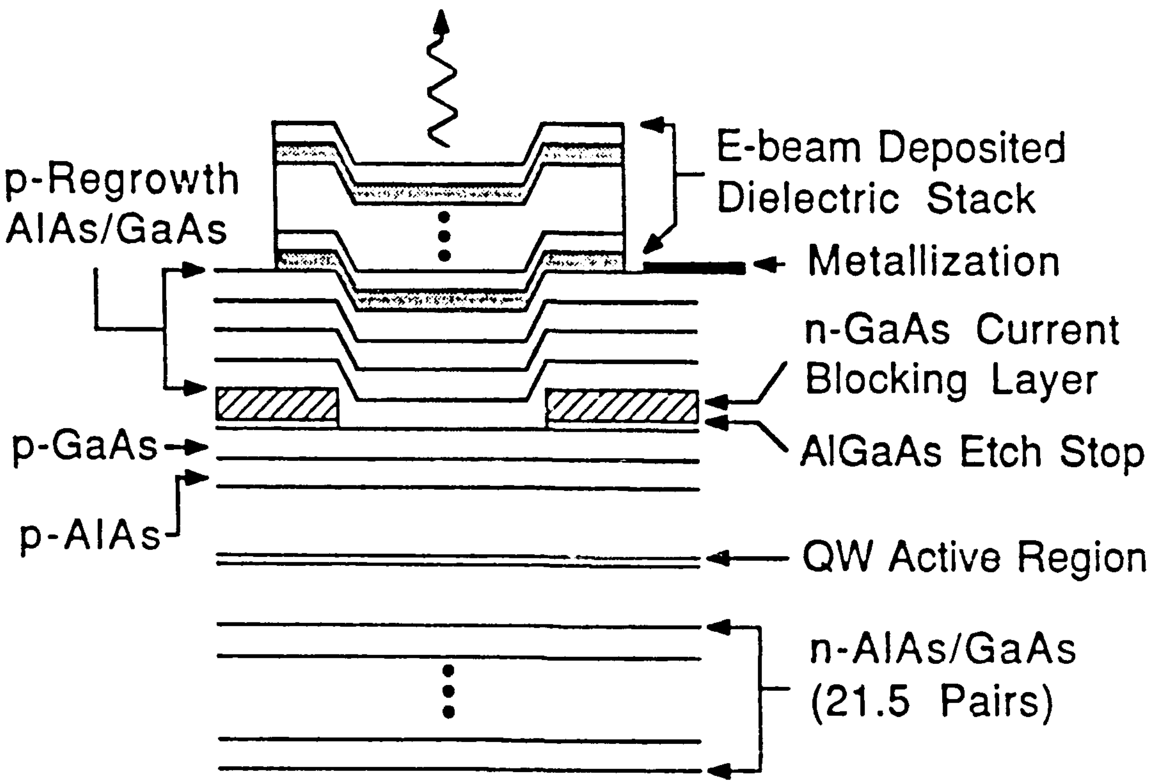
InGaAs-GaAs Quantum Well Vertical-Cavity Surface-Emitting Laser and Mirror-Quantum Well Coupling Effects

JSEP PI: B.G. Streetman

Collaborating Faculty: D.G. Deppe

The vertical-cavity surface-emitting laser (VCSEL) is under intense study in the United States and Japan because it offers unique advantages such as reduced threshold current, ease of integration, extension to large area 2-dimensional phased arrays, and improved beam qualities. This device structure is expected to impact laser technology over a wide range, from futuristic applications such as optical computing to more immediate issues such as reduction of laser cost by allowing wafer scale laser device testing. At UT-Austin we are examining new ways of making VCSEL structures, and are also taking advantage of the VCSEL microcavity to study the basic physics of emission and laser effects. The VCSEL device structure is being used at UT-Austin to study unique quantum mechanical coupling effects which occur when a light emitter is closely spaced (less than an optical wavelength) to a high reflectivity mirror. We have for the first time studied the influence the mirror-quantum well optical coupling on the spontaneous emission of closely spaced quantum wells and have found a quite large effect. A second unique aspect of the UT-Austin JSEP program is the use of a two-step MBE growth technique to achieve lateral current injection into the device active region, allowing optimization of the top mirror.

Vertical Cavity Surface-Emitting Laser (VCSEL)



Objectives:

- Basic emission and laser effects in microcavities
- New ways of fabricating VCSEL structures

Accomplishments:

- Influence of mirror-quantum well optical coupling on spontaneous emission
- Two-step MBE growth to achieve lateral current injection, allowing optimization of the top mirror

JSEP: Multi-Sensor Signal Processing

Principal Investigator: Professor J. K. Aggarwal

Overview:

This viewgraph presents work on an automatic image interpretation system using registered (covering the same 3D solid angle) laser radar and thermal images. The objective is to detect and recognize man-made objects at kilometer range in outdoor scenes using the *multi-sensor fusion* approach. Various image processing techniques are designed to partition (i.e., segment) the scene into small, homogeneous regions.

Descriptions of the Operation Modules and the Result

1. Ladar range data provide information about 3D geometry and object surface structure. The *Surface Fitting* method explores such geometric significance. The *Pixel Statistics* method explores the contrasts in size between man-made objects (vehicles) and general background.
2. Ladar intensity data provide information about object surface reflectivity (which is related to surface color and materials).
3. Ladar velocity data uses surface fitting and pixel statistics to detect regions of different velocity profiles.
4. Thermal image segmentation depends on histogram analysis to detect background cluster. The method is efficient and data-adaptive. For example, everything is hot in the desert. The threshold is adjusted automatically based on the background model (of thermal sensor return values).
5. Multi-sensor integration uses *maximum likelihood detection* for initial fusion of region contours/edges and *multiple image resolutions* to remove noise and unnecessary details. Its result is a single image segmentation (partition) map which is the *consensus* of all segmentation maps. Each small area on the map is a single physical entity or coming from a single physical structure (e.g., the ground).
6. Multi-sensor interpretation uses different knowledge sources for scene interpretation and target recognition. Some interpretation rules use knowledge derived from multiple sensing modalities for cross validation. For example, 3D surface structure alone is not sufficient to classify object surface materials.
7. The final image shows the background, the foreground, and the targets all correctly classified. The targets are recognized as 2.5-ton truck and APC, respectively. A few small regions do not receive high-confidence classifications.

Significant Accomplishments:

1. This work demonstrates the ability to integrate information from disparate sensors to arrive at meaningful interpretations of the scene.
2. This work demonstrates the feasibility of multi-sensor target recognition using actual field test data (as opposed to a carefully-controlled laboratory environment) of the type shown in the viewgraph.

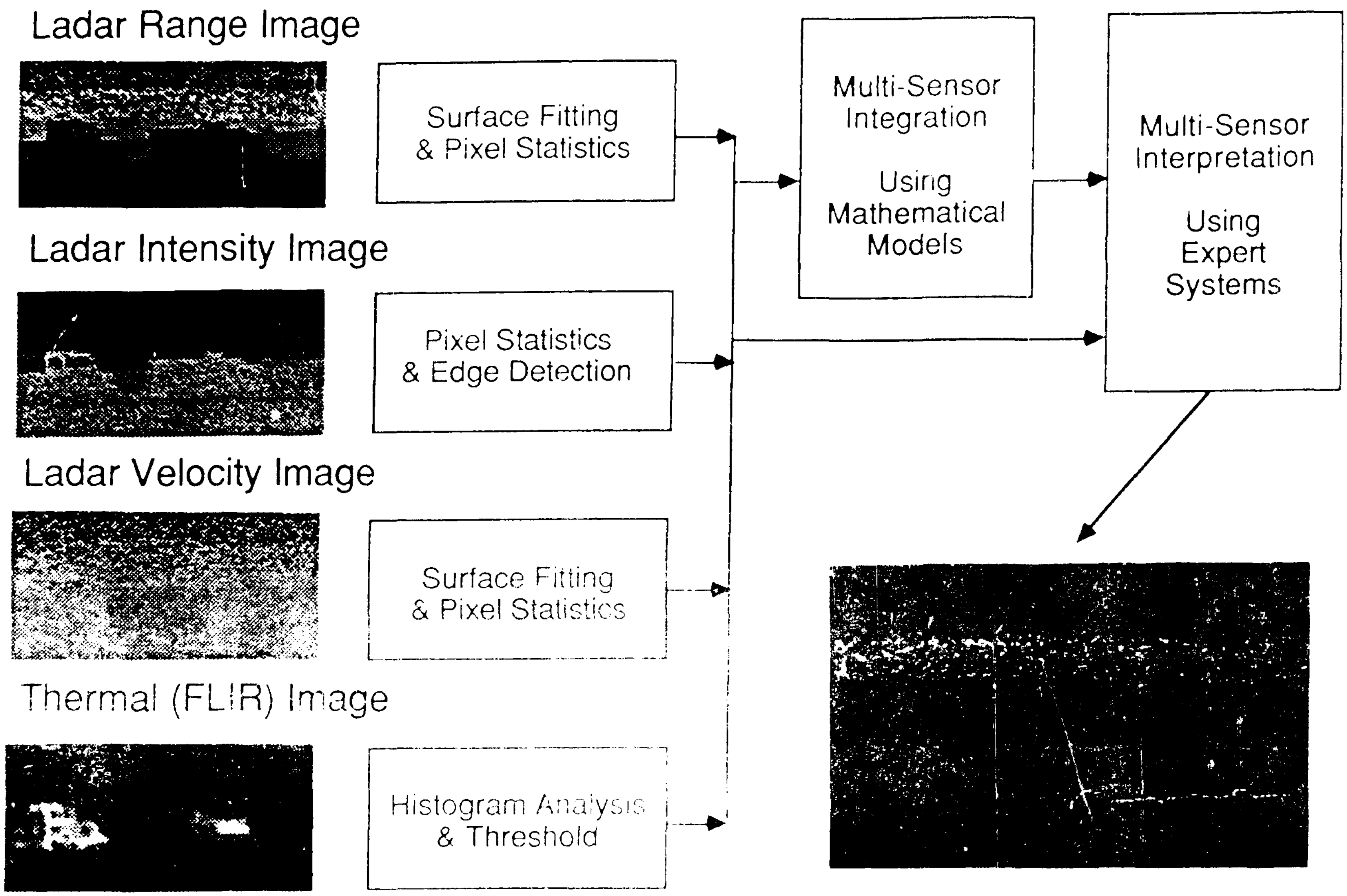
Prominent Features:

1. The multi-sensor image interpretation and segmentation are based on the physical properties (e.g., surface shapes, surface smoothness, reflectivity, thermal capacitance, velocity, etc.) of the targets and imaging physics.
2. System performance degrades gracefully rather than make-or-break in adverse environments because of using multiple sensors and processing techniques.
3. A new algorithm is designed to integrate different versions of image segmentation. The algorithm operates independently of image segmentation algorithms. Therefore, multiple sensors and processing techniques may work in parallel. New types of sensors and segmentation techniques can be added in a modular fashion.

Potential Impact:

1. Multi-sensor systems make hostile concealment/camouflage more difficult.
2. The system can be used on various platforms for different missions, e.g., autonomous vehicle navigation and docking, long-range surveillance, and automatic target recognition.

Multi-Sensor Image Segmentation and Interpretation



I. INFORMATION ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE89-1: Multi-Sensor Signal Processing

Principal Investigator: Professor J. K. Aggarwal (512) 471-1369

Graduate Students: X. Lebegue and C. C. Chu

A. SCIENTIFIC OBJECTIVES: The overall scientific objective of this research unit is to develop algorithms for multi-sensor signal processing. Further, accurate sensor-scene and sensor-sensor relationship will be established based on the physical principles of signal generation, detection and interactions. We shall develop computer methods for concomitant analysis of information in signals from different sensors, and develop efficient and accurate techniques for signal processing and interpretation. In this research, the extraction of information from signals is to be accomplished by using Artificial Intelligence techniques and rule-based methods, so that information gathered from multiple sensors may be easily combined. The sensors to be used in the system will include visual, infrared, range, and laser radar.

Signal processing that integrates multisensory data provides information that cannot be obtained by processing the data individually. By integrating information from different sensors, a more powerful and robust system may be built to interpret the scenes of interest. Also, rule-based methods can better implement the integration task among signal systems that do not have well-understood mathematical models. In addition, detailed analysis of signal generation process, transmission environment and data acquisition models is thoroughly investigated to find out the physical significance of the sensed signals. Thus more meaningful processing techniques can be designed based upon such knowledge.

There are a number of issues to be studied for a multi-sensor system, such as the relationship between different sensors, sensor behavior difference under different imaging conditions, spatial and temporal correspondence between signals, calibration and registration between various sensors, and the strategies for synergistically integration of the extracted information. The differences between the principles on how these sensor devices operate require that individual sensor system be analyzed, and accurate models be established for sensed signals. The strategies to combine the extracted information and to interpret them in a consistent way is critical to multi-sensor signal processing, and is a research area that has not yet been fully explored.

Traditionally, the extraction of information from single and multi-dimensional signals are done by filtering, statistical analysis, and pattern classification. In comparison, adequate attention has not been given to problems where the relationships between the signals and the system cannot be described in terms of mathematically well-understood formulations. Hence, there exists a need for the development of rule-based methods to model diverse mechanisms that generate and distort signals.

(Research Unit IE89-1, "Multi-Sensor Signal Processing)

B. PROGRESS: A significant amount of research has been conducted in this research unit in the analysis and interpretation of multi-sensory signals. These signals are analyzed concomitantly to provide useful information regarding the sensed scene and its characteristics. In our research program, we are developing knowledge-based systems for object detection and image interpretation in various domains of applications. The emphasis on information integration from multiple sensors and detecting man-made objects in images of outdoor scenes. We have two projects under development: (1) the integrated thermal and visual image thesis system, and (2) intelligent integration of information from laser radar and thermal sensors ... man-made objects detection and automatic recognition.

The ideas common to both projects are: (a) to study the physical models of the imaged objects and individual sensors, and (b) to integrate information derived from various sensors. We have approached the problem as follows. First, physical models for signal generation, transmission, and acquisition are studied, leading to a better understanding of fundamental properties of images and the development of effective algorithms. Second, information integration is used to resolve ambiguities that cannot be dealt with in mono-sensor operation. This integration is not a simple concatenation of sets of data, but rather a synergistic integration. Interactions between sensors has to be studied to derive features that are not readily available.

The approaches and results of individual projects are outlined here. For the thermal and visual image synthesis project, the octree data structure is used to model 3D objects. Heat flows within objects are simulated. The resulting surface temperature variation is used to create the thermal image. Cavities within vehicles and the heat generation by engines are also modelled to provide more realistic thermal images. The octree structure also facilitates the generation of the corresponding visual images. For the LADAR project, surface fitting and image statistics are used to segment images. Histogram analysis and thresholding are used to segment thermal images. Maximum likelihood estimation is used to integrate low-level segmentation information into a single segmentation map for the entire scene. This low-level integration algorithm is innovative and contains many desirable properties [8]. A knowledge-based system is used to achieve object classification and scene interpretation. This year, we use FLIR data in addition to LADAR data, the results show further improvement. The progress of both projects are summarized in the following.

Thermal and Visual Image Synthesis

The development of our integrated thermal and visual image synthesis system is within a larger framework of scene interpretation using both thermal and visual images and a sensor fusion approach. In the past, we have established a prototype system for scene interpretation which relies on image segmentation and understanding the physics of individual sensors. A scene segmentation system that uses both thermal and visual information has been built in the past. The thermal and visual image synthesis system is constructed to verify the analysis framework established in previous works of this unit.

The analysis framework can be summarized as the following [1]. The thermal behavior of scene objects is studied in terms of surface heat fluxes. The thermal image is used to estimate surface temperature, and the visual image provides information about surface absorptivity and relative surface orientation. We can compute relative surface orientation by approximating surface reflectivity as opaque and Lambertian. The absorbed heat flux is computed using estimates of surface reflectivity, relative orientation, and the intensity and direction of solar irradiation. The convection heat flux is obtained from available empirical correlations. The radiation heat loss from object surface is computed using the Stefan-Boltzmann law. Subtracting the convected and radiated heat fluxes from the absorbed heat flux gives us the "conducted" heat flux. The ratio of conducted heat flux to absorbed heat flux describes the imaged objects' relative ability to sink or source heat. This ratio depends largely on the normalized lumped thermal capacitance of the imaged objects. Thus, features based on these estimates of heat fluxes serve as meaningful on specific descriptors of imaged objects.Thermal behavior of an object is estimated by using a model which is based on the thermal characteristics of the object (e.g., absorptivity, convection heat transfer coefficient and thermal conductivity) and the thermal parameters of its surroundings (e.g., wind speed, the direction of solar irradiation, the ambient temperature, etc.) The approach has been successfully tested on real data obtained from outdoor scenes [1,2].

We have developed a unified approach for modelling objects which are imaged by thermal (infrared, IR) and visual cameras based on the physical principles described above. The model supports the generation of both infrared ($8\mu m$ - $12\mu m$ wavelength) images and monochrome visual images under a variety of viewing and ambient scene conditions. An octree data structure is used for object modelling. The octree serves two different purposes - (1) surface information is encoded in boundary nodes and efficient tree traversal algorithms facilitate the generation of monochrome visual images, and (2) the compact volumetric representation facilitates simulation of heat flow in the object which gives rise to surface temperature variation, which in turn is used to synthesize the thermal image. The developed techniques may be used in a model-based scene interpretation system which analyzes concomitantly thermal and visual images of scenes.

We have made extensions to the above approach by adding the ability to model non-homogeneous 3D objects. Real-world objects are not homogeneous in the form of internal cavities, material differences, and sources of heat generation (e.g., engine in vehicles). The thermal images of objects with non-homogeneous interior is quite different from the one generated by assuming a solid, homogeneous object. An octree of the simulated object is first constructed from multiple silhouettes. Then the cavity and heat generation are specified by giving multiple sectional views. An octree for the non-homogeneity is constructed from multiple sectional views. These two octrees are then intersected and the thermal properties of the nodes corresponding to the non-homogeneity in the main octree are updated. This procedure is applied to cavity as well as heat generation. Once the octree for the non-homogeneous object is constructed , thermal simulation is performed as described earlier to generate thermal images. An octree with a better surface normal encoding technique called *volume surface octree* (vs-octree) is used. An implicit finite difference technique as opposed to the explicit method used in earlier work is used for thermal simulation.

The vs-octree used in this work has two advantages over the octree used in the earlier work [3]. The first advantage is that the surface encoding technique used in the vs-octree results in finer quantization of the surface normals as compared to the earlier approach. This improves the quality of the visual image generated. The accuracy of the thermal simulation is also improved due to the fact that surface normals are used in the computation of the absorbed solar irradiation. The second advantage of the vs-octree is that the object is decomposed into numerous small surface nodes and internal nodes as opposed to large surface nodes in the earlier approach. This results in improved accuracy of the computed surface temperatures as the temperature of a small surface node corresponds exactly to the surface temperature. Whereas, the temperature of a large surface node does not correspond to the surface temperature alone, but represents some combination of surface and interior temperatures.

The vs-octree of an object can be constructed from multiple views of the object. For each view, the contour is smoothed by a tension spline. Then, a quadtree is constructed for each view which stores the information pertaining to the contour. The quadtrees from multiple views are then intersected to obtain the vs-octree. The surface normals of the surface nodes in the vs-octree are computed based on the contour normals in the quadtrees. To incorporate a cavity in the object, the thermal properties are changed to that of air. To model heat sources, a constant volumetric heat generation rate is specified in the nodes pertaining to the heat source. These extensions result in realistic and accurate thermal images. Thermal images of different objects with cavity and heat generation were generated. It was observed that the generated thermal images were quite different from the ones generated assuming a homogeneous object. The heat flux ratio described earlier were also computed. It was observed that the heat flux ratio was the highest for a solid object and lowest for an object with cavity and heat generation. These results were consistent with the observations in [1].

Since the proposed system is based on 3D models of thermal behavior of an object, it offers several advantages over facet-based approaches [4] for thermal image synthesis. This system allows for effects of lateral heat flow in the surface and also heat flow into the object. In addition, this system does not require large data files of geometric and thermal parameters which is needed by facet-based systems. This system will be used in a model-based vision system which interprets thermal and visual images. Each class of objects to be classified will be represented by distinct octree models. The specification of a unique model for each class of objects to be recognized in the scene allows for more accurate prediction of thermal images of objects and also allows for the prediction of the values of discriminatory features which can be used in classification. Simulations of heat flows on this model yields thermal images specific to scene conditions. These generated images and the discriminatory features calculated in the simulation will be used to identify objects belonging to that particular class.

Intelligent Integration of Information from Laser Radar and Thermal (FLIR) Sensors

Laser radar (LADAR) systems have received much attention in recent years. LADAR gives range, intensity (also known as the reflectance or the amplitude component), and velocity images simultaneously. The velocity image is generated using Doppler Effect. The LADAR image data are extremely noisy. We are interested in using multi-sensory images to detect and recognize man-made objects in outdoor scenes. Last year, we have tried to use the three modalities of LADAR. This year, the thermal images are added into our system as an independent module. Our approach is to segment individual LADAR and thermal images into homogeneous regions first. In the next step, the results from multiple segmentation maps are integrated into one. The final integrated segmentation provides the basis of image interpretation. Our objective of this work is to detect man-made objects (MMO) from background, then interpret the segmented scene by using a knowledge-based system (KBS). Newer results that demonstrate improved scene segmentation by integrating multiple components of LADAR and thermal data has been accepted for publication [5,6,7,8]. A knowledge-based system is developed using *KEE*, an expert system shell, for intelligent system development.

