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MASTER

TECHNICAL PROGRESS

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NUCLEAR RADIATION EFFECTS ON SILICON P-N JUNCTIONS

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I. ABSTRACT

The early work of the principal investigator, the first to point out the importance of p-n junctions (1964) in studying neutron degradation of semiconductor devices, has been greatly expanded. Experimental discoveries and theoretical developments have clearly defined the role of the space-charge region of a p-n junction in semiconductor device degradation. A rate of space-charge volume damage introduction has been defined and its dependence on the neutron fluence and electric field of the junction (i. e., bias during irradiation) have been determined. Equations which accurately predict the behavior of the p-n junction have been developed. The neutron-induced recombination in the adjacent "neutral" regions (i. e., regions where the electric field is small compared to the p-n junction field) have been examined and a model developed to predict the behavior of the "neutral" base region. This model takes account of the electric field of graded-base devices and variation of the lifetime (diffusion length) and base width with neutron fluence. The neutron fluence dependence of the base region electric field parameter has been theoretically postulated and experimentally confirmed. The "neutral" base region recombination current has been theoretically postulated and experimentally confirmed to be several times larger than the corresponding falloff in collector current. This model has been expanded to include the steady-state photo-currents of a combined neutron/gamma radiation field. The dependencies of the collector efficiency and collector multiplication on neutron fluence have been examined and found to be second order effects. The high-frequency behavior of neutron-irradiated devices has been examined and an anomalous increase in transistor current gain has been discovered. The behavior of the surfaces of oxide-passivated silicon planar epitaxial transistors has been examined for gamma irradiation both under passive conditions and under bias for devices with various geometries. The gamma dose-induced surface degradation has been found to be a function of the electric field strength present during irradiation as well as a function of the oxide parameters, dopant impurity and gold concentrations, and the geometry. The dependence of the surface degradation as a function of gamma dose for specially fabricated and matched devices has been determined and predictive equations given. In other studies on devices of varying geometries but similar electric field strengths during irradiation, a dependence of the surface degradation on the junction perimeter-to-area (under the oxide) ratio has been found. In annealing studies, approximately 90% of the neutron-induced defects in "neutral" regions are found to anneal out or become electrically inactive, after annealing to 300°C while only about 60% of the defects induced in space-charge regions of p-n junctions anneal or become electrically inactive for the same isochronal and isothermal annealing runs. The reason for this behavior has not been resolved, but is postulated (by analogy to the rate of damage introduction) to be electric field strength

dependent. A transistor/diode model which gives radiation dependence as well as a-c and d-c parameters over eight (8) decades of current density has been constructed for computer-aided circuit analysis and design. Finally, design criteria for fabricating radiation-hardened devices have been developed and presented.

Note: This report has been kept as short as possible by not repeating in detail the contents of previous reports to the Atomic Energy Commission. Intelligent reading will require access to previous reports.

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II. TECHNICAL PROGRESS

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

Neutron-induced defect clusters in silicon transistors have been shown to behave differently in high field "space-charge" regions than in low field "neutral" bulk base regions during formation and annealing[1-6]. This anomalous behavior has been attributed to carrier injection effects[7] or to a modification of the cluster by an electric field[3,4]. To determine if a field dependence existed, the variation of the rate of space-charge volume introduction, K_V, with junction electric field strength was investigated (Goben, Irani and Johnson, COO-1624-22)[8]. The magnitude of the neutron-induced space-charge component of base current, I_B, the voltage dependence of this component (i.e., the reciprocal slope term, n), the variation of junction parameter in the volume of the emitter-base space-charge region ($A_E \cdot x_m$), and the diffusion potential were examined as functions of neutron fluence and electric field strength to determine the dependence of K_V. Specially fabricated and matched devices were irradiated to 10^{15} n/cm^2 (E>10keV) with their emitter-base junctions biased at different voltages, to produce varying electric field strengths in the junction during irradiation. The gamma-induced surface current component and the neutron-induced neutral bulk base region recombination current had to be subtracted from the total increase in base current before calculating the space-charge volume damage introduction rates.[8] Experimental data show the existence of an electric field strength dependence of K_V, and indicate that neutron-induced recombination is more pronounced for higher junction electric field strengths during irradiation (COO-1624-22)[8]. K_V was observed to decrease with fluence except for the forward biased junction at low fluences. This discrepancy for forward biased junctions was attributed to injection annealing. An empirical expression (equation 6, COO-1626-22)[8] was developed which predicts K_V for fluences between 2×10^{14} and 10^{15} neutrons/cm^2 (E>10keV) and for junction electric field strengths between 10^4 and 10^5 V/cm (the ranges where surface effects and injection annealing can be neglected or subtracted with reasonable accuracy). The exact nature of the field dependence (whether the defect cluster itself or the capture cross sections of the associated recombination centers are modified by the junction electric field) could not be determined and further research in this area is needed.

Investigations by Chow (COO-1624-14)[9] on several devices long periods (over 3 months) after fast neutron irradiation revealed that the net impurity concentration in the vicinity of the junction increases as calculated from forward biased capacitance-voltage data (after removal of surface channel (COO-1624-25)[10] and diffusion capacitance). This increase was observed on both sides of the metallurgical junction. An explanation for this phenomenon could be that the electric field strength in the junction is of sufficient magnitude ($E > 5 \times 10^4$ V/cm) to cause the charged mobile defects to move out of the junction. From this it can be postulated that at least two oppositely charged mobile defect complexes should exist.

Progress on Surface Degradation Studies

Previous experimental and theoretical investigations have established that the response of silicon planar transistors to ionizing radiation varies with the initial conditions[11-13] at the Si-SiO_2 interface and with the junction bias applied during irradiation[12-16]. In recent work (Goben and Irani, COO-1624-26)[17], it was found possible to correlate the surface degradation and the resultant changes in the affected electrical parameters with the average junction electric field strength in the junction during exposure for specially matched devices. Empirical equations were developed showing the dependence of the changes in surface-dependent parameters on the total gamma dose and the average electric field strength in the junction during irradiation. (See Report COO-1624-26 for equations and comparisons with experimental data[17].) Further work in this area (COO-1624-40)[18] for unmatched devices with the same code has confirmed that the surface degradation is dependent on the electric field strength. However, for unmatched devices, it was observed that the introduction of surface recombination generation states cannot be correlated in a simple prediction equation to the junction electric field strengths, possibly because of the vastly varying impurity dopant surface concentrations and initial surface state densities.

The effect of the geometric parameters on the ionizing radiation-induced surface states build-up was investigated (COO-1624-40)[18] using devices with various geometries, junction perimeters, and areas under the passivation layer. The high frequency response of modern transistors has been achieved by using devices with large emitter perimeter-to-area ratios such as the ring-dot, star and interdigitated geometries which reduce base spreading resistance. It is observed that surface damage is an increasing function of the emitter perimeter. This conforms to expectations since the perimeter multiplied by the thickness of the junction space charge region is that surface area where radiation-induced surface states are present which can contribute to the I_{SRG} component of base current. Again the damage factor is observed to be an increasing function of A_{BE} (area of that portion of the p-type base at the emitter base junction which is under the SiO_2 passivation layer). Recombination-generation at the surface is observed to increase with the area of the surface at the emitter-base junction under the SiO_2 passivation layer, A_{BE}. A similar trend is observed when A_{BE} is normalized by the emitter periphery, P_E, requiring for purposes of least surface degradation a minimum value of A_{BE}/P_E. The extent of surface channel formation (predominantly occurring at the collector-base junction) is an increasing function of the ratio A_{BC}/P_C^2; where A_{BC} is the area of the base at the collector-base junction under the SiO_2 passivation and P_C is the collector perimeter. Back-side gold-doped devices show an apparent radiation tolerance when compared to geometrically similar non-gold-doped devices. However, gold-doped devices have a relatively small gain even before irradiation and therefore do not exhibit much change after irradiation to saturation doses. For the reason that the excess density of gold atoms at the Si-SiO_2 interface varies appreciably[19] from device to device for unmatched devices, it will be extremely difficult to find a prediction technique for the response of gold-doped devices to ionizing radiation. Fabrication of ionizing radiation tolerant devices requires careful design, taking into account the various electrical, geometric and doping parameters consistent with device operating specifications and applications (COO-1624-36, COO-1624-40)[18,20].

Determination of the Net Impurity Distribution

It is necessary to know the net impurity distribution for the devices in order to determine the device characteristics. A technique has been developed for approximating the net impurity profile from the high-frequency (1 MHz) capacitance-voltage data of the device whose characteristics are desired. This technique yields not only the effective surface concentrations but also the junction depths, the effects of out-diffusion from the substrate or buried layer, and the width of the epitaxial layer. The technique is non-destructive and is valid in the presence of neutron-induced traps and/or gold centers. Other investigators[21-24] have devised techniques to establish the neutron-induced changes in the electrical characteristics of semiconductor devices by computer-sided modeling. These techniques require knowledge of the net impurity profile of the devices under study. Variations in the fabrication processes make the manufacturer's specification of the impurity profile and junction depths for a particular device unreliable. Junction depths previously were located only by destructive techniques and optical measurements on similar devices.

The effect of the out-diffusion of the substrate has previously been neglected. Work at this facility has demonstrated that the effect of the substrate out-diffusion is non-negligible and does in fact affect the device characteristics (Azarewicz, Bereisa and Goben, COO-1624-18, COO-1624-25, COO-1624-31).[10,25,26]

Since this new technique is valid in the presence of neutron-induced traps and/or gold centers, the effects of neutron radiation on the net impurity profile have been studied using this technique (Azarewicz, Bereisa and Goben, COO-1624-25, COO-1624-31)[10,26]. The net impurity profile can now be determined and it is no longer necessary for device analysts and designers to rely on approximate specifications of the profile or destructive techniques. In addition, the effect of the substrate can now be included in the computer-aided design of devices.

One of the major problems in applying this technique was that it previously required the assumption of a constant R, V_D, m in the expression, $C = R/(V_D+V)^m$, for the capacitances in each cluster which led to questions concerning the accuracy of the technique. This has been overcome by doubly integrating the impurity profile (in closed form) and deriving expressions for the diffusion potential (V_D) and capacitance for each junction. Using these closed form solutions as a starting point, a computer code was written to obtain the variation of the required parameters with applied bias. Figures II-1, -2, -3 illustrate the solutions obtained for a double diffused planar silicon epitaxial transistor while Figures II-4, -5, -6 illustrate the bias dependence of these parameters for a double diffused planar (non-epitaxial) transistor.

Neutral Bulk Base Region Model

It had been postulated in early work[1-5] that two separate physical recombination processes were primarily responsible for neutron-induced current gain degradation. The first process, neutron-induced recombination in the emitter-base space-charge region, was reported by Goben[1] (1964) to dominate current gain degradation at low and intermediate current/injection levels. The second process was attributed to neutron-induced recombination in the bulk base region and was predicted to dominate current gain degradation at moderate and high current levels on theoretical and experimental grounds[1,2,5]. Graphical techniques were employed on current-voltage characteristics to extract the bulk base recombination current with some success, but only at low neutron fluences (COO-1624-11)[27]. An extensive graphical-mathematical analysis by Goben et al.[6] (1968) substantiated the existence and dominance of neutron-induced bulk base recombination at high current/injection levels. The exact behavior of the neutron-induced bulk base recombination current was examined on a theoretical basis and a mathematical model was developed for the bulk base region of graded base devices which accounts for the combined effects of neutron-induced recombination and built-in electric field (COO-1624-10, COO-1624-19, COO-1624-29, and COO-1624-32)[28-31]. This model is general and is directly applicable to any device (silicon or other semiconductor material, graded or uniform base) once the geometry, impurity profile, and material are known (COO-1624-19)[28]. This model, in conjunction with the impurity profile determination technique (COO-1624-12, COO-1624-14, COO-1624-18, COO-1624-25, and COO-1624-31)[9,10,25,26,32], has demonstrated good predictions when compared with experimental data (COO-1624-29)[29]. In more recent work, Goben and Han (COO-1624-39)[33] extended this model to allow prediction of radiation-induced excess carrier densities and steady-state photo-currents as well as

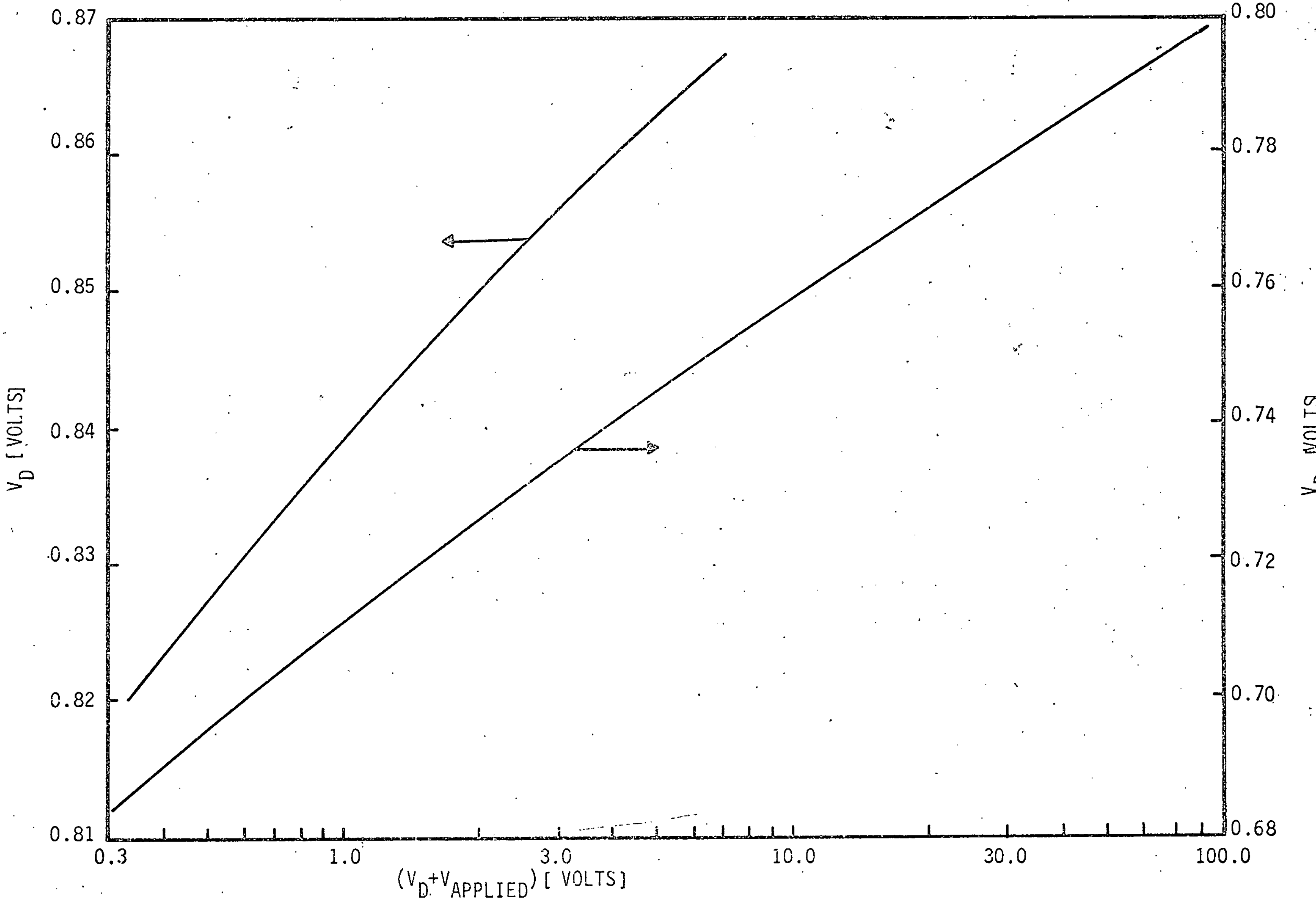


FIG II-1. PLOT OF THE THEORETICAL BIAS DEPENDENCE OF THE DIFFUSION POTENTIAL FOR THE EMITTER-BASE (LEFT SCALE) AND THE COLLECTOR-BASE JUNCTIONS FOR A DOUBLE-DIFFUSED PLANAR EPITAXIAL TRANSISTOR.

