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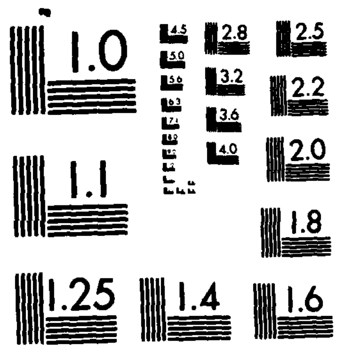

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SEMICONDUCTOR MILLIMETER WAVELENGTH ELECTRONICS

Department of Electrical Engineering
Washington University
St. Louis, MO 63130

November 1985

Final Report ONR 85-1
September 1979 - December 1983

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

This final report summarizes the results of research carried out on topics in millimeter wavelength semiconductor electronics under an ONR Selected Research Opportunity program. Study areas included III-V compound semiconductor growth and characterization, microwave and millimeter wave device modeling, fabrication and testing, and the development of new device concepts. A new millimeter wave mixer and detector, the Gap diode was invented. Topics reported on include ballistic transport, Zener oscillations, impurities in GaAs, electron velocity-electric field calculation and measurements, etc.

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SEMICONDUCTOR MILLIMETER WAVELENGTH ELECTRONICS

1. INTRODUCTION

This is the final report on the Selected Research Opportunity program supported by ONR at Washington University during the period 1 September 1979 - 31 December 1983. The purpose of the program was to investigate innovative approaches to the generation, amplification and detection of electromagnetic signals in the millimeter wave spectrum. It incorporated theoretical and applied studies in four areas:

i) Semiconductor material synthesis and growth

ii) Electrical characterization of these materials

iii) Device modeling and fabrication

iv) New device concepts.

The program provided the catalyst that brought together six electrical engineering professors, a group of nine graduate students and five undergraduate laboratory assistants to address the research problems. During the program period (and shortly after), six Master of Science theses were written and degrees granted, and four Doctor of Science degrees were awarded. Some eleven technical reports were written and nine technical papers published. Several more are presently in preparation. The program provided directions for faculty research which is still being pursued and developed. Two patent disclosures were filed. This report summarizes the principle results of the effort carried out on the SRO program.

2. SUMMARY OF PROGRAM RESULTS

2.1 Epitaxial Material Growth for Device Studies (J. M. Bornholdt, S. J. J. Teng, D. K. Walker, F. J. Rosenbaum and R. E. Goldwasser)

Two vapor phase epitaxial reactors were constructed and operated during the program: one for GaAs, the second for InP. Both systems employ H_2S gas doping to obtain the rapid changes in epitaxial layer concentrations required for millimeter wavelength devices. A rolling furnace design which permits rapid heating and cooling of growth wafers was used in both systems. The GaAs system employs $AsCl_3$ gas transported past a liquid Ga filled boat while the InP system uses PCl_3 and liquid In. However, both systems are compatible with the use of solid polycrystalline GaAs or InP source materials. Device quality material was obtained from both reactors but only GaAs devices were fabricated during the course of the program.

2.2 Material Characterization (G. M. Homsey, S. L. Von Rump, D. K. Walker, F. J. Rosenbaum and R. E. Goldwasser)

Two systems were developed for the characterization of the semiconductor materials. The first is an electrochemical etching system which makes it possible to determine accurately the free carrier concentration profile of GaAs, InP, or other compound semiconductor materials. InP has proven to be a hard material for measuring free carrier concentrations via the capacitance - voltage (C-V) method because of the difficulty in making good quality blocking (rectifying) contacts. The electrolytic C-V method developed for InP by D. K. Walker on this program permits the accurate and reliable measurement of free carrier concentration in InP.

A system to measure the velocity-electric field V(E) dependence of semiconductors was conceived, designed, and realized during the program. This system employs the injection of electrons from an electron beam into the drift region of a reverse-biased Schottky-Barrier junction formed on the material to be measured. Since this region can support non-uniform electric fields an advanced algorithm to account for this effect on the average velocity of electrons had to be developed. The electron beam is modulated at a microwave frequency of 6GHz which induces a current in the drift region of 12GHz. The phase of this current is measured as a function of the voltage across the drift region. This apparatus is the most advanced of its type yet reported and permits measurements of short, highly doped samples from low fields on up to fields where the velocity exhibits saturation.