The range image is segmented by surface fitting to explore the geometric characteristics of object surface. The range segmentation module tends to find smooth fit for man-made objects. Because of the noise and irregularities of shapes, objects in the background, e.g., trees, shrubs, usually cannot be fitted with planar surfaces. The intensity data is segmented based on the mean and standard deviation of the image pixel values. For objects with same surface characteristics (say, metallic body), the areas occupied by the object on the intensity image are likely to present approximately the same degree of busyness. We have found that the statistical method, if applied to the range data, can also provide good segmentation cues that is complementary to the results from the surface fitting method. The velocity component is useful when the objects are moving. The processing of velocity components proceeds along the line of processing range images.

Next, we combine various segmentation maps from different data channels and processed by different methods to produce a single integrated segmentation map. The newly developed algorithm [8] is independent of image sources and specific region-segmentation or edge detection techniques. The algorithm is designed to generate an estimation of the true underlying edges and region contours from multiple observations. The channel resolution width provides spatial control of the fusion. The resultant edge contours are smoothed within the constraint of the channel resolution width. The solution procedure is decomposed into three steps. A maximum likelihood estimator provides initial solutions to the positions of edge pixels from various inputs. An iterative procedure which uses only local information without edge tracing is then used to minimize the contour curvature. Finally, regions are merged to guarantee that each region is large and compact. Experimental results are demonstrated using data from different types of sensors and processing techniques. The results show an improvement over individual inputs and a strong resemblance to human generated segmentation. Therefore, the integration module can use multiple processing modules as front-ends working in parallel to increase the robustness of the system performance. After the segmentation maps are effectively integrated, the new map is used to verify individual segmentation maps, and to provide cues to segmentation modules for refinement.

We have built a prototype knowledge-based scene interpretation system [6] that incorporates reasoning. Each region in the segmented scene is analyzed and given a label. The interpretation system posts hypotheses about the scene and use available data to verify or reject these hypotheses. Other signal sources, such as millimeter wave radars (MMW), can also be incorporated into the system as independent knowledge source modules. The knowledge-based system consists of three major components: the knowledge bases, the data bases, and the inference engine. In our work, the inference engine is provided by *KEE*. The interpretation strategy used in this work follows the paradigm of Clancey's Heuristic Classification [9]. First, numerical parameters are converted into qualitative descriptors, and these descriptors are used to generate intermediate classifications of segments as MMO or background objects. Segments are grouped into objects and these objects are further classified into one of the pre-defined categories. The knowledge of image interpretation is coded as *KEE* rules. The reasoning process is driven in the forward chaining mode.

Five types of knowledge are used to construct these interpretation rules. The first source of knowledge comes from the numerical measurements for each segment and object. This is the knowledge derived from pixel values of input images. The second source of knowledge comes from the neighborhood relationships in the segmentation map. The third type of knowledge comes from the models of potential targets. The fourth type of knowledge comes from the sensor specification and the imaging geometry. This knowledge source determines the transformation between pre-stored object models and detected objects. The last type of knowledge is "common sense" and domain-dependent assumptions that provide guidance to the reasoning process. Each *KEE* rule posts one or more hypotheses, which are expressed as a quadruple of *(segment/object, attribute, value, confidence factor).* The confidence factor is a real number between -1.0 and 1.0 to denote the degree of disbelief (negative numbers) or belief (positive numbers) of the associated hypothesis. This is necessary because all the rules are not equally effective in all the circumstances. The same rule may generate the same hypothesis with different confidence factors when the attributes of the segments under consideration are different.

In a limited test sets, the KBS is able to detect all man-made objects, and correctly recognize most targets articulated in a broad-sided view toward the sensor. The length, speed, body dimensions of the detected vehicles are usually correctly estimated using information of the spatial resolution of the LADAR images. Thermal images provide strong cues for target detection and segmentation. Verifications between data acquired from various modalities usually reveals different physical structure and construction materials. Currently , effort is being devoted to the development of a larger library of 3D models of military vehicles with relevant features that are detectable in LADAR, thermal, MMW radar and visual imagery.

We have added modules to incorporate FLIR data into our image interpretation system. A new segmentation technique is designed to separate high-temperature areas from low-temperature areas in thermal images. This technique is data-adaptive. Therefore, it works well even if the FLIR sensor is saturated due to extreme environmental condition or poor operation practise. Experimental results show that thermal image segmentation generates image partition very similar to those generated from LADAR range data segmentation. However, the thermal segmentation module uses less than one percent of the computing resources used by the range data segmentation module. The discrepancies between range and thermal segmentation usually indicate major structural features that can be used for target recognition. These features include open cavity (space) inside vehicles, exhaust pipes, gun barrels, object occlusions, etc. Therefore, the new low-level sensor integration module is extremely important because it allows some failures in sensors or processing techniques, while enhances system performance by using all information channels.

C. FOLLOW-UP STATEMENT: Past research conducted by this research unit in the analysis and processing of signals from different sensors has demonstrated that multi-sensor fusion is a powerful approach for signal processing and interpretation. Detailed signal modeling based on physical principles and field observations will be undertaken to derive more effective signal processing techniques. This unit will pursue both the investigation of scientific issues and the development of engineering solutions to the practical problems. This research will allow for the design of general, robust systems for signal interpretation that can take the advantage of multiple information sources.

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I. LIST OF PUBLICATIONS (Those supported by JSEP are marked with *)

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(Research Unit IE89-1, "Multi-Sensor Signal Processing)

II. LIST OF CONFERENCE PROCEEDINGS (Those supported by JSEP are marked with *)

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V. GRANTS AND CONTRACTS

National Science Foundation Grant DCR-8517583, "Space Perception from Multiple Sensing," Professor J. K. Aggarwal, Principal Investigator.

National Science Foundation Grant ECS-8513123, "Analysis and Reconstruction of Three-Dimensional Microscopic Images," Professor J. K. Aggarwal, Principal Investigator and Professors A. Bovik and K. Diller, Co-Principal Investigators.

Army Research Office Contract DAAL03-87-K-0089, "Synergetic Multisensor Fusion," Professor J. K. Aggarwal, Principal Investigator.

VI. LIST OF NATIONAL AND GOVERNMENT ACTIVITIES

NATO Advanced Research Workshop on Multisensor Fusion for Computer Vision, Grenoble, France, June 26-30, 1990.

International Symposium on Artificial Intelligence, Robotics, and Automation in Space, Kobe, Japan, November 18-20, 1990.

IAPR International Workshop on Machine Vision Applications, Tokyo, Japan, November 28-30, 1990.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE90-2 NONLINEAR ESTIMATION AND STOCHASTIC ADAPTIVE CONTROL

Principal Investigator: Professor S. I. Marcus (471-3265)

Graduate Students: Emmanuel Fernández-Gaucherand, Ratnesh Kumar, and Enrique Sernik

A. RESEARCH OBJECTIVES: This research unit is concerned with novel methods of extracting information from noisy measurements of the state of a nonlinear stochastic system, for the purpose of real time estimation or control. The problem of nonlinear state estimation is concerned with the extraction of information about the state of a nonlinear stochastic dynamical system from nonlinear noisy measurements. The state cannot be observed directly; instead, we have access to an observation or measurement process which is contaminated by noise and which is related to the state via a stochastic model. The objective is the calculation of either the entire conditional distribution of the state given the past measurements or some particular estimate, such as the conditional mean. In addition, it is desired that the state estimate or conditional distribution be calculated recursively; that is, the observations are being received continuously, and it is required that the estimate be continuously revised to take into account the new data. Thus the state estimate is generated by passing the measurements through a filter or estimator. The basic objective here is the study of the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time.

Adaptive control refers to the control or regulation of a system in the presence of parameters which are unknown or which vary with time. Some type of monitoring of the system's behavior, followed by a suitable control action, is referred to as an adaptive controller. In this research unit, systems which also are affected by noise disturbances, and in which the state of the system is not measured exactly, will be considered. The objective is that of designing and analyzing a control law (or feedback controller) which minimizes a given cost or tracks a given reference signal in the presence of unknown parameters, noise, and incomplete (or noisy) state observations.

Systems in which changes can occur which are more drastic than relatively slow parameter variations are exemplified by systems with failure modes which significantly alter the structure of the system. Reconfigurable aircraft represent one such type of system. In this case, there is a "hybrid" situation in which the state of the system consists of a set of real numbers (the usual "state") together with a set of discrete or Boolean variables (describing, for example, the structure of the system). One eventual result of research on this class of systems will be higher level symbolic modules which will work with lower level adaptive controllers to form a more intelligent multi-level control system.

B. PROGRESS: A major component of our research program involves adaptive estimation and control problems for stochastic systems involving either incomplete (or noisy) observations of the state or nonlinear dynamics. The first class of problems we have studied involves finite state Markov chains with incomplete state observations and unknown parameters; in particular, we have studied certain classes of quality control, replacement, and repair problems. However, we found that work remained to be done for such problems with known parameters; this problem was studied in [1]. In this paper, we consider partially observable Markov decision processes with finite or countable state and observation spaces and finite action set. An equivalent completely observed problem is formulated, with the same finite action set but with an uncountable state space, namely the space of probability distributions on the original core state space. It is observed that some characteristics induced in the original problem due to the finiteness or countability of the spaces involved are reflected onto the equivalent problem. Sufficient conditions are then derived for a bounded solution to the average cost optimality equation to exist. We illustrate these results in the context of machine replacement problems. By utilizing the inherent convexity of the partially observed problem, structural properties for average cost policies are obtained for a two state replacement problem; these are similar to results available for discount optimal policies. In particular, we show that the optimal policy has the "control limit" or "bang-bang" form. The set of assumptions used seems to be significantly less restrictive than others currently available. In [2], necessary conditions are given for the existence of a bounded solution of the average cost optimality equation. We consider in [3] average cost Markov decision processes on a countable state space and with unbounded costs. Under a penalizing condition on the cost for unstable behavior, we establish the existence of a stable stationary strategy which is strong average optimal.

As a prelude to studying adaptive control, the problem of characterizing the effects that uncertainties and/or small changes in the parameters of a model can have on optimal policies is considered in [4]. It is shown that changes in the optimal policy are very difficult to detect, even for relatively simple models. By showing for a machine replacement problem modeled by a partially observed, finite state Markov decision process, that the infinite horizon, optimal discounted cost function is piecewise linear, we have derived formulas for the optimal cost and the optimal policy, thus providing a means for carrying out sensitivity analyses. This work is extended in [5] to several other classes of problems, including an inspection problem with standby units, an optimal stopping problem, input optimization for infinite horizon programs, and Markov decision processes with lagged information.

We have undertaken an in-depth investigation of adaptive nonlinear estimation problems for stochastic systems involving incomplete (or noisy) observations of the state and unknown parameters. In [6], the adaptive estimation of the state x_t of a finite state Markov chain with incomplete state observations y_t taking values in a finite set, and in which the state transition probabilities depend on unknown parameters, is studied. Such problems arise in systems such as computer communication networks. In general, the adaptive estimation problem involves the computation of estimates (e.g., state estimates) in the presence of unknown parameters; in addition, estimates of the parameters are computed simultaneously. In the present context, the adaptive estimation problem is that of computing recursive estimates of the conditional probability vector of the state x_t given the past observations $\{y_0, \dots, y_t\}$, when the state transition matrix Q is not completely known (i.e., it depends on a vector of unknown parameters θ — this dependence is expressed as $Q(\theta)$). The approach to this problem which we have investigated has been widely used in linear filtering: we use our previously derived recursive filter [7] for the conditional probabilities with known parameters, and we simultaneously recursively estimate the parameters, plugging the parameter estimates into the filter. This adaptive estimation algorithm is then analyzed via the Ordinary Differential Equation (ODE) Method [8], [9]. That is, it is shown that the convergence of the parameter estimation algorithm can be analyzed by studying an averaged ordinary differential equation. The most crucial and difficult aspect of the proof is that of showing that, for each value of the unknown parameter, an augmented Markov process has a unique invariant measure. New techniques for the analysis of the ergodicity of time-varying Markov chains are utilized. The convergence of the recursive parameter estimates is studied, and the optimality of the adaptive state estimator is proved. This is the first such analysis of an adaptive nonlinear estimation problem in the literature.

We have begun to apply similar methods to adaptive stochastic control problems with incomplete observations. We have first considered a quality control problem in which a system, such as a manufacturing unit or computer communications network, can be in either of two states: good or bad. Control actions available to the inspector/decision-maker are: (a) produce without inspection, (b) produce and inspect; or (c) repair. Under actions (a) and (b) the system is subject to Markovian deterioration, while a repair puts the unit in the good state by the next decision time. Informative data might become available while producing without inspection, and inspection is not always perfect. Hence the problem is modeled as a partially observed Markov decision process (POMDP). Furthermore, we assume that deterioration of the system depends on an unknown parameter θ, namely the probability of the state going from the good to the bad state in one time epoch when no repair is done. For the case of known parameters, we have shown in [1] that there is an optimal policy for the infinite horizon average cost criterion that is of the control limit (bang-bang) type. The adaptive stochastic control problem is, however, much more difficult than the adaptive estimation problem, because the presence of feedback causes the system transitions to depend on the parameter estimates and introduces discontinuities.

In [10] and [11], we have analyzed algorithms for this quality control problem in which the parameter estimates are updated only after the system is repaired; such algorithms are analogous to those in which estimates in queueing systems are updated only after each busy cycle. Since the system is returned to the "good" state after repair, one obtains a perfect observation of the state at that time, and our algorithm uses the observation at the next time to estimate θ. Hence, we develop parameter estimation techniques based on the information available after actions that reset the state to a known value. At these times, the augmented state process "regenerates," its future evolution becoming independent of the past. Using the ODE method, we show that two algorithms, one based on maximum likelihood and another based on prediction error, converge almost surely to the true parameter value θ_0.

We have studied in [12] controlled diffusion processes on an infinite horizon with three non-standard cost criteria: weighted cost, variance sensitive cost, and overtaking optimality. Under a stability assumption we establish the existence of stationary Markov controls which are optimal for these criteria in certain classes. Also, under very general conditions we establish the existence of an ε-optimal Markov policy for the weighted criterion.

As proposed in our triennial proposal, we have also investigated several problems in the area of discrete event systems, in order to develop the capability for analyzing multi-level systems which can intelligently process different types of information. In discrete event systems, examples of which include flexible manufacturing systems and computer networks, the state of the system changes at asynchronous discrete instants of time instead of continuously and is governed by the intricate interaction of discrete events. Models and control algorithms have begun to be developed by modeling the discrete event dynamical system (or plant) as a finite automaton with certain controllable events, the occurrence of which can be disabled by means of a control action. A number of such problems are understood and have been solved in the case that the supervisor (or controller) can perfectly observe the occurrence of events in the plant [13], but the more interesting case of the supervisor receiving incomplete information is less well understood. In many cases, this can be modeled by constructing a mask, or observation function, M, through which the supervisor observes the occurrence of events; hence, certain events cannot be distinguished from each other or cannot be seen by supervisors. In this case, necessary and sufficient conditions for the closed-loop behavior or language L to be realized by the construction of a suitable supervisor are known for some problems of interest [14]. As opposed to the much simpler case of perfect information, it turns out that the class of sublanguages $\underline{I}(L)$ of a given language L which satisfy the necessary and sufficient conditions do not necessarily possess supremal elements; thus, minimally restrictive solutions may not exist. Therefore we are forced to resort to a solution that is minimally restrictive in some narrower sense. On the other hand, there is a smaller class of sublanguages $\underline{D}(L)$ which is algebraically well-behaved and does possess a supremal element. In [15], we show that the supremal element of this class can be computed via an algorithm which has a simple graphical structure and is well suited to computer implementation; this algorithm recursively removes edges and nodes from the graph of an automaton which generates a particular language. These algorithms provide a good suboptimal solution to the problem; in addition, they involve new classes of automata which are of interest in their own right. In some cases, however, this suboptimal solution is too restrictive, and it is natural to study maximal elements of $\underline{I}(L)$. This is a much more difficult problem, but we have been able in [16] to develop an algorithm which computes such a maximal element as a limit of a decreasing sequence of sublanguages of L.

In a related area of intelligent control, we have also studied some problems in robotics. The motion and internal loads induced on an object manipulated by two or more robotic mechanisms are considered in [17]. In particular, for a desired motion trajectory of the object, the question of load distribution among the arms is analyzed, with particular attention given to the internal loading of the object. A new representation of the load distribution problem is given by the introduction of a particular "non-squeezing" pseudoinverse, which is shown to possess properties which expose the underlying structure of the problem. It is expected that by using this pseudoinverse, new insight will be gained, and necessary analysis simplified, in a number of aspects of multiple manipulator research. A number of these aspects are detailed and illustrated using a two armed example.

(Research Unit IE89-2, "Nonlinear Estimation and Stochastic Adaptive Control")

C. FOLLOW-UP STATEMENT: The research described above will be actively continued under JSEP sponsorship. Some particular directions are the following. Our work [15], [16] on discrete event dynamical systems will be continued; topics being investigated include stability and the study of the sequential (infinite time) behavior of such systems. The stochastic adaptive control problem of [10], [11] will be further analyzed by the design of other parameter estimation algorithms which utilize more of the available information, and the rates of convergence of these algorithms will be analyzed. In addition, these techniques will be generalized for the adaptive control of hybrid systems with continuous state, logical controls, and continuous parameters. Topics being investigated include stability, decentralized control, and the use of decomposed Petri net models.

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17. I.D. Walker, R.A. Freeman, and S.I. Marcus, "Analysis of Motion and Internal Loading of Objects Grasped by Multiple Cooperating Manipulators," Journal of Robotic Systems, to appear.

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II. LIST OF CONFERENCE PROCEEDINGS (*JSEP supported in whole or in part)

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* M.K. Ghosh and S.I. Marcus, "Ergodic Control of Markov Chains," Proceedings of the 29th IEEE Conference on Decision and Control (December 5-7, 1990).

III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

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IV. LIST OF THESES AND DISSERTATIONS

None

V. GRANTS AND CONTRACTS

Air Force Office of Scientific Research, Grant AFOSR-86-0029, "Research in Adaptive and Decentralized Stochastic Control," S.I. Marcus and A. Arapostathis, Principal Investigators, November 15, 1985-November 14, 1990.

Air Force Office of Scientific Research, Grant AFOSR-86-0029, "Adaptive Control of Nonlinear and Stochastic Systems," S.I. Marcus and A. Arapostathis, Principal Investigators, November 15, 1990-November 14, 1991.

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II. SOLID STATE ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE89-1 GROWTH OF III-V COMPOUNDS BY MOLECULAR BEAM EPITAXY

Principal Investigator: Professor Ben G. Streetman (471-1754)

Graduate Students: T. Block, T. Chu, A. Dodabalapur, T. Rogers, K. Sadra

A. SCIENTIFIC OBJECTIVES: Our objective is to study the MBE growth of multilayer heterostructures in GaAs, AlGaAs, InGaAs, and related compounds, to improve the quality and variety of structures available and to apply these structures to electronic and optoelectronic devices. This work contributes to the other units in the UT-Austin JSEP compound semiconductor program by providing access to specialized MBE growth of multilayer heterostructures. We have developed extensive measurement capabilities which allow us to examine details of MBE growth at the monolayer and submonolayer scale, and also to use the resulting controlled growth for device development and studies of transport properties in semiconductor multilayers. Advanced structures grown in this work are used in the transport studies and device development research described in other MBE-related units in this program. Therefore, the major goals of this work are to develop new understanding of MBE growth, apply that understanding to the growth of high-quality multilayer heterostructures, characterize those structures, and work with related JSEP units to advance the science and art of devices based on such multilayers.

B. PROGRESS: Our research during the past year has been concentrated primarily in four areas: MBE growth of high-resistance GaAs and AlGaAs layers at low growth temperatures; studies of Reflection High Energy Electron Diffraction (RHEED) dampening during growth; examination of modulation doped and pseudomorphic quantum wells; and growth of vertical cavity surface-emitting laser structures.

We have used low temperature MBE growth to obtain highly resistive GaAs and AlGaAs layers with potential applications in a variety of devices [1,2]. Using MIS structures, we have examined the resistivity of GaAs and AlGaAs for various aluminum mole fractions and growth temperatures. GaAs resistor and MIS structures grown at 300°C exhibit a resistivity of 5×10^5 Ω-cm. We have grown a HEMT structure with high mobility (μ = 156,000 $cm^2\,V^{-1}s^{-1}$ at 77 K) and electron sheet density ($n_s = 6\times10^{11} cm^{-2}$ at 77 K) on a highly resistive low-temperature grown (LTG) $Al_{0.3}Ga_{0.7}As$/GaAs superlattice buffer. In collaboration with D. Neikirk (Unit EM89-1), a coplanar waveguide (CPW) was fabricated on a 0.75 µm epitaxial $Al_{0.3}Ga_{0.7}As$ layer grown at 270°C. There was virtually no difference in the measured S-parameters for the coplanar waveguide (CPW) fabricated on the 0.75 µm epitaxial $Al_{0.3}Ga_{0.7}As$ layer and the CPW made directly on a semi-insulating GaAs wafer.