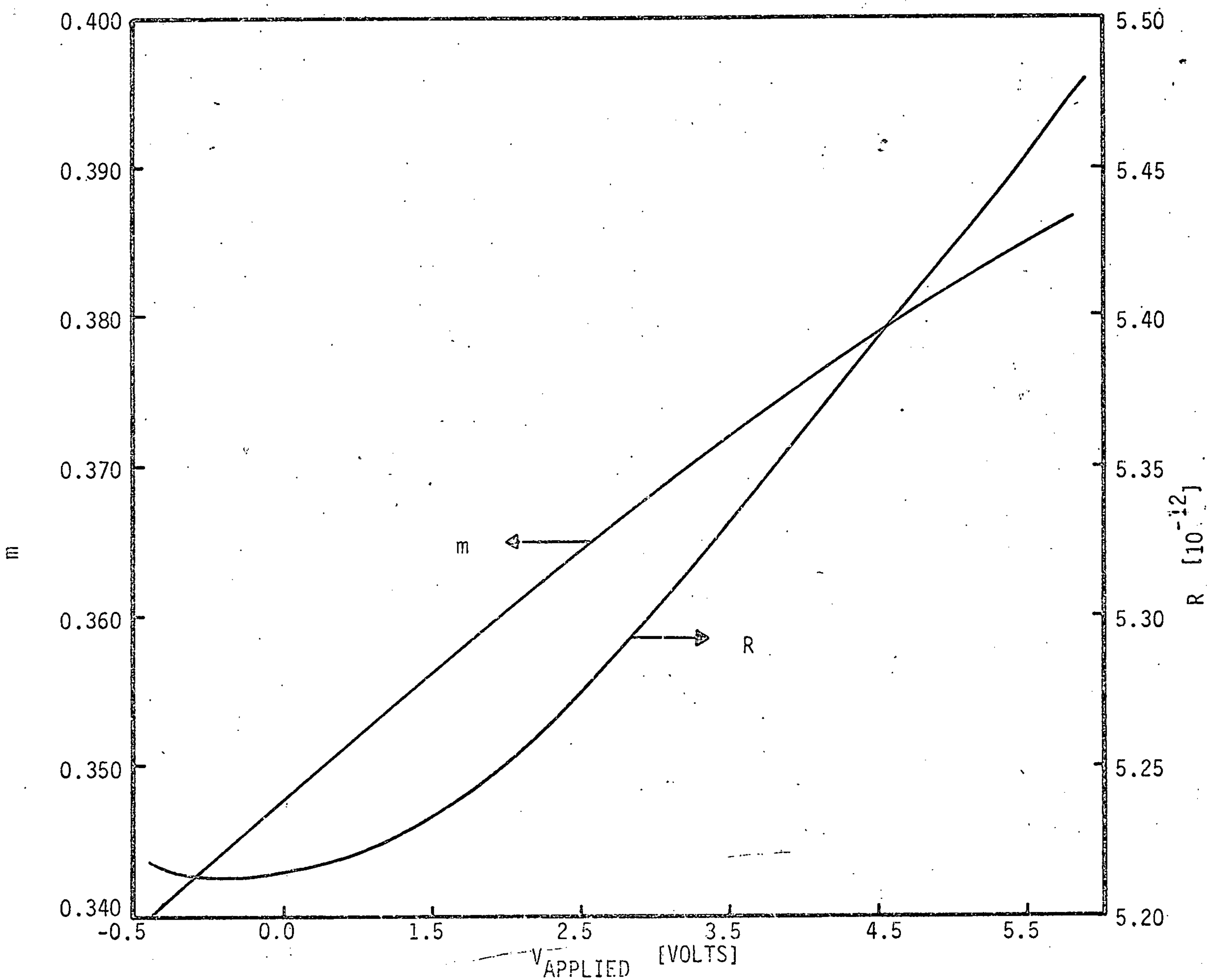


FIG. II-2. PLOT OF THE THEORETICAL BIAS DEPENDENCE OF m (LEFT SCALE) AND R FROM THE EQUATION $C=R/(V_D + V_{APPLIED})^m$ FOR THE EMITTER BASE JUNCTION OF A DOUBLE-DIFFUSED PLANAR EPITAXIAL TRANSISTOR.

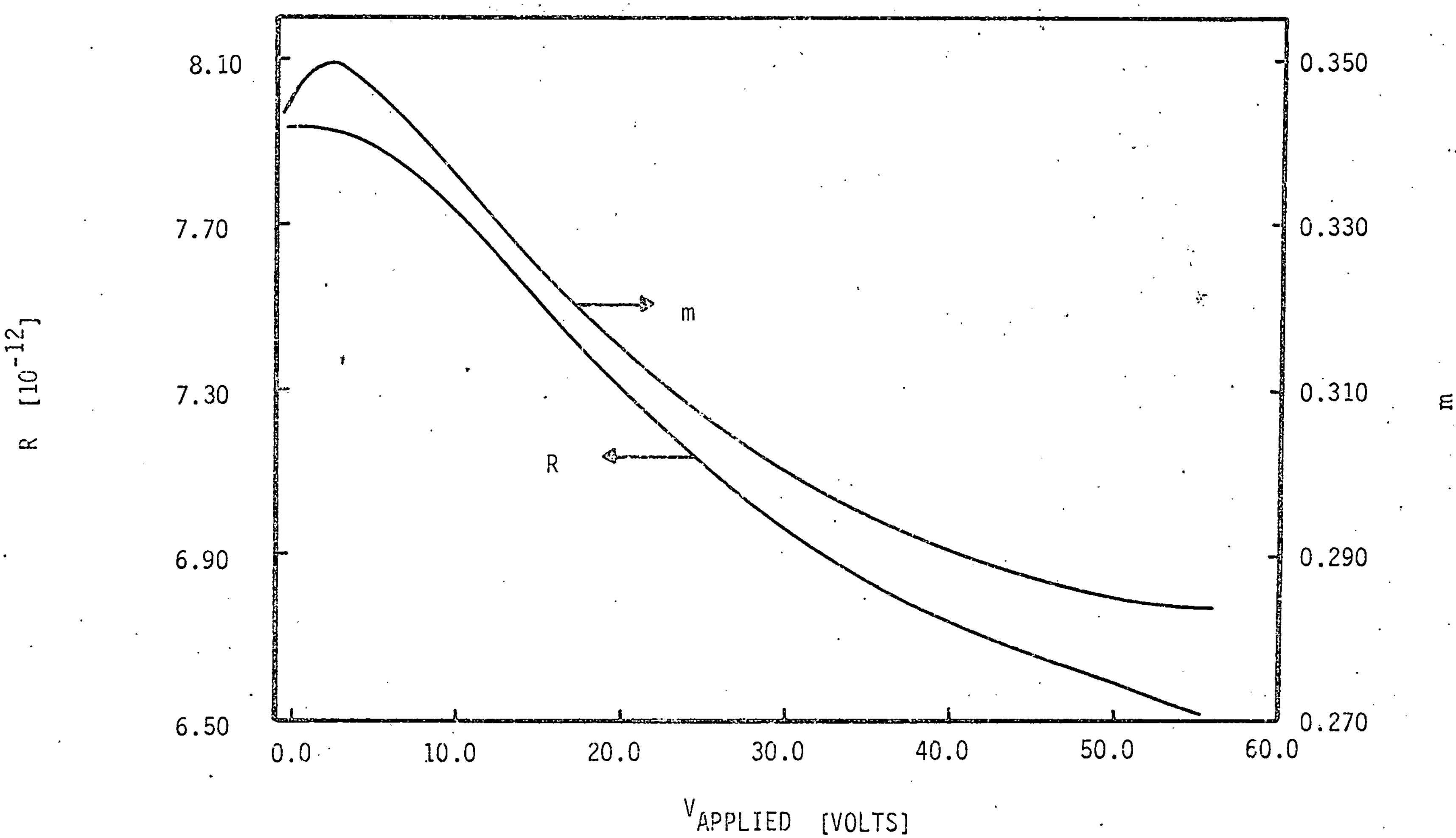


FIG. II-3. PLOT OF THE THEORETICAL BIAS DEPENDENCE OF R (LEFT SCALE) AND m FROM THE EQUATION: $C=R/(V_D + V_{APPLIED})^m$ FOR THE COLLECTOR-BASE JUNCTION OF A DOUBLE-DIFFUSED PLANAR EPITAXIAL TRANSISTOR.

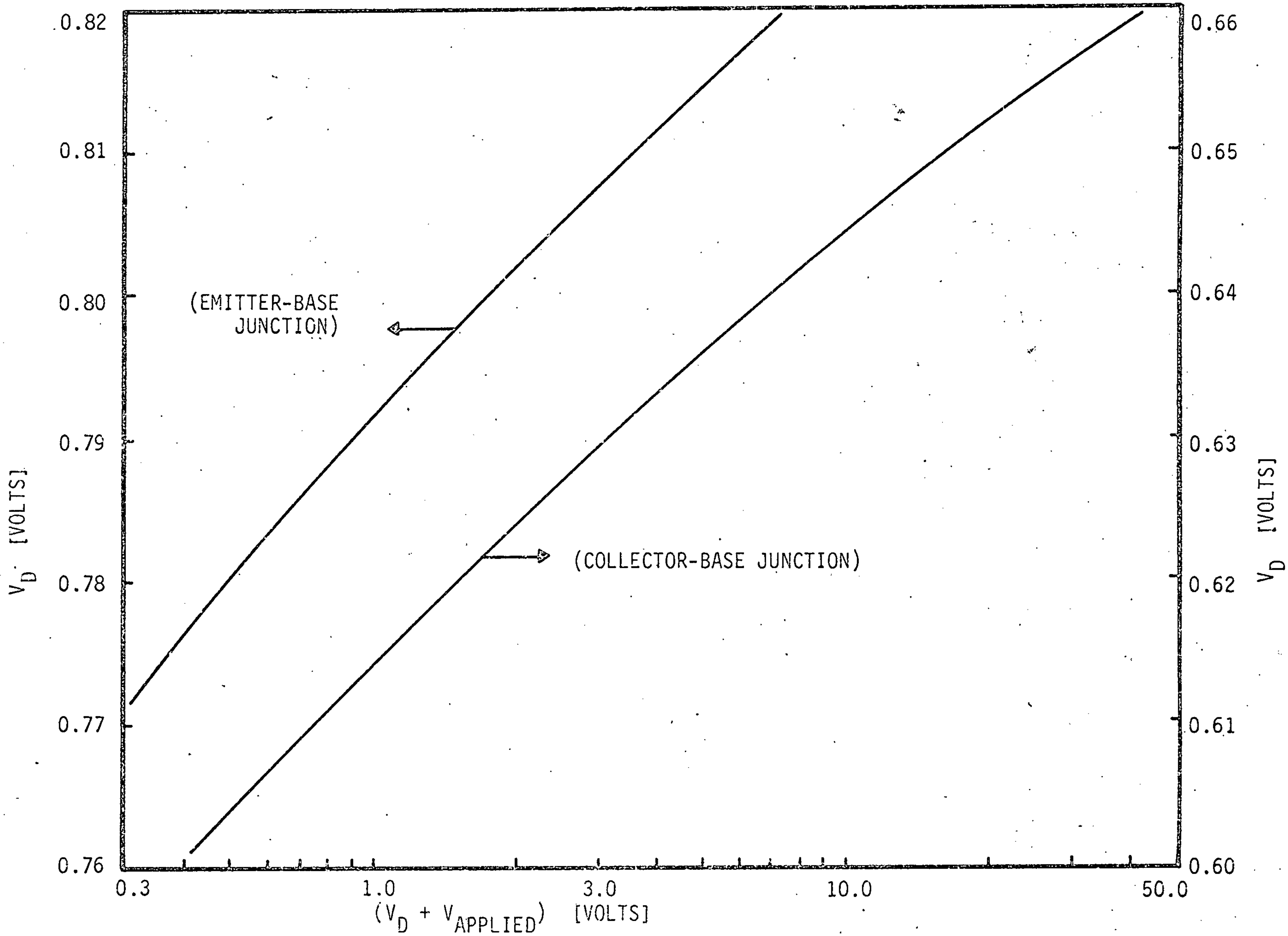


FIG. II-4. PLOT OF THE THEORETICAL BIAS DEPENDENCE OF THE DIFFUSION POTENTIAL FOR THE EMITTER-BASE (LEFT SCALE) AND THE COLLECTOR-BASE JUNCTIONS FOR A DOUBLE-DIFFUSED PLANAR NON-EPITAXIAL TRANSISTOR.