2.3 Device Modeling (P. S. L. Chen and F. J. Rosenbaum)

In order to understand the charge distributions internal to semiconductor devices, a two-dimensional simulation program was developed capable of modeling the static electrical characteristics of semiconductor devices with complex geometries made of arbitrary materials. The simulation is intended for operation on personal computers. A finite difference approach was taken and a two-stage iteration scheme was developed. This method reduces by three quarters the memory requirements needed in the conventional simultaneous solution of Poisson's Equation and the continuity of current equation for the potential and charge distribution interior to arbitrarily shaped devices. Moreover, it yields converged solutions of similar quality to that obtained from the traditional coupled method. This program was used to study several new microwave diodes.

2.4 Device Fabrication and Characterization (S. J. J. Teng, F. J. Rosenbaum and R. E. Goldwasser)

Three types of devices were fabricated during the program: Schottky diodes for V(E) measurements, devices for the study of harmonic operation of Gunn diodes, and a newly invented device for the detection and mixing of millimeter wave signals, called the Gap diode. In this device, the I-V characteristic of the diode is controlled by the top surface contact metallization geometry. In this case, small gaps are left in the blocking contact metallization, exposing thin strips of the semiconductor active layer. These strips and gaps are then covered with an ohmic metal overlay. The principle of this diode is that the blocking (Schottky Barrier) contacts deplete the semiconductor in the gap (under the ohmic contacts) if the gap is small enough, "pinching" them off. In this way, the forward turn on voltage of the Gap diode can be set by choosing the gap width. Gap diodes were measured as detectors up to 94GHz with excellent results.

The advantages of this device are that: a) they can be made to give adjustable "barrier heights" on any semiconductor that has a metallization system capable of a high barrier, b) the device is very sensitive to low fields: conduction occurs as soon as the pinch off region retracts only slightly, c) current is not carried through the Schottky contacts (except at high forward bias) so that the noise and temperature dependence of the device is significantly different then that of conventional SBDs., and d) the devices have high burn-out threshholds and are very rugged. A potent disclosure was filed.

Harmonic generation in millimeter wave Gunn diodes was investigated in the 35-150GHz frequency range. Power outputs at the fundamental, second, and third harmonics were measured on diodes fabricated from flat doped epitaxial wafers and those with a cathode notch. The fundamental power of all devices tested peaked at near 40GHz regardless of their active layer lengths. The harmonic power of the packaged devices were measured and the second and third harmonic powers were found to decrease extremely rapidly above 100GHz for all of the flat doped devices. Significant improvement in the harmonic content above 100GHz was obtained from devices having a cathode doping notch. A power output of 5-6 mW was observed at 144GHz on the cathode notch devices. The highest power obtained from the flat doped devices at this frequency was 0.35 mW.

The improvement observed in the harmonic output of the cathode notch structure is likely due to a reduction in the formation time of the accumulation layer and a reduction in the cathode "dead space" that has been predicted by others using Monte Carlo analysis.

2.5 Ballistic Transport (M. W. Muller and P. Roblin)

High speed devices depend upon rapid response of carriers to applied fields. Even in the absence of collisions, the speed with which carriers can move is limited by the effective mass increase of high energy carriers associated with the non-parabolicity of the band structure. The effect of this limitation on the current-voltage characteristic of a spacecharge limited GaAs diode was calculated and the results were reported in a note published in IEEE Trans. on Electron Devices (1981-1). One result of interest is the change of the I-V characteristic from the well-known $V^{3/2}$ law to a linear V dependence.

Zener Oscillations

Carriers of high enough energy in a band can reach an energy region in which their effective mass is negative. Such carriers would present a negative resistance to an applied field and could serve as the basis for a source of millimeter and submillimeter radiation. We have invented a scheme for the coherent heterojunction injection, phase focusing, and elimination of dephased carriers by a feedback mechanism in a Zener Oscillator. The principle of the scheme was outlined at a Workshop on Submicron Technology (1984-1). The quantum mechanical details of carrier localization essential for understanding and analyzing carrier interactions with electromagnetic fields in semiclassical terms were reported in a paper published in J. Phys. C (1983-3). A detailed analysis of the coherent tunneling injection scheme across a field-modulated triangular potential barrier was carried out and is included in Mr. Roblin's (now Prof. Roblin's) dissertation, but it is as yet unpublished in the wider literature. It was realized early that an experimental demonstration of the scheme in homogeneous semiconductor materials would be prevented by the excessive optical phonon scattering rate at high carrier energies, but it remains the most promising option for the realization of the so-called Bloch oscillator in semiconductor superlattices.

