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TECHNICAL PROGRESS REPORT

NUCLEAR RADIATION EFFECTS
ON
SILICON P-N JUNCTIONS

MASTER

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ABSTRACT

The dependence of neutron-induced space-region recombination on the electric field strength present in the junction during irradiation has been determined. In conjunction with previous work, the behavior of the space-charge region is now reasonably well understood and is predictable. The mechanism of the dependence is not yet clear. Surface effects of ionizing radiation have been studied and a scheme for predicting the surface degradation of matched devices has been implemented. Work is in progress to determine a method of predicting surface degradation for the general case. The junction capacitance variation with neutron fluence and gamma radiation has been determined. A technique has been developed for determining the net impurity profiles of both neutron irradiated (or gold-doped) and unirradiated devices. One result of this has been the discovery that the out-diffusion of the substrate (or buried layer) is non-negligible and has a significant effect on both the base region and collector junction parameters. A discrete, deterministic mathematical model has been developed for the base region of semiconductor transistors which accounts for both the effects of recombination in the neutral base region and the drift field for graded base devices. This model allows the prediction of transistor characteristics from knowledge of the impurity profile, initial lifetimes, currents, and fluence level to which a device is to be exposed. The effects of fast neutrons on the high frequency characteristics of p-n junction transistor was examined via the scattering parameters. The forward gain of transistors was observed to increase with neutron fluence for devices operating at or above $0.8 f_T$. This unexpected result is being examined further. A lumped element transistor model (similar in principle to the Ebers-Moll model) has been developed for use by circuit analysts and designers. It can match device data accurately over six to eight decades of current density and yields such parameters as forward current gain as a function of collector current naturally from the elements without need to resort to the artifice of fitting a polynomial to the data. Thought has been given to implementing an iterative procedure for determining design criteria for radiation tolerance by starting with a trial

impurity profile and operating constraints (bias voltages, currents, current gain, limitations of fabrication processes) and repeatedly generating device characteristics for changes in the impurity profile until optimums are achieved. This subject is under careful investigation.

TECHNICAL PROGRESS

Further Advances in Understanding Neutron-Induced Recombination in the Junction Space-Charge Region.

Neutron-induced defect clusters in silicon transistors have been shown to behave differently in the high field emitter-base "space-charge" region than in the low field "neutral" bulk-base region during introduction and annealing¹⁻⁶. This anomalous behavior in both formation and annealing has been attributed by some authors to carrier density effects⁷ or to a modification of the defect cluster by the presence of an electric field^{3,4}. To determine if such a field dependence existed, the variation of the rate of space-charge volume damage introduction, K_V , with junction electric field strength was investigated (Goben, Irani and Johnson, COO-1624-22)⁸. The magnitude of the neutron-induced space-charge component of base current, $\Delta I_{B\phi}$, the voltage dependence of this component (i.e., the reciprocal slope term, n), and the volume of the emitter-base space-charge region, $(A_E \cdot x_m)$ were examined as functions of fluence and electric field strength to determine the dependence of the rate of the space-charge volume damage introduction, K_V . Sets of specially fabricated, matched devices had their emitter-base junctions biased to different voltages, to produce varying electric field strengths at the junction during irradiation. The value of K_V was determined at each fluence, from 1×10^{13} to 2×10^{14} neutrons/cm² (Energy > 10keV). Experimental data show the existence of an electric field strength dependence on K_V , and indicate that neutron-induced recombination is more pronounced when higher junction electric field strengths are present during irradiation (COO-1624-22)⁸.

Surface effects caused by ionizing gamma radiation are a primary cause of damage at low fluences for the swimming pool reactor used in these experiments and the ionizing-induced surface current had to be subtracted from the total increase in base current along with the neutron-induced change in the neutral bulk-base region recombination current before meaningful space-charge volume damage introduction rates could be calculated. It is noted that the increase in K_V with the junction field strength present during irradiation is more pronounced at low fluences than it is

for high fluences. K_V decreased with increasing fluence at all neutron fluences except for the forward biased case at low fluences. This discrepancy from the general trend for forward biased junctions was attributed to injection annealing. Injection annealing during irradiation was considered not to be a possible explanation for the junction bias dependence since it alone was unable to predict all the observations (zero and reverse bias cases). An empirical expression was developed for K_V , which gives reasonable predictions for fluences between 2×10^{14} and 10^{15} neutrons/cm² ($E > 10\text{keV}$) and junction electric field strengths between 10^4 and 10^5 V/cm (ranges of fluences and electric fields where surface effects and injection annealing can be considered negligible or subtracted with reasonable accuracy for the type of devices tested). This expression along with extensive data and discussion are included in the referenced publication (also COO-1624-22)⁸. The exact nature of the field dependence (whether the defect cluster or the capture cross sections of the associated recombination centers are modified by the junction electric field) could not be determined and further work in this area is needed.

