MAR 11 1968

C00-1620-11

TECHNICAL PROGRESS REPORT

MASTER

NUCLEAR RADIATION EFFECTS ON SILICON P-N JUNCTIONS

**University of Missouri-Rolla
Space Sciences Research Center
Rolla, Missouri**

February 1968

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TECHNICAL PROGRESS REPORT

AEC Contract No. AT(11-1)-1624

Contract Period:

June 1, 1967—May 31, 1968

NUCLEAR RADIATION EFFECTS
ON
SILICON P-N JUNCTIONS

Submitted by
Dr. Charles A. Goben

University of Missouri, Rolla
School of Mines and Metallurgy
Space Sciences Research Center
Rolla, Missouri 65401

Charles A. Goben
Date 15 February 1968

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fy

TABLE OF CONTENTS

	Page
ABSTRACT	1
TECHNICAL PROGRESS	2
EXPERIMENTAL MEASURING SYSTEMS	2
Automatic Data Acquisition System	2
Capacitance-Voltage Measuring System	5
Time Constant Measuring System	7
Delays and Problems	9
EXPERIMENTAL UNITS	10
STATUS OF EXPERIMENTS	13
Parameters of the Collector-Base Junction	13
Base Transport Factor Change at Moderate and High Current Levels	20
Annealing Characteristics in Neutron Bombarded Transistors	24
Variation of Inverse Current Gain with Neutron Fluence	27
Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration	29
Field Dependence of Radiation Induced Defects	31
Quasi-Tunneling Recombination Model	32
Recombination Statistics for the Neutron-Induced Current Component	33
BIBLIOGRAPHY	38
DEVIATIONS	41
PUBLICATIONS	42
PERSONNEL	44

ABSTRACT

Equipment has been purchased (or fabricated) and integrated to form the sophisticated electronic measuring apparatus required for studying nuclear radiation effects in silicon p-n junctions.

The effects of neutron irradiation on the collector junction parameters which indicates that recombination takes place in the collector junction has been noted and apparently can be explained only by adding a term to the normal gain expression to account for this recombination.

In the moderate to high current level region, that is, during and after the onset of conductivity modulation, a bulk recombination phenomena is predicted and observed to account for degradation of transistor current gain. This phenomena is under investigation.

Work is in progress to examine the anomalous annealing phenomena reported by the principal investigator for the neutron-induced defects in the neutral and space-charge regions of p-n junction devices through isothermal and isochronal annealing techniques.

A study is being made of the radiation and annealing behavior of devices operated in the inverse configuration so that a relatively wide depletion region is available for determination of the damage constant for the neutron-induced current component originating in the depletion layer.

It has been determined that the neutron-induced defects are field dependent and a study is under way to determine more about the fundamental properties of these defects.

A quasi-tunneling model is being investigated to determine if this model will correctly predict the observed changes induced by neutron bombardment at low and intermediate current levels.

Work is in progress to construct and fit a statistical recombination model to the observed neutron induced base current component in silicon transistors.

TECHNICAL PROGRESS

EXPERIMENTAL MEASURING SYSTEMS

Three experimental systems are being used for data acquisition. The first system is for the measurement and recording of the voltage versus current characteristics of the test devices used in most of the studies being conducted. The second system is used for the measurement and recording of capacitance versus voltage data, and the third system for the measurement of time constants needed for the calculation of lifetimes of minority carriers in the various regions of the p-n junction device.

Automatic Data Acquisition System

The first system is an Automatic Data Acquisition System which was designed and fabricated using both commercially available and especially fabricated special purpose equipments for obtaining the large amount of current versus voltage data required to define the current-voltage characteristics of semiconductor p-n junction devices. This system is capable of making current and voltage measurements with an absolute accuracy of $\pm 1\%$ of reading and a precision (repeatability) of 0.3% of reading in the range from 10^{-10} amperes to 2×10^{-1} amperes (over 9 decades). A block diagram of this system is shown in Figure 1.

The heart of this system is a Control Center^{1,2} which controls the programming, measurement and recording sequence of the system. A signal is sent to the Programmer^{1,2} to program the John Fluke 383B Voltage/Current Calibrator which applies an emitter-base bias to the test device which is mounted in a sample holder contained within a Delta Design MK2310 Temperature Control Chamber. The collector-base bias is supplied by a manually controlled Harrison Labs 865C Power Supply or a digitally controlled John Fluke 383B Voltage/Current Calibrator. The currents are sampled by the Current Sampler^{1,2} whose output is amplified by low noise amplifiers and measured by a Dymec 2401C-M31 Digital Voltmeter. The emitter-base bias voltage is measured by a second Dymec 2401C-M31 Digital Voltmeter. The voltmeter readings are recorded along with resistor identification information (in digital form) supplied by the Autoranging Current Sampler. This information is serialized by a Dymec 2540B Coupler and recorded on a Friden Model SFD Flexowriter in both typewritten

Figure 1. Block diagram of the Automatic Data Acquisition System

form and on punched paper tape. The punched paper tape is converted to IBM punched cards on an IBM 047 Tape-to-Card Converter and the punched cards are processed by an IBM 360-50 Digital Computer. The computer output is the tabulated voltage versus current characteristics.

To increase the flexibility of the system and to shorten the time required to change programming, a paper tape reader-programmer is being added. Since a paper tape reader-programmer capable of performing the desired functions was not available commercially, one has been designed and is being fabricated. The tape reader, a Friden Model STRA, was purchased commercially. The electronics necessary for programming information storage and interface are being fabricated by personnel of the Space Sciences Research Center. The addition of this paper tape reader-programmer will permit the programming of either or both John Fluke 383B Voltage/Current Calibrators while greatly reducing the time required to change from one set of pre-programmed values to another.

The Master's Thesis of Donald Louis Bartling, who aided in the design and fabrication of the special purpose equipments and the integration of the data acquisition system as his thesis project was included as a reprint (COO-1624-1) with the 1967 Progress Report. The paper by Bartling, Jenkins and Goben (IEEE Trans. on Instrumentation and Measurement) describing this data acquisition system is included as a reprint (COO-1624-2) with this report.

As part of this system, the Autoranging Current Sampler, originally designed and fabricated by the principal investigator at Sandia Laboratory, has been much improved and is felt to be patentable. A patent application was prepared and submitted during 1967.

A program has been written for the processing of the output data from the Automatic Data Acquisition System by the IBM 360-50 Computer. This program performs four major functions.

First, computation of device voltages and currents from the input voltage and resistance data with corrections made for the voltage drop across the current sampling element.

Second, interpolation to values of emitter-base voltages which are integral multiples of 10.0 millivolts. This interpolation provides a means of comparing currents and current gains at fixed values of base-emitter voltage.

Third, the applied base-emitter voltage versus base and collector currents and current gain is provided in tabular form together with heading information which includes device identification and measurement conditions.

Fourth, a machine plot (Calcomp Model 566) of input voltages versus logarithm of base current and logarithm of collector current with printed device identification and fluence level, is output for use by the investigators in comparison studies. Each plotted page is a 14 X 10 inch graph of the form $\log(I)$ vs. V_{BE} . This first program will return a plot of the logarithms of I_B and I_C vs. V_{BE} for each device while a second plot program returns one plotted page depicting either $\log(I_C)$ or $\log(I_B)$ vs. V_{BE} curves for as many devices as desired.