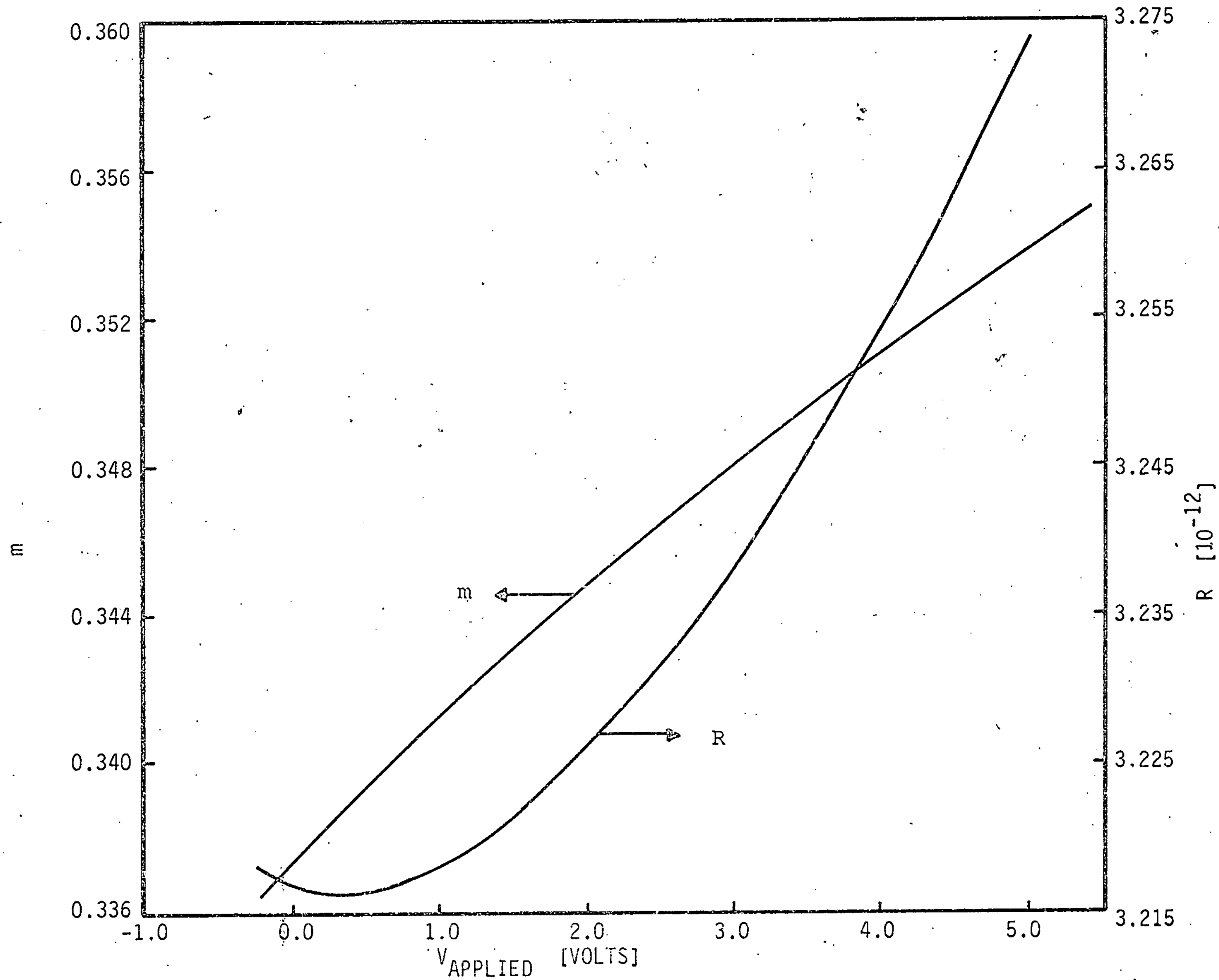


FIG. II-5. PLOT OF THE THEORETICAL BIAS DEPENDENCE OF m (LEFT SCALE) AND R FROM THE EQUATION: $C=R/(V_D + V_{APPLIED})^m$ FOR THE EMITTER-BASE JUNCTION OF A DOUBLE-DIFFUSED PLANAR NON-EPITAXIAL TRANSISTOR.

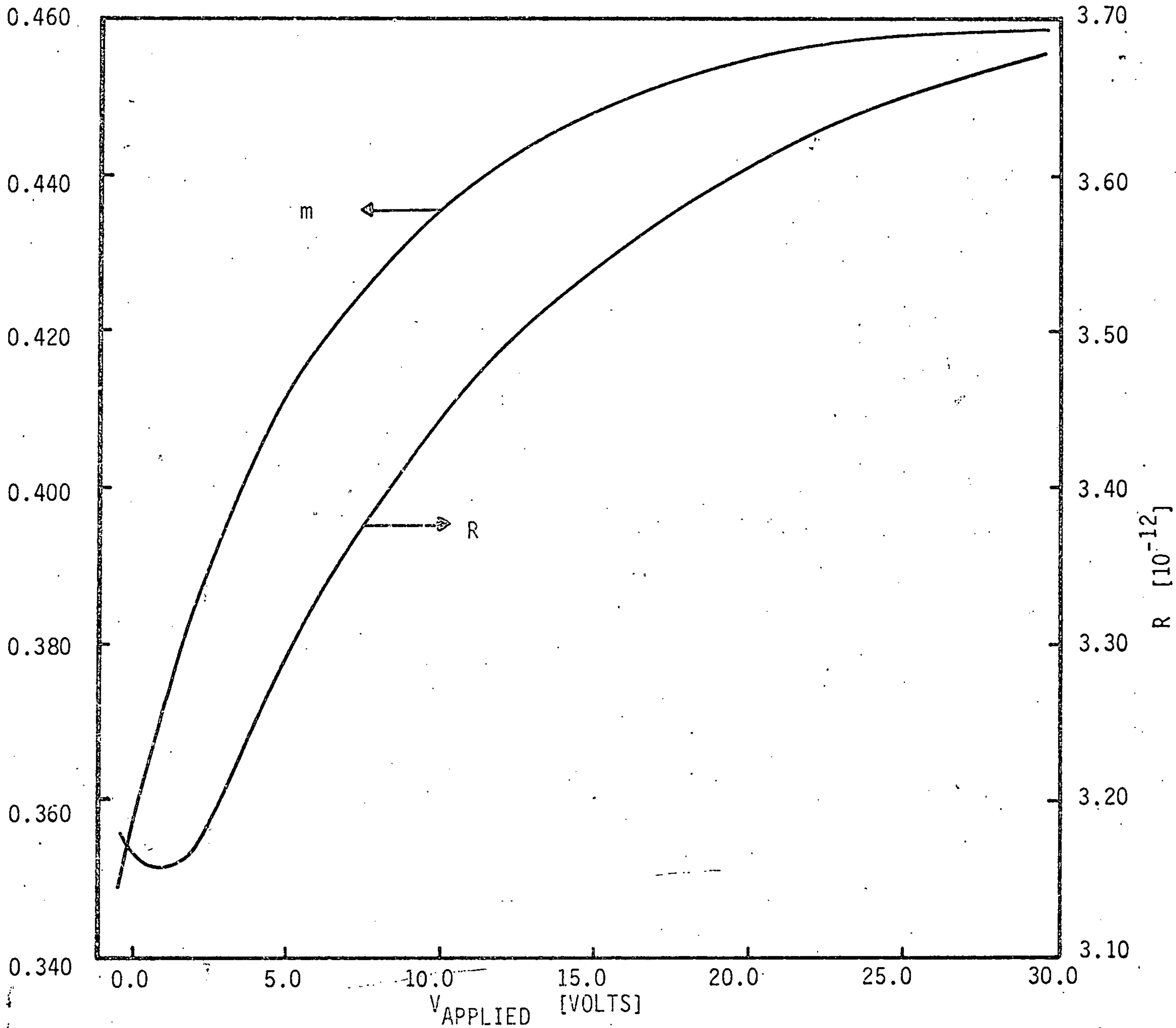


FIG. II-6. PLOT OF THE THEORETICAL BIAS DEPENDENCE OF m (LEFT SCALE) AND R FROM THE EQUATION: $C=R/(V_D + V_{APPLIED})^m$ FOR THE COLLECTOR-BASE JUNCTION OF A DOUBLE-DIFFUSED PLANAR NON-EPITAXIAL TRANSISTOR.

displacement effects without extensive computer-aided analysis. This model involves a closed form general solution of the continuity equations with consideration given to the ionizing radiation carrier generation rate, G, and the internal electric field caused by the impurity gradient in the base region.

Transistor Model for Computer Aided Circuit Analysis and Design

Most existing equivalent circuit models of transistors are based on data fitting techniques (e.g., the Ebers-Moll model in Net-1, Net-1R, Net-2, Sceptre, Circus) which are valid only over a limited range of operation. Additionally, they require such artifices as fitting a polynomial to the gain versus collector current data and then placing constraints in device codes so as not to obtain a "negative gain"[34]. The fundamental physical processes responsible for device behavior are ignored. These models, in spite of their shortcomings, find wide application in the area of computer-aided circuit analysis and design. These models result in poor generation of d-c and a-c parameters even in the absence of radiation and are not capable of accurate predictions when applied to irradiated devices (primarily because they do not account for specific physical processes and their alteration by radiation).[34]

A "lumped element" model has been developed which is based on descriptions of the physical behavior of devices (COO-1624-27)[35]. This lumped element model is general and predicts with great accuracy the normally encountered d-c and a-c parameters of p-n junction devices and the neutron-induced changes in these parameters (COO-1624-13, COO-1624-21, COO-1624-22, COO-1624-25, COO-1624-29, COO-1624-35)[4, 6, 8, 10, 29, 36]. The gamma rate dependence has been included through "standard" primary photocurrent generators and the only significant improvement in these was the inclusion of the voltage dependence of the space-charge region and the electric field-aided transport of created carriers in graded base regions. Gamma dose dependence (surface degradation) has been considered (COO-1624-23)[37], but no suitable means of generating this dependence has been achieved.

The methods for obtaining the necessary device parameters from measured data are specified and are no more involved or difficult to obtain than for the simple Ebers-Moll model. This model establishes a simple and accurate basis for computer-aided analysis and design of circuits operated in a neutron environment.

This model is similar in principle to the Ebers-Moll model in that current generators are used for the junctions; however, the junction currents are represented by a series of individual parallel current generators (rather than a single generator with a reciprocal slope dependence which is valid over only a small range) corresponding to each of the constituent current components at each junction. Carrier multiplication is included for the collector junction, as is the collector efficiency (although the latter seldom deviates appreciably from unity in modern devices). This technique of using individual current generators allows a straightforward prediction of neutron-induced space-charge region and bulk base region recombination. Emission crowding, conductivity modulation, and back injection effects at high current/injection levels are described in terms of non-linear current dependent resistances and a unique "voltage difference generator"[34]. The various junction capacitances are obtained in the conventional manner[34].

This model has demonstrated excellent prediction of device characteristics for both non-irradiated and irradiated devices over eight decades of current. This model establishes an accurate basis for computer-aided analysis and design of circuits operated in a radiation environment. At present, as noted, the accuracy of this model has been verified for the prediction of d-c and a-c characteristics and neutron-induced recombination currents.

Design Criteria for Radiation Tolerance

A significant amount of information has already been obtained concerning the radiation dependence of various physical processes in silicon p-n junctions and junction devices by this laboratory (References 1-5 and reports COO-1624-00 through COO-1624-40). All of the information available was correlated in an effort to implement and improve the design of radiation-tolerant devices. The specific radiation damage to be minimized varies according to particular device and application and includes: (1) neutron-induced emitter-base space-region recombination[1-6]; (2) neutron-induced bulk base region recombination (COO-1624-10, COO-1624-19, COO-1624-29, and COO-1624-32)[28-31]; (3) neutron-induced alteration of the device impurity profile (COO-1624-12, COO-1624-14, COO-1624-18, COO-1624-25 and COO-1624-31)[9,10,25,26,32]; and (4) neutron degradation of collector-base parameters (COO-1624-00)[38]. Ionizing radiation-induced surface degradation has been observed to depend on several parameters: (1) average electric field strength at the emitter-base and collector-base junctions during irradiation (COO-1624-25)[17]; (2) junction perimeters and area under the SiO_2 passivation layer (COO-1624-40)[18]; and (3) initial surface state densities, impurity dopant concentrations and excess gold concentrations at the Si-SiO_2 interfaces.[19]

The effects of neutron bombardment on the high frequency operation of p-n junction devices (COO-1624-21)[36] can also be combined with the neutron dependence of junction capacitance (COO-1624-25)[10] to establish frequency criteria for radiation tolerance.

Preliminary studies have indicated that a device can be constructed with an impurity profile such that neutron bombardment will result in the improvement of some of the electrical characteristics of the device. For example, the active base width has been shown to decrease with fluence (COO-1624-25 and COO-1624-29)[10,29]. The junction capacitance has been shown to decrease with neutron bombardment (COO-1624-25)[10]. The average built-in electric field in graded bases has been observed to improve with fluence (COO-1624-29)[27]. The high frequency gain has been observed to increase at high fluences (COO-1624-21)[36]. The improvements in these electrical characteristics can be designed (in principle) to partially offset the radiation-induced degradation in the other electrical characteristics. Out-diffusion of the collector substrate or buried layer has been shown to be significant (COO-1624-25)[10]. Recent studies have indicated that it is possible to improve the bulk base region and collector junction and bulk collector region parameters by employing a controlled out-diffusion of the substrate or buried layer. Much of this material was published in the Proceeding of the Government Microelectronics Conference (Proc. GOMAC, October 1970) and is included as a reprint with this report (COO-1624-36)[20].

Neutron-Induced Enhancement of High-Frequency Transistor Gain at Low Temperatures

The general effects of fast neutron radiation after defect modification by carrier injection have been characterized by means of S-parameter measurements at high frequencies (0.1-2.0GHz) in this laboratory. It was shown (Goben, Gray and Han COO-1624-21, COO-1624-33 and COO-1624-37)[36,39,40] that S_{21} (forward gain parameter) increased above the pre-irradiation value for frequencies above $Z \cdot f_T$ [where $Z = (\Phi/10^{13})^{0.1}$ for a neutron fluence, Φ, in the range 10^{13} to 10^{15} n/cm^2 ($E > 10$ keV) and f_T is the cut off frequency of the device, 2N914 (340 MHz)]. The effects of carrier injection defect modification after fast neutron irradiation were observed to play an important role in this experiment.

The above investigation was carried out primarily at room temperature. However, the defects caused by neutron-irradiation and altered by carrier injection defect modification are localized states in the band gap and are consequently strongly temperature dependent. These defects determine the carrier generation and recombination rate and hence play an important role in current gain of the transistor. Sander et al.[47] have reported an increase in gain at low temperatures resulting in a "gain hump" for gallium (base) doped transistors. These devices were found to be more tolerant to fast neutron radiation at liquid nitrogen temperature than at room temperature when operated in the d-c mode. Combining the low temperature effects on gallium-doped N-P-N devices with the enhancement of the high frequency characteristics after neutron radiation should prove to be an interesting and informative study. Unfortunately, delay in delivery of a cryostat precluded the completion of this study.

III. DISCUSSION AND CONCLUSIONS

Equipments and Data Acquisition Systems

Equipments purchased with AEC funds were combined into various data acquisition systems and are discussed and described in detail in this report (see section IV) as well as in a paper[42], a thesis[43] (COO-1624-01), and the several annual reports submitted to the AEC (COO-1624-00, COO-1624-11, COO-1624-20, COO-1624-24, COO-1624-38). The lists of presentations and publications (see sections XIII and XIV) make clear how well these equipments were utilized.

