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PROGRESS REPORT

MASTER

NUCLEAR RADIATION EFFECTS ON SILICON P-N JUNCTIONS

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PROGRESS REPORT

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NUCLEAR RADIATION EFFECTS
ON
SILICON P-N JUNCTIONS

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Date February 17, 1967

ABSTRACT

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

A technique for separating the collector multiplication term into its two components, collector efficiency and collector multiplication factor has been developed. Combined with the technique presented by the principal investigator in 1964 for separating the emitter efficiency and base recombination term at low collector voltage and low and intermediate collector currents one now can for the first time study individually each of the four fundamental parameters (emitter efficiency, base recombination term, collector efficiency and collector multiplication factor) making up the common base transistor current gain as functions of neutron fluence at high collector currents and voltages.

In the high current level regime, that is to say, during and after the onset of conductivity modulation, a bulk recombination phenomenon in the neutral base region is predicted and observed to account for the degradation of transistor current gain. This phenomenon is being investigated.

A study is being made of the behavior of the inverse current gain under neutron bombardment in an attempt to learn more about the anomalous behavior reported by the principal investigator.

Work is in process in examining the anomalous annealing effect of the neutron-induced recombination center in the emitter-base space charge region, the collector-base space charge region and the neutral region through isochronal annealing techniques.

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

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

The work is somewhat behind the schedule contemplated because of delays in delivery and debugging problems.

TECHNICAL PROGRESS

EXPERIMENTAL MEASURING SYSTEMS

Three experimental systems are being used for data acquisition. One 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 other two systems are used for the measurement and recording of capacitance versus voltage data and 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 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 for 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 of 10^{-10} amperes to 2×10^{-1} amperes (over 9 decades).

The heart of the first system is a Control Center¹ which controls the programming, measurement and recording sequence of the system. A signal is sent to the Programmer¹ 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 with a Delta Design MK2310 Temperature Control Chamber. The collector-base bias is supplied by a manually controlled Harrison Labs 865C Power Supply. The currents are sampled by the Current Sampler¹ whose output is amplified by low noise amplifiers and measured by a Dymec

FIGURE 1. SYSTEM BLOCK DIAGRAM

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 from the Current Sampler. This information is serialized by a Dymec 2540B Coupler and recorded on a Friden Model SFD Flexowriter in both typewritten 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 360-40 Digital Computer. The computer output is the tabulated voltage versus current characteristics.

The Master's Thesis of Donald Louis Bartling, who aided in the design and fabrication in the special purpose equipments and the integration of the data acquisition system as his thesis project is included as a reprint with this report.) not
here

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 is being prepared for submission later this year.

A program has been written for the processing of the output data from the Automatic Data Acquisition System by the IBM 360-40 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 voltage 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 punched card output of input voltages, logarithm of base current, logarithm of collector current and device identification is provided for use with another program in obtaining machine plots of the voltage versus current characteristics.

The punched card output of the main program is used as data for either of two plot programs. The plotter presently being used is a Calcomp Model 566 plotter which is connected to an IBM 1620 Model I Computer.

Each plot program will return a 14X10 inch graph of the form $\log I$ vs. V_{be} . This first program will return a plot of I_b and I_c vs. V_{be} for each device while the second plot program returns one plot depicting either I_c or I_b vs. V_{be} for as many devices as desired.

The run time for plot program number one is approximately 2 1/2 minutes per device; and the run time for plot program number two 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 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,

or alternately when the system previously described is not tied up with voltage-current measurements, the Dymec 2401C-M31 Digital Voltmeters, Dymec 2540B Coupler and Friden SFD Flexowriter may be used as the output medium. The block diagrams of the two alternative systems for the capacitance-voltage measurements are shown in Figures 2 and 3. When the major system is in use, it is necessary to manually record the applied bias in the capacitance voltage measurement system since the recorder can handle only one input.