We have intentionally introduced AsO during the growth of GaAs and AlGaAs to study its effects on the dampening of RHEED oscillations and the photoluminescence of quantum well (QW) structures [3]. The AsO (as determined by a mass 91 peak in the residual gas analysis of the beam) was obtained from the cracking section of our As cell prior to the baking of the source. This allowed us to introduce a controlled amount of AsO proportional to the cracker temperature. The

AsO was found to affect both the RHEED and the photoluminescence. We found that the dampening of the AlGaAs increased with increasing AsO concentrations, whereas little effect was found upon the dampening of the GaAs. Following the RHEED studies for each set of growth parameters, a set of QWs were grown with various GaAs well thicknesses separated by AlGaAs barriers. The presence of AsO was found to have a dramatic effect on both the integrated intensity and the linewidth of the QW samples. After baking the As cracking section until the AsO peak disappeared, the RHEED dampening became independent of the temperature of the cracking section.

We have performed an extensive study of the relationship between photoluminescence (PL) spectra and low-field electrical properties of modulation-doped AlGaAs/GaAs quantum wells [4,5] and have applied both PL and electroreflectance to study AlGaAs/InGaAs/GaAs structures [6,7]. We find that the 77-K PL linewidth closely tracks the Fermi energy, and is a good measure of free-carrier density. The 4.2 K linewidth is influenced by both the free-carrier density and crystalline quality. However, the high energy cutoff point of the 4.2 K spectra yields the Fermi energy which can easily be related to the carrier density. The ratio of 77 K to 4.2 K PL linewidths is a good index of crystalline quality, as demonstrated by correlation with 77 K Hall mobility. Our work indicates that low-temperature PL can be a very valuable nondestructive characterization technique to probe large area wafers, both under as-grown conditions and after various processing steps. We have used Electron Beam Electroreflectance (EBER) to characterize modulation-doped quantum wells (MDQWs) and undoped quantum wells in the AlGaAs/InGaAs/GaAs material system. Several transitions have been observed and fitted to excitonic Lorentzian lineshapes, providing accurate estimates of transition energy and broadening parameter at temperatures of 96 K and 300 K.

We have used these techniques to study the effects of rapid thermal annealing on the electrical and optical properties of modulation-doped quantum wells [8]. The sheet carrier concentration in MDQW structures which have been annealed in contact with a piece of GaAs tends to decrease with increasing annealing time due to Si auto-compensation in the doped AlGaAs regions. The high energy cut-off point of 4.2 K PL spectra and the 77 K PL linewidth were used to track variations in carrier density produced by annealing. Photoluminescence spectra also provide additional insight into annealing-induced changes such as Si migration, which causes a degradation in the mobility of the two-dimensional electron gas.

In collaboration with Prof. D.G. Deppe of the UT-Austin Microelectronics Research Center, we have used MBE-grown structures to study microcavity effects in vertical cavity surface-emitting lasers (VCSELs) [9-11]. We have found that the spontaneous emission from an InGaAs QW is strongly influenced by a closely spaced, highly reflecting AlAs-GaAs distributed Bragg reflector (DBR). Spontaneous emission is enhanced for a QW to DBR spacing of $\lambda/2$, while the emission is suppressed for a QW to DBR spacing of $\lambda/4$. In addition, we find quite strong cavity effects on the spontaneous emission linewidth, even when one of the cavity mirrors is of relatively low reflectivity, in this case the GaAs-air interface. The fact that the spontaneous photon emission characteristics of a semiconductor QW can be strongly influenced by its close proximity to a highly reflecting interface raises very interesting fundamental questions as well as having useful device implications. We have found intensity enhancements in the normal direction to the mirror of a factor of 10 for a QW placed at an interference antinode as opposed to an interference node. The corresponding change in frequency response increases with the increasing emission intensity, consistent with the change in spontaneous lifetime. The control of the spontaneous lifetime by this external means has important implications for devices such as LEDs and lasers.

C. FOLLOW-UP STATEMENT: We will continue to study the details of MBE growth using imaging RHEED, and the quality of layers in the InGaAlAs system using both electrical and optical measurements. Devices employing multilayer heterostructures will be studied in collaboration with other units in this program and with other faculty in the Microelectronics Research Center. During the upcoming year we will concentrate on MBE growth of VCSELs and other structures of use in various optoelectronic applications.

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III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

* D.G. Deppe, T.J. Rogers, and B.G.Streetman, "Gain Mechanism of the Quantum Well Vertical Cavity Surface-Emitting Laser," presented at the 1990 Device Research Conference, Santa Barbara , CA (1990).

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T.Y. Chu, A. Dodabalapur, A. Srinivasan, D.P. Neikirk, and B.G. Streetman, "Properties and Applications of $Al_xGa_{1-x}As$ (0 <x> 1) Grown at Low Temperatures," presented at the 6th International Conference on Molecular Beam Epitaxy, San Diego, CA (1990).

IV. LIST OF THESES AND DISSERTATIONS (*JSEP supported in whole or in part)

* A. Dodabalapur, Ph.D, August 1990, "MBE Growth and Correlation Between Electrical and Optical Properties of Modulation-Doped Quantum Wells."

* F. Ip, M.S., August 1990, "Study of Pseudomorphic HEMT Structures."

(Research Unit SSE89-1, "Growth of III-V Compounds by Molecular Beam Epitaxy")

- S. Foxworth, M.S., December 1990, "Modeling of Fields in Semiconductor Heterojunctions."

V. GRANTS AND CONTRACTS

Army Research Office, Contract DAAL03-88-K-0060, "Quantitative RHEED Studies of MBE Growth of III-V Compounds," Prof. Ben Streetman, Principal Investigator.

Texas Advanced Technology Program (TATP), "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors Ben G. Streetman and Dean P. Neikirk, Co-Principal Investigators.

Varian Associates, Inc., "Valved Dimer Source," Professor Ben G. Streetman, Principal Investigator.

THE UNIVERSITY OF TEXAS AT AUSTIN — ELECTRONICS RESEARCH CENTER, SOLID STATE ELECTRONICS

Research Unit SSE89-2 EPITAXIAL GROWTH AT III-V SEMICONDUCTOR SURFACES

Principal Investigator: Professor J.L. Erskine (471-1464)

Graduate Students: D.C. Anacker, Craig Ballentine (graduated), and J.E. Yater

A. SCIENTIFIC OBJECTIVES: This research unit is addressing two related scientific objectives. In collaboration with M.C. Downer (Research Unit SSE89-4), we are developing a new probe of hot electron dynamics by combining femtosecond laser technology with angle-resolved photoemission. A second project explores physical phenomena associated with epitaxial growth by using a variety of electron spectroscopic techniques which probe structure, dynamics (phonons), and electronic properties of the substrate surface and thin epitaxial structures.

B. PROGRESS: We have reported the first observation of pure thermionic emission from a solid heated by a femtosecond pulse. This result is described in the PROGRESS Section of Research Unit SSE89-2, and the cited publications. The most important result is that the velocity distribution of thermionically emitted electrons (a direct measure of the electron temperature) is unaffected by space charge effects even at emission densities where space charge effects are found to dramatically suppress electron yield. The significance of this result is that it shows electron time-of-flight spectroscopy provides a new and independent (from optical methods) technique for measuring electron temperatures under pulsed laser excitation.

In order to correctly interpret the time-of-flight spectra from our photoelectron detector, it was necessary to characterize the response efficiency, linearity, and dynamic range of the detection system including the channel plates. We therefore carried out a comprehensive study of the factors that govern energy resolution, dynamic range, and linearity of our time-of-flight photoelectron spectrometer. We have developed a phenomenological model of microchannel plate (MCP) response that corrects for the lowest nonlinear term in MCP gain which results from "bleaching" of MCP pores. We also developed a physical model for the pore bleaching effect. These models successfully account for first order departures from linear response, and provide an accurate criteria for gauging the dynamic range and linearity of our electron spectrometer. These results, along with a complete description of design considerations and construction details of our time-of-flight photoelectron spectrometer, have been submitted for publication in *Review of Scientific Instruments.*[1]

Our studies of surface phonons at Ag(110) using inelastic electron scattering have produced some important results. We have reported the first comprehensive characterization of the dynamics of a single crystal surface which includes shear modes. Shear modes describe surface vibrations parallel to the surface which have odd symmetry with respect to a crystal mirror plane. These modes are particularly sensitive to surface stress, and in systems consisting of ultra-thin epitaxial layers, the shear modes will provide a sensitive probe of the film structure and stress during nucleation and the initial stages of epitaxial growth.

(Research Unit SSE89-2, "Epitaxial Growth at III-V Semiconductor Surfaces)

Our first measurements and lattice dynamical analysis of shear modes at Ag(110) surfaces have yielded a rather surprising result: the lattice dynamical model which accounts for all of the experimentally determined phonon modes departs significantly from models based solely on even symmetry modes[2]. All previous work in this field fails to measure the shear modes and account for them in the analysis. This inconsistency between results implies that a careful re-evaluation of previous conclusions (interaction potential models and assessment of surface stress in the first atomic layer) may be required if the same general trend persists in shear mode studies of other surfaces. Our preliminary results were presented at the International Workshop on Surface Phonons in West Germany and at the Fifth International Conference on Vibrations at Surfaces in New York[2].

C. FOLLOW-UP STATEMENT: We have demonstrated the use of electron time-of-flight spectroscopy following femtosecond laser excitation as a direct time-resolved probe of the temperature of hot electrons in metals. This technique offers unique opportunities for studying hot electron transport, electron-lattice coupling and cooling in solids. We therefore plan to explore these effects in thin film samples (semiconductor-metal, and metal insulator systems) in which the 2-dimensional nature of the sample and the interface of dissimilar materials provide opportunities to vary physical parameters that affect hot electron transport. We also plan to explore the possibility of studying the lifetime of quantum well states in thin film systems. An attractive candidate for an initial study is the p(1x1) Ag on Cu(111) system which has been studied by angle resolved photoemission[3], and which is known to support quantum well states.

Our inelastic electron scattering measurements of shear modes at surfaces suggest a flaw exists in the conventional wisdom of surface dynamics which has evolved form measurements of only even symmetry modes. Before we attempt to utilize inelastic electron scattering to study any additional systems, in particular semiconductor surfaces and epitaxial layers, we must first establish the role shear modes play in obtaining an accurate description of surface lattice dynamics. This requires additional experimental and theoretical analysis of shear modes at simple crystal surfaces, such as Ni(110) and Cu(110).

D. REFERENCES: (* JSEP supported in whole or in part)

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II. LIST OF CONFERENCE PROCEEDINGS (* JSEP supported work)

[Seminar] *"Inelastic Electron Scattering Studies of Surface Phonons", J.L. Erskine, Department of Physics, Indiana University, Bloomington, Indiana, April 7, 1989.

[Workshop] *"Phonons at Metal Surfaces", J.E. Yater and J.L. Erskine, International Workshop on Surface Dynamics, Physics Department, University of Texas at Austin, Austin, Texas, November 9 - 11, 1989.

[Seminar] "Thin Film Magnetism", J.L. Erskine, National Synchrotron Light Source, November 25, 1989.

[Workshop] *"Inelastic Electron Scattering from Surfaces and Thin Epitaxial Layers", J.L. Erskine, Molecular Dynamics Workshop, Captive Island, Florida, Oct. 29-31, 1989.

[Conference] *"Detection of Odd-symmetry Shear Modes at Metal Surfaces by Inelastic Electron Scattering: Experiment and Theory", J.L. Erskine, Eue-Jin Jeong, Joan Yater, Y.

Chen, and S.Y. Tong, 36th National Symposium of The American Vacuum Society, Boston, Massachusetts, Oct. 23-27, 1989.

[Invited Talk] "New Opportunities in Spin-polarized Photoemission Spectroscopy", J.L. Erskine and R.L. Fink, 34th Conference on Magnetism and Magnetic Materials, Boston, Massachusetts, Nov. 28-Dec. 1, 1989.

[Invited Talk] *"Interaction of Super-intense Light Fields with Atoms and Surfaces", M.C. Downer, W.C. Banyai, W.M. Wood, D.C. Anacker, and J.L. Erskine, SPIE OE/LASE '90 Conference on Optics, Electro-optics, and Laser Applications in Science and Engineering, Los Angeles, January 17, 1990.

[Conference] "ARUPS Electronic Structures Studies of Iron Overlayers Grown on W(100)", J.L. Erskine, American Physical Society, Anaheim, California, March 12-15, 1990.

[Conference] *"Measurement of Transient High-temperature Electrons from Solid-density Plasmas", W.C. Banyai, D.C. Anacker, X.Y. Wang, D.H. Reitze, G.B. Focht, M.C. Downer, and J.L. Erskine, Topical Meeting on Ultrafast Phenomena VII, Monterey, CA, May 14-17, 1990.

[Conference] *"Measurement of Transient High-temperature Electrons from Solid-density Plasmas", W.C. Banyai, D.C. Anacker, X.Y. Wang, D.H. Reitze, G.B. Focht, M.C. Downer, and J.L. Erskine, Conference on Lasers and Electro-optics (CLEO '90), Anaheim, CA, May 21-25, 1990.

[Invited Talk] *"Inelastic Electron Scattering Spectroscopy of Atoms and Molecules at Surfaces", J.L. Erskine, Annual Meeting of the American Physical Society, Monterey, CA, May 21-23, 1990.

[Invited Talk] "Thin Film Magnetism", J.L. Erskine, Surface Physics in Material Sciences Conference, University of Texas at El Paso, El Paso, Texas, June 3-4, 1990.

[Invited Talk] "Spin-polarized Angle-resolved Photoemission Studies of Clean and Oxidized 1-3 ML Films of p(1x1) Fe/W (100)", R.L. Fink, G.A. Mulhollan, J.L. Erskine, G.K. Walters, and N.B. Brookes, Physical Electronics Conference, Gaithersburg, Maryland, June 11-13, 1990.

[Invited Talk] *"Surface Phonons of Ag(100) and Ag(110): Measurements of Odd-Symmetry Shear Modes Using Inelastic Electron Scattering", J.E. Yater and J.L. Erskine, Fifth Workshop on Surface Phonons, Rottach Eggern, Bavaria, Germany, June 22-30, 1990.

[Invited Talk] "Surface Magnetism", J.L. Erskine, Molecular Sciences Workshop, Battelle, Pacific Northwest Laboratories, Richland, Washington, July 10, 1990.

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[Seminar] "Thin Film Magnetism", J.L. Erskine, Department of Physics, Cornell University, October 25, 1990.

[Conference] "Spin and Angle-resolved Photoemission Studies of 1-3ML Films of p(1x1) Fe on W(100)", R.L. Fink, G.A. Mulhollan, A.B. Andrews, J.L. Erskine, and G.K. Walters, 35th Annual Conference on Magnetism & Magnetic Materials, San Diego, CA, October 29-November 1, 1990.

[Symposium] *"Magneto-Optical Studies of Ultrathin Fe/W(100) Films", J. Araya-Pochet, C.A. Ballentine, and J.L. Erskine, Sixth Latin-American Symposium on Surface Physics, Cusco, Peru, 1990.

III. LIST OF THESES AND DISSERTATIONS

C.A. Ballentine, Ph.D., October 1989, "Magneto-optical Studies of Fe, Ni, V and Pd Ultra-thin Films on Ag(100), Ag(111), Cu(100) and Cu(111) Single Crystal Substrates", (supported by JSEP).

IV. GRANTS AND CONTRACTS

The Robert A. Welch Foundation Welch F-1015, "Electron Scattering Studies of H/Nb(100)", Dr. J.L. Erskine, Principal Investigator, 1987-1990.

National Science Foundation DMR-8702848, "Experimental Studies of Intrinsic Surface Electronic and Magnetic Properties", Dr. J.L. Erskine, Principal Investigator, 1987-1989.

National Science Foundation DMR-8906935, "Fundamental Studies of Magnetic Materials", Dr. J.L. Erskine, Principal Investigator, 1989-1992.

Air Force Office of Scientific Research 89-NC-090, "High Resolution Electron Energy Loss Studies", Dr. J.L. Erskine, Principal Investigator, 1989-1992.

Joint Services Electronic Program, "Epitaxial Growth at III-V Semiconductor Surfaces", Dr. J.L. Erskine, Principal Investigator, 1988-1991.

National Science Foundation INT-9000058, "Fundamental Studies of Ultra-thin Magnetic Films", Dr. J.L. Erskine, Principal Investigator, Dr. José Araya-Pochet, Co-Principal Investigator, 1990-1992.

(Research Unit SSE89-2, "Epitaxial Growth at III-V Semiconductor Surfaces)

National Science Foundation DMR-8922359, "Experimental Studies of Thin Film Magnetism", Dr. J.L. Erskine, Principal Investigator, 1990-1991.

National Science Foundation DMR-9003179, "Development of Instrumentation for Fundamental Studies of Thin Film Magnetism", Dr. J.L. Erskine, Principal Investigator, 1990-1991.

National Science Foundation MRG DMR-8609635, "Fundamental Studies of Magnetic Materials", Dr. J.L. Erskine, Principal Investigator, 1989-1991.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE89-3 CHARGE TRANSPORT IN NOVEL DEVICE STRUCTURES AND MATERIALS

Principal Investigator: Christine M. Maziar (471-3674)

Graduate Students: Carl Kyono, Paul C. Colestock and Andalib Chowdhury

A. SCIENTIFIC OBJECTIVES: The focus of this research unit is the study of charge transport in semiconductors on ultra-small spatial and temporal scales. We believe that it is essential for a successful modern materials and device research program that strong experimental, modeling and simulation efforts be coordinated for the study of transport phenomena. The understanding and exploitation of promising materials and device concepts is most fully realized when accurate models are available to device researchers and materials scientists. Such models are most successfully developed when a simulation effort is tightly coupled with experimental work. Such coordination is a key feature of the ongoing research in this unit. Our studies are proceeding along three lines, all focused on carrier transport and all making use of the Monte Carlo simulation technique. The three areas of activity, described in more detail below, are (i) charge transport in enhanced velocity structures in InP-lattice matched materials, (ii) development of noise-spectroscopy tools for the analysis of transport through semiconductor tunneling barriers and (iii) development of computationally efficient tools for modeling superlattice bandstructures in III-V and $Si/Si_{1-x}Ge_x$ systems. Substantial collaboration has and is occurring with the JSEP efforts headed up by Neikirk (SSE89-5) and Streetman (SSE89-1). MBE grown films from Streetman and Neikirk's groups are being used as the test vehicles for the noise spectroscopy studies. Neikirk's group has also been especially helpful in developing high-frequency measurement capabilities for studying velocity overshoot phenomena in HBT structures.

B. PROGRESS: *Enhanced Velocity Overshoot in InP-lattice Matched Materials:* One approach to improving heterojunction bipolar transistor (HBT) high-frequency performance is to reduce the transit time across the collector space charge region by carefully tailoring the electric field in the collector in such a fashion as to extend or enhance velocity overshoot in the space-charge region. This technique was first described [1] and demonstrated [2] for $Al_xGa_{1-x}As/GaAs$ HBTs. Recently, structures composed of materials lattice matched to InP substrates [3] have emerged as champions in the race for high-speed and optical applications honors. Because those high-speed devices reported in the literature have utilized conventional collector structures, further gains can be achieved by application of collectors designed for enhanced or extended velocity overshoot. This is easily seen by noting that the extended velocity overshoot condition is more easily achieved in $In_{0.53}Ga_{0.47}As$ than in GaAs, in large part due the larger Gamma-L conduction band separation. We performed Monte Carlo simulations of the InGaAs extended velocity overshoot structures which demonstrated the efficacy of using such a collector structure to achieve short transit times through collector space-charge regions [4]. Figures 1 and 2 illustrate comparisons of average carrier velocity as a function of position for conventional and inverted field (or enhanced velocity) collectors. The two simulation cases differ only in that in Figure 1 the emitter was InP while in Figure 2 the emitter was InAlAs lattice matched to InP. The apparent advantage of the InP emitter over the InAlAs emitter is attributed to the extra scattering introduced into the system due to the larger "energy ramp" at the emitter/base junction for the InAlAs emitter. A cursory consideration of the two emitters might lead one to believe that the InAlAs emitter should be superior because of this "ballistic launching" ramp into the base. Our investigations showed that a more holistic study must be conducted which considers not only base transport but also transport through the collector space region.

We have also had the opportunity to fabricate HBTs which exhibit the enhanced velocity effect using a structure much like that described in [1] and [4]. These devices were fabricated on MOCVD films obtained from Prof. Russ Dupuis' group. These devices exhibited excellent DC current gains (beta ~ 24,000)[5] and reasonable high-frequency performance (f_t ~ 15 GHz)[6]. We were reasonably surprised by the high f_t's since our fabrication process was relative simple, the devices were grown on conducting substrates, and the emitter area was rather large (~9 micron x 9 micron). Nonetheless, extracted base-collector transit times agree quite well with the transit times calculated via Monte Carlo simulation. In addition, these devices exhibited excellent output characteristics (especially as compared with the characteristics of other high gain devices reported in the literature [7]). Representative device characteristics are shown in Figure 3.