Junction Space-Charge Regions

It was first pointed out by the principal investigator[1,2] (1964) that the p-n junction in a semiconductor device was a major source of neutron degradation of device performance at low and intermediate current/injection levels. Work carried on at this laboratory has expanded upon the earlier work and clearly defined the role which the p-n junction space-charge region plays in neutron degradation of device performance. The rate of space-charge volume damage introduction was found to be a function of both neutron fluence and the electric field existing in the space-charge region at the time of radiation through studies of devices operated in the inverse (to expand the junction space-charge region) configuration in addition to operation in the normal configuration.

The results, which yielded the dependencies of the reciprocal slope term and the rate of space-charge volume damage introduction on bias (electric field strength) and neutron fluence, were published in a series of papers[3,4,6,8,32] and detailed in various theses which also have been submitted to the Atomic Energy Commission as reports (COO-1624-06, COO-1624-14, COO-1624-15, COO-1624-28). Equations illustrating the behavior of the p-n junction space-charge region and accurately predicting its response to neutron fluence and electric field strength (bias) were given in this series of papers and theses. Additionally, the behavior of the collector multiplication factor and collector efficiency with neutron fluence were investigated and found to vary only as a second order effect (COO-1624-00, COO-1624-03, COO-1624-11).

Neutral Bulk Regions

Neutron-induced recombination in neutral regions adjacent to the p-n junction was predicted by the principal investigator[5,6], on theoretical and experimental grounds, to dominate device degradation at moderate and high current/injection levels. This prediction has been investigated in this laboratory under this series of contracts and has been confirmed. The behavior of the adjacent "neutral" (i.e., low or zero field) regions has been examined theoretically and the theoretical analysis has been experimentally confirmed. This theoretical analysis led to a mathematical model for the "neutral" base region which, in addition to neutron fluence and d-c and a-c effects, takes account of the aiding electric field in graded base transistors (and its fluence dependence), the fluence dependence of the minority carrier lifetime (diffusion length), and base width variation. These are detailed in a series of papers[10, 28, 30, 31] and theses (COO-1624-14, COO-1624-29) in addition to the annual reports. This model has recently been extended to include steady-state photo-current in a recent paper[33] which is included separately (COO-1624-39) with this report.

Net Impurity Dopant Distribution

One of the problems encountered early in this study was that the manufacturers' specifications of the net impurity dopant distribution and junction depths were not reliable and more accurate information was needed. Since this is a general problem, both within and outside of the radiation effects community, a study was launched to determine a more accurate means of determining this distribution for a multi-junction device by extending the early work of Hilibrand and Gold[44] and Lawrence and Warner,[45] and that of the principal investigator,[46] by using capacitance-voltage measurements and computer-aided fitting techniques. Part of this work has been presented or published[9, 10, 25, 26] and more detail is to be found in a thesis (COO-1624-16) and the various reports to the AEC.

Recent work (still unpublished) has defined the theoretical dependence of the parameters for the capacitance-voltage relationships for double-diffused planar epitaxial and non-epitaxial transistors and has removed the inherent inaccuracies of this technique (See section II).

Degradation of Oxide Passivation over Silicon P-N Junctions

The combined neutron-gamma radiation field of the nuclear reactors used in this work led to a study of the gamma dose-induced degradation of the oxide passivation layer over p-n junctions and a search for a technique to predict and/or remove and separate the neutron-induced bulk changes and gamma dose-induced surface changes. Prediction has been found to be possible for matched devices but the technique fails for unmatched devices, although removal is still possible because of the different voltage and field dependencies of bulk and surface effects. Additionally, the effects of geometry, dopant impurities and gold concentrations have been examined and dependencies or trends determined. These results are given in detailed form in a series of presentations and publications[8, 17, 18, 37] and a thesis (COO-1624-28) as well as the annual reports. (See also section II of this report.)

Annealing and Modification of Neutron-Induced Defects

The anomalous annealing behavior of defects in the space-charge regions compared to the behavior in adjacent neutral regions reported by the principal investigator[1,2,5] has been more closely examined. In a series of isochronal and isothermal annealing studies, defects introduced into the p-n junction space-charge regions have been found to anneal out only to about 60% while defects introduced into the adjacent neutral regions anneal out about 90%. This behavior was attributed to an electric field dependence of annealing behavior as well as of introduction behavior. No theoretical basis has yet been found for this difference and the field dependence has not yet been clearly defined. One may conclude, though, that extreme care must be taken in missions (such as space shuttle systems) where devices are to "anneal out" after nuclear propulsion before re-initiating the nuclear system because the space-charge region does not anneal to the same degree as the neutral regions.

High-Frequency Low-Temperature Current Gain

The high-frequency behavior of semiconductor devices was investigated to determine if the behavior of neutron-irradiated devices at high frequencies was the same as the d-c and low frequency behavior, as had been commonly assumed. It was found that the high-frequency behavior was quite different from the low-frequency and d-c behavior, and the high-frequency response of a neutron-irradiated device could not be predicted from low-frequency or d-c measurements. Moreover, an anomalous neutron-induced increase in high-frequency transistor current was discovered. No theoretical basis for this anomaly has been found to data.

The low-temperature "Gain-Hump" discovered by Sander et al. at d-c and low frequencies leads one to wonder about the behavior of this LN_2 temperature gain-hump at high frequencies. An investigation was planned but could not be completed because of delay in delivery of a cryostat for the low-temperature work. The results to date are detailed in a series of presentations and publications[36,39,40] and a thesis (COO-1624-21) as well as in previous annual reports.

Transistor/Diode Circuit Model

Utilizing the results of the work under this contract and associated work of the principal investigator, a transistor/diode model for computer-aided circuit analysis and design has been developed. This model has been found to be accurate over eight decades of current density and includes neutron fluences and gamma dose rate dependencies as well as d-c and a-c parameters. A paper has been prepared with copies to the AEC as report COO-1624-27 which gives the details of this model.

Device Design Criteria for Radiation Tolerance

The information gleaned from the work performed under this contract as well as work done by others has been integrated and carefully sorted and studied with the intent of giving design criteria for fabricating radiation-tolerant devices. Much of this has been published[20] and is included as a separate report (COO-1624-36) accompanying this final report.

IV. DATA ACQUISITION SYSTEMS

Several measurement systems have been fabricated with equipment purchased with AEC funds and are being used for data acquisition. These are for the measurement and recording of current versus voltage and capacitance versus voltage characteristics, scattering parameters, minority carrier lifetimes and switching characteristics, and small signal dynamic characteristics. Calibration standards are maintained for the purpose of calibrating these measurement systems.

Automatic Current/Voltage Data Acquisition System

The Automatic I/V Data Acquisition System[42,43] is capable of making current and voltage measurements on any two, three, or four lead JFET, MOS or Bipolar device with an overall accuracy of $\pm 1\%$ of reading and a precision (repeatability) of $\pm 0.3\%$ of reading in the range from 10^{-10} amperes to 2×10^{-1} amperes (over 9 decades). This system consists of two Hewlett-Packard/Dymec Model DY-2401C Integrating Digital Voltmeters (DVM-1,-2), a John Fluke Model 383B Voltage/Current Calibrator for junction biasing, a Programmer for control of the 383B, a Control Center and an Autoranging Current Sampler[42,43], a Differential Amplifier (used in the auto-ranging circuit), a Sanborn Model 860-4300 Low Level Amplifier for low noise amplification of the test signal, a Delta Design MK 2310 Temperature Control Chamber, two test jigs (described below), several DC power supplies for multi-junction biasing (See Table 1), a Dymec Model 2540B Coupler (used to change DVM parallel BCD output to a serial code) and a Friden Flexowriter (Model SFD) which translates the Coupler serial output into both printed copy and punched paper tape. (The information on the punched tape is then transferred to IBM cards via an IBM-047 tape-to-card converter with the cards then used in various data reduction computer programs developed by this group.)

The interconnection of these components is shown in Fig. IV-1. One change that has been incorporated in this sytem is an I_B/I_C Mode Switch allowing data to be taken solely on any particular junction of a multi-junction device while applying bias to another or the same junction. This change also allows data to be taken on any JFET, MOS, or Bipolar device. A recent modification to the system is a programmable polarity reversal switch for the junction bias.

A new junction bias programmable controller is being fabricated. Essentially, it is an interface connecting the Digital Equipment Corporation Model PDP-8/I Programmed Digital Processor to the I/V System. This new controller will allow a larger number of data points to be taken and will make bias programming changes easier and more rapid.

QUANTITY	MANUFACTURER	MODEL NUMBER	CAPABILITY (notes 1, 2)
3	H/P Harrison	865C	0-40 VDC 0-0.5 ADC
3	H/P Harrison	6294A	0-60 VDC 0-1 amp.
3	H/P Harrison	6220B	0-25 VDC @ 0-1 amp. or 0-50 VDC @ 0-0.5 amp.
3	John Fluke (note 3)	383B	0-50 VDC 0-2.0 ADC

NOTES:
1. All power supplies capable of floated output or either polarity grounded.
2. All power supplies capable of local control or remote resistance programming.
3. John Fluke 383B power supplies remotely programmable for current or voltage to six decimal digits. (0-50V, 0-5 mA, 0-50mA, 0-500mA, 0-2A).

TABLE 1: LIST OF AVAILABLE PRECISION DC POWER SUPPLIES

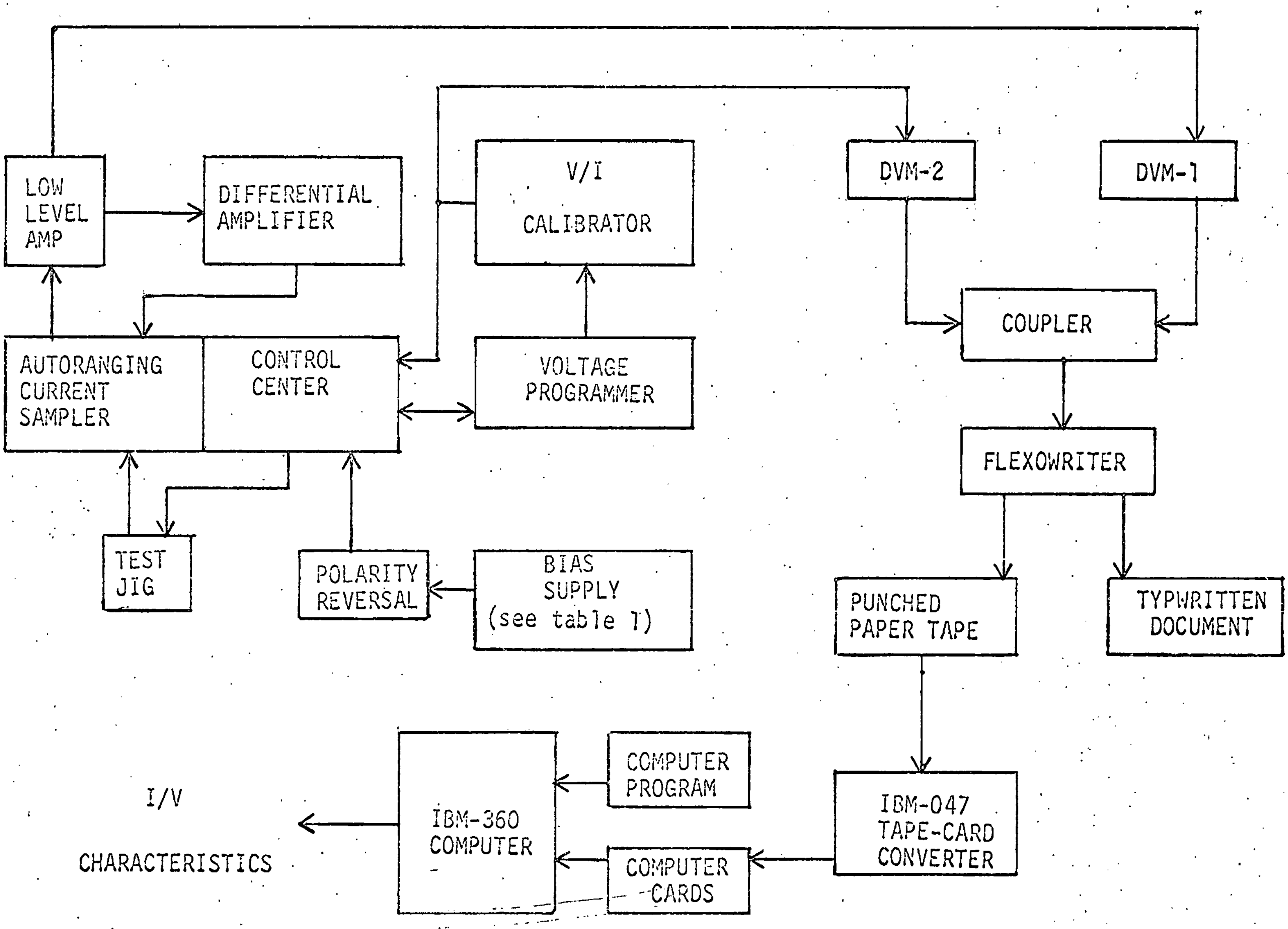


FIG. IV-1: AUTOMATIC CURRENT/VOLTAGE DATA AQUISITION SYSTEM

Autoranging Current Sampler: Fig. IV-2 illustrates the Autoranging Current Sampler and Control Center in a simplified form.

Test Jig. No. 1: Test jig No. 1 has 12 four-pin sockets. Each socket is selected sequentially via a programmable stepping switch thereby allowing 12 devices to be measured in one data run (See Fig. IV-2).