In the first capacitance measuring system, a start command advances the scanner/programmer 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 is taken and recorded on a Hewlett-Packard R66-562AR Digital Recorder and the applied voltage is manually recorded. The printed and written output records are punched on to IBM cards and processed by the IBM 360-40 Digital Computer.

The capacitance bridge provides also an output frequency proportional to capacitance. In the alternative system this frequency is determined by a Dymec 2401C-M31 Digital Voltmeter. The bias voltage applied to the junction of the test device is also measured by a Dymec 2540B Coupler and recorded on the Friden Model SFD Flexowriter. Data processing is accomplished in a similar manner to that described for the Automatic Data Acquisition System.

Time Constant Measuring Systems

Precise determination of the minority carrier lifetimes in this 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 will be made using a Tektronix 555 Oscilloscope with Tektronix Type R and Type

DELTA DESIGN MK 2310

TEMPERATURE CONTROL CHAMBER

FIGURE 2 CAPACITANCE-VOLTAGE MEASUREMENT SYSTEM

Delta Design MK-2310 Temperature Control Chamber

FIGURE 3 CAPACITANCE-VOLTAGE SYSTEM BLOCK DIAGRAM

S plug-in units.

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 measurements rise time, turn on delay, turn on time, fall time, storage time and turn off time. This Test Set is the property of the Materials Research Center and will require some repair work before use.

Delays in Delivery and Debugging Problems

Notification of the award of the contract was made about the first of May, 1966 to take effect the first of June, 1966 rather than September 1, 1966, as requested in the original proposal. Equipment orders for items purchased with AEC money were placed about the 20th of May; but due to some difficulty in getting delivery, some major commercial components of the main system were not delivered until November 17, 1966. This system was integrated by December 1, 1966, and checked out and some data taken. It was found, however, that the circuitry required for the measurement of very low level currents (currents are measured from 10^{-10} amperes to 2×10^{-1} amperes) developed an oscillation problem when certain of the special test devices were being measured. Some time, consequently, was lost in minor modifications to the circuitry and the installation of a large number of ferrite cores on the low level signal leads to suppress this oscillation. Additional time was lost when the LCO_2 valve on the temperature control chamber burned out, and some more time was lost when a blower motor on the Delta Design MK2310 Temperature Control Chamber ceased to function.

The system is now operating correctly, and data is being taken. Additionally, a second temperature control chamber has been ordered for use as a separate isochronal annealing facility and as back up for the temperature control

chamber in the system.

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 used in previous research by the principal investigator 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, $\tilde{N}_A$, majority carrier mobility, μ_n , and base recombination term, β , are related to the collector current as indicated previously²⁻³. 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

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

capacitance for the charge 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 (ring-dot geometry), 2N918 (bar geometry), and 2N2222 (star geometry).

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 earlier. Semiconductor p-n junction devices will be fabricated by normal techniques, on a single wafer of silicon, which was doped on one half its area with impurities to approximate the concentration, energies, and capture cross-sections of those 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 , 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

$$I_c = \frac{q n_i^2 k T \mu_n \beta}{\tilde{N}_a} \exp(qV/kT)$$

where the quantities in the expression have the usual definitions². 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.

Neutron Dependence of Collector Multiplication

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 factor²⁻⁵. 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 .

The emitter efficiency is a function only of V_{be} ²⁻⁴. The base transport factor is independent of V_{be} , V_{cb} , and I_c for V_{cb} less than the "reach-through" voltage²⁻⁶. (The "reach-through" voltage is that voltage necessary for the collector

depletion region to spread through the epitaxial layer to the substrate⁶). Thus, the measurement of the changes in α at constant, although different values of V_{be} , results in a family of curves reflecting only the variation of α^* and M with I_c and V_{cb} .

A technique has been devised whereby the two parameters, α^* and M , can be isolated and studied individually. This technique allows one to study the portion of the characteristics (high collector current and voltage) where both parameters differ appreciably from unity and to determine the fraction of multiplication current due to collection efficiency and the fraction due to the collector multiplication factor.