Progress on Surface Degradation Prediction

Previous experimental and theoretical investigations have established that the response of silicon planar transistors to ionizing radiation varies with the initial conditions⁹⁻¹¹ at the Si-SiO₂ interface and with the junction bias applied during irradiation¹²⁻¹⁴. Although previous investigators observed the surface degradation to follow a general trend, they were unable to obtain definite relations for predicting the changes in the parameters affected by surface damage. In recent work (Goben and Irani, COO-1624-26), it was found possible to correlate the charge accumulation in the SiO₂ layer above the junction transition region and the resultant changes in the parameters with the average junction electric field strength which resulted from the application of various biases to the junctions during exposure for specially matched devices. Empirical equations were developed showing the dependence of the changes in surface-dependent parameters on the total gamma dose and the average electric field strength at the junction during irradiation (See Report COO-1624-26 for equations

and comparisons with experimental data). The normalized base current change is found to be an increasing function of the total gamma dose and the average junction electric field strength during irradiation. The degradation of the surface minority carrier lifetime was found to follow a trend similar to the normalized base current increase. The effect of biasing the collector-base on emitter efficiency was also investigated. The saturation value of the surface damage at the emitter-base junction at larger doses is found to be greater for the reverse biased, than for either the cases of both junctions unbiased or the collector-base junction forward biased. Similar results have been reported previously¹⁴, although no explanation was given for the effect of collector-base biasing on the degradation of the emitter efficiency. These results can be explained if one realizes that a reverse biased collector-base junction has the effect of reverse biasing the emitter-base junction, and a forward biased collector-base junction has the effect of forward biasing the emitter-base junction, to maintain zero emitter current at the open emitter. It was found feasible to use this prediction technique to study changes in junction parameters of silicon planar matched devices having similar initial characteristics, (h_{FE} , I_B , τ_B) and operating under different bias conditions when exposed to various doses of ionizing radiation. It is hoped that further work will lead to a prediction scheme valid for unmatched devices.

Capacitance Variation with Gamma and Neutron Radiation

In analyzing nuclear radiation damage in semiconductor devices, it is frequently necessary to calculate the effect of a mixed spectrum of neutrons and ionizing gamma irradiation. In the present investigations, the neutron radiation source used is a 200 kW, BSR-Type Swimming Pool Reactor with a neutron to gamma ratio 9.0×10^7 (n/cm², E > 10keV)/rad(Si). Hence, at low levels of neutron fluence, the ionizing gamma induced surface effects will dominate the fast neutron induced displacement damage. The accumulation of positive charge in the SiO₂ layer above the junction causes inversion of the p-type base. The extent of surface channel formation is reflected by the increase in the junction capacitance (caused by an effective increase in the junction area). The

capacitance change is larger at the collector-base junction because of its larger perimeter. Recent investigations (Azarewicz and Goben, COO-1624-25) have indicated that the capacitance reaches a maximum value at a neutron fluence of 10^{14} neutrons/cm² (which corresponds to a total dose of 10^6 rads(Si), after which the surface effects are observed to saturate. Irradiation beyond 10^{14} neutrons/cm² causes the depletion layer width to increase because of carrier removal and hence decrease the junction capacitance. The data plotted (Fig. 2 of COO-1624-25) are the C-V characteristics for a combined field of neutron and gamma radiation. The broken curve (Fig. 2 of COO-1624-25) indicates the junction capacitance values caused by neutron-induced carrier removal alone, after the gamma-induced capacitance increase has been subtracted. This technique of removing surface effects is essential for calculations used in determining the impurity profile in the vicinity of the p-n junction at various neutron fluence levels. Su, et al.⁴ (COO-1624-13) made similar studies, to investigate the effect of biasing the collector-base junction during irradiation on the junction capacitance. The surface degradation (surface channel formation) was observed to be greatest for the reverse biased junction and least for the forward biased junction. The electric field strength dependence of the junction capacitance was further examined (COO-1624-26) in specially fabricated matched devices, exposed to pure ionizing gamma radiation. The capacitance is observed to be an increasing function of the junction electric field strength and the total gamma dose (below saturation). This work needs to be further extended to compare the responses of devices with various geometries and surface dopant concentrations to ionizing radiation.

Determination of the Net Impurity Distribution

It is necessary to know the net impurity distribution for the devices in order to determine the device characteristics. A technique has been developed for approximating the net impurity profile from the high-frequency (1 MHz) capacitance-voltage data for a device whose characteristics are desired. This technique yields not only the effective surface concentrations but also the junction depths, the effects of out-diffusion from the substrate or buried layer and the width of the epitaxial layer. The technique

is non-destructive and is valid in the presence of neutron-induced traps and/or gold centers. Other investigators^{15,16} have devised techniques to establish the neutron-induced changes in the electrical characteristics of semiconductor devices by computer aided modeling. These techniques require knowledge of the net impurity profile of the devices under study. Variations in the fabrication processes make the manufacturer's specification of the impurity profile, and junction depths, for a particular device unreliable. Junction depths previously were located only by destructive techniques and optical measurements on similar devices.

The effect of the out-diffusion of the substrate has previously been neglected. Work at this facility has demonstrated that the effect of the substrate out-diffusion is non-negligible and does in fact affect the device characteristics (Azarewicz and Goben, COO-1624-18)¹⁷.