The run time for the first plot program is approximately 2½ minutes per device and the run time for the second plot program is approximately 1 minute per device.

Capacitance-Voltage Measuring Systems

It was not possible to buy a commercial capacitance voltage measurement system of the type desired. Consequently, a system was fabricated using a Micro Instruments 1201DS Capacitance Tester, Dymec 2901A and 2902A Master and Slave Scanner/Programmers, a Dymec 2401C-M31 Digital Voltmeter, and a John Fluke 383B Voltage/Current Calibrator for supplying the precise bias voltages needed for the determination of the change in junction capacitance with neutron fluence and bias voltage. The test devices in both systems are mounted in a sample holder which in turn is mounted in a Delta Design MK2310 Temperature Control Chamber. The output medium is a Hewlett-Packard R66-562AR Digital Recorder which records both the Capacitance measured by the Micro Instruments 1201DS Capacitance Bridge and the applied voltage measured by the Dymec 2401C-M31 Digital Voltmeter (See Figure 2 for block diagram). A start command advances the Scanner/Programmers which digitally programs a voltage or current on a John Fluke 383B Voltage/Current Calibrator. This voltage or current is applied to the device under test. A capacitance reading and a voltage reading are taken and recorded on the Hewlett-Packard R66-562AR Digital Recorder. The system recycles automatically until all pre-programmed measurements have been made. The printed output re-

DELTA DESIGN MK 2310

TEMPERATURE CONTROL CHAMBER

Figure 2. Capacitance-voltage measurement system

cord is punched on IBM cards and processed by the IBM 360-50 Digital Computer.

Alternately, when the Data Acquisition System described previously is not being used for voltage-current measurements, the Dymec 2401C-M31 Digital Voltmeters, Dymec 2540B Coupler and Friden SFD Flexowriter may be used as the output medium. For this mode of operation the frequency output (proportional to capacitance) of the Micro Instruments 1201DS Capacitance Bridge is measured by one of the DVM'S in the Data Acquisition System while the other DVM measures the potential applied to the device under test. This information is then serialized by the Dymec 2540B Coupler and output by the Friden SFD Flexowriter on both punched paper tape and typewriter copy. Data processing is accomplished in a similar manner to that described for the Automatic Data Acquisition System. The block diagram of the alternative system for the capacitance-voltage measurements is shown in Figure 3.

To facilitate the inter-connection of the two systems for this alternative mode of operation, a single cable was constructed carrying all data, control and signal lines. When the two systems are used separately shorting plugs are placed over the chassis connectors on the two systems.

Time Constant Measuring Systems

Precise determination of the minority carrier lifetimes in the various regions of the semiconductor p-n junction device are required for the construction of a recombination statistics model for the neutron-induced current component.

Transistor risetime measurements and diode storage time measurements are made using a Tektronix Type 555 Oscilloscope with Tektronix Type R and Type S plug-in units. A Type 1S1 sampling plug-in unit is used to measure the very short risetimes and storage times of the higher frequency devices. This plug-in unit extends the measurement capability of the oscilloscope to one gigahertz.

The Lumatron Electronics Automatic Switching Time Test Set (Model 420), consisting of sampling section, bias power section, control section and test section, can be used for the measurement of risetime, turn on delay, turn on time, fall time, storage time and turn off time. This Test Set is in the process of being checked and

Delta Design MK-2310 Temperature Control Chamber

Figure 3. Capacitance-voltage system block diagram

calibrated.

Delays and Problems

Considerable difficulty was experienced initially in the taking of capacitance-voltage data in that the applied potential had to be taken as the programmed potential and that these applied potentials had to be transcribed by hand and matched to the automatically recorded capacitance data when the Data Acquisition System was in use. This procedure led to mismatching of data and to errors introduced when the applied potential data and typewritten capacitance data were punched onto IBM cards for data reduction. This difficulty was alleviated by the purchase of another Dymec 2401C digital voltmeter and the modification of the digital recorder to accept both the digital capacitance data and the digital voltmeter data and to print both simultaneously.

Another difficulty was experienced in measuring the very short time constants needed for the calculation of lifetimes in high-frequency devices under study. This problem was alleviated by the purchase of a Tektronix Type 1S1 Plug-in unit for the Tektronix 555 Oscilloscope which extended its range to one gigahertz.

EXPERIMENTAL UNITS

In order to make all the necessary measurements to obtain the parameters needed to compute the quantities of basic interest, it was necessary to have special structures fabricated. Special structures of the type used in previous research by the principal investigator and in current research efforts are illustrated in Figure 4.

Test structure 1 is simply a 2N914 silicon planar epitaxial transistor used for measurement of current-voltage characteristics and junction capacitance.

Test structure 2 is a tetrode type transistor which may be used for standard measurements of voltage-current characteristics and junction capacitance, and which, in addition, may be used for resistivity measurements. The transistor may be biased from one base contact to the other to change the potential distribution under the emitter ring and, consequently, to change the voltage-current characteristics.

Test structure 3 is essentially a van der Pauw sample which may be used for determining resistivity, Hall effect constant, mobility, sheet carrier density, and junction capacitance.

All devices were fabricated in the same diffusion run, and the devices fabricated from a given slice of silicon were so identified. All have the same impurity profile and junction depths as the transistor code of interest.

The sheet carrier density, $\bar{N}_A$, majority carrier mobility, μ_n , and base recombination term, β^* , are related to the collector current as indicated previously ³⁻⁴. The sheet carrier density and the mobility may be obtained from Hall effect and sheet resistance by measurement on the special test structures. The behavior of the recombination sites in the space charge region is related to the non-ideal components of base current, and, of course, to the variation of junction capacitance due to the charged recombination sites.

In the present project year special devices were obtained for radiation effects studies. The devices obtained were fabricated from a single wafer (one wafer for each code group) with the impurity profiles and junction depths of the following transistor codes: 2N914, SA7473, SF2523 (ring-dot geometry); 2N918 (bar geometry); and 2N2222 (star geometry); SA9900, SF2524 (double base geometry); and SF2525 (Hall effect geometry).

TEST STRUCTURE 1:
RING-DOT TRANSISTOR

TEST STRUCTURE 2:
DOUBLE-BASE TRANSISTOR

TEST STRUCTURE 3:
HALL EFFECT TRANSISTOR

Figure 4. Test structures to correlate base region parameters with current-voltage characteristics

The manufacturers were Texas Instruments (Dallas) and Motorola (Phoenix).

More of these special devices will be needed in the next project year; in addition, special devices will have to be fabricated experimentally to substantiate the quasi-tunneling model described below. Semiconductor p-n junction devices will be fabricated by normal techniques, on a single wafer of silicon, which will be doped on one half its area with impurities to approximate the concentration, energies, and capture cross-sections of defect centers induced by neutron bombardment and undoped on the other half of its area, and record kept of devices originating from the two halves of the wafer.