The criterion for isolating α^* and M is their functional dependence on collector to base voltage, V_{cb} , and collector current, I_c . It is assumed in this derivation that α^* is a function only of I_c and M is a function only of V_{cb} ⁵. This assumption can be verified experimentally, as will be seen shortly.

By measuring α as a function of V_{cb} for constant, although different, values of V_{be} , and normalizing, one can obtain a family of curves reflecting only the variation of α^* and M as a function of V_{cb} with V_{be} as the parameter of the family of curves (i.e., the product $[\alpha^* M]$ vs. V_{cb} with V_{be} as a parameter).

Using two other families of curves (viz, I_c and I_b vs. V_{be} with V_{cb} as a parameter) loci of constant current can be drawn on a plot of the above mentioned family of curves. Tracing along a particular constant I_c curve, only M will vary. Therefore, one can, after normalization, obtain a curve portraying the variation of M with V_{cb} . Repeating this procedure for different values of I_c , a family of curves representing M vs. V_{cb} with I_c as a parameter will result.

The coalescing of this last family of curves into a single M vs. V_{cb} curve will verify the assumption that M is a function only of V_{cb} .

By tracing along a constant V_{cb} locus (on the graph of $\alpha^* M$ vs. V_{cb} with

V_{be} or I_c as a parameter), one can, after semilogarithmic reciprocal slope of nkT/q with $n = 1.5$.

Base Current Component Changes at High Current Levels

A second base current component is associated with neutron-induced recombination in the neutral base region. This neutral region recombination reduction in the collector current overrides the tendency of the collector current to increase on account of changes in base doping and of the mobility in the base. The latter current component is not observable at low currents, but dominates the transistor characteristic at very high collector currents as shown by recent work of the principal investigator⁷. The detailed voltage-current characteristic in this region is complicated by emission crowding effects which, however, are relatively easily analyzed for the case of the ring dot structure used for the 2N914 Transistor.

A fall off in the quasi-Fermi levels through the emitter to base space charge region, or recombination in the neutral base region must, therefore, dominate the change in collector current. Of these, the first reason requires detailed numerical calculations to assess its significance.

The second possibility can be examined by considering the base current. Associated with the reduction in collector current due to recombination in the neutral base region must be an increase in base current of a component characterized by $n = 1$. It must be realized that the magnitude of such a base current component is not equal to the change in collector 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 quantitative relation between increase in base current and fall of 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 for the case of 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:

$$\frac{d^2 n}{dx^2} + \frac{2}{f} \frac{dn}{dx} - \frac{n}{L^2} = 0 \quad (8)$$

with

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 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 double 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 is being 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 are being 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.

Variation of the Inverse Current Gain Parameters 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^{2,3,4,5} 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 will allow the study of the anomalous base current component in a relatively wide region and will try 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.

It should be noted that in conjunction with the quasi-tunneling model discussed below 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.

Annealing Characteristics in Neutron Bombarded Transistors

Annealing work will be done using standard isochronal annealing techniques rather than the single long-time annealing used by the principal investigator³ when the anomalous annealing behavior of neutron bombarded devices was first discovered. Using isochronal annealing techniques will enable 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 will enable one to better study and, hopefully, to be able to 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 may be accomplished by an oil bath which is held at a constant temperature, so that the devices can 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 fabricated and special oils (polyphenyl ether fluids) have been purchased. Two types of this oil are needed in order to cover the required annealing temperature range without the oil decomposing.

Some preliminary data has been taken, but the annealing has not been started because of the need to measure the voltage-current characteristics after each stage of bombardment of the devices for later comparison during the annealing process.