Since this new technique is valid in the presence of neutron-induced traps and/or gold centers, the effects of neutron radiation on the net impurity profile have been studied using this technique (Azarewicz and Goben, COO-1624-25). The net impurity profile can now be determined and it is no longer necessary for device analysts and designers to rely on approximate specifications of the profile or destructive techniques. In addition, the effect of the substrate can now be included in the computer aided design of devices.

Neutral Bulk-Base Region Model

It had been postulated in early work¹⁻⁶ that two physical recombination processes were primarily responsible for neutron-induced current gain degradation. The first process, neutron-induced recombination in the emitter-base space-charge region, was reported by Goben¹ (1964) to dominate current gain degradation at low and intermediate current/injection levels. The second process was attributed to neutron-induced recombination in the bulk-base region and was predicted to dominate current gain degradation at moderate and high current/injection levels on theoretical and intuitive grounds. Experimental observation⁵ of the neutron-induced bulk-base recombination was severely complicated by emission crowding, conductivity modulation, and back injection effects. Graphical techniques were employed with some success, but only at

low neutron fluences. An extensive graphical-mathematical analysis by Goben et al.⁶ (1968) substantiated the existence and dominance of neutron-induced bulk-base recombination at higher current/injection levels. The exact magnitude and behavior of the neutron-induced base recombination current component was not accurately determinable and therefore a mathematical model for the recombination process in graded base regions was sought.

A discrete, deterministic mathematical model has been developed for the neutral bulk-base region of graded base devices which accounts for the combined effects of neutron-induced recombination and built-in electric field (COO-1624-10 and COO-1624-19)¹⁸. The model results from a closed form solution of the continuity equation¹⁹ and predicts the steady-state concentration of excess minority carriers as a function of injection level, electric field strength, distance, and neutron fluence. Exact expressions describing current flow through the bulk-base region are in turn developed from the excess carrier concentration. This model is perfectly general and is directly applicable to any device (silicon or other semiconductor material, graded or uniform base) once the geometry, impurity profile, and material are known (COO-1624-19)¹⁸. This model, in conjunction with the impurity profile determination technique (COO-1624-18 and COO-1624-25)¹⁷ has demonstrated excellent predictions when compared with experimental data (COO-1624-10).

The significant contributions of the base region model are:

- (1) Neutron induced current gain degradation is shown to be dominated by bulk-base recombination at moderate and high current/injection levels resulting primarily from minority carrier lifetime degradation.
- (2) Neutron-induced bulk-base recombination current is shown to be non-negligible at moderate and high current/injection levels.
- (3) The neutron-induced bulk-base current component increase is shown to be always greater than the corresponding decrease in collector current ($\Delta I_B \geq 3.0 \Delta I_C$ for uniform bases, and $\Delta I_B \geq 1.0 \Delta I_C$ for graded bases).
- (4) Devices with high built-in electric field strengths in the base region are shown to be affected less by bulk base recombination.

- (5) Theoretical expressions are available for the neutron dependence of the emitter, base and collector currents in terms of easily computed and analyzed exponential and hyperbolic functions.
- (6) Any device (graded or uniform base) is shown to exhibit a more radiation tolerant gain when operated at high current/injection levels where bulk-base region recombination dominates.
- (7) It is shown that for any given device there is an optimum operating current/injection level at a particular neutron fluence (high enough to minimize the effects of space-charge region recombination, and sufficiently low to avoid such high level effects as back injection, conductivity modulation, and recombination in the Kirk region).
- (8) Additionally, the base region model is shown to afford a theoretical basis for evaluating the effect of recombination in the bulk-base region of any device.

Neutron-Induced Enhancement of High-Frequency Transistor Gain

Most of the research concerning radiation effects on semiconductor p-n junction devices has been done at d-c or low frequency. Radiation effects on the high frequency characteristics of semiconductor devices were for the most part unknown. The changes in semiconductor high-frequency parameters caused by neutron radiation are useful in determining the precise characterization of the degradation of semiconductor devices in a radiation environment. It has been demonstrated that the more commonly known device parameters (h -, y -) are not of practical use in high frequency considerations, so that from both measurement and design points of view, the scattering parameters (s -parameters) are of primary interest²⁰. Generalized scattering parameters have been defined by Kurokawa²¹.

A prediction of the effects of neutron radiation on a semiconductor transistor's high-frequency characteristics in an amplifier configuration can be derived once a knowledge of the variation with neutron fluence and frequency of the S -parameters of the device is obtained, since knowledge of the S -parameter leads to a direct method²² of amplifier design.

Nuclear-radiation induced changes in npn silicon transistors operating at high frequencies have been studied at this facility (Gray, COO-1624-21)²³. The general effect of nuclear radiation is to reduce the magnitude of each s-parameter for frequencies below $0.8 f_T$ with negligible phase changes. The increase of the post-irradiation magnitude of S_{21} (insertion gain) above the pre-irradiation values for devices operating at frequencies above $0.8 f_T$ is an unusual and unexpected result. This indicates that the effect of nuclear radiation on transistors operating at frequencies above $0.8 f_T$ are enhancing rather than degrading as would have been expected from previous work carried out at d-c and low frequencies. This work has carried out with single-frequency measurements (120-350 MHz, every 10 MHz). The recent delivery of the HP 8690B Sweep Oscillator with HP 8699B RF Plug-in Unit will allow the detailed examination of this unusual radiation-induced enhancement of gain at frequencies above $0.8 f_T$.