STATUS OF EXPERIMENTS

The common base current gain, α , for a p-n junction transistor is given by the expression:

$$\alpha = \gamma \beta^* (\alpha^* M) \quad (1)$$

where:

γ = emitter efficiency

β^* = base recombination term (base transport factor)

α^* = collector efficiency

M = collector multiplication factor

$(\alpha^* M)$ = collector multiplication

The net number of defect levels (recombination sites) is related to the externally measurable electrical parameters. For instance, the relation of the majority carrier mobility, base recombination term and sheet carrier density of majority carriers in the base region to the collector current are demonstrated by the equation

$$I_C = \frac{A_E n_i^2 k T \mu_n \beta^*}{N_a} \exp(qV/kT) \quad (2)$$

where the quantities in the expression have the usual definitions³. Since the mobilities and sheet carrier densities of the other special structures may be obtained from Hall effect and resistivity measurement, one may compute the base recombination term, β^* , from the above expression. At low collector voltages, the collector multiplication is essentially unity, and one may, from gain measurements at low collector voltages, compute the emitter efficiency. This has been done in previously published work by the principal investigator.

Parameters of the Collector-Base Junction

Most of the previous work on collector multiplication, which has been on non-irradiated devices, has ignored the collector efficiency and has been primarily concerned with the collector multiplication factor^{8a-d}. This was possible because the devices chosen for those studies were alloy devices in which the collector efficiency is unity rather than single ended impurity process devices which are now in common use.

The changes in α^* and M can be deduced from a knowledge of the functional dependence of each of the four factors on base to emitter voltage, V_{BE} , collector to base voltage, V_{CB} , and collector current I_C .

In addition to α^* and M , there are other parameters of the collector base junction which should be considered.

Collector Efficiency - α^*

The collector efficiency is very close to unity as long as the concentration of majority carriers entering the collector is negligible compared to the concentration normally there⁷. For the low to intermediate injection levels used in this study, this criterion should be fulfilled. Therefore α^* should not vary with V_{CB} but should vary with V_{BE} and neutron fluence due to changes in current and collector resistivity.

Collector Multiplication Factor - M

The collector multiplication factor is defined^{8a} as the ratio of the number of carriers (either holes or electrons) leaving the collector junction to the number of carriers (of the same type) entering the collector junction. It should be noted that this definition specifically assumes that there is no recombination within the junction. Ionization due to carrier collisions within the junction will cause this ratio to increase with V_{CB} . Therefore M should be an increasing function of V_{CB} . Preliminary data indicate that M is a decreasing function of neutron fluence.

Collector-Base Breakdown Voltage - BV_{CBO}

The collector-base breakdown voltage of the devices used for this study is related primarily to the impurity concentration in the epitaxial layer⁹. The carrier removal rate¹⁰ for electrons in n-type silicon is approximately $2 \text{ neutron}^{-1} \text{ cm}^{-1}$. The initial impurity concentration for the devices used is approximately $5 \times 10^{15} / \text{cm}^3$. Therefore the impurity concentration and thus the breakdown voltage should not change appreciably for neutron fluences below $2.5 \times 10^{14} \text{ nvt}$. The devices under study have been irradiated to a fluence level of approximately $1 \times 10^{14} \text{ nvt}$ and no appreciable change in the breakdown voltage has been observed. Experiments are continuing.

Collector-Emitter Breakdown Voltage- BV_{CEO}

The collector-emitter breakdown voltage is given by the expression:

$$BV_{CEO} = \frac{BV_{CBO}}{(h_{FE}+1)^{1/m}} \quad (3)$$

where m depends on the resistivity and conductivity type of the collector region. For n-type silicon $m = 4$.

The common emitter current gain, h_{FE} , is a decreasing function of neutron fluence⁴. Therefore BV_{CEO} should increase with neutron fluence. This result has been observed in the experiments performed up to a fluence level of 1×10^{14} nvt.

Collector Output Conductance- g_c

The common base characteristics of each experimental device were photographed after each irradiation, using a Tektronix Type 100 camera and a Tektronix Type 575 curve tracer. The output conductance, g_c , is the slope of any member of this family of curves. Figure 5 shows the characteristics of a typical device before irradiation and Figure 6 shows the characteristics of the same device after irradiation to a fluence level of approximately 1×10^{14} nvt. It is apparent from these photographs that the output conductance has increased after irradiation.

This may be explained by Gossick's¹¹ model for neutron damage to crystal lattices. That is, after neutron irradiation, a conduction path is established either across or through the collector base junction, thus increasing the output conductance.

Collector-Base Leakage Current- I_{CBx}

The collector-base leakage current, I_{CBx} , can be obtained by extrapolating the linear portion of the $\log(I_C)$ vs. V_{BE} curve and taking the difference between the measured value of I_C and the extrapolated value of I_C . Figure 7 illustrates this method.

A close examination of Figure 7 reveals that I_{CBx} decreases as V_{BE} is increased and V_{CB} is held constant. The exact mechanism of this anomalous phenomenon is not well understood at this time. However, if one were to postulate that recombination occurs in the collector depletion region, it could be explained. It should be noted that this recombination phenomena appears to exist whether or not

Scale:

6.25 volts/division Horizontal

0.125 ma/division Vertical

Figure 5. Common base characteristics ($\phi = 0$)

Scale:

6.25 volts/division Horizontal

0.125 ma/division Vertical

Figure 6. Common base characteristics ($\phi \approx 10^{14}$ nvt)

Figure 7. Collector current vs. V_{BE} with V_{CB} as a parameter

the p-n junction is subject to neutron bombardment.

Effect of the Collector Junction on the Emitter Efficiency- γ

When a reverse bias is applied to the collector-base junction, the collector-base depletion region widens. As a result, the base width narrows (Early¹² effect), and the concentration gradient of minority carriers in the base increases (for a fixed base-emitter applied bias). The minority carrier current injected into the base will therefore increase and consequently the emitter efficiency will increase.

It can be concluded, then, that the emitter efficiency is an increasing function of V_{CB} whether or not the device is subjected to neutron irradiation.

Effect of the Collector Junction on the Base Transport Factor (Base Recombination Term) - β^*

The Early¹² effect should cause β^* to increase with V_{CB} whether or not the device is subjected to neutron irradiation since, in a narrower base, the transit time will be decreased.

Anomalous Variation of Common Base Current Gain, α , with V_{CB} .

The theory just discussed should lead to the conclusion that α is an increasing function of V_{CB} . Figure 8 shows a plot of α vs. V_{CB} with V_{EB} as a parameter. It should be noted from this figure that for the lower V_{EB} 's, α decreases with V_{CB} initially and then increases.

It is difficult to explain this anomaly in terms of existing theory. However, if one were to postulate that recombination occurred in the collector-base depletion region then another term would have to be added to the definition of α (see Eq. 1) as follows:

$$\alpha = \gamma \beta^* (\alpha^* M) \delta \quad (4)$$

where δ is the collector recombination term.

If δ were a decreasing function of V_{CB} and an increasing function of V_{EB} then the data of Figure 8 would be explainable.

Further work is presently being done to determine or preclude the existence of recombination in the collector-base junction. Note that this recombination phenomena exists before neutron irradiation and would be expected to be enhanced as a result of neutron irradi-

Figure 8. Common base current gain vs. V_{CB} with V_{BE} as a parameter

ation. Experiments to further investigate this phenomena have been initiated.