In addition, since there is some small possibility that the different behavior of the neutron-induced defect levels in the space charge region from those induced in the neutral region, may be caused, at least in part, by an electric field dependence, the devices for this study are paired as twins. One device is irradiated with a reverse bias on the emitter-base junction to increase the junction field and the junction depletion volume and the other device is to be irradiated without bias to discover any field dependence which may exist.

Additionally, a study of the reverse characteristics during annealing using essentially the same techniques will be carried out to compare the annealing out of the neutron-induced current component associated with the relatively wide collector-base depletion region with the observed behavior of the annealing out of the neutron-induced current component originating in the relatively narrow emitter-base junction (for single-ended impurity process devices).

Study of the behavior of these parameters as a function of annealing will lend insight into the anomalous annealing behavior reported by the principal investigator at the 1965 IEEE Radiation Effects Conference, Ann Arbor, Michigan.

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.

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

Study of models of recombination statistics have been started. An attempt

is being made to fit a theoretical statistical recombination model to the observed reciprocal slope term for the neutron-induced component and the temperature dependence of this reciprocal slope term is being used in this study to aid in obtaining the parameters needed for a good fit. In addition to the standard current/voltage measurements, there will be need to determine the minority carrier lifetimes and capture cross-sections, the "limiting lifetimes," the density of neutron-induced defect levels, and the energies of these defect levels.

The dependence of the variation of the junction depletion layer width on the ionized impurity concentration at the edge of the depletion layer is the basis for the determination of the impurity concentration. The desired relation is obtained from a double integration of Poisson's equation⁸.

Hilibrand and Gold⁸ have developed a method for the determination of the impurity concentration in junction diodes from capacitance-voltage measurements. Their work showed that the transistor impurity profile can be obtained by using correction factors for diffused junctions if X_1/X_m can be measured, where X_1 is the depletion layer in the n-type region (for n p n transistors) and X_m is the total depletion layer width. The work of Lawrence and Warner⁹ will be used in obtaining X_1/X_m .

In order to determine the concentration, one requires the first derivative of capacitance with respect to voltage (dC/dV). A small error in C will cause a large error in dC/dV and undesirable error in the concentrations determined. Therefore, a computer program has been written in Fortran IV language using the least-square fit technique to minimize the least-squares error of a polynomial $(C[V] = \sum_{i=0}^K A_i V^i)$ fitted to the measured data and this polynomial can be used in the determination of the impurity concentrations whose changes with neutron fluence are required in the recombination statistics model.

Additional data required for this statistical model is the energies of recombination centers. By means of the Automatic Data Acquisition System, I_c vs. $1/T$ and I_b vs. $\frac{1}{T}$ can be measured. A Fortran with Format plotting program has been written for the purpose of obtaining $\ln I_c$ vs. $\frac{1}{T}$ plots. The slope term of $\ln I_c$ vs. $\frac{1}{T}$ represents as activative energy for the recombination centers. The activative energy of the recombination centers will be used in the determination of the recombination statistical model.

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

Transistor ristime measurements and diode storage time measurements will be made using Tektronix 555 Oscilloscope with Tektronix Type R and Type S plug-in units. The Lumatron Electronics Automatic Switching Time Test Set (Model 420) can be used for the measurement of rise tiem, turn on delay, turn on time, fall time, storage time and turn off time. From the measured time constants associated with the p-n junction devices the minority carrier lifetimes in the various regions of the device will be calculated¹⁰. A means is being sought to calculate the capture cross-sections of recombination centers from time constant measurements. The determined capture cross-sections will be used in the construction of the recombination statistical model.

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.

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DEVIATIONS

There were no significant deviations in the scope of the work agreed upon under the present contract, but the amount of work accomplished is behind schedule because of equipment delivery delays and debugging problems with the sophisticated electronic measuring apparatus required in this program.

In the employment schedule, rather than four graduate research assistants for 100% time three month summer and 40% time during the academic year, the actual employment schedule was one graduate research assistant for 100% time two month summer, two graduate research assistants for the full summer and academic year, one graduate research assistant for only the academic year (started in September, 1966) and three graduate research assistants for 2/3 of the academic year. (Started in December, 1966.) The total graduate research assistant payroll is roughly equal to that scheduled and the only significance is in the number of graduate students involved.