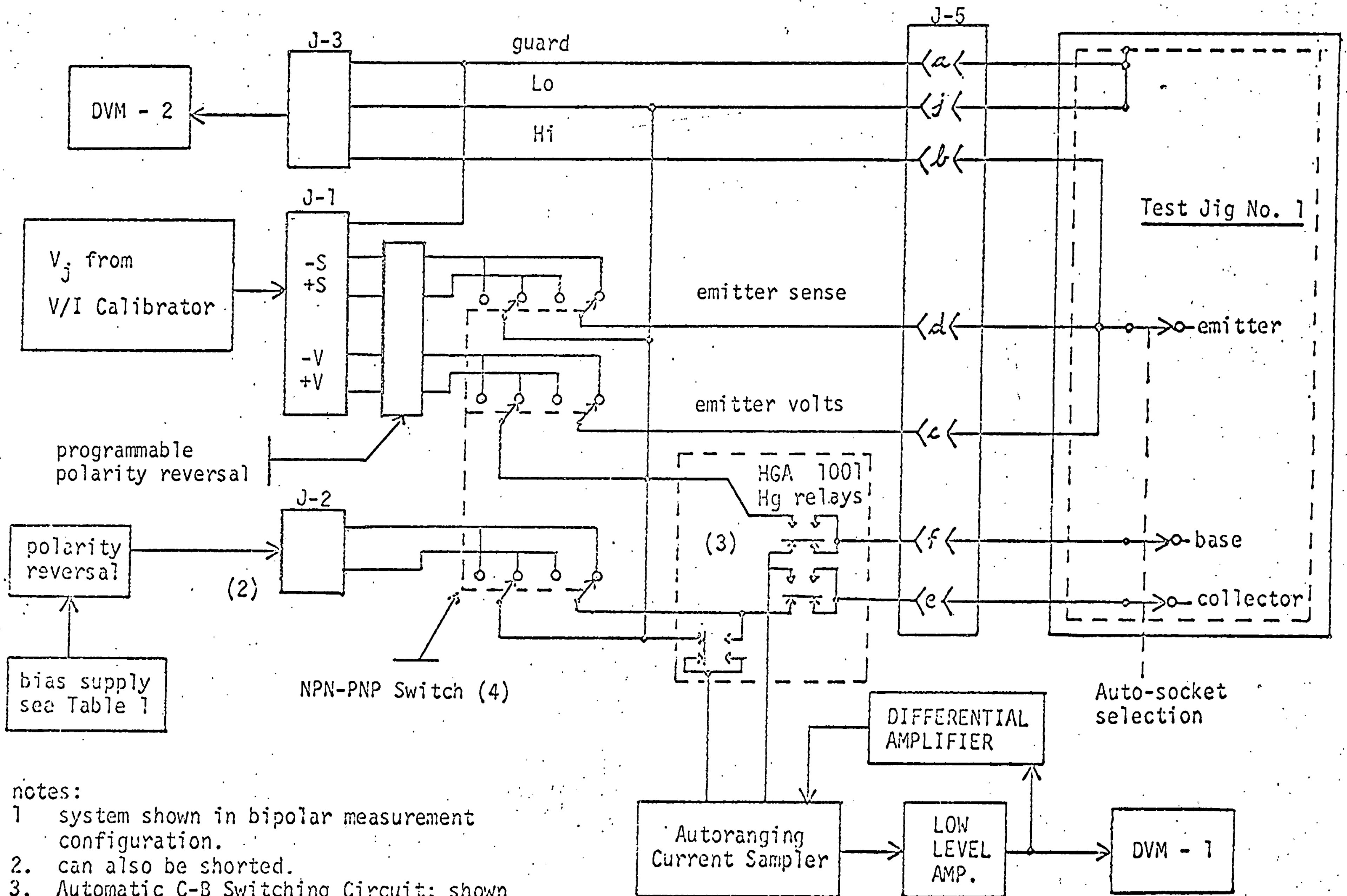
Test Jig. No. 2: Test jig No. 2 is a recent fabrication (Fig. IV-3). It has four switches (each of the four switches can select any lead of a 12 lead device or circuit) that connect the I/V system or the C/V system (described in the following section) to the device under test. A particularly useful feature is that any lead not in the measuring circuit can be connected to a shorting bus which can be grounded, floated, or guarded depending on the type of measurements being made. By using the I/V system I_B/I_C Mode Switch and external power supplies connected to C/V system BNC connectors, data on JFET's and MOS devices can be measured with greater accuracy since static charges can be drained off without removing the device from the stabilized temperature environment provided by the Delta Design Temperature Control Chamber. One other feature inherent in the design is the ease which data can be taken on gated bipolar junction devices (See Fig. IV-4).

Alternate Modes: Alternate modes of semiconductor device measuring configurations available with this system are shown (in simplified form) in Fig. IV-4 and Fig. IV-5. The versatility of the I/V system for use in different modes can readily be seen by viewing Fig. IV-2, IV-3 and/or IV-4, IV-5 simultaneously.

Automatic Capacitance/Voltage Data Acquisition Systems

The Automatic C/V Data Acquisition System uses a Micro Instruments Model 1201DS Digital Capacitance Tester (1 MHz signal frequency) as the basic measuring instrument. A Dymec 2901A Master Scanner/Programmer and a Dymec 2902A Slave Scanner/Programmer are used for control and programming. Test devices are mounted in either test jig. No. 2 or No. 3 (described below) and inserted into a Delta Design MK 2310 Temperature Control Chamber. The model 1201DS has two ranges; 0-100 pF and 0-1000 pF.

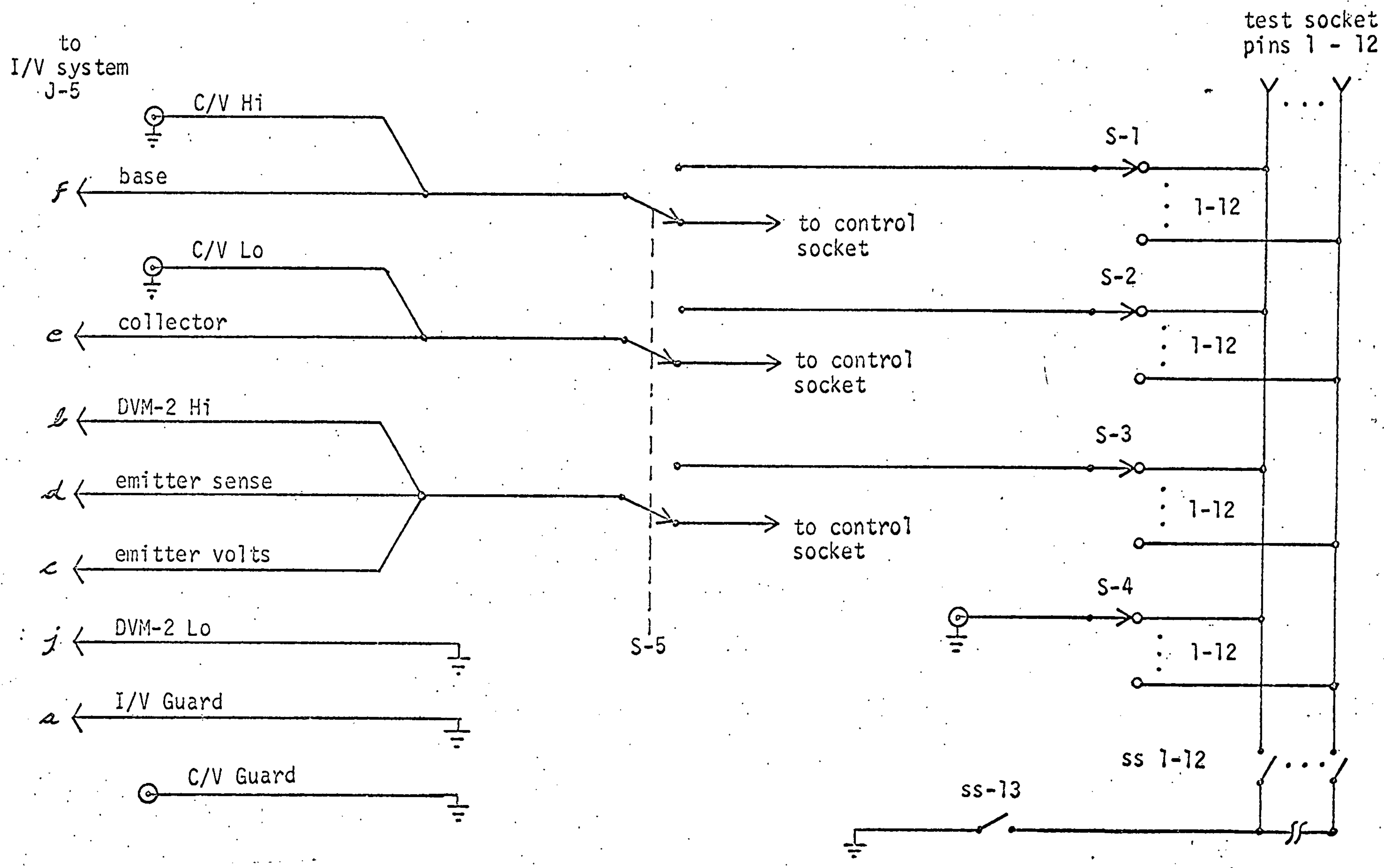
This sytem can be used in two different modes. The first is for off-line informative use (Fig. IV-6). A Hewlett-Packard/Dymec Model DY-2401C Integrating Digital Voltmeter (DVM-3) measures the applied bias voltage supplied by a John Fluke 383B V/I calibrator and provides a BCD signal to a Hewlett-Packard 562A Digital Recorder. This recorder also receives a BCD output from the 1201DS Capacitance Tester. Upon command from the scanners the 562A will print out applied voltage and capacitance (in pico-farads). The second mode (Fig. IV-7) uses DVM-1 and -2 of the I/V system, the Coupler, and the Friden Flexowriter.



notes:

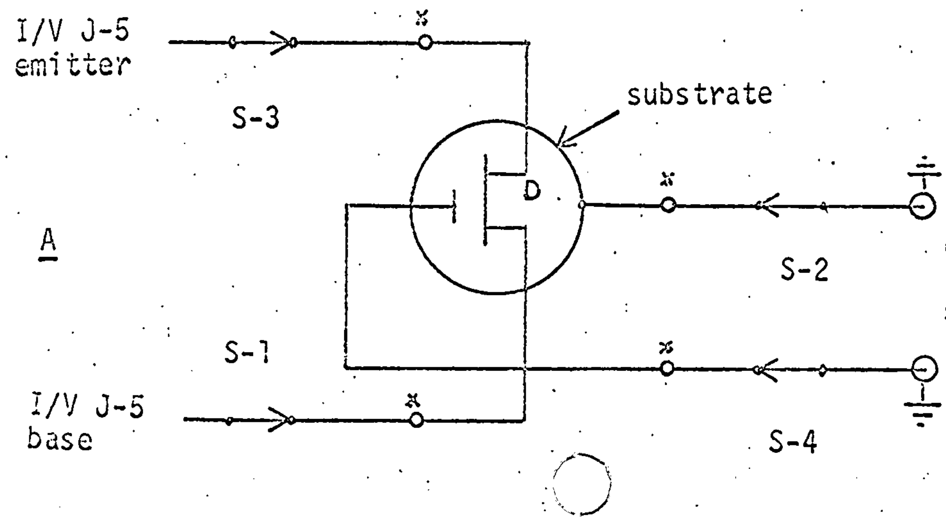
1 system shown in bipolar measurement configuration.
2. can also be shorted.
3. Automatic C-B Switching Circuit; shown in base measurement configuration.
4. NPN-PNP Switch shown in NPN position.

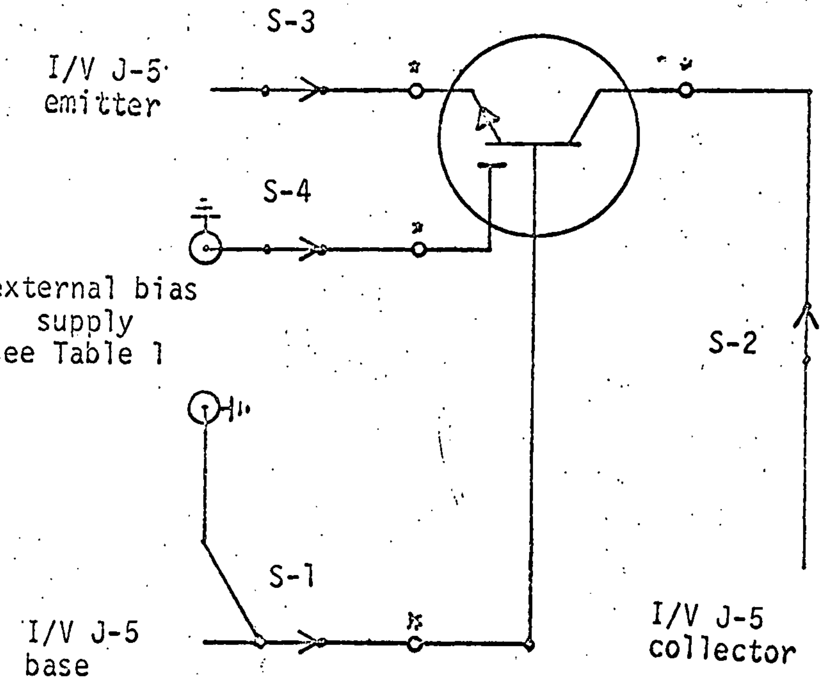
FIG. IV-2: CONTROL CENTER AND AUTORANGING CURRENT SAMPLER



notes: 1. BNC connectors located on jig face.
2. ss - shorting switch (located on jig face).
3. see Fig. IV-2 for I/V J-5 connections.

FIG. IV-3: TEST JIG NO. 2





A. 1. I/V System in Constant I_B Mode.

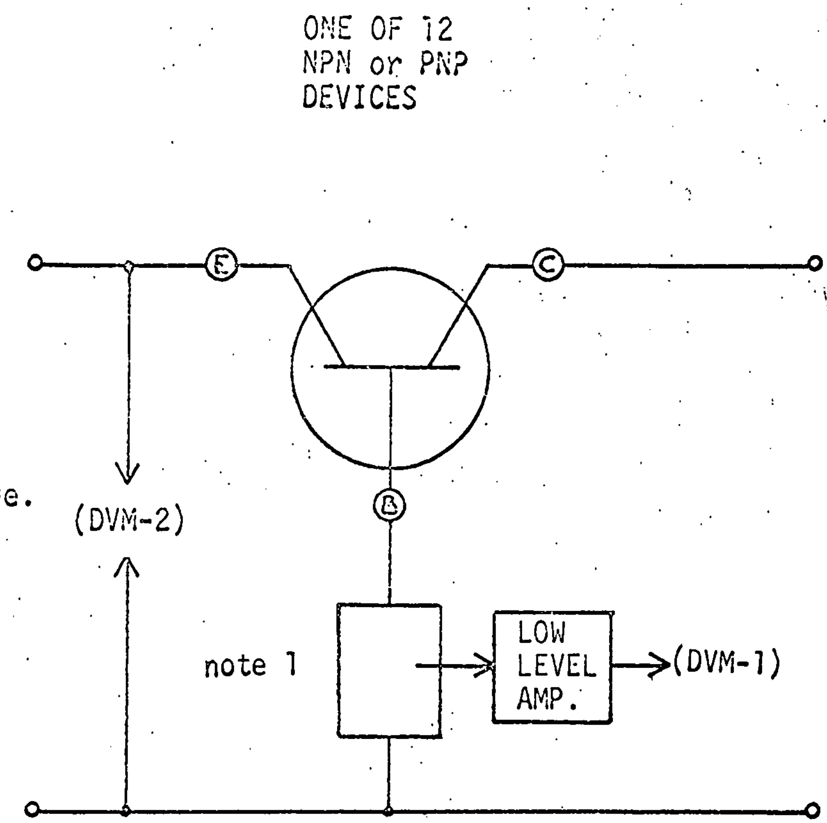
2. same supply possibilities as in Fig. IV-5.

notes: *1. 12 pin socket: any 4 can be selected for testing.