Base Transport Factor Change at Moderate and High Current Levels

It has been shown that neutron radiation induced current gain degradation of a transistor is due primarily to two simultaneously existing mechanisms^{3,4,13}. These are: (1) the neutron radiation induced degradation of the emitter efficiency and (2) the neutron radiation induced degradation of the base transport factor (base recombination term). In recent work of the principal investigator¹³ it had been postulated that the relative significance of these two mechanisms was a function of injection level, i.e., current level. At low and intermediate levels, overall transistor current gain degradation is dominated by a neutron-induced base current component¹³ (originating in the emitter-base space-charge region) which reduces the emitter efficiency. At moderate and high current levels, the current gain degradation appears to be controlled by neutron-induced recombination in the neutral base region, which shows up as a reduction in the base transport factor (base recombination term)¹³. Both mechanisms are present after neutron irradiation, and show up throughout the range of device operation. However, one or the other will dominate the current gain degradation depending on the operating currents (injection level) of the device.

The neutron dependence of the base transport factor can be examined by considering the base current. Since current gain degradation is manifested in a reduction in collector current due to recombination in the neutral base region, there must be a corresponding increase in base current of a component characterized by a reciprocal slope of kT/q . It must be realized that the magnitude of such a base current component is not equal to the change in collector current, but, in general, the increase in base current will exceed the fall off in collector current. This can qualitatively be understood by considering that recombination in the base region will reduce the carrier density everywhere below the one which is present in the case of no recombination. A fixed emitter to base voltage fixes the carrier concentration at the emitter to base junction and a zero or negative collector voltage keeps the carrier concentration zero at the collector junction. This requires that through recombination the carrier gradient at the collector junction is decreased while it

is increased at the emitter side of the base corresponding to a reduction in the collected current and an increase in the current emitted into the base. The change in base current is equal to the sum of increase in injected current and decrease in collected current.

The relation between increase in base current and fall off in collector current can readily be derived for the two special cases of the uniformly doped base, corresponding to no field in the base region, and of the exponential fall off in impurity concentration, corresponding to uniform electric field in the base.

In both cases the steady state continuity equation has to be solved. This equation is given by:

$$\frac{d^2 n}{dx^2} + \frac{2}{f} \frac{dn}{dx} - \frac{n}{L^2} = 0 \quad (5)$$

where

x = length coordinate

$f = \frac{2kT}{qE}$, E the field in the base

$L = \sqrt{Dt}$, t the minority carrier lifetime

Solving the continuity equation subject to the standard boundary conditions and computing the ratio of increase in the ideal ($n = 1$) component of base current to the decrease in the collector current, one finds the ratio to be 3 for the uniformly doped base region and only slightly larger than unity for the exponentially doped base region.

In doubled diffused transistors, as the ones studied in the present work, part of the base region electric field is retarding while over the remainder of the base, the field is aiding. In general, the resulting transit time is less than the one obtained for the same base with no electric field. This case, therefore, falls between the two extremes evaluated above and one may estimate that the base current component associated with the fall off in collector current will be approximately twice the fall off in collector current.

A computer program has been written to solve the continuity equation in the base region for commonly used impurity gradients in the base region (i.e., single-ended impurity) process devices. Experiments have been set up to measure the needed parameters which cannot be obtained from the manufacturers (or are unknown to them). Good cooperation has been obtained from Texas Instruments (Dallas)

and Motorola (Phoenix) in this area.

Quantitatively, the variation of the base transport factor with neutron fluence can be obtained by examining the variations in the ideal component of base current and in the collector current. Since the base transport factor is assumed to be a major factor at moderate to high current levels this mode of device operation causes complications. First, the detailed voltage-current characteristics in this region are complicated by emission crowding and conductivity modulation effects. This, however, can be analyzed for the case of the ring dot structure used for the 2N914 transistor. Second, in the calculation of current gain, the simplifying assumption that collector efficiency, α^* , and collector multiplication, M , are unity when the device is operated with the base and collector leads at essentially the same potential can no longer be safely made. At moderate current levels the assumption appears to be still valid. However, at high current levels there is reason to suspect that collector efficiency can be greater than unity regardless of whether the device has been irradiated or not. This will require further investigation.

Upon examining the equation¹⁴

$$I_C = \frac{A_E n_i^2 k T \mu_n \beta^*}{N_A} \exp(qV_{BE}/kT) \quad (6)$$

where the quantities in the expression have the usual definitions and the usual assumptions have been made, an important relationship for β^* can be derived⁴.

$$\frac{\beta(\phi)}{\beta(\phi=0)} = \frac{I_C(\phi)}{I_C(\phi=0)} \cdot \frac{N_A(\phi)}{N_A(\phi=0)} \cdot \frac{\mu_n(\phi=0)}{\mu_n(\phi)} \quad (7)$$

This, of course, presupposes that α^* and M are unity, which, as mentioned above, may not always be the case, and care must be exercised in using this expression at high current levels.

Figure 9 displays curves of normalized base recombination term and normalized emitter efficiency versus neutron fluence with V_{BE} (i.e., with current level) as a parameter. This is from previous work of the principal investigator^{3,4} and covers only low to intermediate current levels.

Figure 9. Ratios of emitter efficiencies and base transport factor vs. ϕ .

This data is replotted in Figure 10 to show normalized base transport factor and normalized emitter efficiency vs. V_{BE} with fluence as a parameter. This clearly shows that the neutron induced degradation of the emitter efficiency is a function of current level. It also shows that the neutron induced degradation of the base transport factor is definitely not a function of current level.

With our data and our previous experience as a basis we are able to make the following statements: (1) the neutron-induced degradation of emitter efficiency tends to decrease to within some constant value with increasing current levels, (2) since the neutron-induced degradation of the base transport factor is essentially constant with respect to current level, at moderate current levels it becomes comparable to the neutron-induced degradation of the emitter efficiency and at high current level can exceed it. The variation with V_{BE} (with neutron fluence as a parameter) as predicted by our theory is shown in Figure 11 and indicates the expected tendencies at higher fluence levels and higher current densities.

Annealing Characteristics in Neutron Bombarded Transistors

Annealing work has been done using a combination of isothermal and isochronal annealing techniques rather than the single long-time annealing used by the principal investigator^{3,4} when the anomalous annealing behavior of neutron bombarded devices was first discovered. Using these annealing techniques enables one to study the annealing in small increments and to compare the current-voltage characteristics after annealing with previously obtained voltage-current characteristics during the series of irradiations up to the maximum fluence level. This enables one to better study and better understand the anomalous annealing behavior reported by the principal investigator.

In order to insure accurately known annealing times, the time required to stabilize the device at the annealing temperature, and the time required to cool the device out of the annealing range at the end of the annealing run, should be as short as possible compared to the total annealing run time. This was accomplished by an oil bath which was held at a constant temperature, so that the devices could be inserted and withdrawn from the bath very quickly and cooled in a low temperature bath. An aluminum container for the oil bath has been

Figure 10. Ratios of emitter efficiencies and base transport factors vs. V_{BE}

Figure 11. Base transport factor and emitter efficiency vs. V_{BE}

fabricated and special oils (polyphenyl ether and polymethyl phenyl silicone) were used. Two types of oil are needed in order to cover the required annealing temperature range without the oil decomposing. Data obtained in this study were published in a paper by Chott and Goban¹⁵ (COO-1624-4) and is included as a reprint with this report.

From a detailed study of the annealing characteristics of neutron-induced defects in semiconductor devices, it has been shown that the neutron-induced defects in the neutral base region do anneal to a much greater degree than those same defects in the space-charge region. This was a preliminary conclusion reported previously by Goban^{3,4}.