The total level of expenditures is expected to exceed that scheduled by \$525, but this is not felt to be significant, and, in any event, will be provided for by the University.

PUBLICATIONS

Bartling, D. L., "An Automatic Data Acquisition System For Semiconductor Device Testing," M.S. Thesis, University of Missouri at Rolla Library, Rolla, Missouri, 1967.

To Be Submitted for Presentation at 1967 IEEE Radiation Effects Conference:
Beckman, T. D. and Goblen, C. A., "Neutron Dependence of Collector Multiplication."

Chott, J. R. and Goblen, C. A., "Annealing Characteristics in Neutron Irradiated Silicon Transistors."

Gassner, G. E. and Goblen, C. A., "Variation of the Inverse Emitter Efficiency with Neutron Irradiation in Silicon Transistors."

To Be Submitted for Publication In IEEE Trans. on Instrumentation and Measurement:

Bartling, D. L., Jenkins, C. R. and Goblen, C. A., "An Automatic Data Acquisition System for Semiconductor Device Testing."

Patent Applications:

A patent application is being prepared on an Autoranging Current Sampler.

PERSONNEL

Project Director:

Dr. Charles A. Goben, Associate Professor of Nuclear Engineering and Senior Investigator of Electronics Research, University of Missouri at Rolla.

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

Graduate Research Assistants:

<u>Name</u>	<u>Degree/Background</u>	<u>Dept. & Degree Sought</u>
D. L. Bartling	BS/EE, 1963; MS/EE, 1967, Univ. of Mo. at Rolla. Graduate Research Asst., Summer, 1966, Univ. of Mo. at Rolla; Eagle-Picher Co., Couples Dept., 1963-64; Now employed by Westinghouse Electronics, Pittsburgh, Pa.	*
T. D. Beckman	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, 1967, Univ. of Mo. at Rolla.	MS/EE
J. R. Chott	BS/EE, 1966, Univ. of Mo. at Rolla. McDonnell Aircraft Corp., Work Study Program, 1961-65(27 months on job). Graduate Research Asst., June, 1966-May, 1967, Univ. of Mo. at Rolla.	MS/EE
M. C. Chow	BS/EE, 1960, National Taiwan Univ.; MS/EE, 1966, Univ. of Mo. at Rolla. Instructor of Sr. High School, 1961-1964; Graduate Teaching Asst., 1965-1966, Univ. of Mo. at Rolla; Graduate Research Asst., Electronics Research Center, Univ. of Mo. at Rolla, Sept., 1966-May, 1967.	Ph.D/EE
G. E. Gassner	BS/EE, 1964, Univ. of Mo. at Rolla. Graduate Asst., 1964-65, Univ. of Mo. at Rolla; Engineer in Electrical Sect., Sverdrup & Parcel and Assoc., Consultant Engineers, Summer 1965; Electronic Engineer, U. S. Army	MS/EE

Graduate Research Assistants (cont.)

G. E. Gassner (cont.)	Strategic Communications Command, Summer 1966; Graduate Research Asst., Electronics Research Center, Dec., 1966-May, 1967.	
Y. M. Hong	BS/EE, 1965, National Taiwan Univ.	MS/EE
	Graduate Research Asst., Electronics Research Center, Univ. of Mo. at Rolla, Dec., 1966-May, 1967.	
L. S. Su	BS/EE, 1965, National Taiwan Univ.	MS/EE
	Chief of Military Radio Station, Kinmen, Taiwan, 1966; Graduate Research Asst., Electronics Research Center, Univ. of Mo. at Rolla, Dec., 1966-May, 1967.	

*Graduated

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, 1966-67, Univ. of Mo. at Rolla.
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Publication

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