Transistor Model for Computer Aided Circuit Analysis and Design

Most existing equivalent circuit models of transistors are based extensively on data fitting techniques (e.g., the Ebers-Moll model in Net-1, Net-1R, Net-2, Sceptre, Circus) which are valid only over a limited range of operation. Additionally, they require such artifices as fitting a polynomial to the gain versus collector current data and then placing constraints in device codes so as not to obtain a "negative gain".²⁴ The fundamental physical processes responsible for device behavior are ignored. These models, in spite of their shortcomings, find wide application in the area of computer aided circuit analysis and design. These models result in poor generation of d-c and a-c parameters even in the absence of radiation and are not capable of accurate predictions when applied to irradiated devices (primarily because they do not account for specific physical processes and their alteration by radiation)²⁴.

A "lumped element" model has been developed which is based on descriptions of the physical behavior of devices (COO-1624-27). This lumped element model is perfectly general and predicts with great accuracy the d-c and a-c parameters of p-n junction devices and the neutron-induced changes in these parameters. The gamma

rate dependence is included through "standard" primary photocurrent generators and the only significant improvement in these was the voltage dependence of the space charge region. Gamma dose dependence (surface degradation) has been considered, but no suitable means of generating this dependence has yet been achieved. This model is similar in principle to the Ebers-Moll model in that current generators are used for the junctions; however, the junction currents are represented by a series of individual current generators (rather than a single generator with a reciprocal slope dependence which is valid over only a small range) corresponding to each of the constituent current components at each junction. Carrier multiplication is included for the collector junction as is the collector efficiency (although the latter seldom deviates appreciably from unity in modern devices). This technique of using individual current generators allows a straightforward prediction of neutron-induced space-charge region and bulk-base region recombination. Emission crowding and conductivity modulation effects at high current/injection levels are described in terms of non-linear current dependent resistances and a unique "voltage difference generator"²⁴. The various junction capacitances are obtained in the conventional manner.

This model has demonstrated excellent prediction of device characteristics for both non-irradiated and irradiated devices over eight decades of current. This model establishes an accurate basis for computer aided analysis and design of circuits operated in a radiation environment. At present, as noted, the accuracy of this model has been verified for the prediction of d-c and a-c characteristics and neutron-induced recombination currents. Gamma-induced primary photocurrents are taken from the literature and gamma-dose effects are not included. Work is in progress to include the effects of ionizing gamma radiation for both dose and rate effects.

Design Criteria for Radiation Tolerance

A significant amount of information has already been obtained concerning the radiation dependence of various particular physical processes in silicon p-n junctions and junction devices by this laboratory (References 1-6, 17-20, 23, 24). It seems expedient at

this stage of progress to correlate all of the information available in an effort to implement and improve the design of radiation tolerant devices.

Work is in progress to obtain general design criteria for the actual fabrication of radiation hardened devices. The approach centers around a method of sequentially altering a given theoretical device impurity profile by a computer (consistent with device fabrication techniques) with certain operating condition constraints imposed so that a net impurity profile resulting in minimum radiation damage is obtained. The operating constraints can be specified in terms of junction bias voltages, output currents, current gains, and operating environments. The specific radiation damage to be minimized varies according to particular device and application and includes: (1) neutron-induced emitter-base space-region recombination (References 1-6); (2) neutron-induced bulk-base region recombination (COO-1624-10, COO-1624-19); (3) neutron-induced alteration of the device impurity profile (COO-1624-18, COO-1624-25); and (4) neutron degradation of collector-base parameters. The effects of gamma radiation on surface properties (COO-1624-26) will be added and will help to better determine optimum geometry, surface treatment, metalization, and encapsulation. The effects of neutron bombardment on the high frequency operation of p-n junction devices (COO-1624-21) are presently under investigation and could also be added together with the neutron dependence of junction capacitance (COO-1624-25) to establish frequency criteria for radiation tolerance.

Combining all the above results will ultimately result in an optimum device impurity profile and geometry for any given specific application. Precise specification of dopants, diffusion times and temperatures, junction depths, substrate growth and preparation, surface passivation, and metalization and encapsulation should be possible. Once the desired operation, the anticipated environment, and the material from which the device is to be fabricated are specified, the exact fabrication process can be determined for optimum performance. This technique should prove extremely valuable, especially in view of ion implantation fabrication methods whereby the impurity profile and base width can (in principle) be more closely controlled.

EXPERIMENTAL MEASURING SYSTEMS

Several experimental measuring systems are being used for data acquisition. These systems are for the measurement and recording of the voltage versus current, voltage versus capacitance characteristics, scattering parameters, minority carrier lifetimes and switching characteristics, and small signal dynamic characteristics. Calibration standards are maintained for the purpose of calibrating the experimental measuring systems. An integrated circuits test system is being fabricated.

