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ANNEALING CHARACTERISTICS
OF
NEUTRON IRRADIATED
SILICON TRANSISTORS

BY

JOSEPH ROBERT CHOTT - 1943

A

THESIS

Submitted to the Faculty of the

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Approved by

Charles A Goben (Advisor)   Doyle Ray Edwards

Le Roy Venteicher   Albert E. Bolon

ABSTRACT

When a transistor is subjected to neutron irradiation, a component of base current proportional to neutron fluence is induced. From the effects of annealing on the base and collector currents, the conclusion was drawn that there is an apparent difference in the annealing characteristics between the neutral and the space-charge regions of the semiconductor device.

This study of the anomalous annealing indicates that the neutron-induced component of base current is a result of one, or a combination, of the following mechanisms: a quasi-tunneling recombination phenomena in the emitter-base space-charge region, or an influence of the p-n junction electric field on the formation, annealing, and electronic behavior of the neutron-induced defect centers.

A field dependence of the formation and annealing of the neutron-induced defects appears to be present both during the introduction and annealing of the neutron-induced defect centers. It could not be finally determined whether or not the quasi-tunneling phenomena occurred although it can be shown on theoretical grounds that it is possible for such phenomena to occur.

The annealing characteristics of the defects, as represented by changes in the collector and base currents, have been obtained. Three sets of devices were irradiated and then annealed, with one set having a forward bias during annealing, one set having no bias, and one set having a reverse bias.

The dependence of the field on annealing is present but appears quite complex.

The presence of the externally applied electric field during annealing appears to influence the annealing of neutron-induced defects similarly, regardless of whether the junction is forward or reverse biased.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to his advisor, Dr. Charles A. Goben, for his efforts in guiding this Master's thesis effort.

Appreciation is expressed to H. J. Stein for a helpful discussion of his annealing work on bulk material.

The author also wishes to express his appreciation to Mr. C. R. Jenkins for his valuable assistance in the operation of the data acquisition system.

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I. INTRODUCTION

In previous papers[9, 10, 11] an anomalous neutron-induced component of base current was identified. This anomalous base current was found to vary as

$$I_{B_{INC}} = K_1 \cdot A_E \cdot \phi \cdot \exp(\frac{qV_{BE}}{nkT}),$$

where A_E is the emitter area, ϕ is the neutron fluence, K_1 is a constant having dimensions of (amperes/cm^2)/(neutrons/cm^2), and n is approximately 1.5.

An anomalous annealing phenomenon was also found[9, 10, 11] which apparently indicated that neutron-induced defects in the space-charge region of a device anneal differently than defects in the bulk region. After the transistor had been annealed the collector current, which depends on bulk recombination, appeared to change to a much greater degree than the base current, which depends on space-charge recombination.

In Goben's previous work[9, 10, 11], the annealing was done at 150°C for four hours. This enabled him to identify an anomalous annealing phenomena, but no conclusion as to its origin could be made.

This suggests that an annealing experiment should be performed using a combination of standard isothermal and isochronal annealing techniques. This allows one to study the annealing in short time intervals in order to determine the origin of these neutron-induced defects, their annealing characteristics, and the possible existence of annealing steps.

The results of these investigations to better understand the anomalous annealing behavior are contained in this paper.

II. ORIGIN OF ANOMALOUS ANNEALING

The origin of the neutron-induced component of base current, and hence the anomalous annealing is thought to be due to either or both of the following mechanisms: a quasi-tunneling recombination phenomena in the emitter-base space-charge region, or the influence of an electric field on the structure and density of the neutron-induced defect centers.

A. Quasi-tunneling Recombination Phenomena

The quasi-tunneling recombination phenomena is concerned with recombination transitions between the valence band and the conduction band in the emitter-base space-charge region[18, 31]. Neutron irradiation of silicon produces defect levels whose average value is approximately 0.32eV from the valence band edge as determined from the temperature variation of I_C.

This model assumes that an electron from the conduction band, when in the depletion 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 an electron), thus inducing the observed large neutron-induced component of base current. It can be shown that this tunneling is possible due to the bending of the energy band edges in the junction region. The recombination of carriers, according to this model, would differ before and after irradiation in the space charge regions of the device. A schematic diagram of this quasi-tunneling is shown in Fig. 1.

B. Plausibility of Quasi-tunneling Phenomena

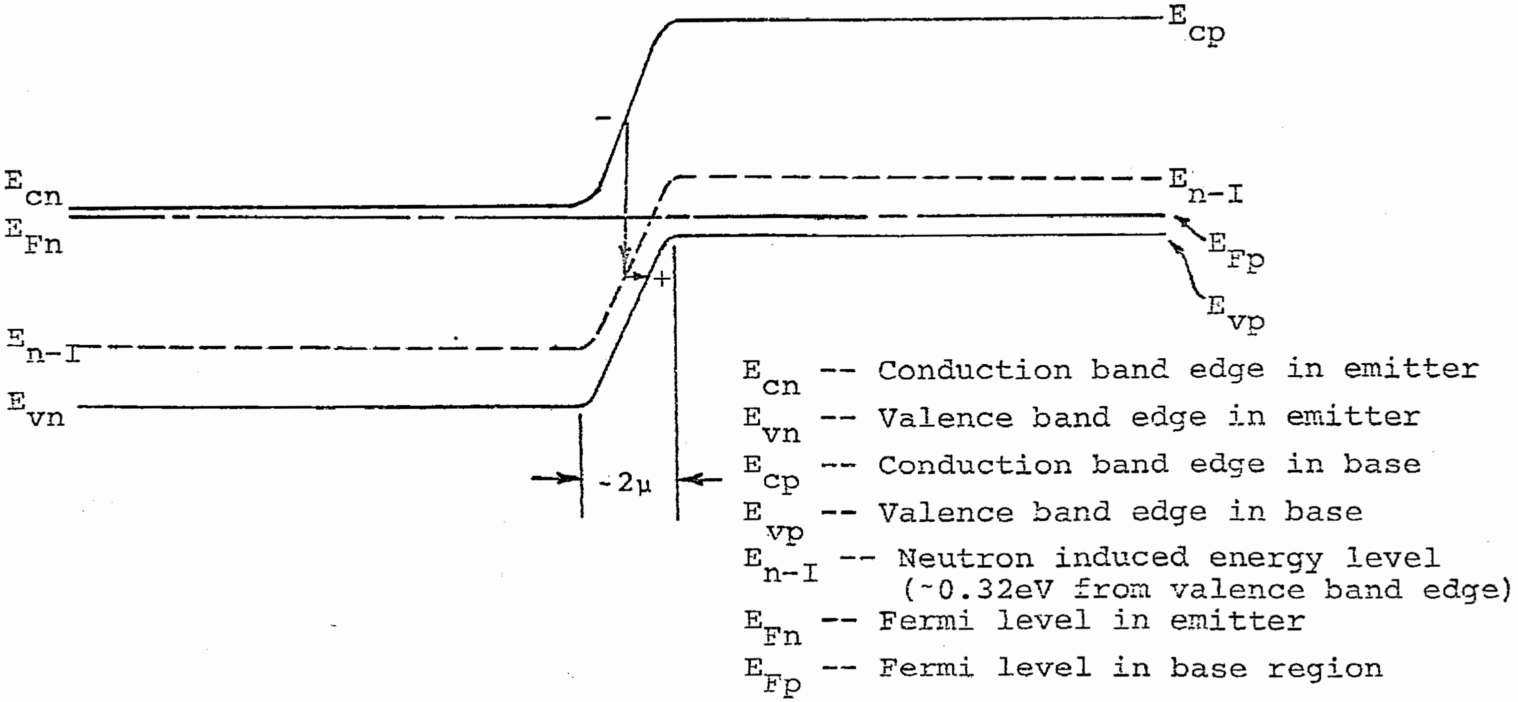
Calculations have been made using the device parameters of the 2N914 transistor to determine whether this tunneling can occur[4]. In an unbiased device, the distance that an electron would have to tunnel from the neutron-induced defect level to the valence band is on the order of 300Å. These calculations imply that this tunneling distance would increase slightly under forward bias.

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

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

Since special devices of this type were not readily available, an experiment of this type could not be performed. Further investigations of this tunneling phenomena are being conducted.

UNBIASED EMITTER BASE JUNCTION REGION IN 2N914 NPN TRANSISTOR



E_{cn} -- Conduction band edge in emitter
E_{vn} -- Valence band edge in emitter
E_{cp} -- Conduction band edge in base
E_{vp} -- Valence band edge in base
E_{n-I} -- Neutron induced energy level (~0.32eV from valence band edge)
E_{Fn} -- Fermi level in emitter
E_{Fp} -- Fermi level in base region

Figure 1 SCHEMATIC DIAGRAM OF QUASI-TUNNELING RECOMBINATION PHENOMENA

C. Field Dependence of Defect Centers

As reported previously[9, 10, 11], the annealing of the neutron-induced defects in the high field space-charge region appeared to differ markedly from the annealing of the defects in the low or zero field neutral base region. This suggests that these defects anneal differently due to the presence of the p-n junction field.

After neutron bombardment, defects (clusters) induced in the neutral base regions would be essentially uncharged since their charge would be neutralized by the free carriers of the material, holes or electrons, depending on the conductivity type of the region in which they are located. However, in the space-charge region, the clusters would probably be multiply charged, and have a large capture cross section, strongly affecting the recombination statistics in the space-charge region.

By increasing or decreasing the field by external means, one can determine the existence or non-existence of a field dependence since the defect centers will reorientate, diffuse or otherwise change their properties under the influence of the field, if indeed they are field dependent.

D. Determination of the Existence of Field Dependence

If the electric field intensity were partially responsible for the anomalous behavior, an increase in the field should result in a noticeable change in the voltage-current characteristics. A reverse bias applied to the emitter-base junction of a transistor during irradiation increases both the depletion region field and volume. A reverse bias of three volts was chosen to approximately double the depletion volume as compared to an unbiased device.

Two devices, having identical characteristics, were chosen for this experiment. Their pre-irradiation voltage-current curves are shown in Fig. 2. These devices were irradiated together; one having the three volt reverse bias applied to the emitter base junction during irradiation, and the other having no bias.

The devices in this experiment were irradiated to the following fluence levels in four steps: 1×10^{13} nvt, 4×10^{13} nvt, 1×10^{14} nvt and 4×10^{14} nvt. The variation of the voltage-current characteristics for the base current of the paired devices which were biased and unbiased during irradiation is shown in Fig. 3 for two fluence levels. The change in the collector current characteristics due to irradiation was very slight; and therefore, the change in the collector characteristics due to the field being applied during irradiation was unnoticeable.