Some of the questions raised in connection with the heterojunction injection were addressed in work carried out under new sponsorship after termination of the present contract. This has produced a semiclassical approach to the treatment of carrier dynamics in materials with spatially varying band structures based on a representation of the crystal electrons in generalized Wannier functions (Phys. Rev. B32, 5222 (1985)).

2.6 Impurities in GaAs (M. W. Muller and H. Rohdin)

Impurities diffuse in GaAs by a variety of disparate vacancy, substitutional, and interstitial mechanisms with widely different diffusion constants and temperature dependences. A particularly vexing problem is the redistribution of impurities during epitaxy between substrate, epitaxial layer, and ambient. This problem is complicated by two factors: the drift of charged impurities under the influence of interfacial and space charge fields, and the previously ignored failure of slowly diffusing impurities to reach their thermal equilibrium distributions. We have developed and published (1982-1) an exact treatment of the Schockley-Poisson diffusion problem that includes the electrostatics of surface states, and takes account of outdiffusion from the substrate, with application to multiple impurity redistribution in n-type GaAs epitaxy of practical interest.

Because the theory renounces the unrealistic approximation of thermal equilibrium, it becomes a dynamic moving-boundary problem that requires novel numerical mathematics. The necessary efficient computer algorithms are expected to be useful in a wider range of problems. Therefore, although they were developed specifically for this calculation, it was considered appropriate to make them available to the computer mathematics community through publication in a specialized journal (1983-2).

An additional complication of paramount importance in the impurity dynamics of GaAs is the chemical behavior of the Cr ion. This ion, which is the most important impurity in compensated semi-insulating material, is thought to exist in at least three different charge states, each with its own diffusion mechanism, vacancy interaction, and surface chemistry. We have succeeded in developing a self-consistent model that reconciles the reliably reported, and apparently incompatible experimental findings on Cr diffusion and anneal redistribution (1983-1). The theory permits the deduction of the previously unknown vacancy diffusion lengths in GaAs.

2.7 Transport Properties in III-V Semiconductors (B. Abraham-Shrauner and Sik Han Soh)

The first project treated ballistic (inertial) transport in submicron III-V semiconductors (1981-2). For materials like GaAs that are well approximated by parabolic energy bands, ballistic transport of electrons was treated in the fluid approximation. Conditions for the onset of negative differential resistance were specified. In the limit of frequent collisions electron transport with optical phonon collisions was treated approximately by analytical expressions. Together with master's student Sik Han Soh several approaches for calculating the electron distribution function were formulated. Simple approximate analytic expressions were given for the electron distribution function for weak electric fields. For strong electric fields an expansion inversely in the electric field gave electron distribution functions that behaved better at low energies (1984-2).

Work began on this contract and completed on another ONR contract included the consideration of p-wave scattering and a comparison of the diffusion and maximum anisotropy approximations. Calculations of optical phonon scattering demonstrated that p-wave of electrons was not responsible for the turn over of the velocity-electric field curve for collisions in the central valley of the energy band for ternary III-V semiconductors. An expansion of the optical phonon collision term inversely in the electric field before the truncation of the Legendre polynomial expansion (diffusion approximation) was made. A modified maximum anisotropy approximation has been shown valid for the electron distribution function for collisions in the central valley for ternary III-V semiconductors. The diffusion approximation is only valid in determining a functional from which the electron density and current can be calculated.

3. PROGRAM PARTICIPANTS

Prof. R. E. Goldwasser, Co. P.I.

Prof. M. W. Muller

Prof. D. L. Rode

Prof. F. J. Rosenbaum, P.I.

Prof. B. Abraham-Shrauner

Prof. C. M. Wolfe

4. DEGREES GRANTED

Master of Science

S. L. Von Rump	December 1982
J. M. Bornholdt	May 1982
S. J. J. Teng	May 1982
G. M. Homsey	December 1982
D. Walker	December 1983
S. H. Soh	December 1984

Doctor of Science

P. S. L. Chen	December 1982
H. Rohdin	December 1982
S. J. J. Teng	December 1983
P. Roblin	December 1984

Students Supported (Undergraduate - U, Graduate - G)

M. H. Riess	(U)	R. Sachs	(G)
S. Ewall	(U)	S. H. Soh	(G)
J. Wachsman	(U)		
J. Wendt	(U)		
D. Walker	(U)		

5. TALKS AND PAPERS PRESENTED

1. M. W. Muller, "Inertial Transport with Non-Parabolic Bands", late news papers given 9-23-80 at the International Symposium on GaAs and Related Compounds, Vienna, Austria.