Barrier Transport Analysis via Noise Measurements: It has been proposed that noise may be used to examine the transport of charge carriers through single barrier heterostructures. Theoretical treatments of scattering processes in semiconductors suggest that these processes will produce excess high frequency electronic noise [8] with a unique structure at a frequency related to the rate of the scattering process. While the high frequency noise structure has not been measured directly, lower frequency noise spectral density vs electric field measurements of the noise associated with intervalley scattering in GaAs have been documented [9] and show that this noise does appear as excess current or voltage fluctuations. Thus, it is possible that the measurement of excess noise in semiconductors can be used to illuminate scattering processes. A previous report [10] of the I-V characteristics of single barrier GaAs/AlAs structures reveals a dependence of the effective barrier height on barrier thickness. Measured temperature -independent currents in excess of calculated theoretical inelastic tunneling currents for thick barriers were shown even when compared to those calculated using a reduced barrier height from measured thermionic current data. It is believed that this excess current is scattering assisted. We are conducting an experiment which has the aim of associating the source of this current with scattering processes by measuring the excess noise characteristics of several GaAs/AlGaAs test structures.

Two different test structures are presently considered. Both structures are composed of MBE grown GaAs with an AlGaAs barrier of varying composition and thickness. One structure includes only a single barrier sandwiched between thin GaAs spacer layers and contacts. The second device structure includes a thick lightly doped GaAs drift region between the spacer and contact layers on one side of the barrier. These structures are shown in Figures 4a and 4b. The first structure is used to directly measure the effect of the barrier on transport and the second device is used to measure the effect of the barrier on the transport in the drift region. Clearly, study of these structures should be productive in providing insight into the details of transport processes through tunneling structures and may affect our effectiveness in designing RTD structures.

The measurement of the fluctuations in current and voltage due to scattering requires a very sensitive measurement system. Noise power spectral density vs electric field measurements can be made at relatively low frequencies compared to the frequency at which the structure of the scattering event appears. This low frequency measurement technique must be used whenever the total noise signal associated with scattering occurs at very high frequencies. Since the noise signatures we are interested in are expected to have very high frequency components, an RF/microwave noise measurement system is necessary. Such a system must include a low noise high frequency receiver capable of very narrow band input filtering and averaging. It is desired that the noise signal averaging gives unbiased results. For the high frequency measurements, a mixer is used to down convert the noise signal into a bandwidth which the receiver can detect. The low and high frequency noise measurement systems are shown in Figure 5. The first system (HF system), shown in Figure 5a, consists of an HP346B calibration noise source, a biasing network, a device under test (DUT), an HP8970T noise figure test system, and a probe station backfitted with coplanar microwave probes from Cascade Microtech. An HP Vectra computer is connected to take and process data from the system. This system provides for the measurement of noise figures as low as -30 dBm from 10 MHz to 18GHz. A second setup (LF system) is shown in Figure 5b. This setup includes a Princeton Applied Research Model 124A lockin amplifier with a 10% bandwidth excess noise ratio mode. This second system can detect noise spectral densities as low as -145 dBV from 2Hz to 210kHz. The HF noise measurement system is designed to measure noise figure. Direct measurement of noise power can be obtained by using special function 9 which gives the measured noise power relative to -174 dBm.

Our status on the noise measurement aspect of this program is as follows:

* Noise Measurement Systems: Installed HF and LF noise measurement systems. Determined minimum detectable shot noise DC currents of 1.56mA (40MHz BW in 50 ohms) and 125 mA (1Hz BW in 50 ohms) respectively. Bandwidth for the HF system is fixed and input impedance is 50 ohms or less depending on the device. Device impedance below a few thousand ohms will degrade minimum specifications. In the low frequency system,the bandwidth is always 10% of center frequency (cf) and thus ranges from 0.2Hz at 2Hz cf to 21KHz at 210KHz cf. In addition, the input impedance is 1Mohm and thus the device impedance fixes the minimum detectable shot noise current. The higher the device impedance the lower the minimum detectable shot noise current.

* DC Characterization: The DC voltage/current characteristics of the single barrier devices are important in determining the proper bias point for noise measurements as well as an indication of the quality of the processing and material. Small voltage drops across the barriers relative to the barrier height are desired to minimize the bending of the conduction bands for the GaAs/AlAs barrier structure. The voltage drop should be kept to within a few tens of millivolts. This requirement combined with the system minimum shot noise currents determine proper device resistance.

The DC I-V characteristics of fifteen 150 micron diameter devices from two barrier thickness groups were measured (30 total devices). The first group included a 50.9 angstrom barrier and the second a 150.9 angstrom barrier. The measurements were made using an HP4145B semiconductor parameter analyzer and probe station. The average and standard deviation of the measured resistances for the two groups were 840 ohms and 93.9 ohms for the 50.9 angstrom devices and 157 kilo-ohms and 7.9 kilo-ohms for the 150.9 angstrom devices. These resistance values together with the DC current can be used to calculate the equivalent shot noise voltage which will be measured by the system and is given by:

$$V^2/Hz = 2^* q^* I_{dc}^* R^2$$

From this equation, the predicted shot noise voltage spectral density in 50 ohms for the 50.9 angstrom group at the largest linear current is ~ -180 dBV. For the thicker 150.9 angstrom barriers, this equation gives ~ -200 dBV. This indicates that lower barrier resistances or higher current levels are required. Recalculated for the LF system, the noise voltage spectral densities are -170 dBV and -150 dBV respectively. Both calculations indicate the difficulties in measuring the noise of these barriers.

* Noise Measurements: Noise measurements of the 50.9 angstrom and 150.9 angstrom barriers were performed on the most sensitive system, the LF system. The 50.9 angstrom and 150.9 angstrom barriers showed no noise above the LF system noise floor. One 50.9 angstrom device was measured at elevated currents. The current was increased in small increments and the noise measured until the device was destroyed, yet no noise above the system noise floor was detected. Recognizing the problems associated with making these measurements (as described above), these <u>very</u> preliminary results have led us to a redesign of the test structure used for the noise measurements. These structures are now being grown and will soon be fabricated and tested.

Superlattice Bandstructure Calculation: $Si/Si_{1-x}Ge_x$ heterostructures offer a wide range of potential applications. This system has attracted particular attention because of the possibility of integrating heterojunction device structures with the existing Si technology and also due to the interesting possibility of making direct bandgap engineering material form indirect bandgap semiconductors by the so called zone folding effect. Also it is a model system for studying the pure influence of strain, because of the large lattice mismatch of Si and Ge (~4.2%) and due to the close relationship in chemistry of Si and Ge. Various HBT [11], modulations doped heterostructures [12], quantum well [13] and superlattice [14] structures have been reported.As reported earlier we have made progress on band structure calculations of superlattices in the past year. For this bandstructure calculation we have used the Envelope Function Approximation (EFA) [15] method which is simple, reasonably accurate and versatile. Of primary importance among its other advantages, is its compatibility with effective mass theory. This makes it relatively easier to include the effects of applied electric field, excitons or hydrogenic impurity states, which are important in understanding the optical as well as transport properties of SLs. In the envelope function framework the self consistent rearrangement of the charge carriers can also be included. Additionally, the effect of magnetic field can be incorporated in a natural way. This is important since magneto-optical and magneto-transport measurements are frequently used to measure SL transport properties.

Starting with the simple Kronig-Penny type calculations, we calculated the band structure of SLs using the one-, two- and multi-band versions of the EFA [16]. First we calculated the band structures in the direction perpendicular to the layers and then went on to calculate the in-plane (plane parallel to the interface) dispersion relationship. The band structure in the direction perpendicular to the layers is easier to describe due to the high degree of symmetry in this direction. The directions parallel to the SL are much more difficult to describe, because the lower symmetry allows the fixing of the bulk bands. This is especially true for the valence bands where the heavy and light hole bans mix significantly even for small wave vectors. For the in-plane dispersion we have used the Altarelli approach [17] which takes into account the coupling of various bands. In that method a variational technique is used in which the boundary conditions are embodied is such a way that the problem reduces to diagonalizing matrices (usually of size 72x72). The result of these calculations have been reported in [16]. In our work, emphasis was given to the systematic formulation of the EFA and on the evaluation of the strengths and weaknesses of this method. Our first calculations were aimed at reproducing the bandstructure results for the III-V material systems which are well studied and for which the EFA formalism was first developed. The results for Si-Ge strained layer superlattices on Si(001) were also reproduced (agreeing well with the results in [18]). We have continued to validate our code by comparing the results of our calculations for the $Si/Si_{1-x}Ge_x$ system as they became available in the literature. Excellent matches were found with [19], [20] and [21] even though the latter methods (extensions to the EFA) were much more complicated. Most importantly, the successful use of the EFA to interpret the recent developments in the experimentally studies in $Si/Si_{1-x}Ge_x$ SL type devices [22], [23] and [24] coupled with the current knowledge (described below) about the effect of strain on the band alignments, the critical layer thickness and the design rules of the buffer layer (virtual substrates) and have put us in a position to simulate new device concepts based on $Si/Si_{1-x}Ge_x$ SLs.

Strain is known to change the band gaps of Si and its alloys. The uniaxial component of strain splits the valence and conduction bands. The six-fold degenerate conduction band minima is split into a two-fold and of four-fold degenerate minima, the four-fold degenerate minima is lowered for compressive strain and the two-fold for tensile strain. Under the compressive strain the light hole valence band moves upward in hole energy and the heavy hole band moves downward while the opposite is true for tensile strain. The hydrostatic portion of the strain shifts the weighted average of the valence and conduction bands thus changing the bandgaps. In Figure 6, the change in bandgaps with strain (% Ge composition) is shown. In this figure the solid lines correspond to the bandgap of $Si_{1-x}Ge_x$ on $Si_{1-x/2}Ge_{x/2}$, the dotted lines to Si on $Si/Si_{1-x}Ge_x$ and the dashed lines to that of $Si_{1-x}Ge_x$ on Si substrates. The band offsets in $Si/Si_{1-x}Ge_x$ heterostructures are also governed by the strain distribution in the individual layers. If $Si/Si_{1-x}Ge_x$ heterostructures are grown on Si substrates, only the alloy layer is under strain and the band offset is of type I (the narrow bandgap material is within the bandgap of the wide bandgap material), but if the structure is grown on an unstrained $Si_{1-y}Ge_y$ buffer layer both the layers are under strain and the band offset is of type II (the conduction band of the narrow gap material is above the conduction band of the wide bandgap material). If $Si/Si_{1-x}Ge_x$ epi-layers of equal thickness (below the critical thickness values) are grown on top of a unstrained $Si_{1-x/2}Ge_{x/2}$ (the mean composition of Si and $Si_{1-x}Ge_x$) buffer layer, the layers are oppositely strained and the strain is symmetrically distributed in the Si and in the $Si_{1-x}Ge_x$ layers [24]. This strain symmetrization makes zero net strain in the $Si/Si_{1-x}Ge_x$ structure and therefore thick multi-quantum well active layers can be grown without the critical thickness limit for the multi-layers. Based on self consistent *ab initio* pseudopotential results of Van de Walle [25] combined with the phenomenological deformation potential theory of People et al. [26] we have calculated the band offsets under different strain condition. Figure 7 is an illustration of the band offset (two fold conduction and heavy hole valence band only) for $Si/Si_{1-x}Ge_x$ grown on unstrained $Si_{1-x/2}Ge_{x/2}$ buffer layer. Since a knowledge of the band offsets and band gap variations are of utmost importance for simulation of heterostructure devices, these results should be very useful.

Based on these calculations and the energy band calculations of MQWs we have designed Si/SiGe multi-quantum well structures in which the quantum confined Stark effect (QCSE) is exploited for device applications in the technologically important wavelengths of 1.3 micron and 1.55 micron [27].

The quantum confined Stark effect (QCSE) [29] arises when an electric field is applied perpendicular to the plane of the quantum wells. The confined energy states are shifted to lower energies and also the absorption edges are altered. This effect has been studied extensively for GaAs/AlGaAs and for other III-V compound semiconductor systems. The first observation of large Stark shifts in $Si/Si_{1-x}Ge_x$ multi-quantum wells (MQW) was reported by Wang et al. [30] for MBE grown 50 period structures with 70/70 angstrom well/barrier thickness. For optical fiber communications it is important to operate these devices at 1.3 micron and at 1.55 micron, the wavelengths at which the fiber loss is minimum. The energy levels of multiquantum wells depends on the depth of the potential and on the period of the quantum wells as well as on the effective masses of the layers. As explained earlier it is possible to vary the strain in the $Si/Si_{1-x}Ge_x$ layers by designing a suitable $Si_{1-y}Ge_y$ buffer layer, which in turn changes the band offsets. Therefore by varying the Ge concentration of the buffer layer, it is possible to vary the potential depth of the quantum wells. Thus by varying the composition and layer thickness, it is possible to achieve the required transition energies without resorting to ultra-narrow wells or barriers. We have calculated the transition energies (Figure 8) as function of the thickness of the strained $Si/Si_{1-x}Ge_x$ layers and the Ge composition of the unstrained buffer layer. The shift of these transition energies under different electric fields is shown in Figure 9. The shift of bound state energies under electric field was calculated using the variational method of Bastard [31]. These results should prove to be useful in designing $Si/Si_{1-x}Ge_x$ MQW structures for QCSE to be applicable in the technologically important wavelengths 1.3 and 1.55 micron.

C. FOLLOW-UP STATEMENT: With the anticipated graduation of Mr. Kyono in early 1991, the focus of this JSEP unit will find itself more centered around the two projects being carried on by Mr. Colestock and Mr. Chowdhury. Our plans for their activities in the coming months are briefly described below.

Noise Analysis of Tunneling Barriers: We will continue growing, fabricating and characterizing single barrier tunneling structures in the AlAs/GaAs system. We are not yet convinced that we have worked with this experiment long enough to put much credence in our initial null results. We anticipate receiving several new samples to work with from the MBE group. These samples were designed using the experience developed from the previous samples (i.e. effective device impedance levels). The study first proposed involved characterizing transport through AlAs tunneling barriers of various thickness by relating noise characteristics to microscopic transport phenomena. A natural first order approach to simulating this noise phenomena is the Monte Carlo simulation technique. During the coming year we will be intensifying our efforts to bring a Monte Carlo noise simulator on line.

In addition to the experiment first proposed, we will also be characterizing transport through (or across?) relatively thick barries of $Al_xGa_{1-x}As$ of varying thickness. This study should further elucidate the relationship between intervalley scattering, barrier transport and noise.

Superlattice Bandstructure Calculation: Currently we are working toward designing MQWs with asymmetric barriers (in which the strain is more pronounced in the thinner layer). We are also working to find the optical transition probabilities, optical transition intensities and selection rules for these structures. We are investigating design methodologies for finding the optimum device structure for resonant tunneling devices in $Si/Si_{1-x}Ge_x$ heterostructures.

(Research Unit SS89-3, "Charge Transport in Novel Device Structures and Materials")

Our future plans are as follows:

* to design and to formulate a method to analyze a SiGe bipolar transistor, the base region of which is a superlattice.

* to calculate the band structure for modulation doped $Si/Si_{1-x}Ge_x$ superlattices. The objective here is to find the E-k relationship and the shift due to doping and compare its relative importance with respect to other kinds of structures. The method to be followed is the Envelope Function approximation taking the entire Brillouin zone Hamiltonian.

* finding a solution for the electronic motion across the boundary of two superlattices, the so called "band aligned" structures, popularized by K. L Wang et al. [31].

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I. LIST OF PUBLICATIONS(*JSEP supported in whole or in part)

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II. LIST OF CONFERENCE PROCEEDINGS (JSEP supported in whole or in part)

* C. M. Maziar, Mark H. Somerville and Carl S. Kyono, "Extended Velocity Overshoot in In GaAs Collectors for High Speed Heterojunction Bipolar Transistors," *Proceedings of the SPIE: High-Speed Electronics and Device Scaling*, March 18-20, 1990, San Diego, CA., vol. 1288, pp. 69-77.

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* A. Chowdhury, K. H. Jung, D. L. Kwong, and C. M. Maziar, "Design of $Si/Si_{1-x}Ge_x$ multi-quantum well structures for quantum confined Stark effect at 1.3 and 1.55 micron," accepted for AAPT/APS Joint Winter Meeting, January 21-24, 1991, San Antonio, TX.

III. LIST OF PRESENTATIONS (JSEP supported in whole or in part)

X. Wang, T. J. Bordelon, C. M. Maziar, P. Blakey and A. F. Tasch, "Development of an Efficient Monte Carlo Simulator for Submicron Devices", presented at *TECHCON '90*, October 16-18, 1990, San Jose, CA.

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(Research Unit SS89-3, "Charge Transport in Novel Device Structures and Materials")

IV. LIST OF JSEP SUPPORTED THESES

Andalib Chowdhury, Masters Thesis, "Calculation of superlattice Bandstructure: The Envelope Function Approximation," May 1990.

V. GRANTS AND CONTRACTS

National Science Foundation, "Modeling and Simulation of Charge Transport in InP Lattice Matched Materials and Device Structures," Principal Investigator: Christine M. Maziar.

Texas Higher Education Coordinating Board, "Analysis and Simulation of Ultra-Small Structures," Profs. Christine M. Maziar and Al F. Tasch, Co-Principal Investigators.

Texas Higher Education Coordinating Board, "Charge Transport in Enhanced Velocity Structures," Prof. Christine M. Maziar, Principal Investigator.

National Science Foundation, "Presidential Young Investigator Award," Prof. Christine M. Maziar, Principal Investigator.

Semiconductor Research Corporation, "Analysis and Development of High Density MOSFET Structures for Deep Submicron CMOS VLSI Technology," Profs. Al F. Tasch and Christine M. Maziar, Co-Principal Investigators.