From Fig. 3 one sees that the base current curve of the reverse biased device increases at low levels and on close examination, changes its voltage dependence and appears to approach a $\frac{2kT}{q}$ reciprocal slope.

At high levels, however, the device characteristics are again identical. This indicates that at the higher fluence levels, some other effect swamps out the influence of the electric field on the neutron-induced defects. The reverse

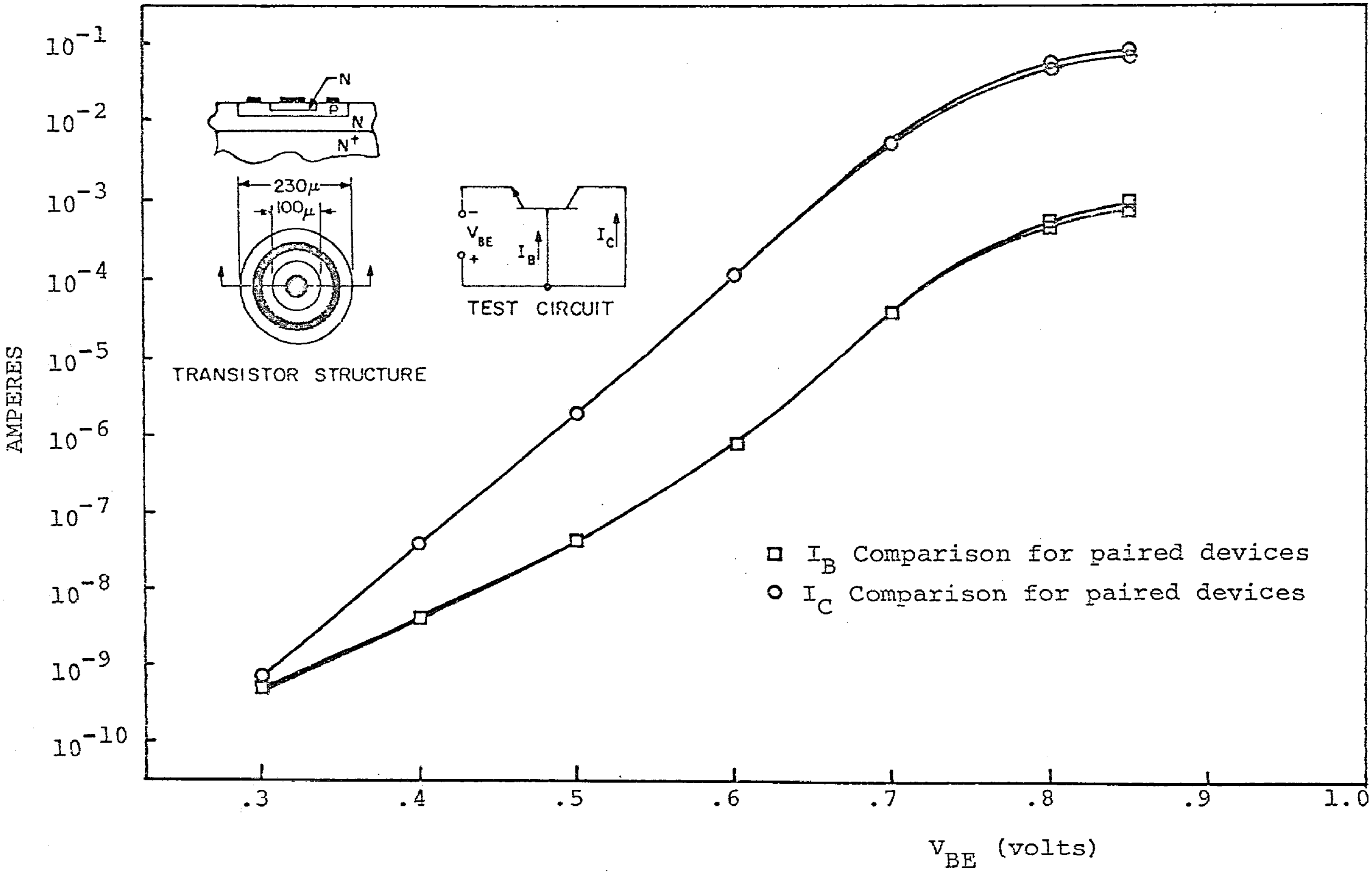


Figure 2 I-V CHARACTERISTICS FOR PAIRED DEVICES

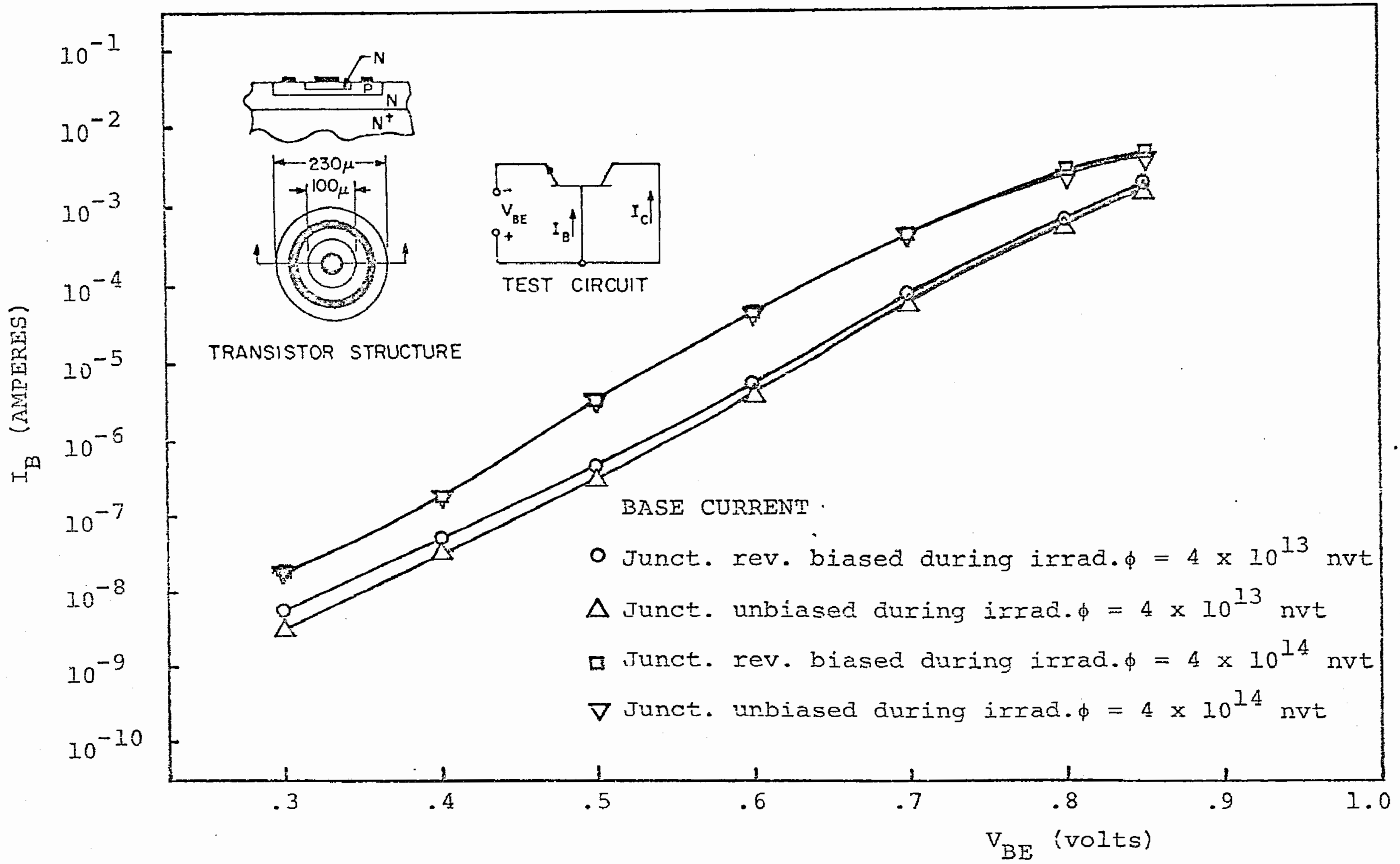


Figure 3 I-V CHARACTERISTICS OF BASE CURRENT FOR PAIRED DEVICES AT TWO FLUENCE LEVELS

voltage of three volts, which increases the field and approximately doubles the depetion volume, is applied only during irradiation. After irradiation, the device characteristics were measured with the emitter-base junction forward biased in normal transistor operation. The effect of the reverse bias applied only during irradiation appears in the change in slope of the base current characteristic. This implies that the change in the defect levels must occur near the center of the junction. From this experiment, it is clear that the formation and electronic behavior of the defects caused by neutron irradiation are affected by the electric field intensity during irradiation.

III. SEARCH FOR FIELD DEPENDENCE IN ANNEALING

Since the formation of the neutron-induced defects is field dependent, the annealing of these defects should also exhibit field dependency.

Three sets of devices were chosen for this experiment: one set to be annealed under forward bias, one set unbiased, and the third set under reverse bias. Three sets of paired devices were used to determine the relative annealing characteristics of these devices under the three given operating conditions: one set of paired devices to determine the relationship between a forward biased device and a reverse biased device, another set to determine the relationship between an unbiased device and a forward biased device, and the third set to determine the relationship between an unbiased device and a reverse biased device. The special devices used in all these experiments were fabricated from a single silicon wafer by Texas Instruments and meet all specifications for 2N914 NPN silicon planar epitaxial transistors.

This series of devices was irradiated (without bias) with fast neutrons (E>10keV) in twenty steps to a neutron fluence of 7.5×10^{14} nvt. These irradiation steps were needed for comparison of the characteristics of the annealed devices with characteristics of the same device at particular irradiation levels to obtain agreement with previous annealing experiments by Goben[9, 10, 11].

The devices' characteristics were measured within 24 hours after their irradiation and it was assumed there was negligible annealing taking place during this time at room temperature.

Typical pre- and post-irradiation current-voltage characteristic curves for two fluence levels are shown in Fig. 4. As reported in previous papers[9, 10, 11], the base current increases with neutron fluence, while the collector current decreases slightly. Typical pre- and post-annealing curves for the base and collector current characteristics are shown in Fig. 5. After annealing, the base current curve decreases towards its pre-irradiation value, and the collector current curve increases towards its pre-irradiation value, as reported previously for devices which were annealed for four hours at 150°C[9, 10, 11].