Automatic Data Acquisition System

The Automatic Data Acquisition System is capable of current and voltage measurement with an overall absolute accuracy of $\pm 1\%$ of reading and a precision (repeatability) of $\pm 0.3\%$ of reading in the range from 10^{-10} amperes to 2×10^{-1} amperes (over 9 decades). This system has previously been described adequately [Bartling²⁵ (COO-1624-1), Bartling, Jenkins and Goben²⁶ (COO-1624-2) and in the Technical Progress Report - February, 1969 (COO-1624-20)]. The only change made in this system was the addition of an automated stepping switch to allow taking data on twelve devices in one data run. An interface is being designed and constructed which will allow this system to be controlled by a Digital Equipment Corporation PDP-8/I Programmed Data Processor (described later). Controlling the system in this manner will provide more flexible system operation and provide some on-line data reduction.

Capacitance-Voltage Measuring Systems

The capacitance measuring systems use a Micro Instruments Model 1201DS Digital Capacitance Tester (1 MHz signal frequency) as the basic measuring instrument. A Dymec 2901A Master Scanner/Programmer and a Dymec 2902A Slave Scanner/Programmer are used for control and programming. The test devices are mounted in a Delta Design MK2310 Temperature Control Chamber. These systems have previously been described adequately (COO-1624-20).

This system will also be interfaced to the PDP-8/I Programmed Data Processor to provide increased system flexibility and on-line data processing.

An additional capacitance-voltage system is used to obtain data as a function of frequency. The system used is a General Radio 1615A Capacitance Bridge with Princeton Applied Research Oscillator and Null Detector Model HR-8 to extend the frequency range.

Scattering Parameters Test System

The S-parameter test system is designed to measure scattering parameters in the frequency range of 0.1 GHz to 2.0 GHz. Selection of the particular parameter (S_{11} , S_{12} , S_{21} , S_{22}) is accomplished by a front panel pushbutton. The test head provides the reference plane for the device under test and provides a simple means of selecting the device configuration. Bias for the device under test is applied through the test set to the test head. To measure any one of the parameters, the test signal is applied through a dual directional coupler to the appropriate test port. A part of the signal is fed from the coupler and is used as the reference channel signal. The reflected signal (S_{11} or S_{22}) or the transmitted signal (S_{12} or S_{21}) is then coupled out as the test channel signal. When making single-frequency measurements, the reference channel signal and the test channel signal are taken from 50-ohm T-pads to a vector voltmeter where their amplitude and phase are measured as described previously (COO-1624-20).

A Hewlett-Packard 8690B Sweep Oscillator with 8699B RF Plug-in Unit was purchased (and only recently delivered) to allow swept-frequency measurements and the rapid and accurate determination of device high-frequency characteristics. When making swept-frequency measurements, the reference channel signal and the test channel from the S-parameter test set are converted into 20 MHz i-f signals (phase and amplitude relationships between the r-f signals are maintained) in the Frequency Converter. The two i-f signals are then fed to the Network Analyzer which includes automatic frequency tuning circuits, i-f amplifiers, precision i-f gain control and power supply for the converter. A front panel switch selects the desired octave range between 0.1 and 12.4 GHz and the rest is automatic. The analyzer phase locks to the frequency and follows it during sweep operation.

The Polar Display provides a Cathode ray tube readout of magnitude and phase in polar coordinate form. Overlays can be used

to provide Smith chart and expanded Smith chart readout of normalized impedance or admittance. Two frequency marker signals may be fed to the Polar Display for accurate frequency reference points.

Analog outputs from the Polar Display are provided for use with an X-Y recorder (HP-136A) to provide permanent Smith chart records of the data. These outputs may also be connected to the digital voltmeters of the Automatic Data Acquisition System where they can be recorded in tabular form.

Lifetime and Switching Characteristics Measuring System

The minority carrier lifetimes are obtained by using a Tektronix Type 555 Oscilloscope with a Tektronix Type S plug-in unit. With this plug-in unit measurements of diode impedance, ohmic resistance, forward and reverse recovery time, junction capacitance and minority carrier lifetimes can be made. A Type R plug-in unit is used to measure transistor rise, fall, delay and storage times. A Type 1S1 plug-in unit is used to extend the measurement capability of the oscilloscope to one gigahertz. Permanent records of these measurements are made using a Tektronix Type C-12 Camera, with Polaroid back, mounted on the oscilloscope.

Small Signal Dynamic Characteristics Measuring System

A Tektronix Type 575 Oscilloscope with a Tektronix Type C-12 Camera is used to obtain and record the small signal dynamic characteristics of the devices under study. This unit provides a means of applying the bias voltages and drive voltages and currents to obtain families of curves which are recorded on photographic film for permanent record.

Integrated Circuits Tester System

An integrated circuit tester designed and under construction by the Graduate Center for Materials Research has previously been described adequately (COO-1624-20).