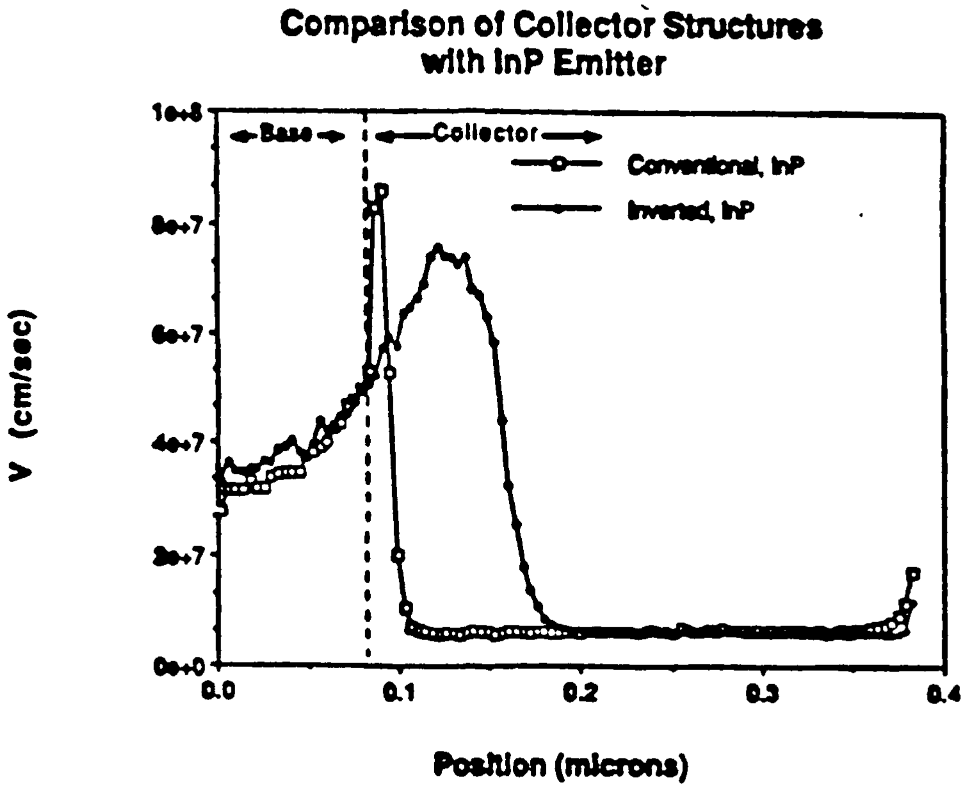


Figure 1

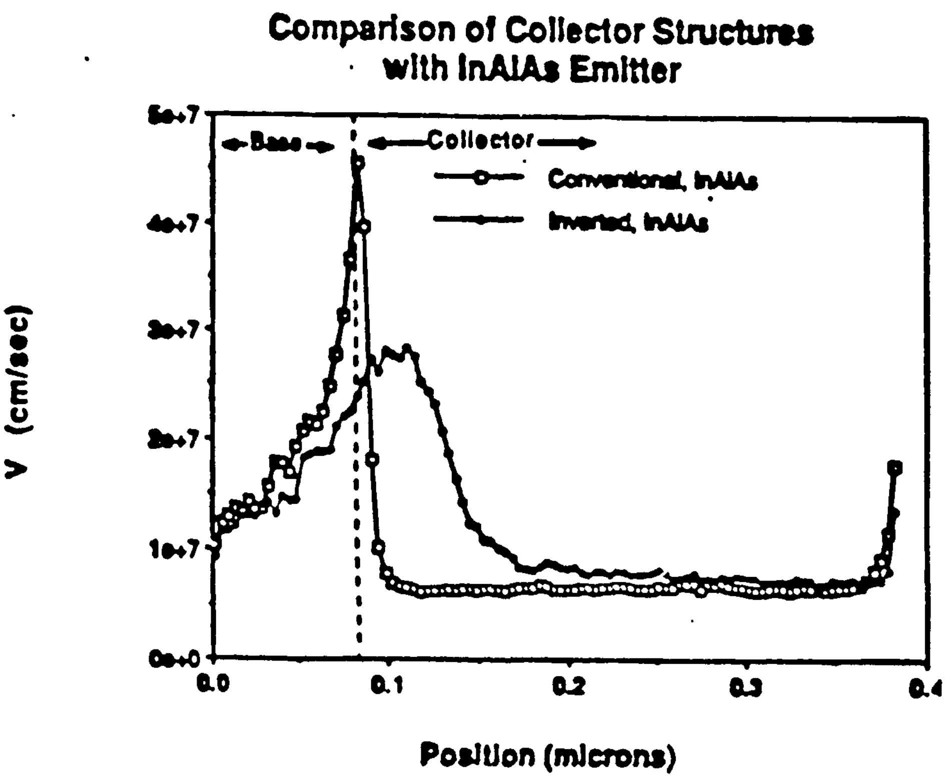


Figure 2

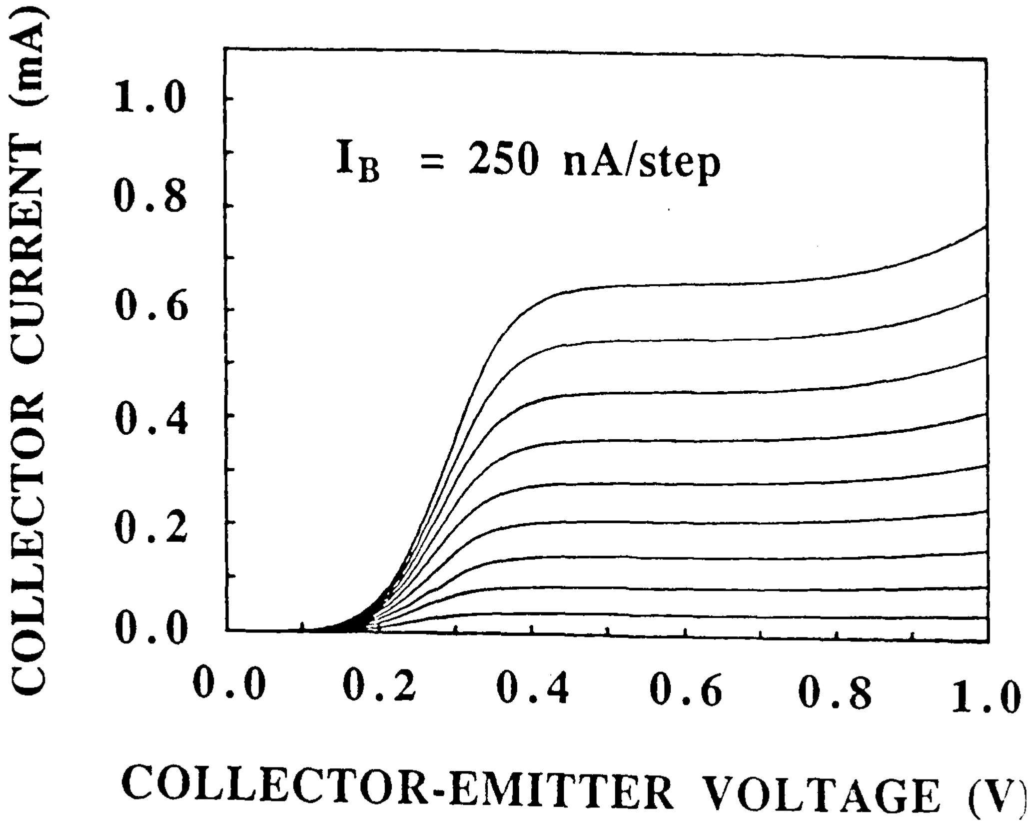
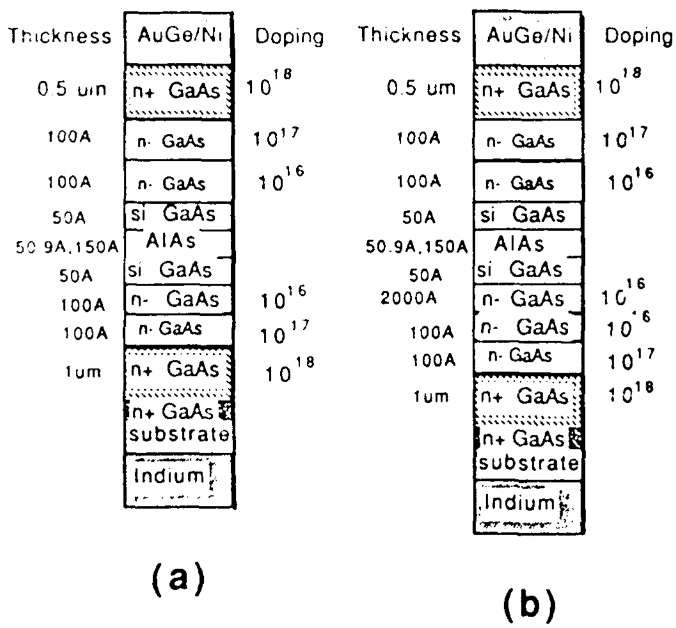


Figure 3



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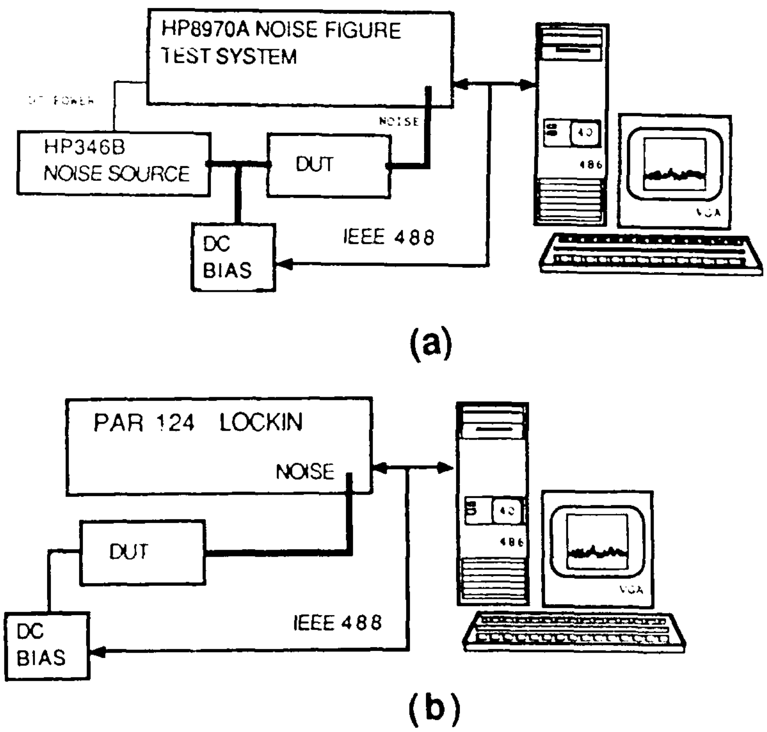


Figure 5

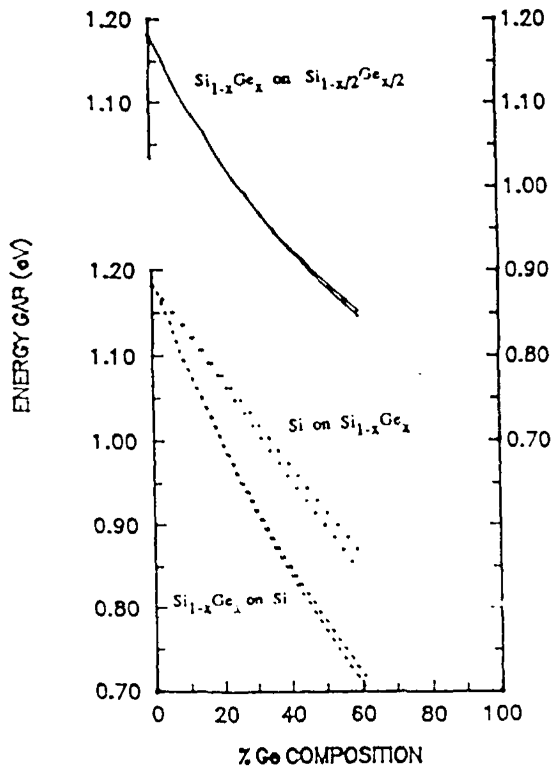


Figure 6

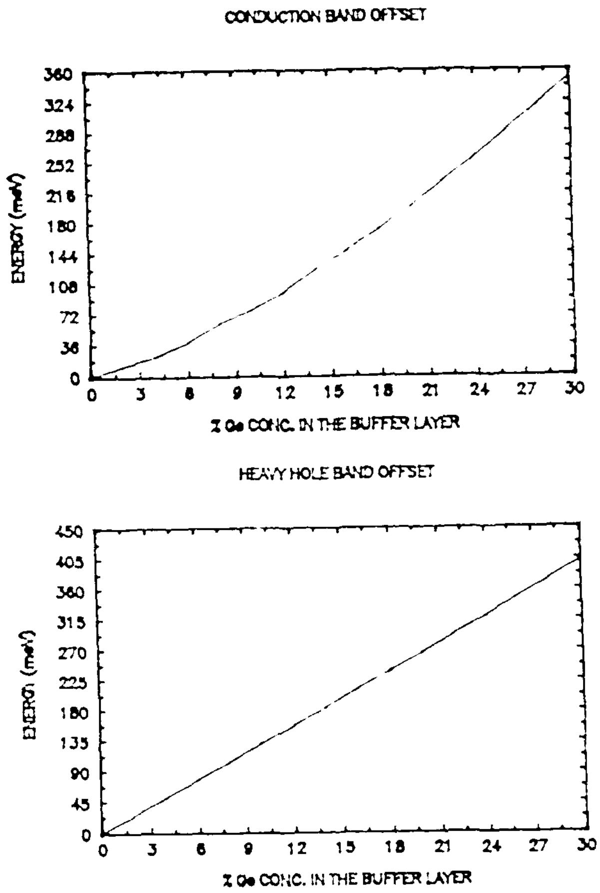
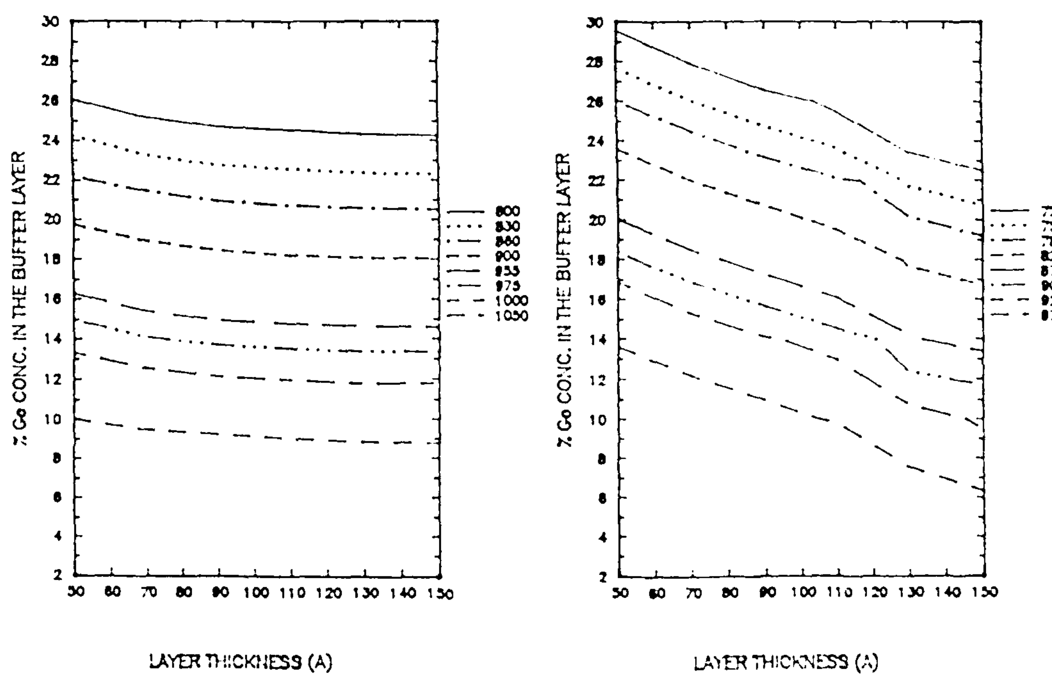


Figure 7

EQUI—ENERGY LINES AS FUNCTION OF Ge COMP. AND LAYER THICKNESS



(a)

(b)

Figure 8

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE89-4: FEMTOSECOND PROCESSES IN III-V SEMICONDUCTORS

Principal Investigator: Professor M. C. Downer (471-6054)

Graduate Students: G. Focht, D. H. Reitze (graduated); H.R. Choo, J.I. Dadap (current)

A. SCIENTIFIC OBJECTIVES: We seek insight into the physics of ultrafast processes in technologically important solids, with emphasis on III-V semiconductors, using the techniques of femtosecond laser spectroscopy.

B. PROGRESS: Significant progress has been made this year in our study of hot electron dynamics at metal surfaces using femtosecond photoemission [1,2], in collaboration with J.L. Erskine (Research Unit SSE89-2), and under joint sponsorship with ONR. We have made the first observation of pure thermionic emission from a nonequilibrium (i.e. electron temperature T_e >> lattice temperature T_i) electron population in a solid. We have shown that the velocity distribution of the thermionically emitted electrons provides a direct, *in situ* measurement of electron temperature and its femtosecond evolution under a wide range of excitation conditions, and have used such measurements to show that the relaxation rates of *very hot electrons* ($kT_e \geq$ work function ϕ) differ significantly from extrapolations based on relaxation rates of colder electrons measured by other experiments [4]. The basic results have been presented as a contributed paper at Ultrafast Phenomena VII conference [2] and as an invited talk at the annual meeting of the Optical Society of America [3], and published in the respective proceedings . A manuscript to be submitted to a refereed journal is in preparation. Such measurements bear directly on the underlying physics of diverse applications in which hot, nonequilibrium solid state electrons play a crucial role, including: desorption of surface adsorbates [5], hot electrons in nanoscale devices [6], generation of femtosecond X-ray pulses [7]. The hope is that these measurements will provide direct experimental measurements of hot electron dynamics relevant to such applications in order to overcome the current total reliance on Monte Carlo or LASNEX simulations.

A description of the apparatus [8,9] and initial results were included in the previous annual report. To summarize briefly, femtosecond pulses, or pairs of pulses with a variable time delay between them, transiently heat electrons in a target (currently bulk silver, but the ultimate interest extends to thin film and semiconductor targets). Nonequilibrium electron temperatures in the range 5 eV < kT_e < 35 eV. have been produced and measured in our experiment. The significant new aspect of this experiment is the method of measuring T_e: the energy distribution of electrons thermionically emitted normal to the metal surface is measured by a time-of-flight (TOF) method. This distribution agrees closely with calculated thermal distributions for the anomalously heated electrons, thus allowing T_e to be determined. A careful study of the influence of space charge effects was required to establish the validity of the measurement - i.e. to ensure that the velocity distribution was not distorted by the space charge field in the time between escape from the metal surface and detection of the electrons. The results show that the velocity distribution of thermionically emitted electrons, a direct measure of T_e, is virtually unaffected by space charge even with emission levels as high as 10^6 electrons per pulse. On the other hand, electron yield (a quantity measured in previous femtosecond photoemission experiments [10]) is strongly suppressed by space charge even at emission levels as small as a few hundred electrons per pulse. The hot electron dynamics were investigated by time-resolving the thermionic emission with an equal pulse correlation experiment, in which excitation was distributed between two equivalent pulses with a variable time delay between them. The results so far show unexpectedly rapid cooling of electrons in the range being studied. For example 35 eV. electrons cool to low temperatures within 500 femtoseconds. The physics behind such rapid relaxation is not yet fully understood, but points to significantly stronger electron-lattice coupling than for lower temperature electrons.

Applications of our unamplified, frequency-doubled colliding pulse mode-locked laser [11,12], described at length in previous reports, to ultrafast semiconductor spectroscopy are continuing. The results of experiments which use time-resolved ultraviolet reflectivity to probe the renormalization of high energy conduction bands, described last year, have been published and presented [13-15] and comprise the concluding section of the Ph.D. dissertation of Glenn Focht, supported by JSEP for the past several years. Since Focht's graduation, the major progress by new JSEP student H.R. Choo has been development of a whole new data acquisition system for this line of experiments, modelled after a rapid scan system developed by Kurz et al. [16]. The motivation for developing the new system is to allow scans of the small signal femtosecond reflectivity/transmission response of a sample to be acquired as much as ten times faster (typically 1 minute or less) than with the old system (10-15 minutes) , with equal or greater signal sensitivity. The concept of the new system [16] is to modulate the time delay rapidly (e.g 100 Hz) in a pump-probe experiment and to digitize the modulated, normalized probe signal with a 250 MHz A/D converter, thus allowing much greater and faster signal averaging than with the older system, based on the conventional approach of amplitude modulating (i.e. chopping) the pump, acquiring the probe with a lock-in detection system and slowly scanning the time delay. Such speed is important not only for convenience, but for opening the possibility of probing the femtosecond response of semiconductor films *in situ* during growth (e.g. in an MBE chamber), or during brief pauses in growth, and using the results as a materials characterization diagnostic. Such a diagnostic can be especially powerful with alloys (e.g. $Al_xGa_{1-x}As$, Si_xGe_{1-x}) where the femtosecond response can be strongly influenced by small changes in alloy composition, film thickness [18], defect density [17], or surface quality, which in turn are functions of growth conditions [17,18]. In order to demonstrate these concepts, and test the new data acquisition system, Choo has acquired femtosecond reflectivity scans of a family of Si_xGe_{1-x} samples grown by remote plasma-enhanced chemical vapor deposition (RPCVD, D.L. Kwong, UT Electrical & Computer Engineering Department), and compared the results to previous scans of pure Si and Ge from Focht's work [14,15]. Significant variations in the femtosecond response are observed for samples with different alloy compositions, and even for different areas on the same sample. Efforts are continuing to correlate these variations quantitatively with changes in sample properties.

Two other experiments involving intense femtosecond excitation of solid or dense gaseous targets, supported in part by other agencies (NSF and Welch Foundation), have progressed further over the past year. JSEP-supported student David Reitze has extended our previously reported study [19] of the optical properties of the controversial liquid state of carbon, which comprised the final section of his Ph.D. dissertation. The significant extensions of the past year were 1. performing experiments on diamond samples [20-22], which showed as expected that graphite and diamond reach a liquid phase with common optical properties, upon melting with a short optical pulse; 2. formulating a comprehensive Drude model of liquid carbon which fits our extensive femtosecond ellipsometry data over the visible and near ultraviolet spectra, and which can now be compared and contrasted with theoretical predictions based on molecular dynamics simulations [23]of the liquid state of carbon. The Drude model yields the following physical properties of liquid carbon: conduction electron density = 1×10^{23} cm-3, corresponding to a monovalent metal, somewhat lower than theoretical predictions (2.5 x 1023 cm-3 [23]), and numerical values of electrical resistivity as a function of temperature. Electrical resistivity shows an interesting temperature dependence, peaking at kT = 5 eV., then decreasing at higher temperatures. This "resistivity saturation" , observed [24] also in high intensity femtosecond experiments on aluminum, and is believed to occur because the electron mean free path can not become smaller than an interatomic spacing. A comprehensive paper summarizing these findings is in preparation. Extensive experimental results and analyses of a second experiment - spectral blueshifts induced by strong field ionization of atmospheric density gases [9,25] (see previous annual report) - have been written up and published this past year [1,26-28]. A comprehensive refereed journal paper is also in preparation.

C. <u>FOLLOW-UP STATEMENT</u>: Femtosecond thermionic emission has now been demonstrated as a direct, time-resolved measurement of the termperature of extremely hot electrons in metals. Diffusion as well as electron-lattice coupling are believed to be equally important in determining cooling rates in bulk samples. Therefore we plan to extend the experiments to thin film samples, where diffusion can be suppressed to highlight the contribution of electron-lattice coupling. Expeiments on both metal and semiconductor films are planned.

Efforts will continue to develop small signal, femtosecond reflectivity experiments as a characterization of semiconductor alloy films. Emphasis will be placed on correlating detailed features of the femtosecond response with known material characteristics, and on continuing improvement of data acquisition procedures compatible with a film growth environment.

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III. LIST OF PRESENTATIONS

[Invited] M.C. Downer, "Interaction of Super-intense Light Fields with Atoms and Surfaces." Society of Photo-Instrumentation Engineers (SPIE) OE/LASE '90 Conference on Optics, Electro-Optics, and Laser Applications in Science and Engineering, Los Angeles, California, 17 January 1990.

[Invited] M.C. Downer, "A New Contribution to Spin-forbidden Rare Earth Optical Transition Intensities." March Meeting of the American Physical Society, Anaheim, California, 15 March 1990; abstract published in *Bulletin of the American Physical Society* **35** (1990), 616 .