The amount of annealing in these experiments was determined by normalizing the base or collector current change with respect to their pre-annealing room temperature (300°K) value as the current changes towards its pre-irradiation value during annealing.

A constant temperature oil bath was used for the isochronal annealing. The devices were quickly inserted and withdrawn from the bath and when withdrawn were cooled in a low temperature bath to insure accurately known annealing times. The time required to cool the device out of the annealing range at the end of the annealing run was negligible compared to the total annealing time. Two types of oil were needed to cover the required annealing temperature range because one fluid decomposed at the higher temperatures and the other fluid was too viscous at low temperatures.

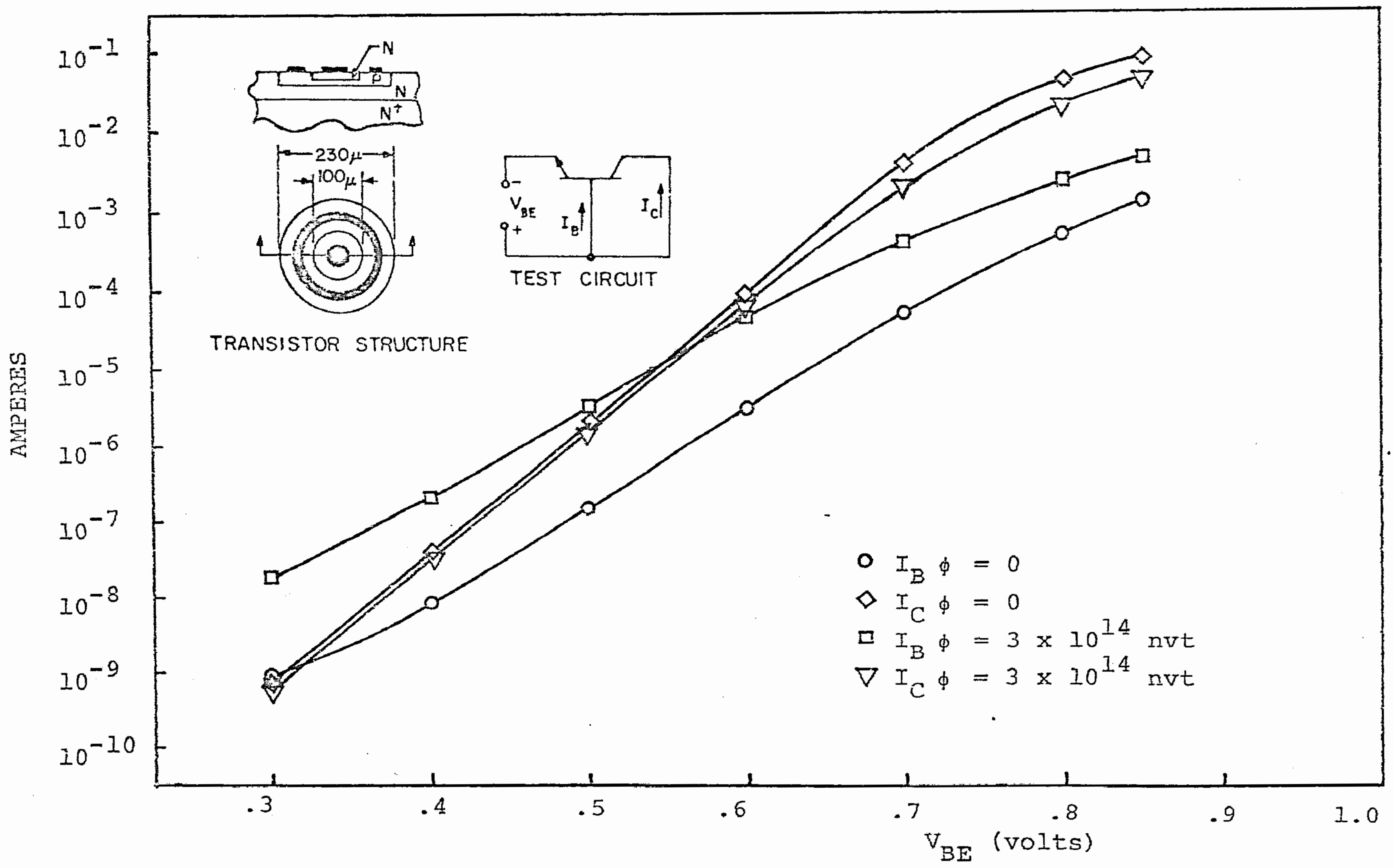


Figure 4 TYPICAL PRE- AND POST-IRRADIATION I-V CHARACTERISTICS

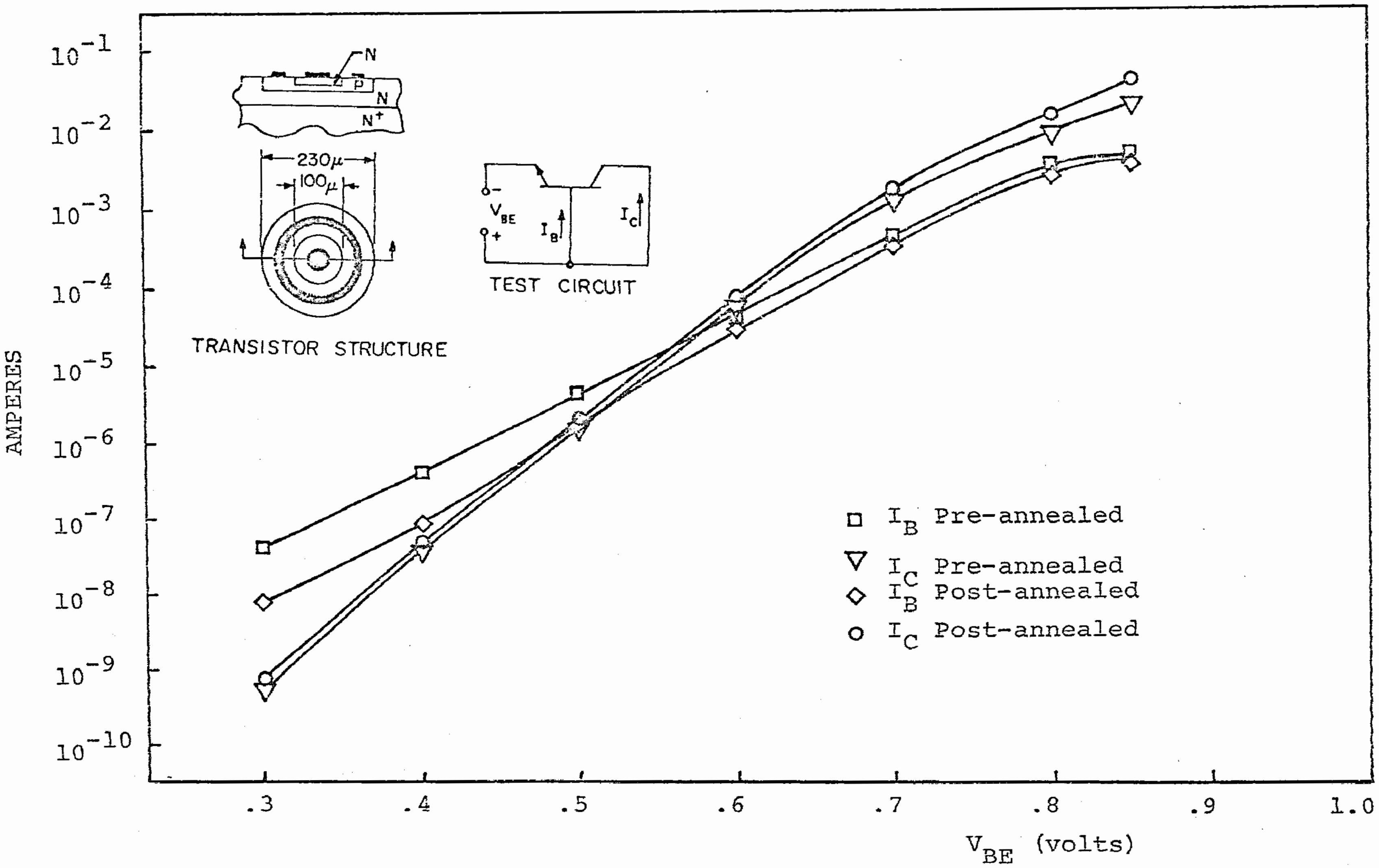


Figure 5 TYPICAL PRE- AND POST-ANNEALING I-V CHARACTERISTICS

The annealing characteristics for the defects in the space-charge region as represented by the normalized base current changes of typical 2N914 silicon transistors with a base-emitter voltage of 500mV. are shown in Fig. 6. These annealing characteristics are for devices which were reverse biased, unbiased, and forward biased during annealing. A similar curve for the neutral base region as represented by the normalized collector current is shown in Fig. 7.

Every point on this curve represents at least one isochronal anneal at the given temperature for a 20 minute interval. The number of isochronal anneals at each temperature which were required to accomplish the total annealing taking place at any given temperature is noted by the digit above the data point on the figure. Each of these points correspond to the final annealed value after the isochronal anneals at any given temperature have been completed.

The lines connecting the data points on the annealing characteristic curves in Fig. 6 and Fig. 7 are for convenience and are not meant to portray the annealing characteristics of the defects between the experimental data points.

Examination of the annealing characteristic curves in Fig. 6 and Fig. 7 reveals that the neutron-induced defects in devices which were unbiased during annealing do not anneal to as great a degree as the defects in devices which were biased during annealing. This is true for both defects in the bulk base region and defects in the emitter-base space-charge region.