It has been shown that the origin of these defects can be attributed to one or both of the following mechanisms: a quasi-tunneling phenomena or a dependence of the neutron-induced defects on the p-n junction field. The defects have been shown to exhibit a field dependency both in their origin and in their annealing.

The quasi-tunneling recombination phenomena has been shown to be theoretically plausible, but experiments verifying this phenomena could not be conducted at the present time.

Additionally, close examination of the annealing characteristic curve for both neutron-induced defects in the space-charge region and those in the neutral region reveal no annealing step. A gradual annealing of these defects has been indicated.

Variation of Inverse Current Gain with Neutron Fluence

A study of the inverse characteristics of semiconductor devices has been started. This work is following the general outline of that done earlier by the principal investigator^{3,4,5,13} except that the device is being operated in the inverse direction. This allows the study of a relatively wide depletion region of the collector-base junction which is now serving as the inverse emitter-base junction. This allows the study of the anomalous base current component in a relatively wide region and one may attempt to correlate the dependence of this current component to the width of the space-charge region and, hence, determine more accurately the behavior and introduction rate of this neutron-induced current component.

The data show that upon neutron irradiation the base current increases considerably and the slope changes. With increasing

irradiation the increasing base current becomes more linear over the range shown and fits a straight line whose slope is 90 mV/decade. A slope of 90 mV/decade has been stated previously to correspond to a voltage dependent current proportional to $\exp(qV/nkT)$ where $n \approx 1.5$. A comparison of the inverse base currents at an emitter-to-base voltage of 0.5 volts shows that when $\phi = 0$, $I_B = 3.84 \times 10^{-5}$ amperes and when $\phi = 7.5 \times 10^{14}$ n/cm², $I_B = 1.52 \times 10^{-3}$ amperes. Thus the base current has increased by a factor of about 39 times its pre-irradiation value. This increase is even larger at the lower voltages. Thus, the base current for the inverse case is seen to contain an anomalous component of base current similar to that for the forward case and has the same exponential voltage dependence as found by Goben^{3,4,5,13}. This anomalous component of inverse base current is seen to dominate the base current over a wide range of current levels. Also, the increase of inverse base current upon neutron irradiation is larger than the increase in base current for the forward case. It should be pointed out that this special device was more sensitive to neutron irradiation than a standard 2N914 transistor when both are operated in the inverse condition due to the afore-mentioned gold doping in the base of the latter. But a comparison of the same 2N914 transistor for the same neutron fluence level showed that the increase of base current, upon irradiation, for the forward case was about an order of magnitude above the pre-irradiated case while the increase of base current for the inverse case was about 16 times the pre-irradiation value. The increase in base current is, therefore, greater in the inverse configuration than in the normal or forward case as expected on theoretical grounds.

A study of the increase in inverse base current with neutron fluence was performed in a manner similar to that used by Goben in order to find a relation between neutron fluence and the increase in base current. The analytical relation found by Goben^{3,4,5,13} is

$$I_{B_{INC}} = K_1 \cdot A_E \cdot \phi \cdot \exp(qV/nkT), \quad (8)$$

where $n \approx 1.5$, A_E is the emitter area, ϕ is the neutron fluence, V is the applied emitter-to-base voltage, and K_1 is a damage constant equal to 3.33×10^{-22} (amperes/cm²)/(neutrons/cm²). Note that the variation

with fluence is area dependent. Since this is a recombination process, a volume dependence rather than an area dependence would be expected. It was pointed out, however, that as the applied bias increases from 0.1 volt to 1.0 volt, the depletion layer width and, hence, volume changed only by a factor of three; the term $\exp(qV/nkT)$ changed by about 30,000,000.

However, recombination is a volume process and even surface recombination requires a finite volume. Previous work has shown that the neutron-induced $n \approx 1.5$ component of base current originates in the bulk space-charge region of the emitter-base junction and should, therefore, be dependent on the volume of that region. Examination of Equation (8) reveals that a volume dependence could result by proper interpretation of the constant, K_1 . If the constant K_1 can be expressed in terms of another constant, K_v , times the emitter-base depletion-layer width, X_{mE} , then Equation (8) would be volume dependent as expected, where X_{mE} times A_E would be the volume of the emitter-base depletion region. The data do not yet permit a final conclusion to be drawn in this area.

It should be noted that in conjunction with the quasi-tunneling model discussed later that the bending of the band edges in the collector-base junction is not so steep as in the emitter-base junction (for double-diffused devices) and thus a study of the inverse characteristics may lend some insight into the quasi-tunneling model.

Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration

Using the inverse characteristics of a 2N914 silicon planar epitaxial transistor (i.e. with the emitter functioning as a collector and the collector functioning as an emitter) the bulk space charge region of the new "emitter-base" junction is increased by a factor of approximately 26.5 times that of the normal emitter-base junction, thus making it easier to investigate the effects of neutron radiation on the space charge region.

Experiments, using reverse biasing of the new "emitter-base" junction during neutron irradiation to further increase the depletion layer width have been performed.

Surface effects have been observed (an inversion layer adjacent to the "emitter-base" junction) which cause the base current to in-

crease by a factor of 5 to 10 in the low voltage region and the "emitter-base" junction capacitance to increase by a factor of approximately 2 at a fluence level of 10^{14} nvt. The "emitter-base" junction was reverse biased at 3.0V during irradiation in this experiment.

A computer program using least-squares fitting technique has been used to estimate the value of the internal built-in voltage (diffusion potential), V_T , by using the measured data of junction capacitance versus externally applied voltage. The decrease in internal built-in voltage of the "emitter-base" junction has been derived theoretically and also observed experimentally after irradiation. The internal built-in voltage increases towards its preirradiation value after both isochronal and isothermal annealing.

For the annealing studies, pairs of devices with nearly identical characteristics (characteristics matched with 10 per cent) have been used with one device used for isothermal annealing and the other for isochronal annealing. One pair of devices was forward biased at 0.5V and the second pair of devices was reversed biased at 3.0V. The third pair of devices was unbiased during both isothermal and isochronal annealing. Activation energies of (0.19 ± 0.02) eV, (0.34 ± 0.03) eV, (0.86 ± 0.09) eV and (0.98 ± 0.1) eV have been calculated from these isochronal and isothermal annealing data which reaffirm previously calculated values^{16,17}.

Reverse annealing of defects in the bulk space charge region, as represented by changes in the base current, have been observed during isothermal annealing at temperatures between 50°C and 100°C. No reverse annealing of defects in the neutral base region, as represented by changes in the collector current, has been observed.

In order to insure accurately known annealing times, the time required to stabilize the device at the annealing temperature, and the time required to cool the device out of the annealing range at the end of the annealing, should be as short as possible compared to the total annealing time. This was accomplished by an oil bath which is held at a constant temperature with the devices inserted and withdrawn from the bath very quickly and cooled in a low temperature bath. An aluminum container for the oil bath has been fabricated and special oils (polymethyl phenyl silicone fluids) have been used. Two types of this oil have been used in order to cover the required annealing temperature range without decomposing the oil.

Field Dependence of Radiation Induced Defects

A study of the effect of bias during irradiation has been started and indicates that the damage constant, K_1 , see Equation (8), is a function of bias applied to the junction during irradiation. A forward bias produces a smaller value of K_1 than does zero bias, which in turn produces a smaller value of K_1 than does a reverse bias.