[Invited] M.C. Downer, "Spectral shifting of femtosecond laser pulses: a new diagnostic of ionization and plasma dynamics in strong light fields." Tenth International Conference on Spectral Line Shapes, Austin, Texas, 25 June 1990.

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[Invited] M.C. Downer, "Femtosecond Plasma Physics at High Light Intensity ." Annual Meeting of the Optical Society of America, Boston, MA, 4 November 1990; abstract published in *OSA Annual Meeting Technical Digest 1990* (Optical Society of America, Washington, D.C.), p.47, paper MNN5.

IV. LIST OF THESES AND DISSERTATIONS

"The Frequency Shifting of Femtosecond Laser Pulses"
Glenn B. Focht, Ph.D. , August 1990

"Femtosecond Dynamics of Phase Transitions in Carbon and Silicon"
David H. Reitze, Ph.D., September 1990

V. GRANTS AND CONTRACTS

National Science Foundation (Presidential Young Investigator Award), "Femtosecond Processes in Condensed Matter" (DMR 8858388), M.C. Downer, P.I.

Office of Naval Research (Young Investigator Award), "Femtosecond Angle-Resolved Photoemission Spectroscopy of Electronic Materials" (Contract N00014-88-K-0663), M.C. Downer, P.I.

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Robert A. Welch Foundation, "Femtosecond Photoemission and Photodesorption Spectroscopy of Excited States at Surfaces," (Grant F-1038), M.C. Downer, P.I.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE

Research Unit SS89-5 HETEROSTRUCTURE DEVICE DEVELOPMENT

Principal Investigator: Professor D. P. Neikirk (471-4669)

Graduate Students: V. Reddy

A. SCIENTIFIC OBJECTIVES: The use of such techniques as molecular beam epitaxy has allowed the fabrication of devices in which tunneling is the dominant transport mechanism. In this unit devices which use resonant tunneling through a quantum well are being investigated. Through the use of appropriate doping profiles outside the quantum well region, we have shown that significant improvements in terminal device characteristics can be achieved. As an oscillator, these devices promise low noise performance, and may be capable of operating at high millimeter wave frequencies with higher output power than other transit time devices or pure quantum well oscillators. Since the device uses quantum well injection and transit effects, it is called a QWITT diode. The issues which must be addressed to allow successful QWITT fabrication and operation center on (i) quantum well design for optimization of field-current characteristics, (ii) the choice of optimum drift region characteristics and iii) the design of microwave and millimeter wave resonator structures to allow QWITT oscillation at a selected frequency. Each of these issues requires that certain tasks be accomplished These include: i) AlAs/GaAs QWITT diode growth and dc characterization; ii) investigation of InGaAs/InAlAs quantum well structures for enhanced peak-to-valley ratios and current densities; and iii) through interactions with the Electromagnetics Unit EM89-1 "Millimeter Wave Active Guided Wave Structures" construction of rf circuits to allow measurements on QWITT oscillators designed and grown by our research group.

B. PROGRESS: During the 1990 time period we have completed a thorough study of the factors which influence the I-V characteristics of AlAs/GaAs double barrier resonant tunneling diodes (DBRTD). Two figures of merit for microwave applications are the peak-to-valley current ratio (PVCR) and the peak current density (J_p). Much work has been done by various workers to obtain high DBRTD PVCR combined with high J_p since this results in a large current swing, which is important for oscillator applications. Huang et al. obtained a PVCR of 3.9 at 300K by incorporating a "two-step" spacer layer in an $Al_{0.48}Ga_{0.52}As$/GaAs DBRTD [1] but with J_p less than 8 kA/cm^2. Recently, Cheng et al. reported a PVCR of 5.1 with J_p of 15 kA/cm^2 in an AlAs/GaAs DBRTD by utilizing an $Al_{0.14}Ga_{0.86}As$ "chair" barrier adjacent to one of the AlAs barriers [2]. They attributed the improved PVCR to a reduction in the coherent tunneling and X-valley mediated tunneling components of the valley current. The highest DBRTD PVCR achieved hitherto at 300K on a GaAs substrate has been 5.9 (with J_p = 17 kA/cm^2) by Reichert et al. who incorporated an InGaAs "pre-well" adjacent to an $Al_{0.60}Ga_{0.40}As$ barrier [3]. One of our activities during the last year has been the further study of AlGaAs/GaAs DBRTDs, where we have achieved, to the best of our knowledge, the highest PVCR for an AlGaAs/GaAs DBRTD. In addition, a reasonably high peak current density of over 30 kA/cm^2 has been maintained for these diodes.

We have also continued the growth and testing of QWITT diodes during this period. The motivation for the QWITT diode is that the voltage and current differences between the peak and valley, ΔV_{pv} and ΔI_{pv}, must be as large as possible to increase the oscillator output power. In the QWITT diode ΔV_{pv} is increased through the inclusion of a depleted region while ΔI_{pv} remains essentially the same, which effectively increases the specific negative resistance and impedance of the device so that higher oscillator power can be obtained [4,5].

Device Growth and Fabrication

For the study of quantum well effects, two types of structures, schematically shown in Fig. 1, were grown by molecular beam epitaxy (MBE) at 600° C in a Varian GEN II system. Silicon-doped (n = 2 x 10^{18}cm^{-3}) liquid encapsulated Czochralski (LEC) grown GaAs substrates were used. The first structure, sample **I** is a symmetric, baseline DBRTD. The device structure is grown on top of a 1.5 µm silicon-doped (2 x 10^{18} cm^{-3}) GaAs buffer layer. A nominally undoped GaAs quantum well is sandwiched between a three-step dopant transition region consisting of 100Å n-type (10^{17} cm^{-3}) GaAs, 100Å n$^-$ (10^{16} cm^{-3}) GaAs, and finally 50Å of nominally undoped GaAs adjacent to the AlAs barrier. The barrier and well nominal thicknesses are 17 Å and 50 Å , respectively. The growth rates of GaAs and AlAs were 1.1 Å/s and 0.85 Å/s, respectively. A four second growth interruption at each hetero-interface was employed. The AlAs barrier was kept thin to increase the current density and also to promote Γ(GaAs)-Γ(AlAs) tunneling [6]. A 0.5 µm thick (2 x 10^{18} cm^{-3}) GaAs contact layer is used to facilitate formation of a topside ohmic contact. The second structure, **II**, is similar to **I** except that a four monolayer $Al_{0.20}Ga_{0.80}As$ "step" barrier , similar to that reported by Cheng et al , is grown adjacent to the top AlAs barrier. The aluminum mole fraction of the "step" barrier is 0.2, which is higher than the value of 0.14 used by Cheng et al.

For the QWITT study, an AlAs/GaAs DBRTD, two AlAs/GaAs QWITTs (QWT I and QWT II), and an AlAs/InGaAs QWITT were also grown by molecular beam epitaxy. A layer schematic diagram of the three AlAs/GaAs based quantum-well structures is given in Fig. 2, where the layer thickness parameters W_1, W_2, and W_3 are varied for the three devices. For the DBRTD, which serves as a baseline device, W_1 = W_3 = 0 Å and W_2 = 100 Å. For QWT I, W_1 = 2000 Å, W_2 = 100 Å , and W_3 = 0 Å. For QWT II, W_1 = 0 Å, W_2 = 200 Å, and W_3 = 2000 Å. The fourth device is an AlAs/InGaAs QWITT grown on an InP substrate where the quantum well is formed by sandwiching a 47 Å $In_{0.53}Ga_{0.47}As$ well between 25 Å strained AlAs barriers [7]. The quantum well is between a symmetric layer profile consisting of 15 Å of undoped $In_{0.53}Ga_{0.47}As$ adjacent to the well followed by 1000 Å n$^-$ (8 x 10^{16}cm^{-3}) $In_{0.53}Ga_{0.47}As$, and then 1000 Å of n$^+$ (2 x 10^{18}cm^{-3}) $In_{0.53}Ga_{0.47}As$.

For all the diodes, the front side contact pattern was defined using a standard lift-off process. The front contact was evaporated Ni/AuGe/Ni. The backside contact was formed by the indium used to mount the wafer to the molybdenum sample block during MBE growth. To improve ohmic contact adhesion and to remove surface oxides, the substrate was etched in a (2:1) $HCl:H_2O$ solution for 20 s prior to metal evaporation. Using the topside metal contact as an etch mask, 1 µm deep mesas were formed by wet chemical etching with a (8:1:1) $H_2SO_4:H_2O_2:H_2O$ solution. The Ni/AuGe/Ni contacts were annealed at 450° C for 30 s. Device areas tested ranged from 9 µm^2 to

49 μm². All measurements were made with a programmable Keithley K230 digital voltage source and K195 digital multimeter, controlled by an IBM PC AT. For the QWITT diodes, measurements were made through the microstrip circuit shown in Fig. 3, using the same voltage source and multimeter, with the addition of a Tektronix 492A spectrum analyzer to monitor RF oscillations.

Results and Discussion

The current density - voltage (J - V) characteristics (average and standard deviation) for the structures with varying AlGaAs step barrier are summarized in Table 1. In these measurements, forward bias is defined as electron injection from the substrate through the quantum well to the top contact. Typical J - V curves for samples I and II are shown in Fig. 4. The highest PVCRs obtained at room temperature for structures I and II are 3.9 and 6.3, respectively. Both of these values were obtained in reverse bias. To the best of our knowledge, a PVCR of 6.3 at 300K is the highest ever reported for an AlGaAs/GaAs DBRTD. Furthermore, for operation in the "chair" barrier mode, J_p is more than 30 kA/cm², which is approximately twice as large as that reported previously for high PVCR AlGaAs/GaAs DBRTDs. The average PVCRs (reverse bias) of more than 30 diodes measured on each sample are 3.7 and 6.0 for structures I and II, respectively. The enhancement in PVCR in sample II incorporating the "chair" barrier over that obtained from sample I is similar to that seen by Cheng et al. This work clearly shows the dramatic impact of barrier structure on both peak and valley currents. Here, with the addition of a four monolayer $Al_{0.20}Ga_{0.80}As$ "chair" barrier, a PVCR of 6.3 at room temperature was obtained, which is the highest PVCR value ever reported for an AlGaAs/GaAs DBRTD.

The I-V curve for another baseline DBRTD is shown in Fig. 5. The I-V curves for the AlAs/GaAs QWITTs are given in Fig. 6. Notice that ΔV_{pv} has increased due to the addition of a depleted drift region. Furthermore, the peak voltage for QWT II is lower than that for QWT I, which should lead to a higher DC to RF power conversion efficiency. The I-V curve for the AlAs/InGaAs QWITT is given in Fig. 7. A summary of experimental oscillator results is given in Table 2. The RF output power was measured by placing each sample in the microstrip circuit and adjusting the DC bias voltage in the NDR region until a maximum output power was obtained. For these measurements the RF circuit was not intentionally designed to yield oscillations at any particular frequency, although a large RF to ground bypass capacitor was placed across the spectrum analyzer to suppress microwave oscillation, and care was taken to prevent very low frequency DC bias line oscillation. Under these conditions oscillations did still occur for all samples, at a frequency between 250-500 MHz. No other attempts were made to tune the circuit. All diodes produced an oscillation which had a very sharp spectrum (less than 1MHz bandwidth) and was stable for many hours. A major result is the significant increase in output from the AlAs/InGaAs QWITT, mainly due to the suppression of a rapid rise in the current for voltages beyond the valley point. For the AlAs/InGaAs QWITT, by simply removing the RF to ground bypass capacitor from its circuit, the diode oscillation frequency increased from about 250 MHz to about 3 GHz, while maintaining an output power of over 2 mW. These are encouraging results, since for an oscillation frequency increase of between 10 and 30 over the low frequency results, the output power dropped by only a factor of about 2. Since no attempt has been made to account for losses in the microstrip circuit, and no direct circuit tuning was used, it is possible these diodes may actually produce nearly as much power at 10 GHz as they did near 300 MHz. Further discussion of these results, comparing the measured RF power to simple estimates for the maximum available output power, can be found in the report for Unit EM89-1, "Millimeter Wave Active Guided Wave Structures."

C. FOLLOW-UP STATEMENT: Further improvements in the performance of DBRTD oscillators will require more investigation of the quantum well injection region itself. For instance, the very great sensitivity of the quantum well characteristics to very small changes in barriers presents both challenges and opportunities. One challenge is simply to achieve sufficient control over the growth environment to repeatably produce similar devices. On the other hand, it may be possible through proper use of asymmetric barriers, to produce very high peak-to-valley current ratios, while maintaining very high current densities. Considerable work remains in fully exploiting the InGaAs/AlAs system, and evaluating the impact of barrier asymmetry on these devices. Such efforts will be pursued during the next period of this research program.

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(Research Unit SS89-5, "Heterostructure Device Development")

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- "Optically-Controlled Tunable CPW Resonators," IEEE MTT-S International Microwave Symposium Digest, Vol. II, May 8-10, 1990, pp. 949-950 (M.S. Islam, P. Cheung, C.-Y. Chang, D.P. Neikirk, and T. Itoh).

- "MM Wave /FIR Twin Slot Antenna Structures," AP-S International Symposium and URSI Radio Science Meeting, May, 1990 (J.G. Heston, S.M. Wentworth, R.L. Rogers, D.P. Neikirk, and T. Itoh).

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- "Small Signal Measurements of the Microwave Impedance of QWITT Diodes," to be presented at the 20th European Microwave Conference, Budapest, Hungary, Sept. 10-14, 1990, pp. 715-718 (A. Mortazawi, D. Miller, D.P. Neikirk, and T. Itoh).

- "Quantum Well Injection Transit Time (QWITT) Diode Oscillators," to be presented at the 15th International Conference on Infrared and Millimeter Waves, Dec. 10-14, 1990 (V.K. Reddy, A.J. Tsao, S. Javalagi, D.R. Miller, and D.P. Neikirk).

- "Microwave response of a coplanar waveguide phase shifter to pulsed optical illumination," to be presented at the 15th International Conference on Infrared and Millimeter Waves, Dec. 10-14, 1990 (M.S. Islam, P. Cheung, D.P. Neikirk, and T. Itoh).

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III. LIST OF PRESENTATIONS (*JSEP Supported in whole or in part)

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- "Realistic Band Structure Effects of GaAs/AlAs Quantum Well Diodes: Theory and Experiment," Proceedings of the SPIE Symposium on Advances in Semiconductors and Superconductors: High Speed Electronics and Device Scaling, SPIE Vol 1288, San Diego, CA, March 17-21, 1990, pp. 167-176 (D.R. Miller).

- "Microwave and Millimeterwave Oscillators using Quantum Well Diodes," Joint IEEE MTT/ED Dallas Chapter meeting, Sept. 27, 1990 (Dean P. Neikirk).

IV. LIST OF THESES AND DISSERTATIONS (*JSEP Supported in whole or in part)

<u>Master of Science</u>

- Vijay Reddy, thesis title: "Molecular Beam Epitaxial Growth of AlAs/GaAs Double Barrier Resonant Tunneling Diodes," Spring 1990 (D. P. Neikirk, Supervisor).

- Saiful Islam, thesis title: "Optically Controlled Tunable Coplanar Waveguide Resonator," Spring 1990 (D. P. Neikirk, Supervisor).

- John Heston, thesis title: "Development of Twin Slot Antenna Structures for Millimeter Wave Imaging Applications," Summer 1990 (D. P. Neikirk, Supervisor).

<u>Ph.D.</u>

Stuart Wentworth, dissertation title: "Far Infrared Microbolometer Detectors," May, 1990 (D. P. Neikirk, Supervisor).

- Philip Cheung, dissertation title: "Coplanar Waveguide Phase Shifters," Aug, 1990 (D. P. Neikirk, Supervisor).

V. GRANTS AND CONTRACTS

IBM Corp., "IBM Faculty Development Award," Professor D. P. Neikirk, Principal Investigator.

National Science Foundation, "Presidential Young Investigator Award," Professor D. P. Neikirk, Principal Investigator.

Texas Advanced Technology Program, "Quantum Well Device based Circuits for Millimeter Wave Communications Applications," Professors D. P. Neikirk and T. Itoh, Co Principal Investigators.

Texas Advanced Research Program, "Quantum Transport Models for Heterostructures Devices," Professor D. P. Neikirk, Principal Investigator

Table 1: DC J - V data for DBRTDs with varying AlGaAs barriers.

	Baseline AlAs/GaAs DBRTD. Sample I		AlAs/GaAs DBRTD with $Al_{0.2}Ga_{0.8}As$ Chair Barrier. Sample II	
Highest Peak to Valley Current Ratio	3.9 (Reverse Bias)		6.3 (Reverse Bias)	
Average Values	Reverse Bias	Forward Bias	Reverse Bias	Forward Bias
Peak to Valley Current Ratio	3.7 ± 0.2	3.4 ± 0.2	6.0 ± 0.13	3.4 ± 0.15
Peak Voltage V_p (V)	0.93 ± 0.02	0.98 ± 0.03	0.47 ± 0.02	0.72 ± 0.02
ΔV (V)	0.33 ± 0.03	0.33 ± 0.05	0.30 ± 0.02	0.33 ± 0.03
Peak Current Density J_p (kA/cm^2)	52.4 ± 4.1	53.2 ± 4.2	31.3 ± 4.1	44.9 ± 5.3
Valley Current Density, J_v (kA/cm^2)	14.4 ± 1.3	15.8 ± 1.2	5.2 ± 0.6	13.3 ± 1.4
ΔJ (kA/cm^2)	38.0 ± 3.2	37.4 ± 3.5	26.1 ± 4.7	31.6 ± 6.7

Table 2: QWITT diode oscillator output powers.

	Estimated Power (mW)		Experimental Results	
Device	$\frac{3}{16}\Delta I \cdot \Delta V$	Quasi-Static I-V Calculation	RF Power (mW)	RF Power Conversion Efficiency, η (%)
Bare RTD	0.236	0.242	0.206	7.5
QWT I	1.55	2.6	2.66	8.5
QWT II	2.34	3.5	3.54	20.4
InGaAs/AlAs QWITT	4.59	4.87	4.79	29.2

5000 Å	n^+	GaAs	$5 \times 10^{18}\ cm^{-3}$
100 Å	n	GaAs	$5 \times 10^{17}\ cm^{-3}$
100 Å	n^-	GaAs	$5 \times 10^{16}\ cm^{-3}$
50 Å	UNDOPED	GaAs	
T	UNDOPED	$Al_{0.2}Ga_{0.8}As$	
17 Å	UNDOPED	AlAs	
50 Å	UNDOPED	GaAs	
17 Å	UNDOPED	AlAs	
50 Å	UNDOPED	GaAs	
100 Å	n^-	GaAs	$5 \times 10^{16}\ cm^{-3}$
100 Å	n	GaAs	$5 \times 10^{17}\ cm^{-3}$
15000 Å	n^+	GaAs	$5 \times 10^{18}\ cm^{-3}$
	n^+	GaAs	SUBSTRATI

Fig. 1: Schematic diagram of samples I (T = 0 ML) and II (T = 4 ML).

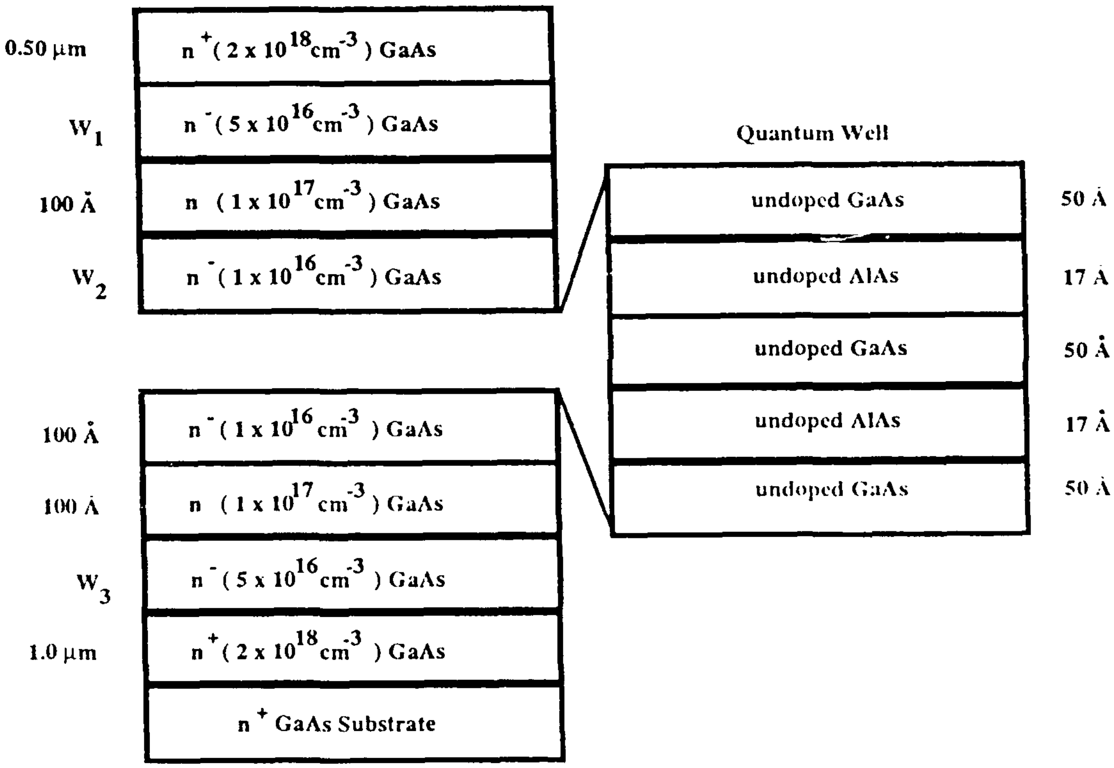

Fig. 2: Schematic cross section of the QWITT diode structures tested.