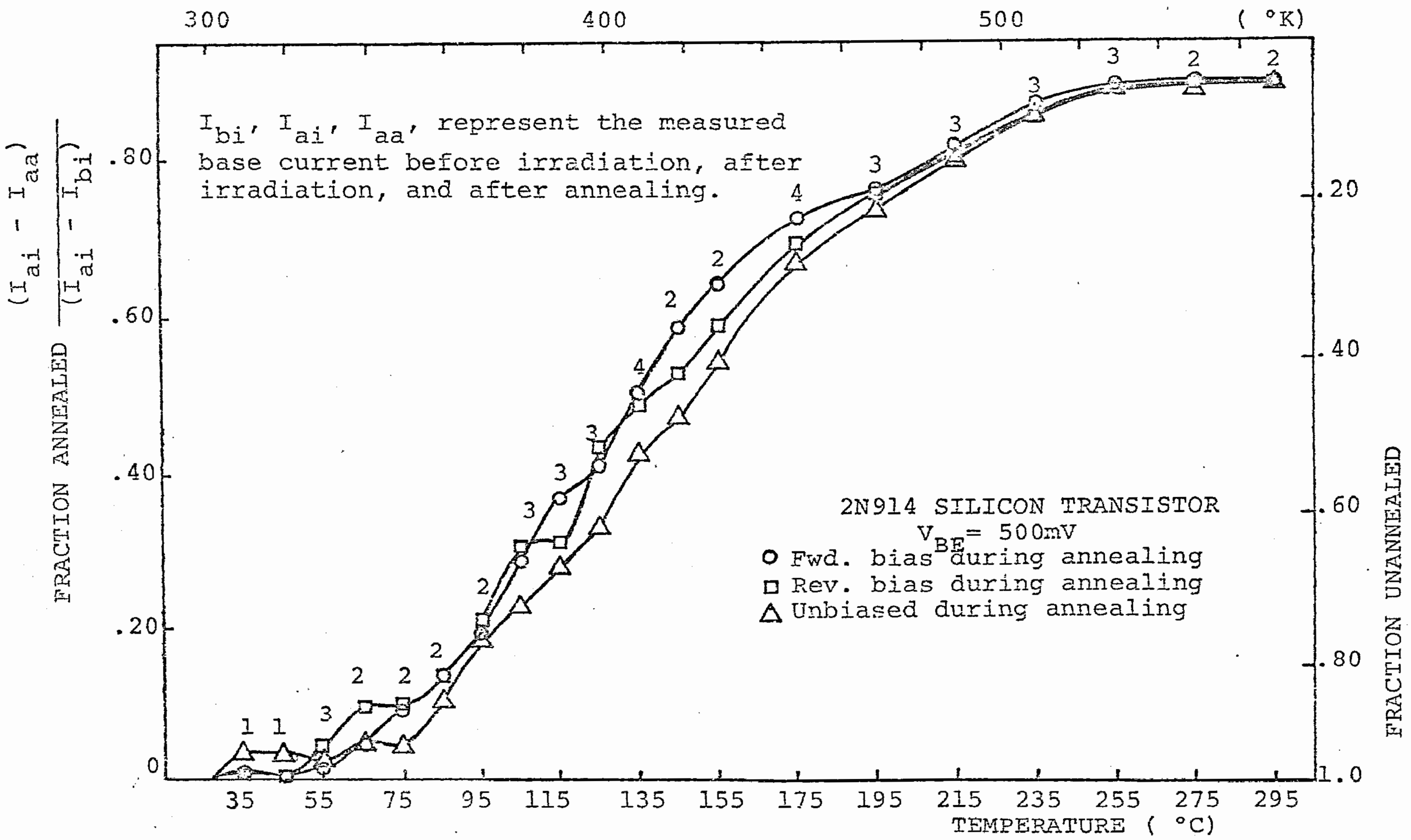


Figure 6 FRACTION OF NEUTRON-INDUCED DEFECTS IN E-B SPACE-CHARGE REGION ANNEALED (REPRESENTED AS CHANGE IN I_B) vs ANNEALING TEMPERATURE.

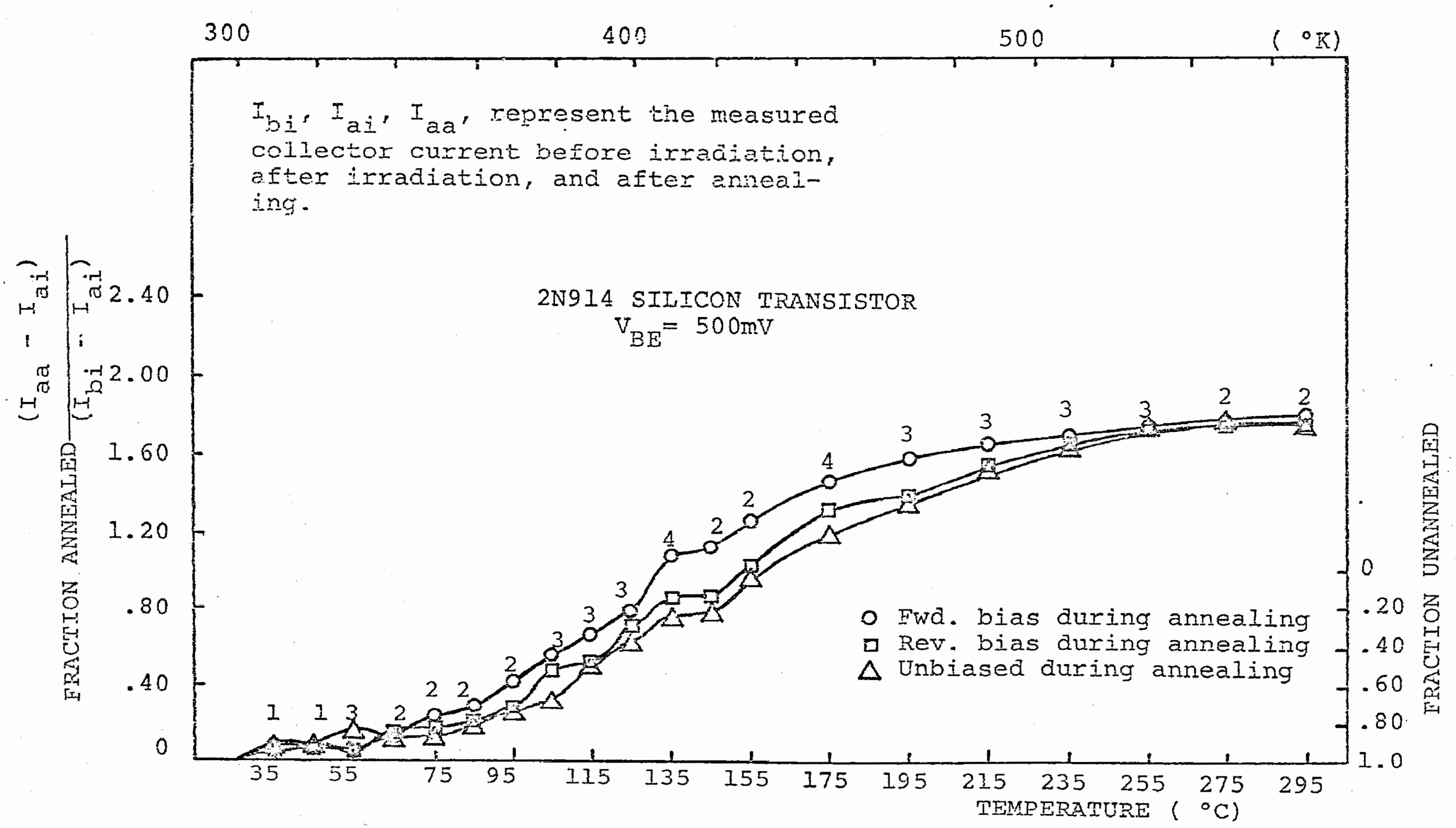


Figure 7 FRACTION OF NEUTRON-INDUCED DEFECTS IN BULK BASE REGION ANNEALED (REPRESENTED AS CHANGE IN I_C) vs ANNEALING TEMPERATURE.

The presence of a forward bias during annealing also enhances the degree of annealing as compared to either the zero bias or the reverse biased cases.

In Fig. 7 the defects in the bulk base region, as reflected in the collector current, are shown to anneal in all cases to more than 100%, implying that there is not only annealing of neutron-induced defects, but also annealing of other defects (e.g., oxygen vacancy complexes, etc.). The improvement in the post-annealing collector characteristics as compared to the pre-irradiation collector characteristics is very slight due to this annealing.

At each point on the annealing curve, the complete device characteristics were measured for base-to-emitter voltages from 300mV. to 850mV. in 10mV. increments. From this data one can see that the annealing characteristics shown in Fig. 6 and Fig. 7 at base-emitter voltage of 500mV. are representative of the annealing characteristics at any measured base-emitter voltage.

In these devices, as in the devices annealed previously by Goben, the defects in the neutral base region, as represented by the change in collector current, anneal to a much greater degree than the defects in the space-charge region as represented by the change in the base current.

Inspection of the annealing characteristics reveals, in agreement with Stein's work[26] on bulk material, that there are no sudden changes in annealing with respect to temperature which might be referred to as annealing steps. The absence of annealing steps occurs in the annealing of defects in both the neutral base region, as was expected, and also the space-charge region. This might have been expected from the knowledge that the type of defect induced due to neutron bombardment is normally a cluster and hence, unlikely to completely anneal suddenly at any temperature.

All irradiations were made simultaneously on the transistors in the University of Missouri at Rolla Research Reactor to insure equal fluence levels upon exposure. The transistors were irradiated in an aluminum sample holder containing boron carbide to shield the devices from thermal neutrons which allows one to consider only the effects of fast neutrons (E>10keV).

IV. SUMMARY AND CONCLUSIONS

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

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

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

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

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VITA

The author was born on August 9, 1943 in St. Louis, Missouri. He received his primary and secondary education in his home town of Ellisville, Missouri. He received his Bachelor of Science Degree in Electrical Engineering from the University of Missouri at Rolla in May, 1966.

The author's practical work experience includes participation in a cooperative work study program with the McDonnell-Douglas Company during his under-graduate schooling. Over two and one-half years were spent on various work assignments throughout the company.

APPENDIX A: REVIEW OF THE LITERATURE

Loferski, in 1958, investigated emitter efficiency in the simple terms of the ratios of sheet resistivities and predicted that the emitter efficiency would increase with neutron bombardment, but by a negligible amount[15].

Assuming a linear dependence of the reciprocal lifetime on neutron fluence, Loferski evaluated Webster's equation as a function of neutron fluence and asserted that the reciprocal common-emitter current gain varied linearly with fluence. Discrepancies between theory and experiment were attributed to experimental error and incorrect theoretical constants.

Also in 1958, Messenger and Spratt analyzed transistor gain degradation due to neutron irradiation assuming the emitter efficiency independent of fluence[16]. They applied Schockley-Read statistics to Webster's equation to calculate a single energy level for the recombination site, assuming that the sites were only in the bulk base region and acting only through lifetime degradation. Discrepancies between theoretical and experimental results were attributed to experimental error and inexact theoretical constants.

Easley and Dooley, in 1960, also assumed the emitter efficiency to be independent of fluence and equal to unity, which made the base transport factor the single variable in the current gain[8]. A flux dependent lifetime and base width were assumed to alter the base recombination term. Disagreements with experiments were attributed to radiation annealing.