2. remaining leads can be connected to a shorting bus which can be floated or guarded.

3. all configurations of Test Jig No. 1 (Fig. IV-5) are possible with Test Jig No. 2.

FIG. IV-4: TEST JIG NO. 2 - POSSIBLE CONFIGURATIONS



1. Programmable Voltage (0-50V)
   a. with or without programmable polarity change.
   b. manual polarity change via "NPN-PNP" switch.
2. Programmable Current (1 A-2A)

1. Junction bias supplies
   a. either polarity.
   b. see Table 1.
2. shorted
3. open

note 1: Autoranging Current Sampler - sampling resistance alternates from base lead to collector lead or can be selected to remain in either lead.

FIG. IV-5: TEST JIG NO. 1 - POSSIBLE CONFIGURATIONS

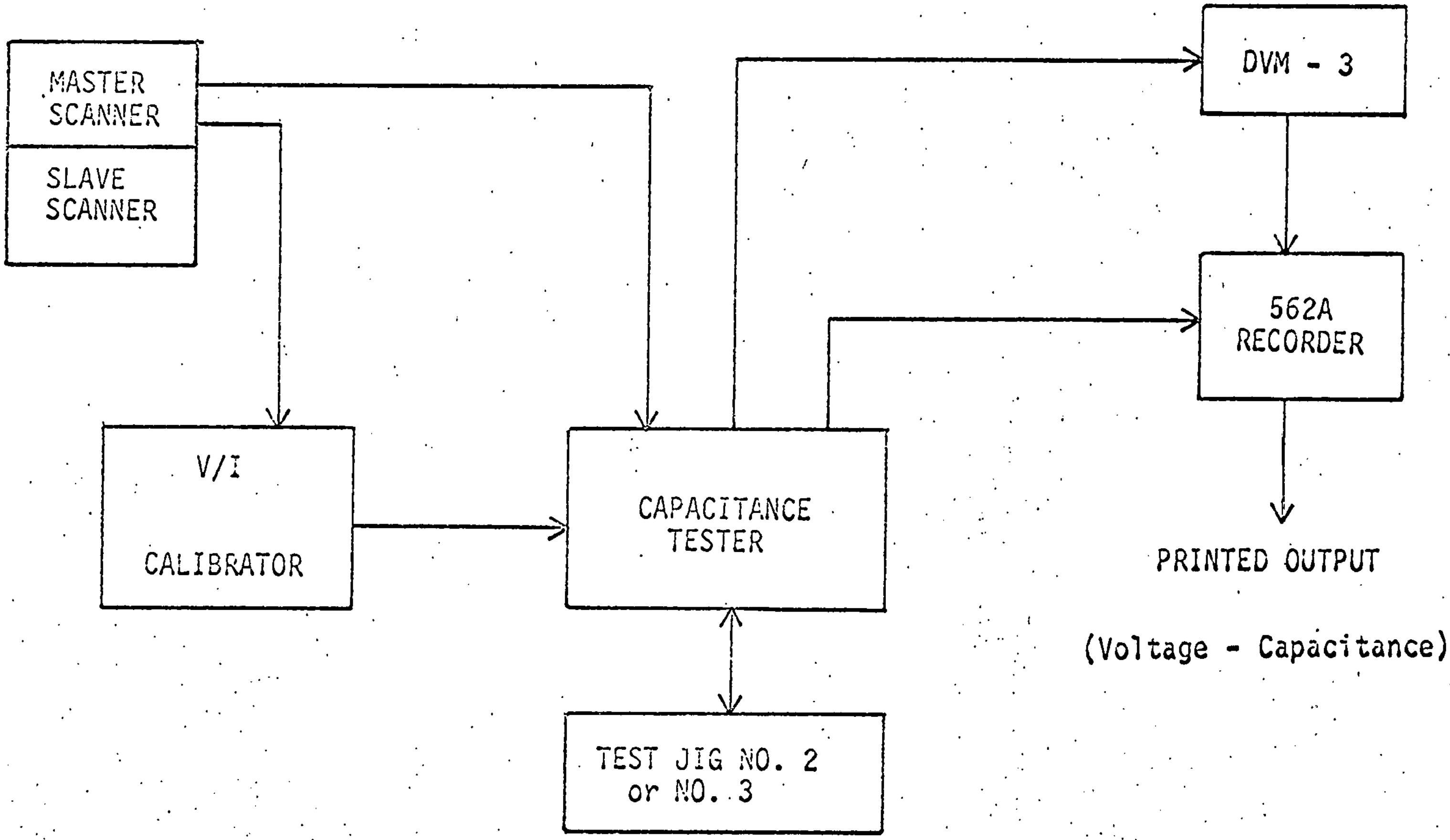


FIG. IV-6: C/V SYSTEM - PRINT ONLY MODE

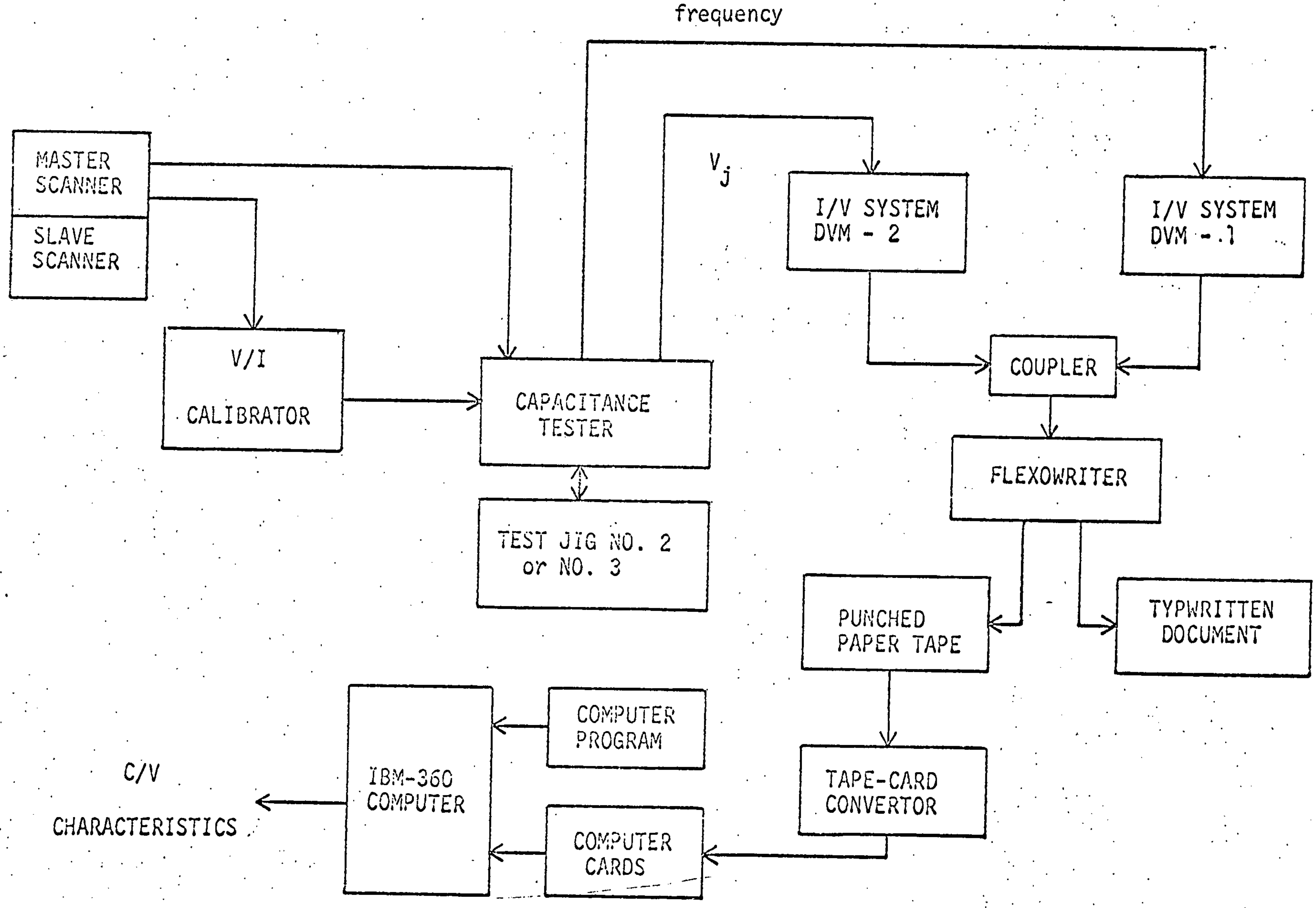


FIG. IV-7: C/V SYSTEM - PRINT AND PUNCH MODE

This configuration gives a printed copy along with a punched paper tape of capacitance-voltage data. DVM-1 is operated in the frequency sensing mode (output frequency of 1201DS is proportional to capacitance) while DVM-2 senses the applied voltage. (The information on the punched tape is then converted to IBM cards via the IBM-047 tape-to-card converter and the cards are then used in various data reduction programs developed by this group.)

Previously, to obtain C/V data under forward and reverse bias conditions, the device under test had to be physically reversed in the test socket. A recent addition to this system has been the incorporation of two polarity reversal switches. One switch, labeled "NPN/FWD-REV, PNP/REV-FWD", is used to change the junction bias polarity. The second switch, labeled "NPN-PNP", allows the digital voltmeters to sense the bias voltage in the correct polarity, thereby allowing the proper sign to be encoded.

Test Jig No. 3: Test jig No. 3, like test jig No. 1, has 12 four-pin sockets. However, here, each socket is manually selected. Since the 1201DS has only three test leads, one of which carries a guard signal, provisions have been made to switch the Hi and Lo test leads to either the first or second junction, and to place the other junction in the guard circuit at the same time. It should be noted that test jig No. 2 has the same features except that the guard circuit does not necessarily have to be applied to the opposite junction.

Scattering Parameters Data Acquisition System

The S-parameter data acquisition system is designed to measure scattering parameters in the frequency range of 0.1 GHz to 2.0 GHz. Selection of the particular parameter (S_{11}, S_{12}, S_{21}, S_{22}) is accomplished by a front panel pushbutton. The test head provides the reference plane for the device under test and provides a simple means of selecting the device configuration. Bias for the device under test is applied through the test set to the test head (see Table 1 for list of bias supplies). To measure any of the parameters, the test signal is applied through a dual directional coupler to the appropriate test port. Part of the signal is fed from the coupler and is used as the reference channel signal. The reflected signal (S_{11} or S_{22}) or the transmitted signal (S_{12} or S_{21}) is then coupled out as the test channel signal.

A Hewlett-Packard 8690B Sweep Oscillator with 8699B RF Plug-in Unit allows swept-frequency measurements in the range from 0.1 Hz to 2.0 Hz and the rapid and accurate determination of device high-frequency characteristics. When making swept-frequency measurements, a reference and a test channel signal from the S-parameter test set are converted into 20 MHz i-f signals (phase and amplitude relationships between the r-f signals are maintained) in the Frequency Converter. The two i-f signals are then fed to the Network Analyzer which includes automatic frequency tuning circuits, i-f amplifiers, precision i-f gain control and power supply for the converter. A front panel switch selects the desired octave range between 0.1 and 12.4 GHz. The analyzer phase locks to the frequency and follows it during sweep operation.

The Polar Display provides a Cathode ray tube readout of magnitude and phase in polar coordinate form. Overlays can be used to provide Smith chart and expanded Smith chart read-out of normalized impedance or admittance. Two frequency marker signals may be fed to the Polar Display for accurate frequency reference points.

Analog outputs from the Polar Display are provided for use with an X-Y recorder (HP-136A) to provide permanent Smith chart records of the data. These outputs may also be connected to the digital voltmeters of the Automatic Data Acquisition System where they can be recorded in tabular form. Fig. IV-8 shows the interconnection of the S-parameter system.

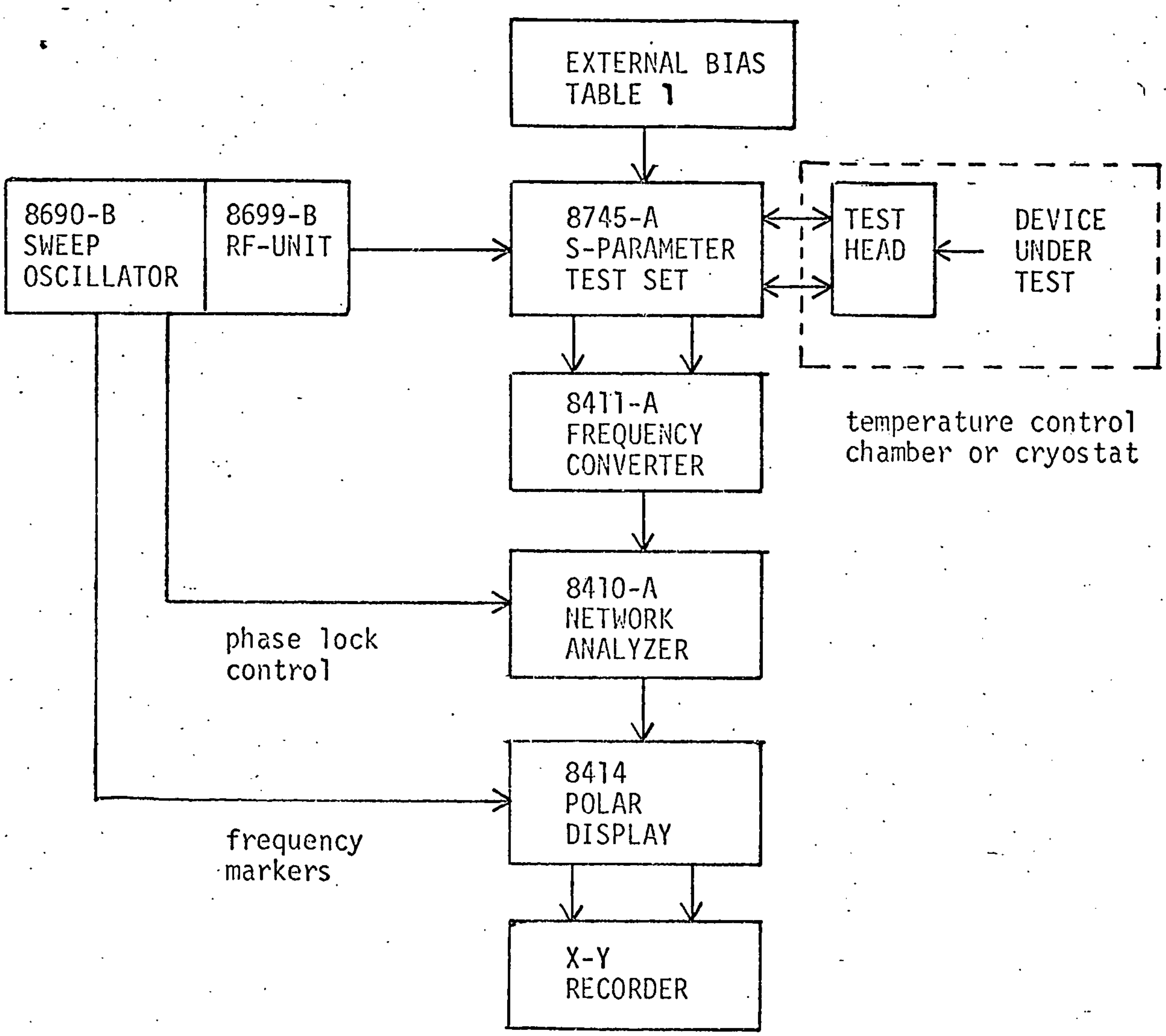
Recently a Pope Scientific Crystat (Model 30086-2) was purchased. It is 28 inches in height with an I. D. of 3 inches and an O. D. of 9 inches. This cryostat will be connected to an existing vacuum system located in the High Vacuum Research Laboratory at the Graduate Center for Materials Research of the University of Missouri - Rolla. With this unit temperatures down to that of liquid helium can be obtained. A special test head is being developed to allow swept-frequency measurements at these low temperatures. Also in the design and planning stages are special test jigs to allow I/V and C/V data to be taken at these same low temperatures.