Programmed Data Processor

The Programmed Data Processor is a Digital Equipment Corporation Model PDP-8/I. The processor has 8192 words (12 bits per word) of core memory with a 1.5 microsecond cycle time and hardware multiply

and divide option. The input-output unit for the processor is an ASR-33 Teletype Automatic Send/Receive, Reader/Punch Unit. This unit reads or punches at a rate of 10 characters per second. To shorten the input-output time, a high speed reader-punch Model PC-8/I has been added. This unit reads paper tape at a rate of 300 characters per second and punches at a rate of 50 characters per second.

Scanning Electron Microscope

The Scanning Electron Microscope (SEM) recently acquired by the Space Sciences Research Center of the University of Missouri-Rolla is a Model JSM microscope, manufactured by the Japan Electron Optics Laboratory, Ltd. It has a magnification of approximately 70,000 X in both the secondary and backscattered electron modes. Sample sizes can be on the order of 1.5 cm in diameter. The sample chamber, which is evacuated to the order of 10^{-6} Torr, is fitted with vacuum electrical feedthroughs which enable the investigator to make electrical connections to both the sample and peripheral electrical equipment which may be placed in the sample chamber. This machine requires less rigid sample preparation techniques than the conventional electron beam microscopes. Specifically, the elimination of the replication step allows the investigator to more easily conduct large involved investigations and to conduct real-time investigations where, for example, the voltages and currents of a semiconductor p-n junction may be varied concurrently with sampling.

Calibration Standards

Calibration standards are maintained for the purpose of calibrating the experimental measuring systems. These standards consist of four Eppley Standard Cells (Certified) mounted in a temperature control chamber, seven NBS type resistors (Certified) ranging in decade values from one ohm to one megohm, two standard capacitors (Certified) of 50 pf and 500 pf, and a Leeds and Northrup type K5 precision Potentiometer (Certified). A John Fluke Model 750 Reference Voltage Divider is used in the calibration of precision voltmeters, and d-c calibrators. A John Fluke Model 720A Kelvin-Varley Divider is used in the calibration of bridge elements, voltage

dividers and precision potentiometers.

A DC Voltage Standard/Differential Voltmeter is used to supply standard voltages up to 1111.1110 volts needed for the calibration of some instruments in the experimental measuring systems. This instrument is also used as a differential voltmeter and null detector for measurements made with the calibration standards.

EXPERIMENTAL UNITS

In order to make all the necessary measurements to obtain the parameters needed to compute the quantities of basic interest, it is necessary to have special structures fabricated. Special structures of the type used in this research effort have been described previously (COO-1624-20). A device currently on order and to be delivered shortly and used in both this and the following year are a set of three devices (Bipolar transistor, gated diode and MOS field effect transistor) all fabricated on the same die. These will be used to attempt the extension of the prediction of surface degradation from matched devices to the general case and in the high-frequency S-parameter studies. An additional device to be used in the further development of the base region model is a diffused-emitter ion implanted face device which offers the possibility of shaping the field in base region more accurately than can be accomplished in a double-diffused device.

DEVIATIONS

There were no significant deviations in the scope of the work agreed upon in the present contract.

REPORT OF EQUIPMENT PURCHASED WITH AEC FUNDS

John Fluke	335A Voltage Standard/Differential Voltmeter/Null Detector	2,499.48
John Fluke	383B Voltage/Current Calibrator	2,005.61
Hewlett Packard	8690B Sweep/Oscillator with 8699B Plug-in Unit	4,814.40
Hewlett Packard	136A X-Y Recorder	2,660.65

REFERENCES

1. C. A. Goben and F. M. Smits, "Anomalous Base Current Component in Neutron Irradiated Transistors," IEEE Radiation Effects Conference, Seattle, Washington, 1964. Also, Sandia Laboratory (Albuquerque, New Mexico), (Publication) SCR-64-195 (1964).
2. C. A. Goben, "Neutron Bombardment Reduction of Transistor Current Gain," Ph. D. Dissertation, Iowa State University Library (Ames, Iowa) 1965. Also, Sandia Laboratory (Albuquerque, New Mexico), (Publication) SCR-64-1373 (1964).
3. J. R. Chott and C. A. Goben, "Radiation and Annealing Characteristics of Neutron Irradiated Silicon Transistors," IEEE Trans. on Nuclear Science, NS-14:6, 134-146 (1967). Also, AEC Report COO-1624-4.
4. L. S. Su, G. E. Gassner and C. A. Goben, "Radiation and Annealing Characteristics of Neutron Bombarded Silicon Transistors," IEEE Trans. on Nuclear Science, NS-15:6, 95-107 (1968). Also, AEC Report COO-1624-13.
5. C. A. Goben, "A Study of the Neutron-Induced Base Current Component in Silicon Transistors," IEEE Trans. on Nuclear Science, NS-12:5, 134-146 (1965).
6. C. A. Goben, F. M. Smits and J. L. Wirth, "Neutron Radiation Damage in Silicon Transistors," IEEE Trans. on Nuclear Science, NS-15:2, 14-29 (1968).
7. B. L. Gregory and H. H. Sander, "Injection Dependence of Transient Annealing in Neutron-Irradiated Silicon Devices," IEEE Trans. on Nuclear Science, NS-14:6, 116-126 (1967).
8. C. A. Goben, C. H. Irani and P. E. Johnson, "Neutron Fluence and Electric Field Strength Dependencies of the Rate of Volume Damage Introduction in Silicon P-N Junctions," IEEE Trans. on Nuclear Science, NS-16:6, 43-52 (1969). Also, AEC Report COO-1624-22.
9. G. J. Brucker, W. J. Dennehy, and A. G. Holmes-Siedle, "Ionization and Displacement Damage in Silicon Transistors," IEEE Trans. on Nuclear Science, NS-13:6, 188-196 (1966).
10. W. Pock and A. G. Holmes-Siedle, "A Prediction and Selection System for Radiation Effects in Planar Transistors," IEEE Trans. on Nuclear Science, NS-15:6, 213-223 (1968).
11. M. A. Littlejohn and R. W. Lade, "Influence of Co-60 Gamma Irradiation on the Surface and Bulk Recombination Rates in Silicon," IEEE Trans. on Nuclear Science, NS-14:6, 305-318 (1967).
12. P. R. Measel and R. R. Brown, "Low Dose Ionization-Induced Failures in Active Bipolar Transistors," IEEE Trans. on Nuclear Science, NS-15:6, 224-231 (1968).