In 1964, Hood allowed the emitter efficiency to vary with neutron fluence by including the back injection term and a simplified Sah-Noyce-Schockley current expression. Discrepancies in his work were attributed to neglecting the collector leakage current[14].

Goben, in 1964, found a neutron induced component of base current which indicated a strong dependence of emitter efficiency on neutron fluence[9]. The emitter efficiency was shown to be the dominant factor in the current gain expression, since the collector efficiency and collector multiplication were made to be equal to 1, and the base recombination term varied slightly with neutron fluence. In his study, Goben annealed 2N914 silicon planar eqitaxial transistors and found an anomalous annealing phenomenon which seemed to indicate that neutron induced defects annealed differently in the space charge regions as compared to the neutral regions. His work involved annealing at a high temperature for a long period of time, disregarding annealing steps.

H. H. Sander and B. L. Gregory have recently studied annealing in semiconductor devices[21]. Their work is concerned with transient annealing which disappears in times on the order of the lifetime in the particular material.

Recent work by Stein[26] has shown that the introduction rate of neutron damage does not exhibit temperature dependence and that the recovery extends over a broad temperature range from 60°C to 220°C with no distinct annealing stages. This is consistent with production and annealing of large clusters.

Goben's annealing work suggests a study of this anomalous annealing phenomena to determine its origin and also to study small changes in annealing for various short annealing times, and temperature periods. This paper is such a study.

APPENDIX B: BACKGROUND OF PROBLEM

When a semiconductor crystal is subjected to neutron bombardment, the neutrons collide with the lattice atoms, creating high energy recoil atoms which, in turn, collide with other lattice atoms, and a snowball effect results, until the recoil atoms' energy is expended[3]. Large areas of damage, corresponding to the range and energy of the recoil atoms, are created. Some channeling may occur, increasing the depth of the penetration. This lattice damage[5] consists of vacant lattice sites, interstitial atoms, as well as clusters of both types. These defects are caused by the displacement of atoms from their periodic arrangement by elastic collisions with the incoming neutrons or their recoil atoms.

The fast neutrons in a reactors' spectrum generally produce the majority of the total radiation-produced lattice defects. Recent estimates based on the theory of the displacement process[6] indicate that it is the neutrons between the energies of 0.1 and 10 MeV which produce essentially all the displacements.

The gamma-rays associated with the reactor spectrum are able to produce displacements only indirectly by means of collisions of their energetic Compton electrons with atoms of the lattice. The probability of producing these defects is very small and the effect of gamma-ray produced defects on displacement damage is negligible.

The radiation damage may be divided into two categories:

1. Transient effects

2. Permanent effects (room-temperature-stable damage)

Transient effects involve ionization (hole-electron pairs) and point defects, which, at room temperature, are unstable and disappear shortly after the radiation is terminated. If the recoiling atom is sufficiently energetic, it will be partially stripped of its outer electrons[5] and this moving charged particle may be thought of as similar to proton bombardment and, as such, is capable of ionizing or exciting the lattice atoms it passes. The moving charged particle must have a velocity equal to or greater than the velocity of the orbital electrons of the atom to be ionized or excited. This process only becomes important for energetic recoils. Transient effects of radiation disappear after the termination of the irradiation in times comparable to the minority carrier lifetime of the material being bombarded.

Permanent effects result from displacements of atoms from their periodic arrangement in the crystal lattice (Frenkel defects and complexes). This permanent damage is associated with damage to the lattice whether or not it anneals out with time and temperature.

It is thought that neutron bombardment of silicon introduces damage in the form of clusters[21]. Various electrical measurements on neutron irradiated silicon indicate that clusters probably do exist in this material. The shape of the damage cluster may be thought of as a lit cigar, with the long axis approximating the primary recoil atoms' range while the lit end simulates a thermal spike.

Near the end of the primary recoil atoms' path, there may be a spike of some sort produced[3,24]. In a thermal spike, the kinetic energy given up by a moving particle in collisions not causing displacements is originally highly concentrated along the particle's path. This concentration of energy may raise the temperature instantaneously to a very high value. The thermal spike becomes particularly significant if the colliding particle is an atom. Its temperature typically has been estimated at over 1000 °K, but lasts only for a period of about 10^{-11} seconds[3]. In this case, the material may actually melt and resolidify. The regrown region may be amorphous and generate defects to the surrounding material upon annealing. These spikes may result in an annealing out of previously introduced defects (radiation annealing). The spikes may also accelerate diffusion, although they generally produce no defect pairs.

A displacement spike also occurs near the end of the primary recoil atoms' path. As the path between successive displacements becomes comparable to, or less than, the interatomic spacing, a rapid succession of adjoining displacements occurs. This results in a substantial void which is surrounded by a region with a high density of interstitial atoms. This unstable configuration rapidly collapses with a resulting "melting" or intermixing of atoms, generating some dislocation loops at the same time. Since the displacement cascade must occur over distances comparable to the range of the primary recoil atom, severely disordered regions (regions of high defect density) are produced. The number of atoms affected by a displacement spike has been estimated at approximately 10^4 to 10^5.

When the local defect density is high[6], the opportunity for mutual interaction between defects becomes great and a variety of complex imperfections can be formed. These interactions would occur to a great extent only at the higher fluence values.

Almost all physical properties[5] are influenced to some degree by lattice imperfections. The various properties are affected to varying degrees because of their originating in different mechanisms or different defects in the structure. This structure-sensitive behavior may be a result of two different effects associated with the imperfections: electronic effects and lattice effects.

Silicon is the only semiconductor material yet studied that seems to approach intrinsic behavior after prolonged neutron exposure[3]. The formation of vacancies, interstitials, and their complexes creates new energy levels in the forbidden energy gap of the silicon crystal. These levels appear to depend upon certain pre-irradiation properties of the crystal, such as oxygen concentration and defect density[25]. The new energy levels are close enough to the center of the forbidden gap so as to lie well below the Fermi level in the p-doped crystals. These defects act as recombination centers decreasing the lifetime of excess carriers. Since the Fermi level lies between the energy levels introduced and the energy band containing the majority carriers (the conductive band in n-doped and the valence band in p-doped silicon crystals), there is a trapping effect on the majority carriers.

For example, in an n-doped crystal, the trap levels lie below the Fermi level and, as a result, have a high probability of occupancy by electrons. The electrons filling these traps come from doping impurities which normally supply electrons to the conduction band. This trapping of electrons decreases the effective doping concentration and causes an increase in the crystals' resistivity. Irradiation causes the resistivity of both n- and p-type silicon to increase[9], as expected.

The efficacy of a defect level[6] to act as a recombination center increases rapidly with the depth of the center measured from the band edge. The reason for this is that the center must be occupied by a majority carrier before it can capture a minority carrier. This means that the position of the defect level must be known in order to determine its role in the recombination process.

In order to study annealing, the types of defects which are introduced by irradiation must be determined. The number of defects[21] which are created as complexes, relative to the number created as isolated defects, depends on the number and distribution of defects created by each encounter of a recoil atom with the crystal. The possible defect reactions are:

1. V + V → VV (divacancy formation)
2. V - I (recombination)
3. VV + I → V   II + V → I   etc.
4. V + O → VO (A center formation)
5. Higher order complex formation (trivacancy, di-interstitials, VOV centers, etc.

where V denotes a vacancy, I denotes an interstitial atom, and O denotes an oxygen atom.

Although all of these processes are probably allowed, their probability of occurrence will vary due to their originating in different mechanisms. Inside or around the cluster, process (2) will depend on the fraction of the interstitial atoms that stay in the cluster, while process (4) depends on both the density of oxygen atoms present and also the stability of the complex at a given temperature. Process (5) will be less probable than the others and the defect complexes formed may be unstable and slowly release defects to the surrounding material.

Outside the cluster[21], the interstitials and vacancies will undergo similar reactions; however, in this region the density of interstitials is much greater than the density of vacancies, thereby eliminating V-I recombination as a significant reaction.

The defects produced by neutron irradiation have the following effects[13] on the electrical characteristics of the crystal:

1. Majority carriers are trapped and cannot contribute to the conductivity. This trapping increases the resistivity of both the

n- and p-type crystals. Whether the resistivity increases equally in the n- and p-type material depends on the location and number of the traps (energy levels) in the particular material.

2. Increased scattering of the free carriers results in a decrease in mobility, which increases the resistivity even more.
3. Excess carriers recombine sooner, resulting in a shorter diffusion length and a higher recombination rate.
4. The emergence of the neutron-induced component of base current reduces the emitter efficiency and thereby causes the degradation of transistor current gain.

It can be expected that the dominating effect[12] causing changes in transistor parameters is the decrease in minority carrier lifetime. Second order effects will be caused by the property of the radiation-induced centers to act as deep lying traps or recombination centers as discussed previously. At higher exposure levels, more defects are created which scatter free carriers, causing changes in the mobiiity.

The dependence of collector current density[17] on emitter-base voltage is given by

$$J_C = \frac{q\, n_i^2\, D_n \exp(qV_{BE}/kT)}{\tilde{N}_A}\, \beta^* \quad , \qquad (1)$$

$$\text{where } D_n = \frac{kT}{q}\, \mu_n \quad , \qquad (2)$$

which is valid for the diffusion length much larger than the base width. This equation applies only to an NPN transistor. In the above equations, q is the electronic charge, D_n is the minority carrier diffusion coeffiecient, $\tilde{N}_A$ is the number of majority carriers per unit area in the base region, n_i is the intrinsic carrier density, and μ_n is the electron mobility in the p-type base region.

Of the terms appearing in the collector current density equation, only μ_n, β^*, and $\tilde{N}_A$ will change upon neutron bombardment.

It has been shown by Goben that the major reduction in the collector current after neutron bombardment results from a decrease in the base recombination term β^* or, in other words, increased recombination at neutron-induced defects in the neutral base region. The effect of neutron radiation on the combined term $(\mu_n/\tilde{N}_A)$ is slight because both μ_n and $\tilde{N}_A$ cedrease and approximately compensate each other.

In Goben's work, [9,10,11,12] it was shown that neutron irradiation induces an anomalous component of base current. This induced base current component varies as:

$$I_{B_{INC}} = K_1 \cdot A_E \cdot \phi \cdot \exp\left(\frac{qV_{BE}}{nkT}\right) , \qquad (3)$$

where A_E is the emitter area, is the neutron fluence, the constant K_1 has dimensions of (amperes/cm^2)/ (neutrons/cm^2), and n is approximately 1.5.