Lifetime and Switching Characteristics Data Acquisition System

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

Small Signal Dynamic Characteristics Data Acquisition System

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



note: 1. all model numbers Hewlett-Packard

FIG. IV-8: S-PARAMETERS DATA AQUISITION SYSTEM

Programmed Data Processor

The Programmed Data Processor is a Digital Equipment Corporation Model PDP-8/1. The processor has 8192 words (12 bits per word) of core memory with a 1.5 microsecond cycle time and hardware multiply and divided option. The input-output unit for the processor is an ASR-33 Teletype Automatic Send/Receive, Reader/Punch Unit. This unit reads or punches at a rate of 10 characters per second. Additionally, to shorten the input-output time, a high speed reader-punch Model PC-8/I has been added. The Model PC-8/I reads paper tape at a rate of 300 characters per second and punches at a rate of 50 characters per second.

Calibration Standards

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

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

Scanning Electron Microscope

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

V. DEVIATIONS

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

VI. REPORT OF EQUIPMENT PURCHASED WITH AEC FUNDS

Pope Scientific Cryostat $589.00

VII. STATEMENT OF AEC FUNDS UNEXPENDED

AEC Funds provided by June 1, 1970 through May 31, 1971, Contract Supplement No. 3-1	$32,423
Unexpended Funds from previous period	0
Total AEC Funds June 1, 1971, through May 31, 1971	32,423
Costs from June 1, 1970, through May 31, 1971	32,423
Total AEC Funds expended June 1, 1970 through May 31, 1971	32,423
AEC Funds unexpended	0

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COO-1624-01 "An Automatic Data Acquisition System for Semiconductor Device Testing", D. L. Bartling (M.S. Thesis, University of Missouri - Rolla Library) 1967.

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COO-1624-03 "Neutron Dependence of Collector Junction Parameters", T. D. Beckman and C. A. Goben, 1967.

COO-1624-04 "Annealing Characteristics of Neutron Irradiated Silicon Transistors", J. R. Chott and C. A. Goben, IEEE Trans. on Nuclear Science, NS-14; 6, 134-146, 1967. (GCMR-23)

COO-1624-05 "Variation of the Inverse Parameters with Neutron Irradiation in Silicon Transistors", G. E. Gassner and C. A. Goben, 1968.

COO-1624-06 "Annealing Characteristics of Neutron Irradiated Silicon Transistors", J. R. Chott (M.S. Thesis, University of Missouri - Rolla Library) 1967.

COO-1624-07 "Recombination Statistics for the Neutron Induced Current Component", J. Bereisa, Jr., M. C. Chow and C. A. Goben, Presented at the 1968 IEEE Nuclear and Space Radiation Effects Conference, Missoula, Montana, July 1968. (Summary, pp. 39-42, July 1968.)

COO-1624-08 "Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration", P. E. Johnson, L. S. Su, T. D. Beckman and C. A. Goben, Presented at the 1968 IEEE Nuclear and Space Radiation Effects Conference, Missoula, Montana, July 1968. (Summary pp. 43-46, July 1968.)

COO-1624-09 "Field Dependence of Neutron-Induced Defects in Silicon p-n Junctions", P. E. Johnson and C. A. Goben, 1968.

COO-1624-10 "Neutron Dependence of Neutral Base Region Recombination", J. Bereisa, Jr. and C. A. Goben, IEEE Trans. on Nuclear Science, NS-17; 6, 317-324, 1970. (GCMR-98)

COO-1624-11 "Technical Progress Report-February 1968", C. A. Goben, 1968.

COO-1624-12 "Recombination Statistics for Neutron Bombarded Silicon Transistors", M. C. Chow, J. L. Azarewicz and C. A. Goben, IEEE Trans. on Nuclear Science, NS-15; 6, 88-94, 1968. (GCMR-40)

COO-1624-13 "Radiation and Annealing Characteristics of Neutron Bombarded Silicon Transistors", L. S. Su, G. E. Gassner and C. A. Goben, IEEE Trans. on Nuclear Science, NS-15; 6, 107, 1968. (GCMR-41)

COO-1624-14 "Recombination Statistics for the Neutron-Induced Base Current Component", M. C. Chow (Ph.D. Dissertation, University of Missouri - Rolla Library)

COO-1624-15 "Radiation and Annealing Characteristics of Neutron Bombarded Silicon Transistors", L. S. Su (M.S. Thesis, University of Missouri - Rolla Library) 1968.

COO-1624-16 "Determination of Transistor Characteristics after Neutron Radiation", J. L. Azarewicz, T. D. Beckman, J. Bereisa, Jr., and C. A. Goben, 1969.

COO-1624-17 "Investigation of Defect Clusters in Silicon P-N Junctions", C. H. Irani, P. E. Johnson, J. L. Van Meter and C. A. Goben, Presented at the 1969 IEEE Nuclear and Space Radiation Effects Conference, State College, Pennsylvania, July 1969. (Summary, pp. 27-30, July 1969.)

COO-1624-18 "Determination of the Doping Profile of Double Diffused P-N Junction Device", J. L. Azarewicz and C. A. Goben, SWIEEECO RECORD, 70C5; 72-75, April 1970. (GCMR-77)

COO-1624-19 "Determination of Graded Base Parameters in the Presence of Recombination at Low to Moderate Injection Levels", J. Bereisa, Jr. and C. A. Goben SWIEEECO RECORD, 70C5; 181-185, April 1970. (GCMR-78)

COO-1624-20 "Technical Progress Report-February 1969", C. A. Goben, 1969.

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

COO-1624-22 "Neutron Fluence and Electric Field Strength Dependencies of the Rate of Volume Damage Introduction in Silicon P-N Junctions", C. A. Goben, C. H. Irani and P. E. Johnson, IEEE Trans. on Nuclear Science, NS-16; 6, 43-52, 1969. (GCMR-55)

COO-1624-23 "The Nucleus", C. A. Goben IEEE Trans. on Nuclear Science, NS-16; 6, 6, 1969. (GCMR-66)

COO-1624-24 "Technical Progress Report-February 1970", C. A. Goben, 1970.

COO-1624-25 "Neutron Radiation Effects on the Net Impurity Doping Profile of Double Diffused Transistors", C. A. Goben and J. Bereisa, Jr., Presented at the 1970 IEEE Nuclear and Space Radiation Effects Conference, San Diego, California, 1970.

COO-1624-26 "Electric Field Strength Dependence of Surface Damage in Oxide Passivated Silicon Planar Transistors", C. A. Goben and C. H. Irani, IEEE Trans. on Nuclear Science, NS-17; 6, 18-26, 1970. (GCMR-100)

COO-1624-27 "An Improved Transistor Model for Computer Aided Analysis and Design of Circuits Operated in Radiation Environments", C. A. Goben and G. R. Case, Submitted to IEEE Transactions on Nuclear Science, 1971. (GCMR-102)

COO-1624-28 "Electric Field Strength Dependency of the Rate of Radiation Induced Degradation in Silicon Planar Devices", C. H. Irani and C. A. Goben (Project Director) 1970; C. H. Irani (M.S. Thesis, University of Missouri - Rolla Library) 1970.

COO-1624-29 "A Mathematical Model for the Neutron Dependence of Neutral Base Region Recombination", J. Bereisa, Jr. and C. A. Goben (Project Director), 1970; J. Bereisa, Jr., (M.S. Thesis, University of Missouri - Rolla Library) 1970.

COO-1624-30 "Radiation Damage in n-type Silicon: Si-A and Si-E Centers", C. H. Irani and C. A. Goben (Project Director) 1970; C. H. Irani (Presented at the Seventh Mid-America American Nuclear Society Student Conference, Columbus, Ohio) April 1969. (Proc., p. 68, April 1969.)

COO-1624-31 "Calculation of the Neutron-Induced Changes in the Net Impurity Concentration of Planar-Epitaxial Transistors", J. L. Azarewicz and C. A. Goben (Project Director) 1970; J. L. Azarewicz (Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri) April 1970. (Proc., p. 54, April 1970).

COO-1624-32 "Neutron Dependence of Electric Field-Aided Minority Carrier Transport", J. Bereisa, Jr. and C. A. Goben (Project Director) 1970; J. Bereisa, Jr. (Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri) April 1970. (Proc., p. 51, April 1970).

COO-1624-33 "Nuclear Radiation Effects on Transistors Operating at High Frequencies", D. L. Gray, Y. P. Han and C. A. Goben (Project Director) 1970; D. L. Gray and Y. P. Han (Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri) April 1970. (Proc., p. 55, April 1970).

COO-1624-34 "Prediction of Gamma Induced Surface Degradation in Oxide Passivated Bipolar Transistors", C. H. Irani and C. A. Goben (Project Director) 1970; C. H. Irani (Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri) April 1970. (Proc., p. 52, April 1970).

COO-1624-35 "Neutron Radiation Damage in Silicon Transistors", C. A. Goben, F. M. Smits and J. L. Wirth, IEEE Trans. on Nuclear Science, NS-15; 2, 14-29, 1968. (GCMR-42)

COO-1624-36 "Optimum Initial Design Criteria for the Impurity Profiles and Geometries of Radiation Hardened Diffused Silicon P-N Junction Devices", C. A. Goben, J. Bereisa, Jr., C. H. Irani and Y. P. Han, Presented at the 1970 Government Microcircuits Applications Conference: GOMAC, Fort Monmouth, N. J., October 1970, Proc. GOMAC, October, 1970.

COO-1624-37 "Nuclear Radiation Enhancement of Transistors Forward Current Gain at High Frequencies", C. A. Goben, D. L. Gray and Y. P. Han, IEEE Trans. on Nuclear Science, NS-17, 6, 380-388, 1970. (GCMR-101)

COO-1624-38 "Technical Progress-Final Report-June 1970", C. A. Goben, 1970.

COO-1624-39 "A Mathematical Model for Primary Photo-Currents Induced in Transistor Base Regions", C. A. Goben and Y. P. Han, Presented at the 1971 IEEE Nuclear and Space Radiation Effects Conference, Durham, N. H., 1971; also, submitted to IEEE Transactions on Nuclear Science, 1971.

COO-1624-40 "Effect of Electric Field Strength, Geometry and Impurity Dopants on Surface Degradation in Silicon Passivated Planar Transistors", C. A. Goben and C. H. Irani, Submitting to IEEE Tranactions on Nuclear Science, 1971.

COO-1624-41 "Technical Progress-Final Report-Period: 1 June 1966-31 May 1971", C. A. Goben, 1971.

X. THESES AND DISSERTATIONS BASED ON WORK SUPPORTED BY THE U.S.A.E.C.

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

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

3. "Recombination Statistics for the Neutron-Induced Base Current Component", M.C. Chow (Ph.D. Dissertation, University of Missouri-Rolla Library), 1968.

4. "Radiation and Annealing Characteristics of Neutron Bombarded Silicon Transistors", L.S. Su (M.S. Thesis, University of Missouri-Rolla Library), 1968.

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

6. "Electric Field Strength Dependency of the Rate of Radiation Induced Degradation in Silicon Planar Devices", C.H. Irani (M.S. Thesis, University of Missouri-Rolla Library), 1970.

7. "A Mathematical Model for the Neutron Dependence of Neutral Base Region Recombination", J. Bereisa, Jr. (M.S. Thesis, University of Missouri-Rolla Library), 1970.

8. "Variation of Inverse Transistor Parameters with Neutron Radiation in Silicon Transistors", G.E. Gassner (M.S. Thesis, Expected Completion Date, Summer 1971).

9. "Field Dependence of Neutron-Induced Defects in Silicon p-n Junctions", P.E. Johnson (M.S. Thesis, Expected Completion Date, Summer 1971).

10. "Ionizing Radiation Induced Perturbations of the Physical and Electrical Properties of the Silicon-Silicon Dioxide Interface", C. H. Irani (Ph.D. Dissertation-work in progress), 1971.

XI. THESES AND DISSERTATIONS USING AEC-PURCHASED EQUIPMENT BUT NOT SUPPORTED BY THE U.S.A.E.C.

1. "Small-Signal Impedance of a Junction Diode at High Injection Levels", J.E. Lundy (M.S. Thesis, University of Missouri-Rolla Library), 1967.

2. "Models for the PN Diode and the NPN and PNP Transistor for Use in Computer Aided Design and Analysis Programs", G.R. Case (Ph.D. Dissertation, University of Missouri-Rolla Library), 1969.

3. "Temperature Dependent Diode and Transistor Models for Computer Aided Network Analysis and Design", J.I. Giem (Ph.D. Dissertation-work in progress), 1971.

XII. NON-THESIS STUDENTS SUPPORTED BY AEC FUNDS

J. L. Azarewicz	(August 1868-May 1970)
T. D. Beckman	(June 1966-May 1968)
Y. P. Han	(December 1969-March 1971)
Y. M. Hong	(December 1966-August 1967)
J. L. Van Meter	(June 1968-May 1969)

XIII. PRESENTATIONS BASED ON WORK SUPPORTED BY THE U.S. ATOMIC ENERGY COMMISSION

1 June 1966-31 May 1970, Contract AT(11-1)-1624

"NUCLEAR RADIATION EFFECTS IN SILICON P-N JUNCTIONS"

1. "An Automatic Data Acquisition System for Semiconductor Device Testing", D. L. Bartling, C.R. Jenkins and C.A. Goben, Presented at the 1967 Meeting of the Missouri Academy of Science, Rolla, Missouri, April 1967 (C.A. Goben-Abstract), Trans. Missouri Academy of Science, 1; 86-87, August 1967.