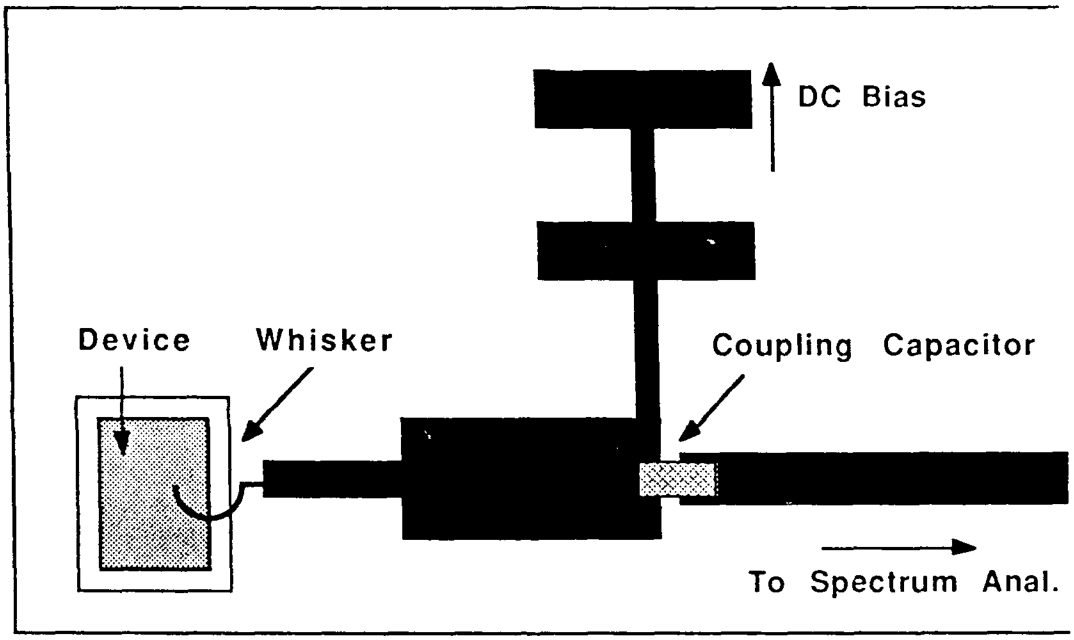

Fig. 3: Schematic diagram of oscillator circuit.

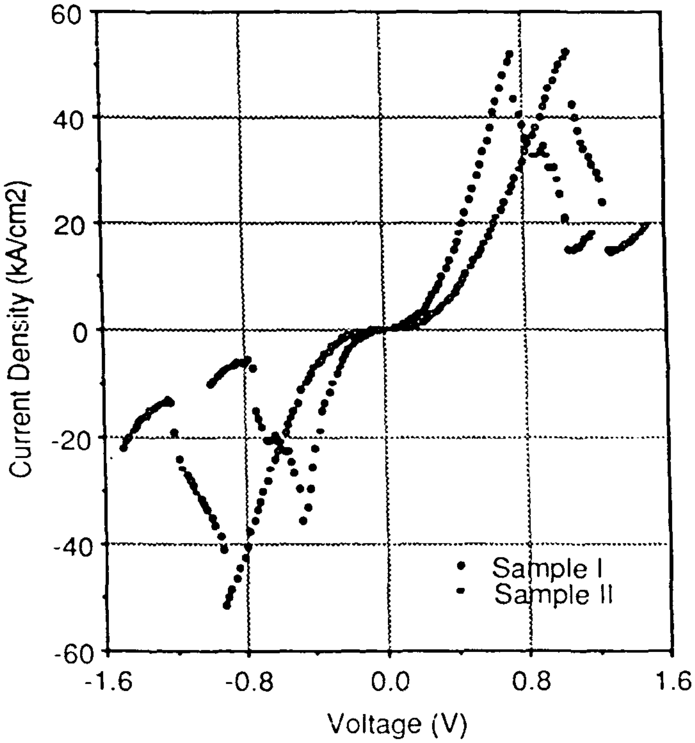

Fig. 4: Typical J_p - V curves for samples I (open circle) and II (closed circle).

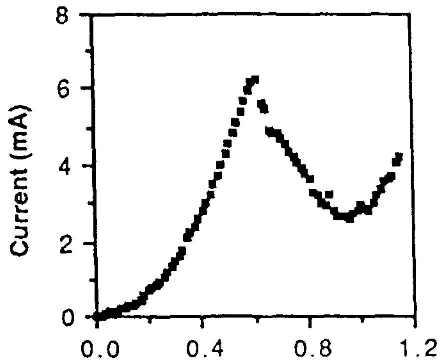

Fig. 5: I - V curve for symmetric DBRTD (Area = 1.39 x 10^{-7} cm^2).

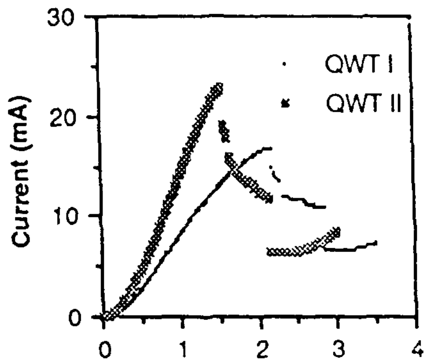

Fig. 6: I - V curves for QWT I (Area = 2.61 x 10^{-7} cm^2) and QWT II (Area = 3.34 x 10^{-7} cm^2).

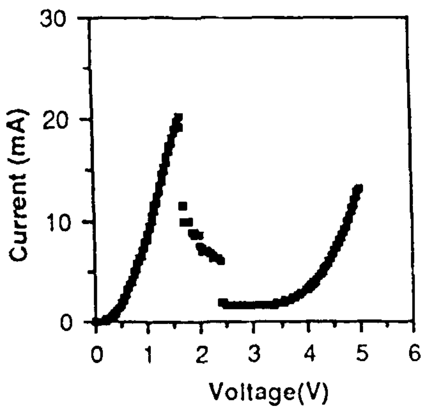

Fig. 7: I - V curve for AlAs/InGaAs QWITT (Area = 5.57 x 10^{-7} cm^2).

III. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM89-1: MILLIMETER WAVE ACTIVE GUIDED WAVE STRUCTURES

Principal Investigators: Professor T. Itoh (471-1072)
Professor D. P. Neikirk (471-4669)

Graduate Students: A. Mortazawi, C. W. Kuo, K. S. Kong, M. S. Islam

A. SCIENTIFIC OBJECTIVES: The primary objective is to conceive and develop novel circuit configurations for new solid state devices for millimeter-wave integrated oscillator structures. These circuit structures are intended to provide an electromagnetic environment that maximizes the potential capability of the solid state devices. The secondary objective is to characterize these nonlinear active millimeter-wave circuits for a better understanding of the electromagnetic wave interactions of the devices with the microwave planar circuits so that a proper design procedure can be developed.

B. PROGRESS: The effort during this reporting period is in the following areas. (1) Experimental characterizations of the QWITT diodes, (2) Improvement of the QWITT, (3) Planar periodically loaded structure for space combiner. These subjects have a common goal of integrating the QWITT diodes in an appropriate high frequency circuit so that the electromagnetic interaction with active devices is effectively used for development of more efficient millimeter-wave components.

QWITT Diode Characterizations

The QWITT diode developed at The University of Texas is found to be an interesting and useful device for microwave and millimeter-wave oscillators, harmonic oscillators and self oscillating mixers [1-3]. Although a large signal model is required for the design of oscillators, a small signal model is still useful in many phases of design and device characterizations. Our QWITT diode model [4] provides a direct calculation of the device impedance based only on dc measurements and knowledge of the device structure. To verify this model, we have developed a small signal measurement method. Due to the broad band nature of the negative differential resistance of the resonant tunneling diodes, it is difficult to measure their negative resistance under a stable condition. Measurement of the device impedance in the positive resistance region can, however, provide valuable information about device operation and physics. By using an HP 8510B network analyzer, we carried out the measurement up to 30 GHz [5]. The measured results verified the rf impedance calculated by the method previously developed.

Improvement of QWITT Diodes

An AlAs/GaAs QWD, two AlAs/GaAs QWITTs (QWT I and QWT II), and an AlAs/InGaAs QWITT have been grown by molecular beam epitaxy in a Varian Gen II system. Mesa isolated diodes with Ni/AuGe/Ni contacts were then fabricated with standard photolithographic techniques and wet chemical etching.

A summary of experimental oscillator results is given in Table 1. The RF output power was measured by placing each sample in the microstrip circuit and adjusting the DC bias voltage in the NDR region until a maximum output power was obtained. For these measurements the RF circuit was not intentionally designed to yield oscillations at any particular frequency; although a large RF-to-ground bypass capacitor was placed across the spectrum analyzer to suppress microwave oscillation, and care was taken to prevent very low frequency DC bias line oscillation. Under these conditions oscillations did still occur for all samples, at a frequency between 250 - 500 MHz. No other attempts were made to tune the circuit. All diodes produced an oscillation which had a very sharp spectrum (less than 1MHz bandwidth) and were stable for many hours.

The measured output power was compared to two types of simple calculations for the maximum power available from these devices. The first estimate for the maximum available power, given in the second column of the table, is equal to (3/16) $\Delta Vpv \cdot \Delta Ipv$. The second estimate is obtained by calculating, in the low frequency limit, the time-averaged power (PAC), assuming a sinusoidal RF voltage swing about a DC bias point, with the instantaneous current (I) taken from the DC I-V curve evaluated at the total instantaneous voltage (VDC + VRF sinwt). The maximum power is found by numerically varying the bias voltage and RF swing. As can be seen in Table 1, the close match between this quasi-static calculation and the measured results suggest that these devices are indeed delivering their maximum available RF output power. Furthermore, the QWITT diodes, as expected, deliver much more power than the QWD Also, QWT II and the AlAs/InGaAs QWITT exhibit very high DC-to-RF power conversion efficiencies.

The above method for comparing a device's expected power and actual results at a low frequency allows one to easily decide whether or not a circuit for higher frequency operation should be designed and fabricated. In light of this fact, QWT I was placed in an oscillator circuit that was iteratively designed for 10 GHz operation, and an output power of 1.2 mW was obtained at this frequency. For the AlAs/InGaAs QWITT, by simply removing the RF-to-ground bypass capacitor from its circuit, the diode oscillation frequency increased from about 250 MHz to about 3 GHz, while maintaining an output power of over 2 mW. [6]

Planar Periodically Loaded Structures

At millimeter-wave frequencies, solid state devices have limited capability to produce microwave power To compensate for deteriorating efficiency and power output. it is desirable to combine the power generated from many single devices in a coherent fashion. In addition, beyond a certain frequency, the negative resistance of the device becomes too small to compensate the resonator loss In this case, power combining alone cannot help. One way to resolve the problem in such cases is to use harmonic generation. We have developed a periodically loaded planar configuration to generate the second harmonics which are combined in free space Figure 1 shows the plan view of the structure. The microstrip line is loaded periodically with several (four in this case) Gunn diodes with the period equal to one half of the guide wavelength at the fundamental Therefore, the structure provides the surface wave stopband and all devices are injection locked to each other for oscillation. Due to the nonlinearity in the diode, the second harmonic will be generated from each diode. At this frequency, the period of the periodic placement is one guide wavelength. Therefore, the structure is in the leaky wave stopband. The second harmonic so generated are radiated into free space in the broadside direction and the power from each device is combined in free space. To enhance radiation at the harmonic, each diode is loaded with a microstrip patch antenna resonant at the second harmonics. The effective radiating power for the four diode second harmonic power combiner was 25.7 dBm and the isotropic conversion efficiency was 10.2% at 18 GHz harmonic. The cross polarization was 17 dB below the peak power in the broadside direction. The power radiated at the fundamental was 15 dB below the one at the second harmonic in the broadside direction. [7] This structure was also tested as a self oscillating subharmonic mixer. The maximum isotropic conversion gain at IF of 100 MHz was 6 dB.

A modified structure with two diodes was tried for scond harmonic self oscillating transceiver. In this scheme, a low pass filter was introducted between the two diodes so that they are phase locked at the fundamental. The diodes are isolated at the second harmonic. The effective radiating power was 13 dBm at 17 GHz and the isotropic conversion gain as a receiver was 10 dB.[8]

C. FOLLOW-UP STATEMENT: The immediate goal is to develop an efficient QWITT oscillator at X band and beyond. It is envisaged that the AlAs/InGaAs QWITT has a better performance.

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II. LIST OF CONFERENCE PROCEEDINGS (* JSEP Supported in whole or in part)

* "An experimental method for large signal characterization of solid state negative resistance devices," National Radio Science Meeting, p. 32, January 3-5, 1990, Boulder, CO, (A Mortazawi and T. Itoh).

* "Quasi-optical circuit applications of GaAs devices," GaAs '90, Gallium Arsenide Applications Symposium, pp. 12-15, April 19-20, 1990, Rome, Italy, (T. Itoh).

"Measurements of an optically controlled coplanar-waveguide phase-shifter," MIOP, pp. 643-646, April 24-26, 1990, Stuttgart, W. Germany, (P. Cheung, D. P. Neikirk and T. Itoh).

"A new time domain method in solving guided wave structures," 1990 URSI Radio Science Meeting," p. 4, May 7-11, 1990, Dallas, TX, (C.-W. Kuo and T. Itoh).

* "MM Wave/FIR twin slot antenna structures," 1990 IEEE Anmtennas and Propogation Symposium, pp. 788-790, May 7-11, 1990, Dallas, TX, (J. G. Heston, S. M. Wentworth, R. L. Rogers, D. P. Neikirk and T. Itoh).

"Physically-small frequency scanning antenna," 1990 IEEE Antennas and Propagation Symposium, pp. 799-802, May 7-11, 1990, Dallas, TX, (Y.-D. Lin and T. Itoh).

"Spectral domian analysis of electrically wide short-circuit discontinuities in slot line," 1990 IEEE Antennas and Propagation Symposium, PP. 1242-1245, May 7-11, 1990, Dallas, TX, (J. McLean, H. Ling and T. Itoh).

"Experimental and theoretical characterizations of very thin coplanar waveguide and coplanar slow-wave structures," 1990 IEEE MTT-S International Microwave Symposium, pp. 175-178, May 8-10, 1990, Dallas, TX, (H.-Y. Lee and T. Itoh).

(Research Unit EM89-1, "Millimeter Wave Active Wave Structures")

"Performance and modeling of superconducting ring resonators at millimeter-wave frequencies," 1990 IEEE MTT-S International Microwave Symposium, pp. 269-272, May 8-10, 1990, Dallas, TX, (K. B. Bhasin, C. M. Chorey, J. D. Warner, R. R. Romanofsky, V. O. Heinen, K. S. Kong, H.-Y. Lee and T. Itoh.)

"A varactor-tuned, active microwave band-pass filter," 1990 IEEE MTT-S International Microwave Symposium, pp. 499-502, May 8-10, 1990, Dallas, TX, (C.-Y. Chang and T. Ith).

"Asymmetric coplanar waveguide with finite metalization thickness containing anisotropic media," 1990 IEEE MTT-S International Microwave Symposium, pp. 673-676, May 8-10, 1990, Dallas, TX, (T. Kitazawa and T. Itoh).

"Optically-controlled tunable CPW resonators," 1990 IEEE MTT-S International Microwave Symposium, pp. 949-950, May 8-10, 1990, Dallas, TX, (M.S. Islam, P. Cheung, C.Y. Chang, D. P. Neikirk and T. Itoh).

"Full wave modeling of electrically wide microstrip open end discontinuities via a deterministic spectral domain method," 1990 IEEE MTT-S International Microwave Symposium, pp. 1155-1158, May 8-10, 1990, Dallas, TX, (J. McLean, H. Ling and T. Itoh).

An accurate CAD algorithm for E-plane type bandpass filters using a new passband correction method combined with the synthesis procedures," 1990 IEEE MTT-S International Microwave Symposium, pp. 1179-1182, May 8-10, 1990, Dallas, TX, (J.-B. Lim, C.-W. Lee and T. Itoh).

- "Recent efforts on planar components for active quasi-optical applications," 1990 IEEE MTT-S International Microwave Symposium, pp. 1205-1208, May 8-10, 1990, Dallas, TX, (K. D. Stephan and T. Itoh).

- "A periodic second harmonic spatial power combining oscillator," 1990 IEEE MTT-S International Microwave Symposium, pp. 1213-1216, May 8-10, 1990, Dallas, TX, (A Mortazawi and T. Itoh).

"Spatial power combining using push-pull FET oscillators with microstrip patch resonators," 1990 IEEE MTT-S International Microwave Symposium, pp. 1217-1220, May 8-10, 1990, Dallas, TX, (J. Birkeland and T. Itoh).

- "Planar quasi-optical active circuits (Invited)," XXIII General Assembly of the Interantional Union of Radio Science (URSI), August 28 - Septermber 5, 1990, Prague, Czechoslovakia, (T. Itoh).

- "Planar quasi-optical circuit technology (Invited)," 20th European Microwave Conference, pp. 83-88, September 10-13, 1990, Budapest, Hungary, (T. Itoh).

(Research Unit EM89-1, "Millimeter Wave Active Wave Structures")

"Spectral domain analysis of microstrip gap discontinuities and gap coupled resonators," 20th European Microwave Conference, pp. 555 559, September 10 13, 1990, Budapest, Hungary, (J. McLean, H. Ling and T. Itoh).

"Modified parallel-coupled filter structure improves the upper stop-band performance," 20th European Microwave Conference, pp. 925-927, September 10-13, 1990, Budapest, Hungary, (C.-Y. Chang and T. Itoh).

"An injection locking method for multiple FET oscillators suitable for active phased arrays and quasi-optical power combining," 20th European Microwave Conference, pp. 1505-1510, September 10-13, 1990, Budapest, Hungary, (J. Birkeland and T. Itoh).

* "Small signal measurement of the microwave impedance of QWITT diodes," 20th European Microwave Conference, pp. 623-627, September 10-13. 1990, Budapest, Hungary, (A. Mortazawi, D. Miller, D. P. Neikirk and T. Itoh).

"Analysis of the superconducting coplanar waveguide," 20th European Microwave Conference, pp.793-797, September 10-13, 1990, Budapest, Hungary, (K.-S. Kong, H.-Y. Lee and T. Itoh).

"Analysis of microstrip lines with alternative implementations of conductors and superconductors," 3rd Asia-Pacific Microwave Conference, September 18-21, 1990, Tokyo, Japan, (K.-S. Kong, H.-Y. Lee, T. Itoh, C. M. Chorey and K. B. Bhasin).

* "A second harmonic power combining transceiver," 3rd Asia-Pacific Microwave Conference, September 18-21, 1990, Tokyo, Japan, (A. Mortazawi, S. Kawasaki and T. Itoh).
"A modified end-coupled filter structure designed to broaden the bandwidth of an active filter," 3rd Asia-Pacific Microwave Conference. September 18-21, 1990, Tokyo, Japan, (C.-Y. Chang and T. Itoh).

* "Millimeter wave applications in USA (Invited)," Yagi Symposium on Advanced Technology Bridging the Gap between Light and Microwaves, September 25-27, 1990, Sendai, Japan, (T. Itoh).

"Nonlinear analysis of quantum devices," International Workshop on Integrated Nonlinear Microwave and Millimeter Wave Circuits, October 3-5, 1990, Duisburg, W. Germany, (H. D. Foltz, A. Mortazawi, J. H. Davis and T. Itoh).

"Wave interactions in planar active circuit structures," International Conference on Directions in Electromagnetic Wave Modeling, October 22-24, 1990, New York, NY, (J. Birkeland, S. El-Ghazaly and T. Itoh).

* "Acti' ɟ antennas (Invited)" 6^{e} Journees Internationales de Nice sur les Antennas, November 13-15, 1990, Nice, France, (T. Itoh).

"Analysis of the superconducting transmission line," 15th International Conference on Infrared and Millimeter Waves, December 10-14, 1990, Lake Buena Vista, FL., (K.-S. Kong and T. Itoh).

III. LIST OF PRESENTATIONS (*JSEP Supported in whole or in part)

"Active microwave filters," 1990 W. Germany MTT/AP Chapter Workshop, Reisensburg, W. Germany, Feb. 8, 1990.

"Microwave research at The University of Texas," Arizona State University, Tempe, AZ, April 11, 1990.

"Optical microwave interactions," Emerging Technologies in Optoelectronics Workshop, Tempe, AZ, April 12, 1990.

"Perspecuves of coplanar waveguide," Workshop, International Microwave Symposium, Dallas, TX, May 11, 1990.

"Overview of numerical field modeling methods," International Workshop on Modeling and Simulation of Guided and Radiated Electromagnetic Waves, Ottawa, Canada, May 14-17, 1990.