At low current levels, the increase in the base current due to neutron irradiation is dominated by a current component originating in space charge recombination in the emitter-base space charge region. At high current levels, another base current component dominates, but this current component originates in recombination in the neutral base region. This component causes a reduction in the collector current which overrides the tendency of the collector current to increase. This effect is complicated by emission crowding. These changes in the respective currents are physically observed as a reduction in current gain. At fixed base-to-emitter voltage, the base current increases, while the collector current decreases as a result of neutron irradiation.

As the neutron induced defects causing these changes partially anneal out, the collector and base current tend toward their pre-irradiaiton values; the collector current increases towards its pre-irradiated value, and the base current decreases towards its pre-irradiated value, as expected.

When these voltage-current curves are compared to voltage-current curves of the same transistor measured at lower fluence levels, it can be seen that the defects causing a decrease in the collector current seem to anneal to a much greater degree than the defects causing the increase in the base current. The slope of the voltage-current curve for the base current changes slightly during annealing signifying a different voltage dependence (i.e., different "n" in the exponential voltage dependence) and, possible, therefore, a different distribution of states for the defect centers remaining after annealing.

The change in the collector current after neutron bombardment arises primarily from an increase in the recombination rate (decrease in bulk lifetime) in the neutral base region. The change in the base current (primarily due to the neutron induced component) arises from recombination in the emitter-base space charge region. When a transistor is annealed, the defects produced by neutron irradiation are partially annealed out, and less recombination takes place. Since the degree of annealing of defects in the space charge region and in the neutral region apparently differ, the origin of this difference must be investigated. This work is an extension of the work done by Goben at Sandia Laboratories.

APPENDIX C: PLAUSIBILITY OF QUASI-TUNNELING MODEL

The quasi-tunneling model can be a practical model only if an electron is capable of tunneling from the neutron-induced defect center to the valence band. This tunneling can occur only if the tunneling distance is on the order of 100 Å. The quasi-tunneling model is plausible then, only if the distance between the neutron-induced defect level and the valence band is on the order of 100 Å.

This tunneling distance can be found by calculating the height of the diffusion potential and the width of the emitter-base space charge region to determine the relative positions of the energy band edges near the transition region. From a scale model of the band edges near the junction, the approximate tunneling distance can be found geometrically.

The required electrical characteristics for these calculations using a 2N914 transistor were obtained from Texas Instruments. These characteristics are given below:

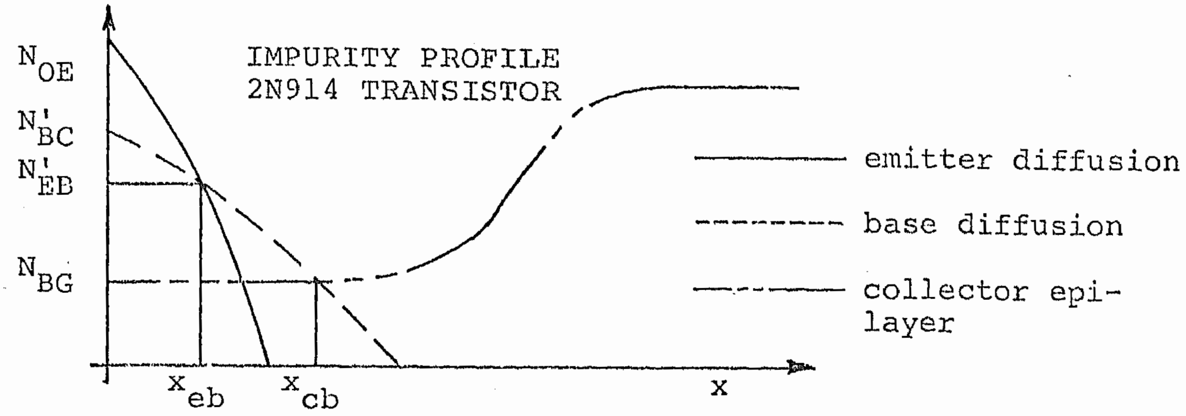
Base Diffusion-Gaussian
Emitter Diffusion-erfc
Base Penetration-0.116 mils
Base Width-0.0232 mils

$N_{OB} = 6 \times 10^{18}$ surface concentration

$N_{OE} = 10^{21}$ surface concentration
$N_{BG} = 6 \times 10^{15}/\text{cm}^3.$
L_B (the diffusion length for the base diffusion) = 1.4×10^{-4} cm.

Charge neutrality must exist in a transistor. The general equation, before the emitter diffusion, is given by:

$$N(x) = N_{BG} - N'_{BC} \exp\left(\frac{-x^2}{L_B^{\,2}}\right)$$



At the collector base junction, this equation reduces to

$$N_{BG} = N'_{BC} \exp\left(\frac{-x_{cb}^2}{L_B^2}\right)$$

$$x_{cb} = 2.95 \times 10^{-4} \text{cm.}$$

$$N'_{BC} = 2.3 \times 10^{17}/\text{cm}^3.$$

$$x_{eb} = 2.36 \times 10^{-4} \text{cm.}$$

$$N'_{EB} = 2.3 \times 10^{17} \exp\left(\frac{-x_{eb}^2}{L_B^2}\right) = 2.4 \times 10^{16}/\text{cm}^3.$$

This is the concentration in the base region at the point where the emitter junction will be after the emitter diffusion.

The emitter diffusion will change this value slightly, but this value of the base doping at the emitter junction will be used in the following calculations and will be shown to be accurate.

Because the emitter-base junction is heavily doped, it will be treated as a step-junction. The diffusion potential for a step junction in equilibrium can be found from this equation:

$$V_T = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2} \quad .$$

at room temperature, assuming the emitter is degenerate material, this equation reduces to

$$V_T = 0.88 \text{ volts}$$

As a check on these calculations, the equilibrium capacitance of an unbiased emitter-base junction (2N914 transistor) was measured after it was irradiated and C_T was found to be 3.98pf.

The area of the emitter-base junction is known to be $7.85 \times 10^{-5} \text{cm}^2$.

$$\frac{C_T}{\text{Area}} = \frac{3.98 \times 10^{-12}}{7.85 \times 10^{-5}} = 5 \times 10^{-8} \text{pf/cm}^2.$$

The equilibrium capacitance can be determined analytically[17] to be $5 \times 10^{-8} \text{pf/cm}^2$ agreeing with the measured value.

The width of the depletion region can be determined analytically[17] to be approximately 2.5×10^{-5} cm.

The calculated values of the diffusion potential and the depletion width were used to draw a scaled schematic diagram of the depletion region. The approximate tunneling distance was geometrically calculated from this scaled diagram, which is shown in Fig. 1. The tunneling distance, as can be seen from this diagram, is on the order of 300Å.

The curvature of the band edges decreases under forward bias lengthening the tunneling distance even though the width of the junction decreases.

APPENDIX D: EXPERIMENTAL PROBLEMS

The transistors were irradiated in the University of Missouri at Rolla Research Reactor (UMR Research Reactor) in an aluminum sample holder having an inner boron carbide chamber for the transistors. The boron carbide shield is needed to allow only fast neturons ($E > 10keV$) to bombard the devices. Boron carbide has a high capture cross section for slow ($E>10keV$) neutrons.

The aluminum used in the fabrication of the sample holder contained impurities whose radioactive half-life was long compared with aluminum. As a result, the sample holder could not be removed from the pool until this radioactive decay decreased to a point which was considered safe.

A cadmium cylinder was used to shield the sample holder from the thermal neutrons causing this activation. This allowed the samples to be removed from the pool on the day that they were irradiated.

At the higher fluence levels, the temperature inside the sample chamber would tend to increase, which required a flow of nitrogen through the sample chamber during irradiation to cool the devices. This coolant was necessary to insure that annealing did not take place during irradiation.

Further complications were presented by the reactor being operated at 200kW in another experiment which raised the water temperature at times to as high as 57°C. This required the nitrogen coolant to be used as long as the devices were in the reactor pool, otherwise annealing would take place and the flux levels could not be accurately determined.

Aluminum wires were used to bias the transistor during irradiation because radioactive isotopes of copper have a long half-life. Since aluminum wire is quite brittle, extreme care had to be exercised in handling this entire experiment.

To conserve space, one wire used to bias the emitter-base junction during irradiation was placed in the exhaust hose while the other wire was placed in the intake hose.

A photograph of the sample holder which was used for the transistors in all the irradiations is shown in Fig. 8.