2. "Annealing Characteristics of Neutron Irradiated Silicon Transistors", J.R. Chott and C.A. Goben, Presented at the 1967 Nuclear and Space Radiation Effects Conference, Columbus, Ohio (J.R. Chott-Summary), Summaries of Papers IEEE Annual Conference on Nuclear and Space Radiation Effects; III-5-8, 1967.

3. "Recombination Statistics for the Neutron Induced Current Component", J. Bereisa, Jr., M.C. Chow and C.A. Goben, Presented at the 1968 IEEE Nuclear and Space Radiation Effects Conference, Missoula, Montana, July 1968 (C.A. Goben-Summary), Summaries of Papers-IEEE Annual Conference on Nuclear and Space Radiation Effects; 39-42, July 1968.

4. "Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration", P.E. Johnson, L.S. Su, T.D. Beckmann and C.A. Goben, Presented at the 1968 IEEE Nuclear and Space Radiation Effects Conference, Missoula, Montana, July 1968 (C.A. Goben-Summary), Summaries of Papers-IEEE Annual Conference on Nuclear and Space Radiation Effects; 43-46, July 1968.

5. "Radiation Damage in n-type Silicon: Si-A and Si-E Centers", C.H. Irani and C.A. Goben (Project Director) Presented at the Seventh Mid-America American Nuclear Society Student Conference, Columbus, Ohio, April 1969 (C.H. Irani-Abstract), Proc. Annual Midwestern Student Conference of the American Nuclear Society; 68, April 1969.

6. "Investigation of Defect Clusters in Silicon P-N Junctions", C.H. Irani, P.E. Johnson, J.L. Van Meter and C.A. Goben, Presented at the 1968 IEEE Nuclear and Space Radiation Effects Conference, State College, Pennsylvania, July 1969 (C.A. Goben-Summary), Summaries of Papers-IEEE Annual Conference on Nuclear and Space Radiation Effects; 27-30, July 1969.

7. "Determination of the Doping Profile of Double Diffused P-N Junction Devices", J.L. Azarewicz and C.A. Goben, Presented at the Twenty-Second Annual IEEE Southwestern IEEE Conference, Dallas, Texas, April 1970.

8. "Determination of Graded Base Parameters on the Presence of Recombination at Low to Moderate Injection Levels", J. Bereisa, Jr. and C.A. Goben, Presented at the Twenty-Second Annual Southwestern IEEE Conference, Dallas, Texas, April 1970.

9. "Calculation of the Neutron-Induced Changes in the Net Impurity Concentration of Planar-Expitaxial Transistors", J.L. Azarewicz and C.A. Goben (Project Director), Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri, April 1970 (J.L. Azarewicz-Abstract), Proc. Eighth Mid-America American Nuclear Society Student Conference; 54, April 1970.

10. "Neutron Dependence of Electric Field-Aided Minority Carrier Transport", J. Bereisa, Jr. and C.A. Goben (Project Director), Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri, April 1970 (J. Bereisa, Jr.-Abstract), Proc. Eighth Mid-America American Nuclear Society Student Conference; 51, April 1970.

11. "Nuclear Radiation Effects on Transistors Operating at High Frequencies", D.L. Gray, Y.P. Han and C.A. Goben (Project Director), Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri, April 1970 (D.L. Gray and Y.P. Han-Abstract), Proc. Eighth Mid-America American Nuclear Society Student Conference; 55, April 1970.

12. "Prediction of Gamma Induced Surface Degradation in Oxide Passivated Bipolar Transistors:, C.H. Irani and C.A. Goben (Project Director), Presented at the Eighth Mid-America American Nuclear Society Student Conference, Rolla, Missouri, April 1970 (C.H. Irani-Abstract), Proc. Eighth Mid-America American Nuclear Society Student Conference; 52, April 1970.

13. "Neutron Dependence of Neutral Base Region Recombination", J. Bereisa, Jr. and C.A. Goben, Presented at the 1970 IEEE Nuclear and Space Radiation Effects Conference, San Diego, California, July 1970 (C.A. Goben-Summary), Summaries of Papers-IEEE Annual Conference on Nuclear and Space Radiation Effects; 221-224, July 1970.

14. "Neutron Radiation Effects on the Net Impurity Doping Profile of Double Diffused Transistors:, C.A. Goben and J. Bereisa, Jr., Presented at the 1970 IEEE Nuclear and Space Radiation Effects Conference, San Diego, California, July 1970 (C.A. Goben-Summary), Summaries of Papers-IEEE Annual Conference on Nuclear and Space Radiation Effects; 229-231, July, 1970.

15. "Electric Field Strength Dependence of Surface Damage in Oxide Passivated Silicon Planar Transistors", C.A. Goben and C. H. Irani, Presented at the 1970 IEEE Nuclear and Space Radiation Effects Conference, San Diego, California, July 1970 (C.H. Irani-Summary), Summaries of Papers-IEEE Annual Conference on Nuclear and Space Radiation Effects; 5-8, July 1970.

16. "Optimum Initial Design Criteria for the Impurity Profiles and Geometries of Radiation Hardened Diffused Silicon P-N Junction Devices," C.A. Goben, J. Bereisa, Jr., C.H. Irani and Y.P. Han, Presented at the 1970 Government Microcircuits Applications Conference: GOMAC, Fort Monmouth, N.J., October 1970.

17. "A Mathematical Model for Primary Photo-Currents Induced in Transistor Base Regions", C.A. Goben and Y.P. Han, Presented at the 1971 IEEE Nuclear and Space Radiation Effects Conference, Durham, N.H., July 1971, (C.A. Goben-Summary), Summaries of Papers, IEEE Annual Conference on Nuclear and Space Radiation Effects; 176-179, July 1971.

XIV. PUBLICATIONS BASED ON WORK SUPPORTED BY THE U.S. ATOMIC ENERGY COMMISSION

1 June 1966 - 31 May 1970, Under Contract AT(11-1) - 1624;

"NUCLEAR RADIATION EFFECTS IN SILICON P-N JUNCTIONS."

1. "Annealing Characteristics of Neutron Irradiated Silicon Transistors", J. R. Chott and C.A. Goben, IEEE Trans. on Nuclear Science, NS-14;6, 134-146, 1967. (GCMR-23)

2. "Recombination Statistics for Neutron Bombarded Silicon Transistors", M.C. Chow, J.L. Azarewicz and C.A. Goben, IEEE Trans. on Nuclear Science, NS-15;6, 88-94 1968. (GCMR-40)

3. "Radiation and Annealing Characteristics of Neutron Bombarded Silicon Transistors", L.S. Su, G.E. Gassner and C.A. Goben, IEEE Trans. on Nuclear Science, NS-15;6, 95-107, 1968. (GCMR-41)

4. "Neutron Radiation Damage in Silicon Transistors", C.A. Goben, F.M. Smits and J.L. Wirth, IEEE Trans. on Nuclear Science, NS-15;2, 14-29, 1968. (GCMR-42)

5. "An Automatic Data Acquisition System for Semiconductor Device Testing", D.L. Bartling, C.R. Jenkins and C.A. Goben, IEEE Trans. on Instrumentation and Measurement, IM-17;1, 19-28, 1968. (GCMR-43)

6. "Neutron Fluence and Electric Field Strength Dependencies of the Rate of Volume Damage Introduction in Silicon P-N Junctions", C.A. Goben, C.H. Irani and P.E. Johnson, IEEE Trans. on Nuclear Science, NS-16;6, 43-52, 1969. (GCMR-55)

7. "The Nucleus", C.A. Goben, IEEE Trans. on Nuclear Science, NS-16;6, 5, 1969. (GCMR-66)

8. "Determination of the Doping Profile of Double Diffused P-N Junction Devices", J.L. Azarewicz and C.A. Goben, SWIEEECO Record 70C5; 72-75 April 1970. (GCMR-77)

9. "Determination of Graded Base Parameters in the Presence of Recombination at Low to Moderate Injection Levels", J. Bereisa, Jr. and C.A. Goben, SWIEEECO Record, 70C5; 181-185, April 1970. (GCMR-78)

10. "Neutron Dependence of Neutral Base Region Recombination", J. Bereisa, Jr. and C.A. Goben, IEEE Trans. on Nuclear Science, NS-17;6, 317-324, 1970. (GCMR-98)

11. "Neutron Radiation Effects on the Net Impurity Doping Profile of Double Diffused Transistors", C.A. Goben and J. Bereisa, Jr., Presented at the 1970 IEEE Nuclear and Space Radiation Effects Conference, San Diego, California, July 1970; Also, submitted to IEEE Trans. on Nuclear Science, 1971. (GCMR-99)

12. "Electric Field Strength Dependence of Surface Damage in Oxide Passivated Silicon Planar Transistors", C.A. Goben and C.H. Irani, IEEE Trans. on Nuclear Science, NS-17;6, 18-26, 1970. (GCMR-100)

13. "Nuclear Radiation Enhancement of Transistor Forward Current Gain at High Frequencies", C.A. Goben, D.L. Gray and Y.P. Han, IEEE Trans. on Nuclear Science, NS-17;6, 380-388, 1970. (GCMR-101)

14. "An Improved Transistor Model for Computer Aided Analysis and Design of Circuits Operated in Radiation Environments", C.A. Goben and G.R. Case, Submitted to IEEE Transactions on Nuclear Science, 1971. (GCMR-102)

15. "Optimum Initial Design Criteria for the Impurity Profiles and Geometries of Radiation Hardened Diffused Silicon P-N Junction Devices", Proc. GOMAC, October 1970.

16. "A Mathematical Model for Primary Photo-Currents Induced in Transistor Base Regions", C.A. Goben and Y.P. Han, Submitted to IEEE Transactions on Nuclear Science, 1971.

17. "Effect of Electric Field Strength, Geometry, and Impurity Dopants on Surface Degradation in Passivated Silicon Planar Transistors", C.A. Goben and C.H. Irani, Submitted to IEEE Transactions on Nuclear Science, 1971.

XV. PERSONNEL

Project Director:

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

Eighty percent time, academic year; 100 percent time, summer ($2\frac{1}{2}$ months).

Graduate Research Assistants:

Fifty percent time.

Name	Degrees/Background	Department and Degree Sought
J. Bereisa, Jr.	BS/EE, 1967, U. of Missouri-Rolla MS/EE, 1970, U. of Missouri-Rolla Western Electric Co.-Summers 1965-66; Collins Radio Co.-Engr. in Data Systems Division R&D-Summer 1967; Graduate Research Asst., Space Sciences Research Center (Materials), Univ. of Missouri-Rolla, Sept. 1967-August 1970.	*
V. K. Dutta	B.Sc. (Hons)/P.E., 1968, Indian School of Mines. India - MS/PE University of Missouri Rolla, 1970. Graduate Research Assistant, Space Sciences Research Center (Materials), University of Missouri-Rolla, July 1970-May 1971.	MS/C.Sc.
Y. P. Han	BS/EE, 1959, Taipei Institute of Technology, Taiwan, China. MS/EE, 1969, Wichita State Univ. Ordnance Officer in Chinese Army, 1959-1961; Engr. Nuclear Instrumentation, Institute of Nuclear Science, National Tsing Hwa Univ., 1961-1963; Teaching Asst. and Laboratory Director of E.E., Taipei Inst. of Tech., 1963-66; Engr., Flight Test-Cessna Air Craft Co., 1968-69; Graduate Research Assistant, Space Sciences Research Center (Materials), Univ. of Missouri-Rolla, Dec. 1969-Feb. 1971.	Ph.D./EE

*Graduated

Name	Degree/Background	Department and Degree Sought
K.C. Ho	BS/EE, 1968, Taiwan University, Taiwan, China MS/C.Sc., 1970, University of Missouri-Rolla Officer in Chinese Army, 1968-1969; Graduate Research Assistant, Space Sciences Research Center (Materials), Univ. of Missouri-Rolla, July 1970-May 1971.	*
C. H. Irani	B. Tech. (HONS)/Met.-NE, 1968 Indian Institute of Tech.-Bombay, India MS/NE, University of Missouri-Rolla, 1970 Kirloskar Cummins, Poona, India, Summer 1967, Trainee Engineer; Graduate Research Asst., Space Sciences Research Center (Materials), Univ. of Missouri-Rolla, Sept. 1968-May 1971.	Ph. D./NE
P. E. Johnson	BS/MET-NE, 1967, U. of Missouri-Rolla. Summers 1962, 1963, 1964, 1965, 1966-Laboratory Technician, Alco Value Co., St. Louis, Mo.; Graduate Research Assistant, Space Sciences Research Center (Materials), Univ. of Missouri-Rolla, June 1967-Nov. 1968. Nov. 1968-Nov. 1970 - On active duty with the U.S. Army as Chief of System Analysis Programming Branch, 7COSCOM, MMC; Graduate Research Assistant Space Sciences Research Center (Materials), University of Missouri-Rolla, Jan. 1971-May 1971.	MS/MET

Research Technicians:

Name	Degree/Background	Department and Degree Sought
C. R. Jenkins	Associate in Science, Electronic Engineering Technology, 1963 BS/EE University of Missouri-Rolla, 1970. 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 Corporation; Electronic Research Technologist, Space Sciences Research Center (Materials), Univ. of Missouri-Rolla, June 1966-August 1970. Publications C. R. Jenkins, "Passive Temperature Monitoring in Radiation Environment," SC-TM-66-282, Sandia Laboratory (Alburquerque, New Mexico) 1966.	*

*Graduated

Name	Degree/Background	Department and Degree Sought
Research Technicians:		
C. R. Jenkins (Cont.)	Publications (Cont.)	
	D. L. Bartling, C. R. Jenkins and C. A. Goben, "An Automatic Data Acquisition System for Semiconductor Device Testing," IEEE Transactions on Instrumentation and Measurement, IM-17:1, 19-28 - 1968.	*
S. W. Joseph	U. S. Navy, 1961-68; Electricians Mate 'A' School, 1961; Basic Enlisted Submarine School, 1962; USS Bang SS385 1962; Naval Nuclear Power School - Bainbridge, Md., 1963; Naval Nuclear Prototy PE School - Westmilton, N.Y., 1963; USS Nathan Hale SSBN-623 (Polaris) 1964-68; Naval Air Station-Cecil Field, Florida, 1968. General Dynamics, Quincy Shipbuilding Division, 1969; Research Technician, Space Sciences Research Center (Materials) Univ. of Missouri-Rolla 1970-71.	BS/NE-EE

* Graduated