IV. LIST OF JSEP SUPPORTED THESES AND DISSERTATIONS

Ph.D.

Hai-Young Lee, "GaAs traveling-wave optical modulators using cross-tie slow-wave electrodes and characterization of conductor loss in a wide range of field penetration," December 1989 (T. Itoh, Supervisor)

Yu-De Lin, "Analysis and applications of the crosstie-overlay slow-wave structure," May 1990 (T. Itoh, Supervisor)

Chi-Yang Chang, "Microwave active filters based on coupled negative resistance method," May 1990 (T. Itoh, Supervisor)

James S. McLean, "The application of a dieterministic spectral domain method to the analysis of planar circuit discontinuities on open substrate," May 1990 (T. Itoh, Supervisor)

(Research Unit EM89-1, "Millimeter Wave Active Wave Structures")

- Amir S. Mortazawi, " Microwave ana millimeter-wave oscillators and planar power comining structures for QWITT and Gunn diodes," August 1990 (T. Itoh, Supervisor)

V. GRANTS AND CONTRACTS

Army Research Office Contract, DAAL03-88-K-0005, "Guided Wave Phenomena in Millimeter Wave Integrated Circuits and Components," Professor T. Itoh, Principal Investigatror.

Office of Naval Research Grant, N00014-89-J-1006, "High Temperature Superconducting Planar Circuit Structures for High Frequency Applications," Professor T. Itoh, Principal Investigator.

Texas Advanced Technology Program, "Monolithic Millimeter-Wave Integrated Circuits," Professor T. Itoh, Principal Investigator.

Texas Advanced Technology Program, "Computer Aided Design of Millimeter-Wave Integrated Circuits, " Professors T. Itoh and H. Ling, Co-Principal Investigators.

Texas Advanced Technology Program, "Heterostructure Tunneling Devices for Ultra-High Speed Device Applications," Professors D. P. Neikirk and B. G. Streetman, Co-Principal Investigators.

Texas Advanced Research Program, "Quantum Transport Studies and Double Barrier Heterostructures," Professor D. P. Neikirk, Principal Investigator.

NASA Lewis Research Center, "Analysis and Characterizations of Planar Transmission Structures and Components for Superconducting and Monolithic Integrated Circuits," Professor T. Itoh, Principal Investigator.

Texas Advanced Technology Program, "Quantum Well Device-Based Circuits for Millimeter Wave Communications Applications," Professors T. Itoh and D. P. Neikirk, Co-Principal Investigators.

Texas Advanced Technology Program, "Microwave-Optical-Interaction Devices and Circuits," Professors T. Itoh and J. C. Campbell, Co-Principal Investigators.

NTT Radio Communication Systems Lab., "Research on New Configurations for Microwave and Millimeter-Wave IC's," Professor T. Itoh, Principal Investigator.

ATR Optical and Radio Communications Research Lab., "Analysis of Waveguides for Millimeter-Wave and Optical Integrated Circuits," Professor T. Itoh, Principal Investigator.

(Research Unit EM89-1, "Millimeter Wave Active Wave Structures")

VI. CONSULTATIVE AND ADVISORY FUNCTIONS

T. Itoh participated in the panel for MIMIC CAD Workshop organized by DARPA MIMIC Office and Dr. B. Perlman of ETDL on January 17-19, 1990 in San Jose, CA.

	Estimated Power (mW)		Experimental Results	
Device	$\frac{3}{16}$ DI*DV	Quasi-Static I-V Calculation	RF Power (mW)	RF Power Conversion Efficiency, h (%)
QWD	0.236	0.242	0.206	7.5
QWT I	1.55	2.6	2.66	8.5
QWT II	2.34	3.5	3.54	20.4
InGaAs/AlAs QWITT	4.59	4.87	4.79	29.2

Table 1. Calculated and Measured Output Powers

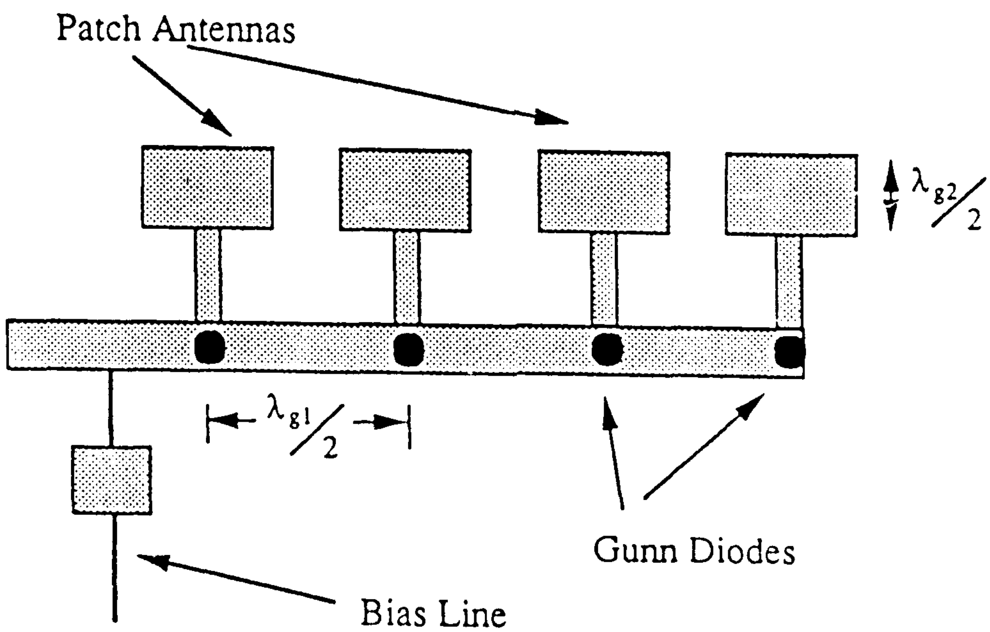

Fig. 1. Diagram of a four diode spatial second harmonic power combiner
λ_{g1} is the guide wavelength at fundamental frequency
λ_{g2} is the guide wavelength at fundamental frequency

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM89-2: Nonlinear Wave Phenomena

Principal Investigator: Professor Edward J. Powers (512) 471-3954

Graduate Students: S. W. Nam and Y. S. Cho

A. SCIENTIFIC OBJECTIVES: The overall scientific objective of this research program is to conceive and implement novel digital time series analysis techniques that may be utilized to analyze and interpret experimental time series data associated with nonlinear wave interactions and related phenomena. The underlying philosophy is to concentrate on those high-risk canonical questions that are relevant to many areas of science and technology. Based on our past experience, we have found that the results of such studies have been readily transferable to a diversity of technical fields where nonlinear phenomena are important. Examples include nonlinear scattering, nonlinear instabilities in high performance aircraft, underwater acoustics, energy cascading associated with transition to turbulence, nonlinear response of ships and offshore structures to random seas,and nonlinear signatures.

We are specifically concerned with answering the following questions given time series data characterizing the excitation and response of a potentially nonlinear physical system:

(1) How does one detect nonlinearities in the physical system that gave rise to the data?
(2) How does one quantify the type of nonlinearity (e.g., quadratic or cubic) and the "strength" of the nonlinearity in various frequency bands?
(3) Finally, one can further process the time series data to quantify the rate at which energy is extracted from the interacting spectral components in the excitation to subsequently reappear at sum or difference frequencies in the response.

Our approach may be briefly summarized as follows. The presence of nonlinearities in the physical system that gave rise to the time series data may be detected using higher-order spectra, such as the bispectrum and trispectrum. Such spectra are sensitive to the phase coherence and, hence, correlation between various interacting frequencies resulting from either three-wave or four-wave interactions. These interactions are, in turn, associated with quadratic and cubic nonlinearities, respectively. To quantify the strength of the interaction, the fluctuation or wave field is measured at two closely spaced (with respect to wavelength and correlation length) spatial points, and the observed linear and nonlinear wave physics is modeled with the aid of a hierarchy of linear, quadratic, cubic, etc. transfer functions. These transfer functions can then be related, via the fundamental "equations of motion" governing the linear and nonlinear physics of the system, to the three-wave (quadratic) and four-wave (cubic) coupling coefficients. Experimental knowledge of the coupling coefficients is important, since the relevant physics is imbedded in the coupling coefficient. Furthermore, experimental knowledge of the nonlinear transfer functions and coupling coefficients is necessary in quantifying the rate and direction of energy transfer between various interacting waves or modes of the system. Our progress is summarized in the next section.

B. PROGRESS: As indicated in the previous section our approach very much rests upon our ability to model the linear, quadratic, and cubic wave physics that occurs between the two spatial points where the fluctuation field is measured. The model consists of a hierarchy of linear, quadratic, and cubic transfer functions. The determination of these transfer functions is a state-of-the-art research project in its own right. For example, the transfer functions are calculated from higher-order spectral moments which in turn are estimated from the experimental time series data. Estimation of higher-order spectra also is a current research topic. Other important and practical issues involve Gaussian vs non-Gaussian excitation since the higher-order spectral moments are very sensitive to departures from Gaussianity. Algorithm development is also an important practical matter, particularly with respect to trying to minimize the amount of experimental data necessary to make good estimates of higher-order spectral and nonlinear transfer functions and, ultimately, such nonlinear wave parameters as interacting coefficients.

With respect to three-wave interaction phenomena we have previously reported upon our ability to measure quadratic transfer functions and, based on this knowledge, three wave interaction coefficients and the resulting energy cascading [1]. We have also extended our ability to measure quadratic transfer functions to dual-inputs [2]. This latter result was motivated by the fact that it is often desirable to quantify three-wave interaction phenomena between spectral components of two different physical parameters as they propagate through space. Also in [23], adaptive algorithms have been developed for use in determining quadratic transfer functions.

During this past year the bulk of our effort has been devoted to developing the theorectical approach, algorithms, and digital implementations for estimating linear, quadratic, and cubic transfer functions, in order to model the simultaneous presence of linear, quadratic (three-wave), and cubic (four-wave) wave phenomena occurring between the two spatical points where the fluctuation wave field is measured. The extension of our approach to cubic (and hence to four-wave interactions) is considerably more complex since cubic transfer functions (and four-wave coupling coefficients) are intrinsically three dimensional functions of frequency. This complexity also manifests itself in terms of a considerably increased computational burden. In any event, we have successfully developed an approach to estimate the linear, quadratic, and cubic transfer functions from time series data collected from two closely spaced points in the wave or fluctuation field. This work and considerations of symmetry conditions in three-dimensional frequency space, discussion of the role of Gaussianity vs nonGaussianity, estimation of spectral moments up to sixth order, and various applications to test the validfy of the results are discussed in [7,8,12,14,15,16,18].

There have been several spinoff's of earlier work dealing with three-wave interactions and which involved experimental determination of quadratic transfer functions in the frequency domain. The frequency domain work motivated analogous investigations in the time domain, where the goal is to estimate linear and quadratic impulse responses which, when implemented digitally, correspond to linear and quadratic (second-order Volterra) digital filter coefficients. This work has involved investigation of fast algorithms and has been incorporated into a feedforward compensator to stabilize nonlinear systems [3,9,20,22]. Other extensions of our past work have included the use of variable forgetting factors as a means of estimating time-varying spectra [6,13], measurement of nonlinear distortion using random excitation [11], and time-delay measurements using bispectra [21].

Other applications: As was mentioned in Sec. A, SCIENTIFIC OBJECTIVES, we have found our ability to quantify nonlinear wave phenomena in terms of a hierachy of linear and nonlinear transfer functions to exhibit high technology transfer potential in other areas of science and technology. In the following we mention work sponsored by other agencies but which make use of nonlinear signal processing capabilities originally developed under JSEP sponsorship. This fact is acknowledged in the LIST OF PUBLICATIONS by a double asterisk. For example, in work supported by the Texas Advanced Research Program, bispectral techniques have proved to be very powerful tools with which to quantify nonlinear interactions underlying the transisition to turbulence [4]. Similar frequency-domain and time-domain techniques have proven to be very useful in quantifying the nonlinear response of ships and offshore structures to nonGaussian random sea excitation [3,5,9,10,19]. This latter work is sponsored by ONR, NSF, and the Texas Advanced Technology Program. Lastly, we mention that higher-order spectral analysis techniques are being used to investigate unusual nonlinear aeroelastic phenomena in high performance aircraft in work sponsored by the Texas Advanced Technology Program. All of the above research projects have a common theme, the quantification of energy transfer from one set of frequencies or modes of the system to others as a result of nonlinear interactions.

C. FOLLOW-UP STATEMENT: This work is continuing with primary focus on experimental determination of cubic transfer functions and four-wave coupling coefficients, and measurement of energy transfer resulting from four-wave interactions, i. e., cubic nonlinearities.

I. LIST OF PUBLICATIONS (* denotes JSEP supported in whole or part; ** denotes a publication principally supported by another grant(s)/contract(s) in which JSEP is acknowledged for its nonlinear signal processing contributions.)

1. *Ch. P. Ritz, E.J. Powers, and R.D. Benston, "Experimental Measurements of Three-Wave Coupling and Energy Cascading," Physics of Fluids, **B1**, pp. 153-163, 1989.

2. *C.K. An, E.J. Powers, and Ch.P. Ritz, "A Digital Method of Modeling Two-Input Quadratic Systems with General Random Inputs," accepted for publication in IEEE Transactions on Acoustics, Speech, and Signal Processing, (in press).

3. **Y.C. Cho, S.B. Kim, E.J. Powers, and R.W. Miksad, "Stabilization of Moored Vessels Using a Second-Order Volterra Filte and Feedforward Compensator," accepted for publication in the Journal of Offshore Mechanics and Arctic Engineering.

4. **M.R. Hajj, R.W. Miksad, and E.J. Powers, "Subharmonic Growth by Parametric Resonance," submitted for publication.

(Research Unit EM89-2, "Nonlinear Wave Phenomena")

5. **S.B. Kim, E.J. Powers, R.W. Miksad, and F.J. Fischer, "Experimental Determination of Frequency-Domain Volterra Kernels for Second-Order Wave-Drift Phenomena," submitted for publication.

6. *Y.S. Cho, S.B. Kim, and E.J. Powers, "Time-Varying Spectral Estimation Using AR Models with Variable Forgetting Factors," submitted for publication.

7. *S.W. Nam and E.J. Powers, "Frequency-Domain Algorithms for the Identification of Third-Order Volterra Nonlinear Systems with a General Random Input," to be submitted for publication.

II. LIST OF CONFERENCE PROCEEDINGS (* denotes JSEP supported in whole or in part; ** denotes a publication principally supported by another grant(s)/contract(s) but in which JSEP is acknowledged for its nonlinear signal processing contributions.)

8. *S.W. Nam, S.B. Kim, and E.J. Powers," Nonlinear System Identification with Random Excitation Using Discrete Third-Order Volterra Series," Proceedings of the 8th International Modal Analysis Conference, Vol. 2, pp. 1278-1283, Kissimmee, Florida, January 29-February 1, 1990.

9. **Y.S. Cho, S.B. Kim, E.J. Powers, and R.W. Miksad, "Stabilization of Moored Vessels Using a Second-Order Volterra Filter and Feedforward Compensator," Proceedings of the Ninth International Conference on Offshore Mechanics and Arctic Engineering, Vol. 1, pp. 165-170, Houston, Texas, February 18-23, 1990.

10. **S. B. Kim, E. J. Powers, R. W. Miksad, F. J. Fischer, and J. Y. Hong, "Spectral Estimation of Second Order Wave Forces on a TLP Subject to NonGaussian Irregular Seas," Proceedings of the Ninth International Conference on Offshore Mechanics and Arctic Engineering, Vol. 1, pp. 159-164, Houston, Texas, February 18-23, 1990.

11. **Y.S. Cho, S.B. Kim, E.L. Hixson, and E.J. Powers, "Nonlinear Distortion Analysis Using Digital Higher-Order Coherence Spectra," Proceedings of the 1990 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 2, pp. 1165-1168, Albuquerque, New Mexico, April 3-6, 1990.

12. *S.W. Nam, S.B. Kim, and E.J. Powers, "On the Identification of a Third-Order Volterra Nonlinear System Using a Frequency-Domain Block RLS Adaptive Algorithm," Proceedings of the 1990 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 2, pp. 2407-2410, Albuquerque, New Mexico, April 3-6, 1990

(Research Unit EM89-2, "Nonlinear Wave Phenomena")

13. *Y.S. Cho, S.B. Kim, and E.J. Powers," Time-Frequency Analysis Using AR Models with Variable Forgetting Factors," Proceedings of the 1990 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. 5, pp. 2479-2482, Albuquerque, New Mexico, April 3-6, 1990.

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16. *S.W. Nam, S.B. Kim, and E.J. Powers, "Identification and Parameter Estimation of Nonlinear Systems Using Uniqueness of a Basic Nonlinear Structure," Proceedings of the 1990 IEEE International Symposium on Circuits and Systems, Vol. 2, pp. 1446-1449, New Orleans, Louisiana, May 1-3, 1990.

17. S.K. Kniffen, M.F. Becker, and E.J. Powers, "Applications of an Acousto-Optical Bispectrum Processor," Proceedings of the SPIE 1990 International Symposium on Optical and Optoelectronic Applied Science and Engineering, 13 pp., San Diego, California, July 8-13, 1990.

18. *S.W. Nam, E.J. Powers, and S.B. Kim, "Applications of Digital Polyspectral Analysis to Nonlinear System Identification," Proceedings of the 2nd IASTED International Symposium of Signal Processing and its Applications, pp. 133-136, Gold Coast, Australia, August 27-31, 1990.

19. **S.B. Kim, E.J. Powers, C.H. Kim, and S.Y. Boo, "Nonlinear Spectral Identification of Sway Drift Force of a Moored Vessel in NonGaussian Irregular Waves," Final Program and Paper Summaries for the 1990 Digital Signal Processing Workshop, pp. 8.5.1-8.5.2, New Paltz, New York, September 16-19, 1990.

20. *K.H. Kim, S.B. Kim, and E.J. Powers, "Least Squares Theory of a Second-Order Volterra Filter," Final Program and Paper Summaries for the 1990 Digital Signal Processing Workshop, pp. 8.4.1-8.4.2, New Paltz, New York, September 16-19, 1990.

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European Signal Processing Conference. Barcelona, Spain, September 18-21, 1990), L. Torres, E. Masgrau, and M.A. Lagunos, Editors, El Sevier, Amsterdam, pp. 111-114, 1990.

22. *K.H. Kim, S.B. Kim, and E.J. Powers, "Fast RLS Algorithms for General Filters," Signal Processing V, (Proceedings of the Fifth European Signal Processing Conference, Barcelona, Spain, September 18-21, 1990), L. Torres, E. Masgrau, and M.A. Lagunas, Editors, El Sevier, Amsterdam, pp. 181-184.

23. *E.J. Powers, S.W. Nam, and S.B. Kim, "Adaptive Algorithms for the Frequency-Domain Identification of a Second-Order Volterra System with Random Input," Proceedings of the Fifth ASSP Workshop on Spectrum Estimation and Modeling, pp. 25-29, Rochester, New York, October 10-12, 1990.

24. *K.H. Kim and E.J. Powers "Fast RLS Algorithms for a Second-Order Volterra Filter," Proceedings of the 29th IEEE Conference on Decision and Control, pp. 3520-3521, Honolulu, Hawaii, December 5-7, 1990.

IV. LIST OF THESES AND DISSERTATIONS

Master of Science

R.B. O'Donnell, M.S., December 1989, "Bispectral Investigation of Active Control Processes".

Ph.D.

* S.W. Nam, Ph.D., December 1990, "Application of Higher-Order Spectral Analysis to Nonlinear System Identification".

S.K. Kniffen, Ph.D., December 1990, "Acousto-Optical Bispectrum Processing of Wide-Bandwidth Signals".

V. CONTRACTS AND GRANTS

E. J. Powers and R. W. Miksad, "Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing to Nonlinear Hydrodynamics Research," Office of Naval Research, Contract N00167-88-K-0049, April 22, 1988 - September 30, 1989.

E. J. Powers and R. W. Miksad, "Applications of Frequency and Wavenumber Nonlinear Digital Signal Processing To Nonlinear Hydrodynamics Research," Office of Naval Research, Contract N00014-88-K-0638, September 1, 1988 - September 30, 1991.

(Research Unit EM89-2, "Nonlinear Wave Phenomena")

E. J. Powers and R. W. Miksad, "Application of Nonlinear Digital Time Series Analysis Techniques to Tension Leg Platform Model-Test Data," Texas Advanced Technology Program, TATP Grant 4604, May 1988 - August 1990.

R. W. Miksad and E. J. Powers, "An Experimental Study of the Nonlinear Dynamics of Unsteady Mixing Layers," Texas Advanced Research Program, TARP Grant 3280, May 1988 - August 1990.

E. J. Powers and R. W. Miksad, "Nonlinear System Identification of Tension Leg Platform Dynamics," Texas Advanced Technology Program, Grant No. 003658-392, Jan. 1, 1990 - December 31, 1992.

R. O. Stearman and E. J. Powers, "Aeroelastic System Identification of Advanced Technology Aircraft Through Higher Order Signal Processing," Texas Advanced Technology Program, Grant No. 003658-224, Jan. 1, 1990 - December 31, 1992.

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