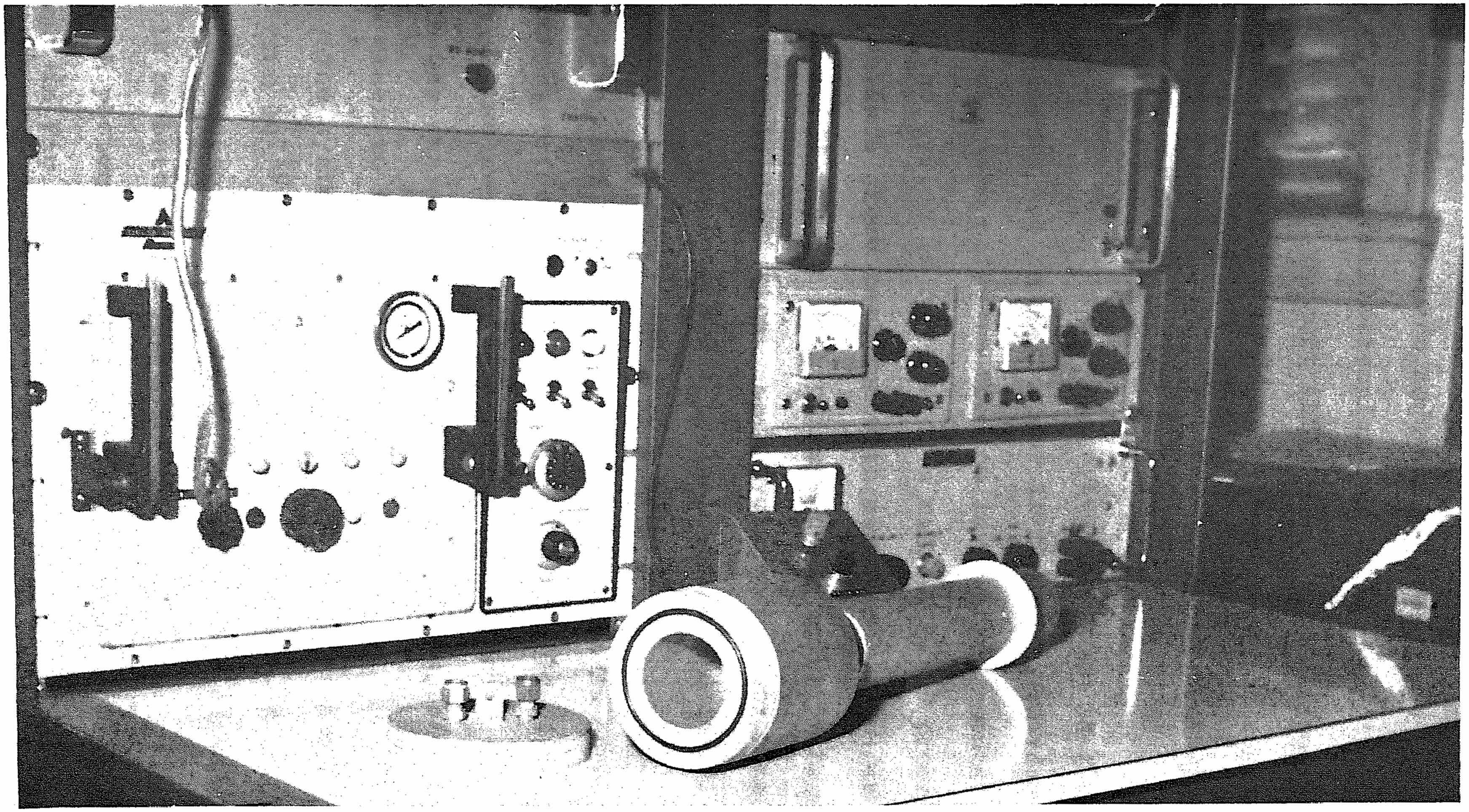


Figure 8 PHOTOGRAPH OF SAMPLE HOLDER

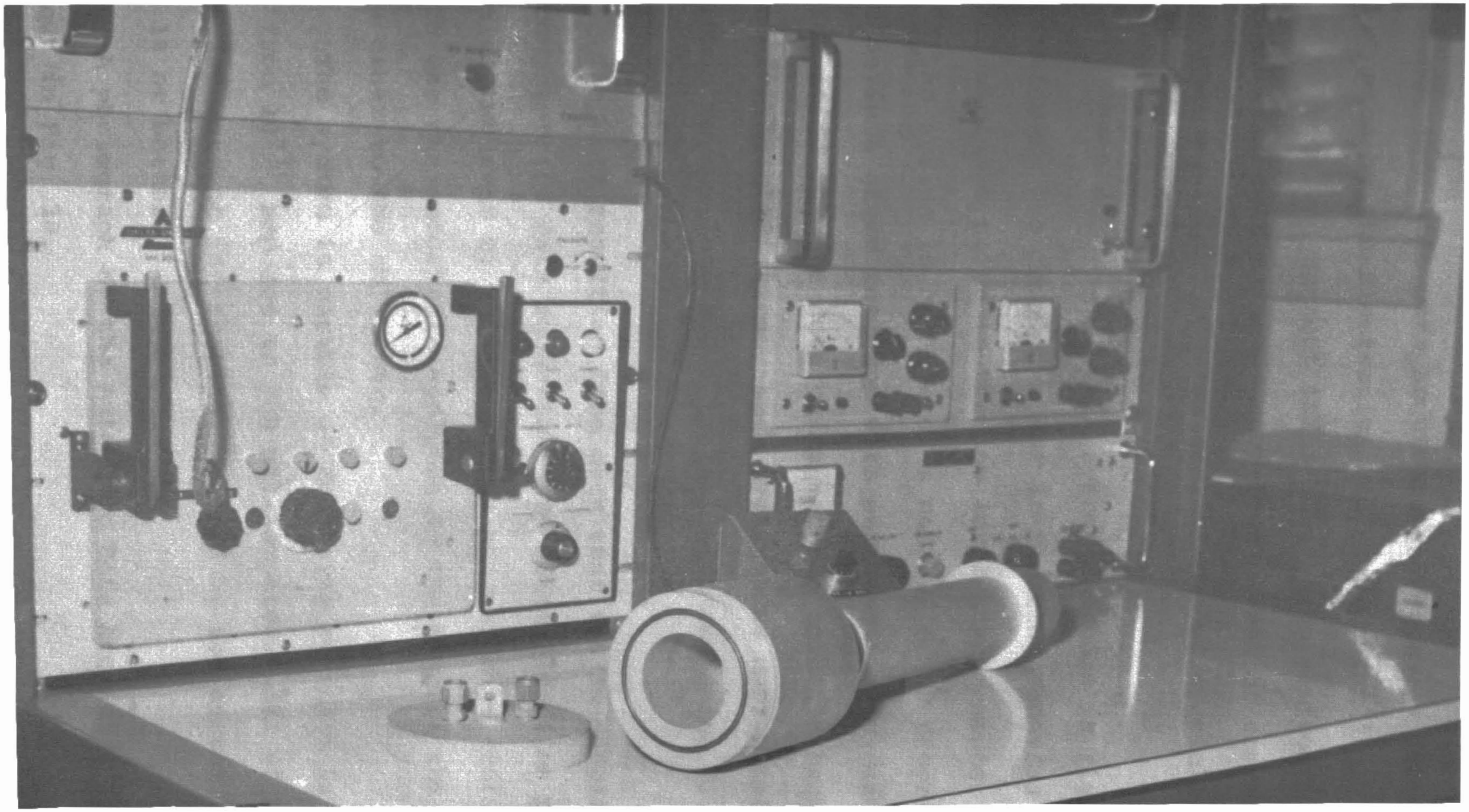


Figure 8 PHOTOGRAPH OF SAMPLE HOLDER

APPENDIC E: AUTOMATIC DATA ACQUISITION SYSTEM

The Automatic Data Acquisition System was designed and fabricated by the Electronics Research Center[1,2] to determine voltage and current information from semiconductor devices. The system includes various pieces of commercially available equipment plus several pieces of specially designed and fabricated equipment.

A block diagram of this system is shown in Fig. 9. The circuitry in the Sample Holder is floating, guarded and grounded to minimize noise in the low level measurements.

The system is capable of a maximum of 59 programmed cycles in a given test run with each cycle providing enough information for one data point each on both the base and collector characteristics. Each cycle takes approximately nine seconds to complete and a typical test run using all 59 available cycles takes roughly nine minutes.

The data resulting from each test run is supplied to a computer for data reduction. The data reduction process yields two sets of voltage versus current characteristics with one characteristic applying to the base of the device and the other to the collector.

The system is capable of measuring currents in the range of from 10^{-10} amperes to 200 milliamperes. All of the voltage and current information obtained by the system is accurate to 1% or better.

A photograph of the Automatic Data Acquisition System is shown in Fig. 10.