13. H. L. Hughes, "Surface Effects of Space Radiation on Silicon Devices," IEEE Trans. on Nuclear Science, NS-12:6, 53-63 (1965).
14. D. L. Nelson and R. J. Sweet, "Mechanisms of Ionizing Radiation Surface Effects on Transistors," IEEE Trans. on Nuclear Science, NS-13:6, 197-206 (1966).
15. C. W. Gwyn, D. L. Scharfetter and J. L. Wirth, "The Analysis of Radiation Effects in Semiconductor Junction Devices," IEEE Trans. on Nuclear Science, NS-14:6, 153-169 (1967).
16. V. A. J. van Lint, J. H. Alexander, D. K. Nichols and P. R. Ward, "Computer Model for Response of Transistors to a Pulse of Ionizing Radiation," IEEE Trans. on Nuclear Science, NS-14:6, 170-178 (1967).
17. J. L. Azarewicz and C. A. Goblen, "Determination of the Doping Profile of Double Diffused P-N Junction Devices," SWIEECO RECORD, April, 1970. Also, AEC Report COO-1624-18.
18. J. Bereisa, Jr., and C. A. Goblen, "Determination of Graded Base Parameters in the Presence of Recombination at Low to Moderate Current Levels," (Accepted for Publication) SWIEECO RECORD, April, 1970. Also, AEC Report COO-1624-19.
19. J. Bereisa, Jr., "A Mathematical Model for the Neutron Dependence of Bulk-Base Region Recombination," M. S. Research, University of Missouri-Rolla, 1970.
20. T. J. Herrick, "Scattering Parameter Measurements and Amplifier Design," M. S. Thesis, University of Missouri-Rolla Library (Rolla, Missouri 65401) 1968.
21. K. Kurokawa, "Power Waves and the Scattering Matrix," IEEE Trans. on Microwave Theory and Techniques, MTT-13:2, 194-202 (1965).
22. W. H. Frochner, "Quick Amplifier Design With Scattering Parameters," Electronics, 40, 21, 100-109 (1967).
23. D. L. Gray, "Fast Neutron Effects on Transistor Scattering Parameters," University of Missouri-Rolla Library, 1969. Also, AEC Report COO-1624-21.
24. G. R. Case, "Models for the PN Diode and NPN and PNP Transistor for Use in Computer Aided Design and Analysis Programs," Ph. D. Dissertation, University of Missouri-Rolla Library, 1969.
25. D. L. Bartling, "An Automatic Data Acquisition System for Semiconductor Device Testing," M. S. Thesis, University of Missouri-Rolla Library, 1967. Also, AEC Report COO-1624-1.
26. D. L. Bartling, C. R. Jenkins and C. A. Goblen, "An Automatic Data Acquisition System for Semiconductor Device Testing," IEEE Trans. on Instrumentation and Measurement, IM-17:1, 19-28 (1968).

PUBLICATIONS

"Determination of the Doping Profile of Diffused P-N Junction Devices," J. L. Azarewicz and C. A. Goben, (Accepted for publication) SWIEECO RECORD, April, 1970 (COO-1624-18).

"Determination of Graded Base Parameters in the Presence of Recombination at Low to Moderate Injection Levels," J. Bereisa, Jr., and C. A. Goben (Accepted for publication) SWIEECO RECORD, April, 1970 (COO-1624-19).

"Fast Neutron Effects on Transistor Scattering Parameters," D. L. Gray, M. S. Thesis, University of Missouri-Rolla Library, 1969 (COO-1624-21).