The diffusion potential, V_T , was found to decrease with neutron fluence and the junction capacitance was found to increase. This change can be related to physical changes in the junction depletion region through,

$$C = \frac{A_E \epsilon_r \epsilon_o}{d} \quad (9)$$

Equation (9) gives the junction capacitance, C , as a function of the junction area, A , the depletion layer width, d , and the permittivity.

The equation,

$$C = \frac{K}{(-V + V_T)^{1/m}} \quad (10)$$

gives the junction capacitance, C , as a function of: K , which is a material constant; m , which is related to the type of junction and assumes the values of 2 for a step junction and 3 for a linearly graded junction; V_T , the diffusion potential; and V , the applied voltage during measurement.

Computer programs have been written using Equations (9) and (10) to calculate V_T , K , m , and d as a function of neutron fluence and applied bias.

For the junction reverse biased during irradiation an increasing dominance of a component of base current which has a reciprocal slope term of approximately 2 was observed. This may be due to a channel; measurements are being taken to determine the origin of this current component.

A more detailed study is being carried out to determine the damage constant, K_1 , as a function of applied bias during neutron irradiation. The junction capacitance as a function of bias voltage is being measured to determine possible causes for the observed

changes in V_T and K_1 . From these measurements it may be possible to gain some knowledge of the fundamental nature of the neutron-induced defects.

Quasi-tunneling Recombination Model

The reason for the large increase in recombination in the emitter-base space charge region which dominates the transistor current gain at low and intermediate current levels has previously been unexplained.

A model has been conceived in an attempt to explain this neutron-induced phenomena. This model assumes that a quasi-tunneling recombination transition takes place in the emitter-base space charge region. The model here presented assumes that an electron from the conduction band, when in the transition region, drops (energetically) to the neutron-induced recombination center in the band gap. Then, rather than dropping directly on to the valence band (or equivalently a hole from the valence band moving directly up to the recombination center to recombine with the electron), the electron tunnels (with no change in energy) to the valence band (or equivalently, a hole tunnels, with no change in energy, to the recombination site and recombines with the electron), thus inducing the observed large (and previously inexplicable) neutron-induced component of base current.

Preliminary calculations have been made to show that this model is plausible and possible from the known warping or curvature of the conduction and valence band edges in the emitter-base transition region of a semiconductor p-n junction and using the Boltzmann tail of the probability distribution function and the energy level differences as activation energies. These calculations indicate that quasi-tunneling phenomena of the type postulated in the emitter-base space charge region is 3 to 4 orders of magnitude more likely to occur than a "normal" conduction band to valence band recombination transition via a recombination center.

Calculations have been made using the device parameters of the 2N914 transistor to determine whether this tunneling can occur¹⁸. In an unbiased device, the distance that an electron would have to tunnel from the neutron-induced defect level to the valence band is some fraction of 200 Å. These calculations imply that this tunneling distance would increase slightly under forward bias.

It is well known that the tunneling distance in a tunnel diode is on the order of 100 Å. It would appear, then, that it is possible for an electron to tunnel from the neutron-induced defect level to the valence band. Figure 12 shows a schematic diagram of the quasi-tunneling recombination phenomena.

If the concentrations, capture cross sections, and energies of the neutron-induced defect centers are known, a device could be doped to simulate a device after neutron irradiation. Such a device could be used to substantiate the quasi-tunneling phenomena.

Detailed calculations will be made to replace the crude "order of magnitude" calculations and more accurate measurements made to determine needed parameters.

Special devices will have to be fabricated to experimentally substantiate this model. Semiconductor p-n junction devices may be fabricated by normal techniques on the single wafer of silicon which is doped on one half its area with impurities to approximate the concentrations, energies and capture cross-sections of defect centers induced by neutron bombardment and undoped on the other half of the wafer and records kept on devices originating on the two halves of the wafer.

Comparison of current-voltage characteristics measured on devices from the doped half of the wafer may be compared with measurements on semiconductor devices from the undoped half of the wafer before and after neutron bombardment of this undoped devices to substantiate the model presented.

Recombination Statistics for the Neutron-Induced Current Component

A search for a recombination statistical model for the reciprocal slope term has been started. In order to construct the model, it will be necessary to determine the minority carrier lifetimes, the capture cross-sections for holes and electrons, the density of neutron-induced defect levels, and the energies of these defect levels.

It has been shown¹⁹ that the dependence of the collector current of a transistor at constant bias on the activation energy of the defect can be expressed as

$$I_C = K \cdot T \cdot \exp(-E_R/kT), \quad (11)$$

UNBIASED EMITTER BASE JUNCTION REGION IN 2N914 NPN TRANSISTOR

Figure 12. Schematic diagram of quasi-tunneling recombination phenomena.

where: K = proportionality constant (amperes/ $^{\circ}\text{K}$)

T = temperature ($^{\circ}\text{K}$)

E_R = activation energy (eV)

k = Boltzmann constant (8.63×10^{-5} eV/ $^{\circ}\text{K}$).

The Automatic Data Acquisition System was used to obtain $\log(I_C)$ vs. V_{BE} for a specified temperature and repeated for other specified temperatures. Finally, $\log(I_C)$ vs. $10^3/T$ is plotted by machine (Calcomp Model 556 Plotter). If one chooses 10°C increments in temperatures, Equation (11) can be rewritten, for $T > 200^{\circ}\text{K}$, after some algebra, as²⁴

$$E_R = 0.1987 \cdot ms - 0.021 \text{ (eV)}, \quad (12)$$

where ms is the slope of the plotted curve.

This is the equation employed throughout this work to obtain the activation energy, E_R , which is required for the statistical model. The activation energy of 0.35 ± 0.04 eV inferred for this process is similar to that reported^{20,21} for neutral vacancy and interstitial annealing.

Transistor risetime measurements and diode storage time measurements have been made using Tektronix 555 Oscilloscope with Tektronix Type R risetime, Type S recovery-time and Type 1S1 plug-in units. From the measured time constants associated with the p-n junction devices, the minority carrier lifetimes in base and collector regions, τ_B and τ_C , of the transistor have been calculated. These lifetimes vary with neutron fluence as

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_{\tau} \phi, \quad (13)$$

where; τ_0 = pre-irradiated lifetime

τ = post-irradiated lifetime

K_{τ} = lifetime damage factor

ϕ = neutron fluence.

Using the least-squares fit for the measured data, the values for K_{τ} have been found as 1.8×10^{-7} to 2.7×10^{-7} for τ_B and 1.1×10^{-8} ($\text{cm}^2/\text{neutron-sec}$) for τ_C .

The dependence of the variation of the junction depletion layer width on the ionized impurity concentration at the edge of the de-

pletion layer is the basis for the determination of the impurity concentration. Hilibrand and Gold¹⁴ have developed a method for the determination of the impurity concentration in p-n junction diodes from capacitance-voltage measurements. The outline of that method is summarized as:

(a) Measure Capacitance vs. Voltage. Six voltage capacitance points at one or two per cent intervals in capacitance are made. It is assumed for purposes of calculation that the capacitance is given by

$$C = \frac{K}{(-V+V_T)^{1/m}} \quad (14)$$

(b) A computer program written in Fortran IV language was employed: to estimate the constants K , V_T and m in Equation (14); to calculate the average voltage $V_a = \sum_{i=1}^6 V_i / 6$, where the V_i are the 6 voltages used in getting the six voltage-capacitance points; to calculate the average capacitance, C_a , from Equation (14) using estimated K , V_T and m , and calculated V_a .