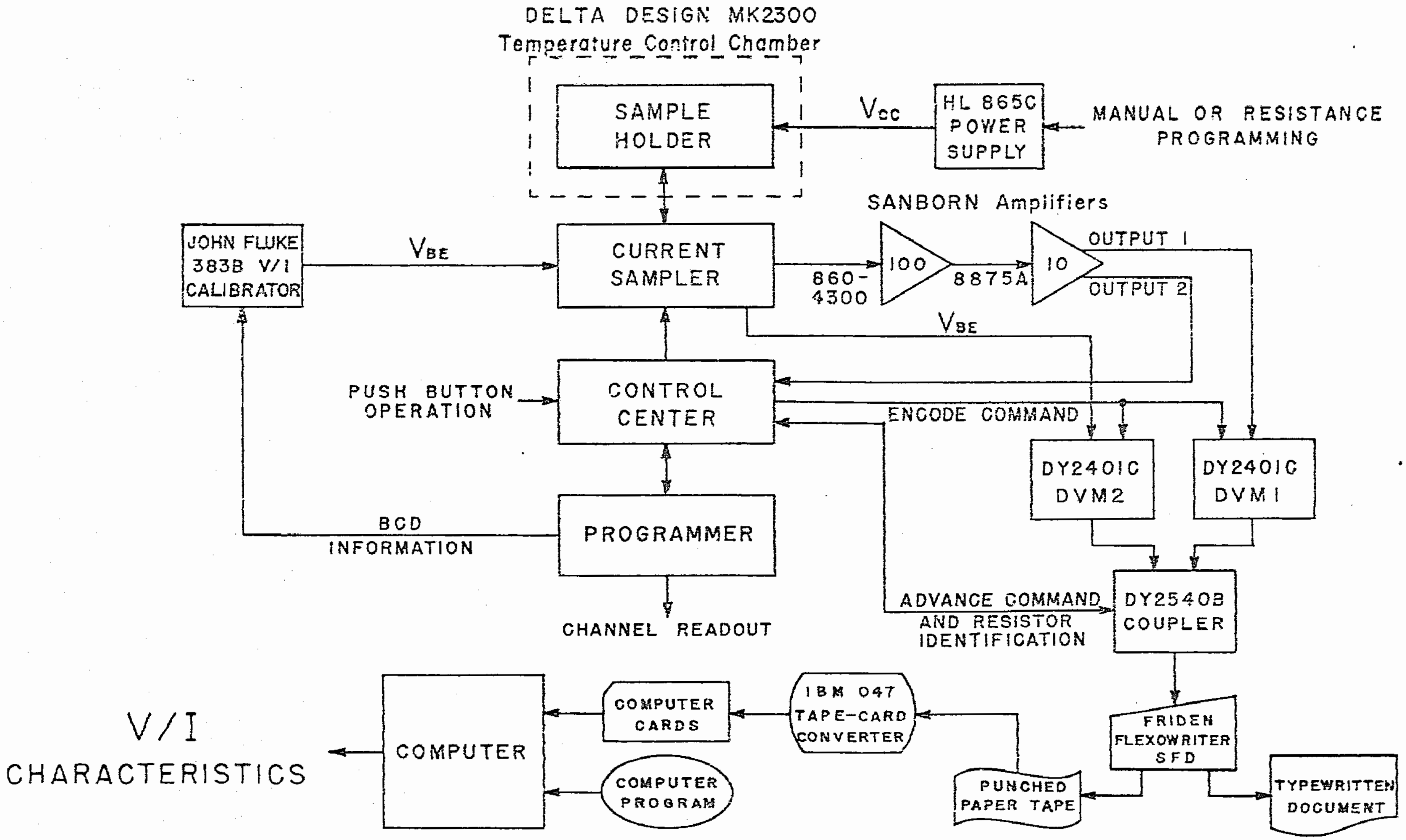


Figure 9 BLOCK DIAGRAM OF THE AUTOMATIC DATA ACQUISITION SYSTEM

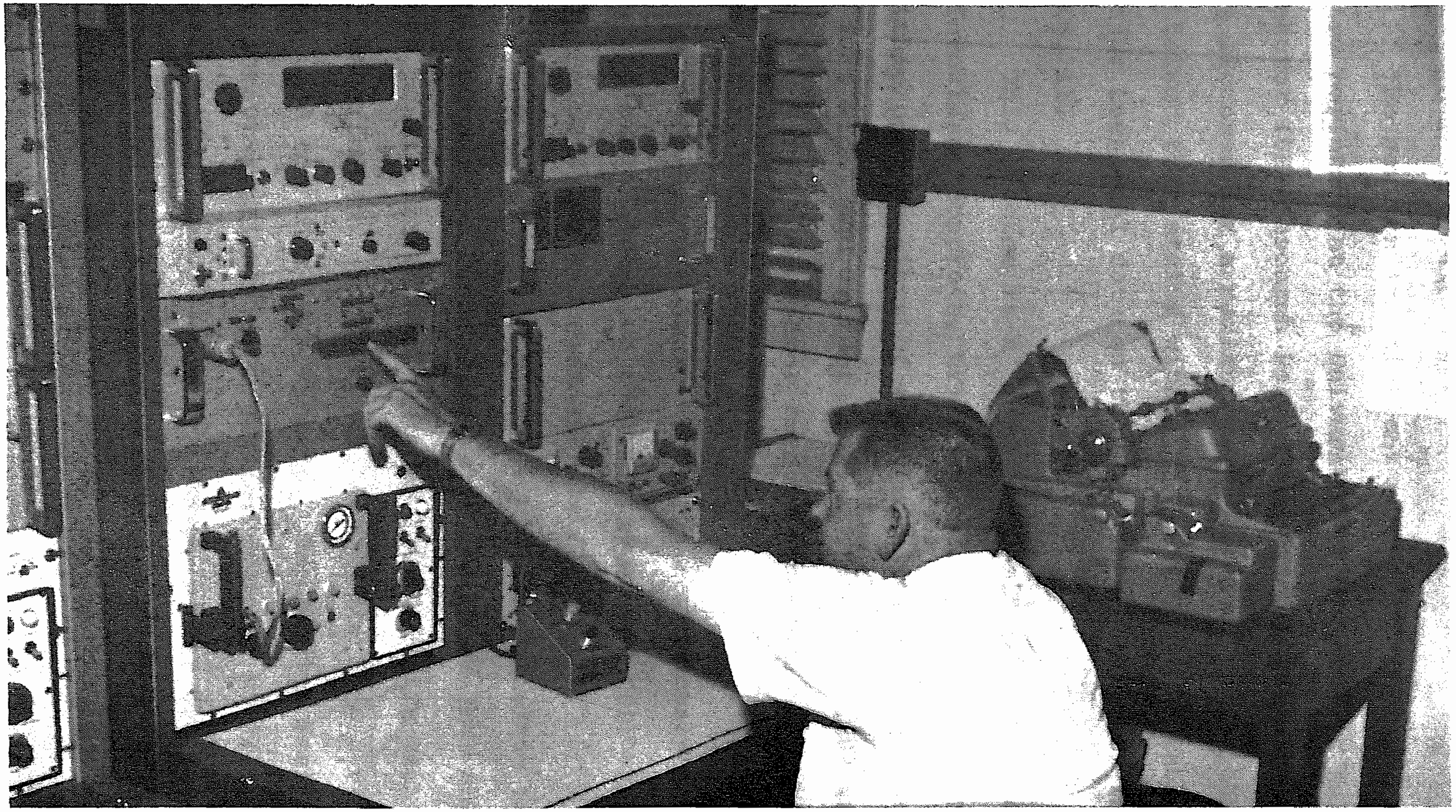


Figure 10 PHOTOGRAPH OF AUTOMATIC DATA ACQUISITION SYSTEM

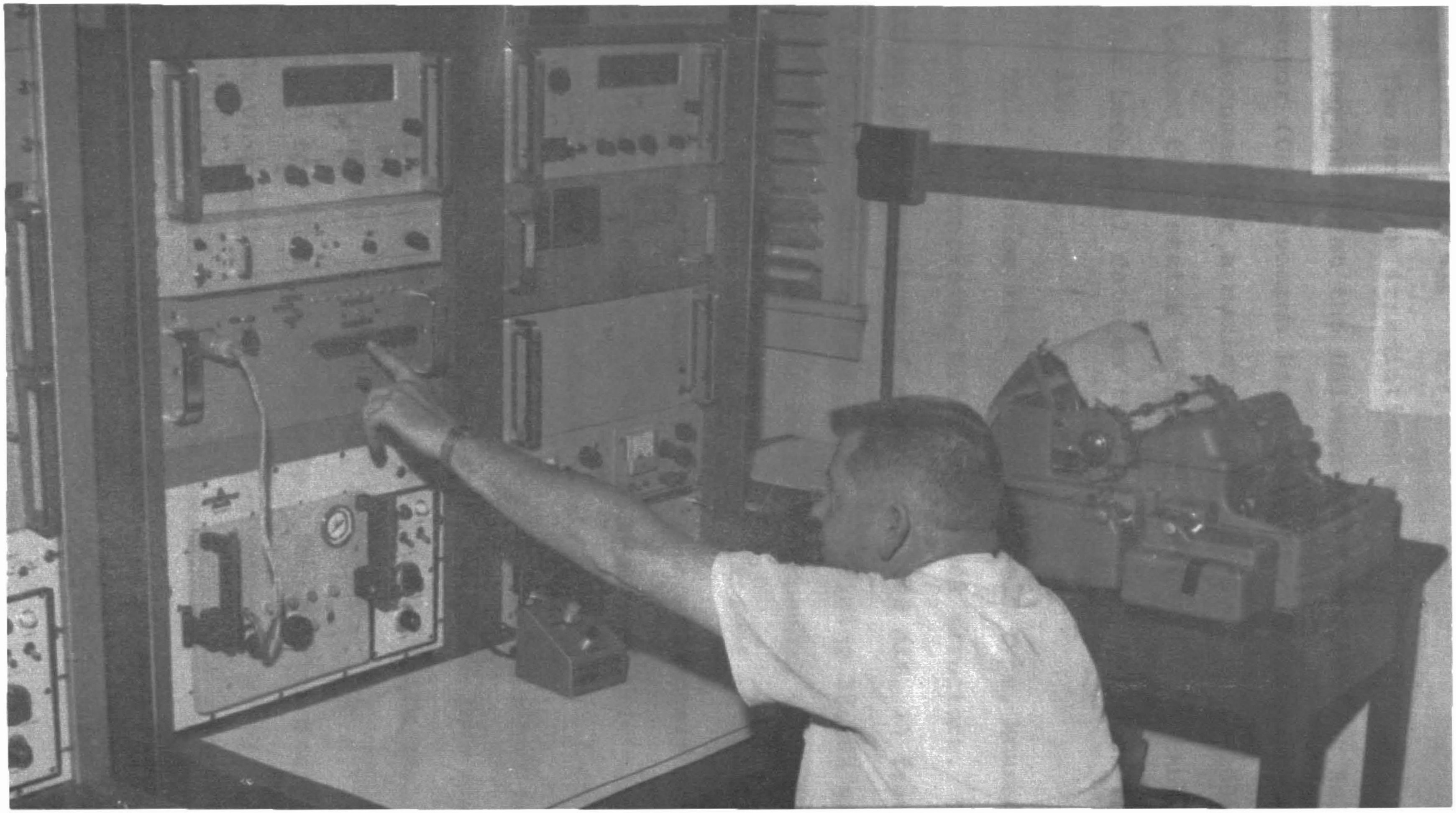


Figure 10 PHOTOGRAPH OF AUTOMATIC DATA ACQUISITION SYSTEM

APPENDIX F: NUCLEAR REACTOR FACILITY

The neutron irradiations needed for this investigation were performed at the University of Missouri at Rolla Research Reactor (UMR Research Reactor). The UMR Research Reactor is licensed for a maximum power level of up to 200kW, having attained that status within the past year. A table of the major technical data on the UMR Research Reactor is given in Fig. 11.

This reactor is a "swimming pool" type, housed in a windowless, concrete, brick and steel structure. The monolithic pool consists of a thick walled pit, 19 feet long, 9 feet wide, and 27 feet deep, containing 32,000 gallons of pure water. The reactor core is suspended near the bottom of the pool, being covered with some 19 feet of shielding water. To prevent corrosion, the water is continuously purified by an ion exchanger which removes anions and cations, while also minimizing the radioactivity.

The reactor grid plate, a racklike aluminum tray containing several rows of holes, contains 22 fuel elements. Open positions in this plate are available as sample holders in experiments. Position B2, mapped for fast flux irradiations, was used for these experiments. The maximum fast flux (E>10keV) available at 200kW for position B2 is 2.25 x 10^{11} neutrons/cm^2-sec. Dosimetric measurements for the neutron irradiations were performed at the UMR Research Reactor. Nickel foils were used to determine the fluence level for each exposure.

The UMR Research Reactor, in addition to being available for laboratory training, is used extensively for research by students from both the University of Missouri at Rolla and other nearby universities.

Type:	Swimming pool (modified BSR-type)
Core:	Heterogeneous: 90% U-235 enriched uranium oxide-aluminum-water.
Moderator:	Light water
Reflector:	Light water
Coolant:	Light water
Biological shield:	Light water and normal concrete
Critical mass:	Approximately 2.7 kilograms of U-235
Power level:	Up to 200kW
Maximum thermal flux:	1.5 x 10^{12} neutrons/cm^2-sec
Maximum fast flux (E>10keV):	2.25 x 10^{11} neutrons/cm^2-sec
Fuel elements:	MTR type, each fuel element has 10 fuel plates, each plate approximately 17 gms. U-235. Each fuel element 3" x 3" x 36". We have on campus 22 full fuel elements, 1 left hand, half element, 1 right hand, half element, and 4 control rod elements.
Control rods:	3 shim-safety rods 1 regulating rod
Auxiliary equipment:	Neutron diffraction multi-channel analyzer, nuclear counting equipment, neutron generator, subcritical assembly, neutron chopper.

Figure 11 TABLE OF TECHNICAL DATA FOR THE UMR RESEARCH REACTOR