"Neutron Fluence and Electric Field Strength Dependencies of the Rate of Volume Damage Introduction in Silicon P-N Junctions," C. A. Goben, C. H. Irani and P. E. Johnson, IEEE Trans. on Nuclear Science, NS-16:6, 43-52, 1969 (COO-1624-22).

"The Nucleus," C. A. Goben, IEEE Trans. on Nuclear Science, NS-16:6, 5, 1969 (COO-1624-23).

Papers in Preparation:

"Calculation of the Neutron Induced Changes in the Net Impurity Concentration of Planar Epitaxial Transistors," (J. L. Azarewicz for Mid-America ANS Conference, 1970).

"Neutron Dependence of Electric Field-Aided Minority Carrier Transport," (J. Bereisa, Jr. for Mid-America ANS Conference, 1970).

"Nuclear Radiation Effects on Transistors Operating at High Frequency," D. L. Gray and Y. P. Han for Mid-America ANS Conference, 1970).

"Prediction of Gamma Induced Surface Degradation in Oxide Passivated Bipolar Transistors," (C. H. Irani for Mid-America ANS Conference, 1970).

"Neutron Radiation Effects on the Net Impurity Doping Profile of Double Diffused Transistors," (J. L. Azarewicz and C. A. Goben for submission to IEEE Trans. on Nuclear Science).

"Neutron Dependence of Neutral Base Region Recombination," (J. Bereisa, Jr. and C. A. Goben for submission to IEEE Trans. on Nuclear Science).

"Electric Field Strength Dependence of Surface Damage in Oxide Passivated Silicon Planar Transistors," (C. A. Goben and C. H. Irani for submission to IEEE Trans. on Nuclear Science).

"Problems in High Frequency Amplifier Design Using Scattering Parameters," (D. L. Gray, Y. P. Han and C. A. Goben for submission to IEEE Trans. on Microwave Theory and Techniques).

"An Improved Transistor Model for Use in Computer-Aided Analysis and Design of Circuits Operated in a Radiation Environment," (J. Bereisa, Jr. and C. A. Goben for submission to IEEE Trans. on Nuclear Science).

"The Effect of Out-Diffusion of the Substrate or Buried Layer on Transistor Characteristics," (J. Bereisa, Jr. and J. L. Azarewicz and C. A. Goben for submission to IEEE Trans. on Electron Devices).

"Design Criteria for the Impurity Profiles and Geometries of Radiation Hardened Diffused Silicon P-N Junction Devices," (C. A. Goben, J. L. Azarewicz, J. Bereisa, Jr. and C. H. Irani for submission to the Government Microcircuit Applications Conference, 1970).

Presentations:

"Investigations of Defect Clusters in Silicon P-N Junctions," P. E. Johnson, J. Bereisa, Jr., C. H. Irani and C. A. Goben (Presented by C. A. Goben at the IEEE Nuclear and Space Radiation Effects Conference - July 1969).

Presentations to be given at the forthcoming American Nuclear Society Meeting in April, 1970:

- (1) "Determination of Neutron-Induced Changes in the Net Impurity Concentration of Planar Epitaxial Transistors," by J. L. Azarewicz.
- (2) "Neutron Dependence of Electric Field-Aided Minority Carrier Transport," by J. Bereisa, Jr.
- (3) "Nuclear Radiation Effects on Transistors Operating at High Frequencies," by Y. P. Han.
- (4) "Prediction of Gamma Induced Surface Degradation in Oxide-Passivated Bipolar Transistors," by C. H. Irani.

Presentations to be given at the forthcoming Southwestern Institute of Electrical and Electronic Engineers Convention in April, 1970:

- (1) "Approximating the Doping Profile of Double-Diffused P-N Junction Devices," by J. L. Azarewicz (COO-1624-18)*
- (2) "Determination of Graded Base Parameters in the Presence of Recombination at Low to Moderate Injection Levels," by J. Bereisa, Jr. (COO-1624-19)*

* Accepted for Publication in SWIEECO RECORD, April, 1970.

Submitted for presentation at the IEEE Nuclear and Space Radiation Effects Conference - July, 1970:

- (1) "Neutron Radiation Effects on the Net Impurity Doping Profile of Double-Diffused Transistors," by J. L. Azarewicz.

- (2) "Neutron Dependence of the Neutral Base Region Recombination,"
by J. Bereisa, Jr.
- (3) "Electric Field Strength Dependence of Surface Damage in
Silicon Planar Transistors," by C. H. Irani.

PERSONNELProject Director:

Dr. Charles A. Goben, Associate Professor of Electrical Engineering and Senior Investigator of Space Sciences Research Center (Materials), University of Missouri-Rolla.

Eighty percent time, academic year; 100 percent time, summer (two months).

Graduate Research Assistants:

Fifty percent time.

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Publications

Jenkins, C. R., "Passive Temperature Monitoring in Radiation Environment," SC-TM-66-282, Sandia Laboratory (Albuquerque, New Mexico) 1966.

Bartling, D. L., Jenkins, C. R. and Goben, C. A., "An Automatic Data Acquisition System for Semiconductor Device Testing," IEEE Transactions on Instrumentation and Measurement, IM-17:1, 19-28 (1968).