2. H. Rohdin and M. W. Muller, "A Model of Cr in GaAs" 1982 Workshop on Compound Semiconductors for Microwave Materials and Devices, 2-21,22,-82, Scottsdale, Arizona.

3. P. Chen, S. J. J. Teng, F. J. Rosenbaum, and R. E. Goldwasser, "Control of GaAs Diode I-V Characteristics by Contact Geometry", 1982 WOCSEMMAD, Scottsdale, Arizona.

4. S. J. J. Teng, P. Chen, F. J. Rosenbaum, and R. E. Goldwasser, "The Gap Diode: A New High Frequency Mixer and Detector", 1982 IEEE MTT-S International Microwave Symposium, Dallas, Texas, June 1982.

6. REPORTS ISSUED

1. Semiconductor Millimeter Wavelength Electronics

F. J. Rosenbaum
R. E. Goldwasser
M. W. Muller
B. A. Shrauner
P. Chen
H. Rohdin
J. Teng

Annual Report ONR 80-1
October 1980

2. System for the Transport Analysis of Semiconductor Materials

S. L. Von Rump
F. J. Rosenbaum
R. E. Goldwasser
M. H. Riess
G. M. Homsey
J. M. Bornholdt

Technical Report ONR 80-2
October 1980

3. Control of GaAs Microwave Schottky Diode Electrical Characteristics by Contract Geometry

S. J. J. Teng
R. E. Goldwasser
F. J. Rosenbaum

Technical Report ONR-82-1
May 1982

4. VPE Growth of InP for Electronic Devices

J. M. Bornholdt
R. E. Goldwasser
F. J. Rosenbaum

Technical Report ONR-82-2
May 1982

5. Numerical Analysis of Semiconductor Devices Using Microcomputers

P. S. L. Chen
F. J. Rosenbaum
R. E. Goldwasser

Technical Report ONR-82-3
July 1982

6. System to Measure Carrier Drift Velocity in Semiconductor Materials

G. M. Homsey
F. J. Rosenbaum
R. E. Goldwasser

Technical Report ONR-82-4
August 1982

7. Impurity Redistribution Durring Epitaxy and a Model of Cr in GaAs

H. Rohdin
M. W. Muller
C. M. Wolfe

Technical Report ONR-82-5
September 1982

8. Zener Oscillations

P. Roblin
M. W. Muller

Technical Report ONR-82-6
September 1982

9. The Gap Diode: A Low-Barrier High-Frequency GaAs Diode

S. J. J. Teng
F. J. Rosenbaum

Technical Report ONR-83-1
September 1983

10. VPE Growth and Characterization of InP for Millimeter Wave Devices

D. K. Walker
F. J. Rosenbaum

Master's Thesis
December 1983

11. Electronic States in Submicron Heterostructures

P. Roblin

D.Sc. Thesis
August 1984

7. PAPERS PUBLISHED

1981

1. M. W. Muller, "Collisionless Space-Charge Limited Currents in Semiconductors with Nonparabolic Bands", IEEE Trans. on Electron Devices, vol. ED-28, No. 5, 604-605, May 1981.

2. B. A. Shrauner, "Instabilities of Inertial Transport in Semiconductors", IEEE Trans. on Electron Devices, vo. ED-28, No. 8, pp 945-950, Aug. 1981.

1982

1. H. Rohdin, M. W. Muller, and C. M. Wolfe, "Impurity Redistribution During Epitaxial Growth", J. of Electronic Materials, vol. 11, No. 3, pp 517-540, May 1982.

2. S. J. J. Teng, P. Chen, F. J. Rosenbaum, and R. E. Goldwasser, "The Gap Diode: A New High Frequency Mixer and Detector", 1982 IEEE MTT-S International Microwave Symposium Digest, IEEE Cat. No. 82CH1705-3, pp 24-26, June 1982.

1983

1. H. Rohdin, M. W. Muller, and C. M. Wolfe, "A Model of Cr in GaAs", J. Physics and Chemistry of Solids, vol. 44, No. 11, pp 1049-1057, 1983, Pergamon Press.

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1984

1. M. W. Muller, P. Roblin, and D. L. Rode, "Proposal for a Terahertz Zener Oscillator", in Physics of Submicron Structures, H. L. Grubin, K. Hess, G. J. Iafrate, and D. K. Ferry, Editors, Plenum, New York and London, 1984, pp 261-266.

2. B. Abraham-Shrauner and S. H. Soh, "Electron Distribution Function in GaAs for High and Low Electric Fields", ibid., pp 195-201.

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