(c) It has been shown that²² the impurity density for "one-sided" junctions, N_T , is given by

$$N_T = \frac{K^2}{A^2 q \epsilon n} (-V_a + V_T)^{1-2m} \quad (15)$$

and that the location of the edge of the depletion layer, i.e., the total depletion layer width for the applied bias of V_a , is

$$x_m = \frac{A \epsilon}{C_a}$$

(d) The work of Lawrence and Warner²³ is used in obtaining x_1/x_m , where x_1 is the width of the depletion layer in the more heavily doped side of the diffused junction. By use of the values of x_1/x_m , N_T , and the correction factors prepared by Hilibrand and Gold²² (Chow has prepared a more complete table of these correction factors for this work²⁴) the impurity profile can be determined. The computer program for the impurity profile is being written now and the desired outputs will be obtained soon. The method employed for the determin-

ation of impurity profiles are used repeatedly for different levels of neutron fluence. The change in impurity concentration is formulated as

$$\Delta N = N_0 (1 - e^{-\phi/K_N}) \quad (17)$$

where N_0 = the pre-irradiated impurity density

ϕ = neutron fluence

K_N = carrier removal coefficient

From the value ΔN , one can obtain the concentration of the defect levels, N_R .

From Shockley-Read-Hall Statistics^{25,26,27}, it has been proven that²⁴

$$\tau_C \approx \tau_{pr} [1 + \exp((E_R - E_F)/kT)] \quad (18)$$

$$\tau_B \approx \tau_{nr} + \tau_{pr} \exp((E_R + E_F - 2E_i)/kT) \quad (19)$$

Knowing τ_B , τ_C , E_R , E_i , and E_F , the limiting lifetimes, τ_{pr} and τ_{nr} , are obtainable. The capture cross-sections for holes and electron will be calculated from

$$\tau_{pr} = \frac{1}{N_R C_p} \quad (20)$$

$$\tau_{nr} = \frac{1}{N_R C_n} \quad (21)$$

The values of C_p and C_n differ because of differences in the effective mass values for holes and electrons. All the previously mentioned parameters are now or will shortly be available. In the "fitting," a statistical model will be assumed. A computer program for statistical testing using Fortran IV language has been found and will be used to test the hypothesis. If the model fitted is rejected, then a higher order model will be assumed and the same procedure will be used to test "the lack of fit" until the model is true and is one which can be used as the predicting statistical model. The dependence of the neutron-induced base current component on the above mentioned transistor parameters can be predicted by the fitted model.

BIBLIOGRAPHY

1. Bartling, D. L., "An Automatic Data Acquisition System for Semiconductor Device Testing," M.S. Thesis, University of Missouri Library, Rolla, Missouri, 1967.
2. Bartling, D. L., Jenkins, C. R. and Goben, C. A., "An Automatic Data Acquisition System for Semiconductor Device Testing," IEEE Trans. on Instrumentation and Measurement. To be published March, 1968.
3. Goben, C. A. and Smits, F. M., "Anomalous Base Current Component in Neutron Irradiated Transistors," IEEE Radiation Effects Conference, Seattle, Washington, 1964.
4. Goben, C. A., "Neutron Bombardment Reduction of Transistor Current Gain," Ph.D. Dissertation, Iowa State University Library, Ames, Iowa, 1965.
5. Goben, C. A., "A Study of the Neutron-Induced Base Current Component in Silicon Transistors," IEEE Radiation Effects Conference, Ann Arbor, Michigan, 1965. IEEE Trans. on Nuclear Science, NS-12, 5, pp. 134-146, 1965.
6. Phillips, A. B., Transistor Engineering, p. 161, New York, McGraw-Hill, 1962.
7. Phillips, A. B., Transistor Engineering, pp. 184-185, New York, McGraw-Hill, 1962.
- 8a. McKay, K. G., "Avalanche Breakdown in Silicon," Physics Review, 94, 4, pp. 877-884, May, 1954.
- 8b. McKay, K. G. and McAfee, K. B., "Electron Multiplication in Silicon and Germanium," Physical Review, 91, 5, pp. 1079-1084, 1953.
- 8c. Miller, S. L., "Avalanche Breakdown in Germanium," Physical Review, 99, 4, pp. 1234-1241, 1955.
- 8d. Miller, S. L., "Ionization Rates for Holes and Electrons in Silicon," Physical Review, 105, 4, pp. 1246-1249, 1957.
9. Phillips, A. B., Transistor Engineering, pp. 138-139, New York, McGraw-Hill, 1962.
10. Bass, R. F., "Influence of Impurities on Carrier Removal and Annealing in Neutron Irradiated Silicon," IEEE Trans. on Nuclear Science, NS-14, 6, pp. 78-81, 1967.
11. Gossick, B. R., "Disordered Regions in Semiconductors Bombarded by Fast Neutrons," J. App. Phys., 30, pp. 1214-1218, 1959.

12. Early, J. M., "Effects of Space Charge Layer Widening in Junction Transistors," Proc. IRE, 40, 6, pp. 1401-1406, 1952.
13. Goben, C. A., Smits, F. M. and Wirth, J. L., "Neutron Radiation Damage in Silicon Transistors," IEEE Trans. on Nuclear Science. To be published April, 1968.
14. Moll, J. L. and Ross, I. M., "The Dependence of Transistor Parameters on the Distribution of Base Layer Resistivity," Proc. IRE, 44, 1, pp. 72-78, 1956.
15. Chott, J. R. and Goben, C. A., "Annealing Characteristics of Neutron Irradiated Silicon Transistors," IEEE Trans. on Nuclear Science, NS-14, 6, pp. 134-146, 1967.
16. Hasiggati, R. R., and Ishino, S., "Defect Mobility and Annealing in Irradiated Germanium and Silicon," 7th International Conference on the Physics of Semiconductors, Radiation Damage in Semiconductors, Academic Press, New York and London, pp. 259-273, 1964.
17. Davoust-Saltiel, E., and Baruch, P., "Drift Mobility of Radiation Induced Defects in Silicon," 7th International Conference on the Physics of Semiconductors, Radiation Damage in Semiconductors, Academic Press, New York and London, pp. 275-280, 1964.
18. Chott, J. R., "Annealing Characteristics of Neutron Irradiated Silicon Transistors," M.S. Thesis, University of Missouri Library, Rolla, Missouri, 1967.
19. Meechan, E. J. and Brinkman, J. A., "Electrical Resistivity Study of Lattice Defects Introduced in Copper by 1.25-Mev Electron Irradiated at 80°K," Phys. Rev., 103, 5, pp. 1193-1202, 1956.
20. Stein, H. J. and Vook, F. L., "Transient Radiation Defects," Sandia Corp., SC-R-67-1048, March, 1967.
21. Sander, H. H. and Gregory, B. L., "Transient Annealing in Semiconductor Devices Following Pulsed Neutron Irradiation," IEEE Trans. on Nuclear Science, NS-13, 6, pp. 53-62, 1966.
22. Hilibrand, J. and Gold, R. D., "Determination of the Impurity Distribution in Junction Diodes from Capacitance-Voltage Measurements," RCA Review, 21, pp. 245-252, 1960.
23. Lawrence, H. and Warner, R. M., "Diffused Junction Depletion Layer Calculations," Bell System, Tech. J., 39, pp. 389-604, 1960.
24. Chow, M. C., Unpublished Ph.D. Research, University of Missouri, Rolla, Missouri, 1968.
25. Shockley, W., "The Theory of p-n Junctions in Semiconductors and p-n Junction Devices," Bell System Tech. J., 28, pp. 435-589, 1949.

26. Sah, C. T., Noyce, R. M., and Shockley, W., "Carrier Generation and Recombination in p-n Junctions and p-n Junction Characteristics," Proc. IRE, 45, pp. 1228-1243, 1957.
27. Shockley, W. and Read, W. T., "Statistics of the Recombination of Holes and Electrons," Phys. Rev., 87, pp. 835-842, 1952.

DEVIATIONS

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

There was a deviation in the equipment purchased in that it was necessary to purchase a Dymec 2401C-M31 Digital Voltmeter and a Tektronic Type 1S1 Plug-in unit which were not called out in the contract.

The level of expenditures of Atomic Energy Commission fund will not exceed that called out in the contract, so these deviations are not felt to be significant.

PUBLICATIONS

Bartling, D. L., "An Automatic Data Acquisition System for Semiconductor Device Testing," M.S. Thesis, University of Missouri Library, Rolla, Missouri, 1967. (COO-1624-1)

Bartling, D. L., Jenkins, C. R. and Goben, C. A., "An Automatic Data Acquisition System for Semiconductor Device Testing," IEEE Trans. on Instrumentation and Measurement, to be published March, 1968. (COO-1624-2)

Chott, J. R. and Goben, C. A., "Annealing Characteristics of Neutron Irradiated Silicon Transistors," IEEE Trans. on Nuclear Science, Vol. NS-14, No. 6, pp. 134-136, December, 1967. (COO-1624-4)

Chott, J. R., "Annealing Characteristics of Neutron Irradiated Silicon Transistors," M.S. Thesis, University of Missouri Library, Rolla, Missouri, 1967. (COO-1624-6)

To Be Submitted for Presentation at 1968 IEEE Nuclear and Space Radiation Effects Conference:

Beckmann, T. D. and Goben, C. A., "Neutron Dependence of Collector Junction Parameters." (COO-1624-3)

Gassner, G. E. and Goben, C. A., "Variation of the Inverse Parameters with Neutron Irradiation in Silicon Transistors." (COO-1624-5)

Chow, M. C. and Goben, C. A., "Recombination Statistics for the Neutron Induced Current Component." (COO-1624-7)

Su, L. S. and Goben, C. A., "Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration." (COO-1624-8)

Johnson, P. E. and Goblen, C. A., "Field Dependence of Neutron-Induced Defects in Silicon p-n Junctions." (COO-1624-9)

Bereisa, J., Jr. and Goblen, C. A., "Neutron Dependence of Neutral Base Region Recombination at Moderate to High Current Levels." (COO-1624-10)

Presentations:

Goben, C. A., "An Automatic Data Acquisition System for Semiconductor Device Testing," Meeting of the Missouri Academy of Science, Rolla, Missouri, April, 1967. Trans. of the Missouri Academy of Science, 1, pp. 86-87, 1967.

Chott, J. R., "Annealing Characteristics of Neutron Irradiated Silicon Transistors," IEEE Nuclear and Space Radiation Effects Conference, Columbus, Ohio, July, 1967.

Patent Applications:

A patent application was prepared on an Autoranging Current Sampler in 1967.

PERSONNELProject Director:

Dr. Charles A. Goben, Associate Professor of Nuclear Engineering and Senior Investigator of Space Sciences Research Center, University of Missouri, Rolla.

66 2/3% time, academic year; 100% time, summer.

Graduate Research Assistants:

<u>Name</u>	<u>Degree/Background</u>	<u>Dept. & Degree Sought</u>
T. D. Beckmann	BS/EE, 1963, Univ. of Mo. School of Mines and Metallurgy. Mo. Research Laboratory, 1963-64; Atlas Tool and Mfg. Co., 1964-65; Graduate Research Asst., June, 1966-May, 1968, Univ. of Mo., Rolla.	MS/EE+
J. Bereisa Jr.	BS/EE, 1967, Univ. of Mo., Rolla. Western Electric Co.-Summers 1965, 1966; Collins Radio Co.-Engineer in Data Systems Division R&D-Summer 1967; Graduate Research Asst., Space Sciences Research Center, Univ. of Mo., Sept., 1967-June, 1968.	MS/EE
J. R. Chott	BS/EE, 1966, Univ. of Mo., Rolla. MS/EE, 1967, Univ. of Mo., Rolla. Mc Donnell Aircraft Corp., Work Study Program, 1961-65 (27 months on job). Graduate Research Asst., June 1966-July, 1967. Univ. of Mo., Rolla; now employed by Mc Donnell-Douglas Aircraft Corp.	*
M. C. Chow	BS/EE, 1960, National Taiwan Univ; MS/EE, 1966, Univ. of Mo., Rolla. Instructor of Sr. High School, 1961-64; Graduate Teaching Asst., 1965-66 Univ. of Mo., Rolla; Graduate Research Asst., Space Sciences Research Center, Univ. of Mo., Rolla, Sept., 1966-May, 1968.	Ph.D/EE

Graduate Research Assistants (cont.)

G. E. Gassner	BS/EE, Univ. of Mo., Rolla.	MS/EE++
	Graduate Asst., 1964-65, Univ. of Mo., Rolla; Engineer in Electrical Sect., Sverdrup & Parcel and Assoc., Consultant Engineers, Summer 1965, Electronic Engineer, U.S. Army Strategic Communications Command, Summer 1966, Graduate Research Asst., Electronics Research Center, Dec., 1966-July 1967. Now on active duty, U.S. Army.	
P. E. Johnson	BS/MET-NE, L967, Univ. of Mo., Rolla.	MS/MET
	Summers 1962, 1963, 1964, 1965, 1966-Laboratory Technician; Alco Value Co., St. Louis, Mo. Graduate Research Assistant, Space Sciences Research Center, Univ. of Mo., Rolla, June 1967-May 1968.	
L. S. Su	BS/EE, 1965, National Taiwan Univ.	MS/EE
	Chief of Military Radio Station, Kinmen, Taiwan, 1966; Graduate Research Asst., Space Sciences Research Center, Univ. of Mo., Rolla, Dec., 1966-January, 1968.	

* Graduated

+ No longer on payroll

++Called to Active Duty, United States Army

Research Technician

C. R. Jenkins	A.S., Electronic Engineering Technology, 1963 Central Technical Institute; Instructor, 1956-57, Intermediate Speed Radio Operator School, Baumholder, Germany (U.S. Army); Service Technician, 1959-61; Staff Assistant, 1963-66, Sandia Corp; Electronic Research Technologist, 1966-68, Univ. of Mo., Rolla.
---------------	--

Publication

Jenkins, C. R., "Passive Temperature Monitoring in a Radiation Environment," SC-TM-66-282, Sandia Corp., 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. To be published in March, 1968.