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METHODS OF PREDICTING THE PERFORMANCE OF SEMICONDUCTOR ELECTRONIC CIRCUITS AND SYSTEMS IN A NUCLEAR ENVIRONMENT

by

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METHODS OF PREDICTING THE PERFORMANCE OF SEMICONDUCTOR ELECTRONIC CIRCUITS AND SYSTEMS IN A NUCLEAR ENVIRONMENT

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Mr. S. C. Rogers received a BSEE from Louisiana State University and an MSEE from Purdue University. He spent two years in the army at Ballistic Research Laboratory, Aberdeen Proving Ground, Md. developing an electric control system for drone aircraft prior to joining Bell Telephone Laboratories in 1953. During his eight years at Bell Telephone Laboratories he worked on military weapon systems, including Nike Ajax, Hercules and Zeus. In 1961 he went to the research organization of Sandia Corporation to study the effects of radiation on electronic circuits and systems.

Abstract

The performance of electronic circuits and systems in a radiation environment can be determined if the radiation induced component changes are known and if system performance as a function of component changes can be determined. The most economical way of determining alterations of system performance caused by radiation combines analysis with an experimental technique intended for laboratory use. The analytical method requires that the performance of the system be expressed mathematically in terms of component performance. These equations are then solved using component parameters appropriate to discrete radiation levels. This approach also can be used to determine the probability of system failure as a function of radiation exposure. The experimental technique involves measuring system performance after substituting radiation degraded components into it. Although this latter technique only yields the radiation levels for zero and 100% probability of failure, it is a simple and powerful tool. Exposing a system to radiation in order to determine failure levels or failure probabilities is not practical because the large variations normally encountered in semiconductor device parameters may cause failure to occur over a large range of radiation exposure levels. Therefore, a few observations on a specific system are not a reasonable basis for predicting radiation performance of similar systems.

Introduction

The demand for electronic systems which must perform properly in a nuclear environment is increasing at a rapid rate. In general, designers of semiconductor electronic systems are able to cope with those problems inherent in the commonly encountered physical environments such as temperature, shock, vibration, acceleration, etc. However, satellites, nuclear powered vehicles and refined weapon systems require sophisticated electronic systems which must also operate in complex nuclear environments. Therefore, designers must understand the environment and its effects, use methods which will result in designs capable of surviving the nuclear environment and devise means of testing to verify the design integrity of the systems.

To determine the effects of radiation on circuits and systems, predict their performance in a given radiation environment and determine the design changes required to make them less sensitive to radiation, the following must be known: (1) the behavior of the circuit components in a radiation environment, (2) the system performance as a function of component changes and (3) the radiation environment and the effects of shielding. Detailed circuit investigation and statistical analysis are required to accurately predict the probability of system failure as a function of radiation. The minimum radiation level at which a system may fail can be determined, however, by using simpler techniques.

In this report the effects of radiation on components are briefly reviewed. Several methods are then presented and illustrated for determining the probability of failure as a function of radiation and the minimum radiation level at which a circuit or system may fail. Environmental testing and its limitations are also discussed. Finally, it is shown how the effects of radiation on semiconductor electronic circuits can be minimized by using good design practices.

Component Damage

The performance of passive electronic components, such as resistors, capacitors, coils and insulators, has been measured many times in various radiation environments. The results show that these components are orders of magnitude less sensitive to radiation than most semiconductor devices. In general, it is reasonable to assume, therefore, that the maximum radiation level at which a circuit

will operate satisfactorily is determined by radiation damage to the semiconductor devices and that prediction of circuit performance based upon device performance gives accurate results.

Radiation exposure of semiconductor components can cause crystal lattice damage, ionization effects and surface effects. Although they occur simultaneously, these effects can be considered individually.

Lattice damage is caused by the interaction of energetic radiation with the electrons and atoms of the lattice. Any radiation which is sufficiently energetic can cause, by either primary or secondary processes, lattice defects which alter the characteristics of the semiconductor. For the temperature range over which most semiconductor devices operate, the damage introduced by radiation does not anneal appreciably and is, to a good approximation, permanent. The two effects of lattice defects causing the most significant changes in semiconductor device behavior are a decrease of minority carrier lifetime and a change in majority carrier concentration.

Minority carrier lifetime is related to radiation exposure by

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{\phi}{K},$$

where

τ = minority carrier lifetime after exposure,

τ_0 = initial minority carrier lifetime,

K = radiation damage constant for the material and type of radiation and

ϕ = integrated radiation flux.

The value of the radiation damage constant, K , depends upon the type of semiconductor material and its excess carrier concentration, impurities which may be present in the lattice, and the type and energy of the radiation. Although the lattice defects and the rate at which lifetime is changed for various radiations are not identical, a given change in lifetime, regardless of the type of radiation causing it, results in a given change in component performance. It is possible, therefore, to relate lifetime changes caused by one type of radiation to those caused by another and thereby establish a damage equivalency between particles. Furthermore, when damage calculations must be made for a mixed flux which cannot be simulated in the laboratory, such as Van Allen Belt radiation, it is convenient to express this flux in terms of an equivalent radiation flux which can be produced in the laboratory. Because component data

are more readily available, neutron radiation is used in this report when discussing permanent damage; the following approach and techniques, however, apply equally well to any radiation which causes lattice defects.

Displaced lattice atoms have the effect of changing the conductivity of the semiconductor material.^{1, 2, 3} It has been observed that the conductivity of both n and p type silicon decreases with neutron radiation. The conductivity of germanium on the other hand, is changed in a manner so that it approaches a value of about $10 \text{ ohm}^{-1} \text{ cm}^{-1}$ p-type, at high neutron flux levels, regardless of its initial conductivity.

For purposes of this report the circuit predictions are based on and the component investigations are limited to the performance of transistors in a radiation environment because they are, generally, the semiconductor components most crucial to proper circuit operation and most sensitive to radiation. The methods of circuit analyses discussed in this paper are applicable, however, to any component.

Reduction of minority carrier lifetime in transistor increases the number of minority carriers that recombine with majority carriers in the base layer and thereby decreases the common base current gain, α . The effect of base layer minority carrier lifetime reduction can be expressed as a change in α as a function of radiation,^{4, 5, 6}

$$\alpha(\phi) = \alpha(0) - \frac{\bar{t}\phi}{K},$$

where $\alpha(0)$ is the initial common base current gain and $\bar{t}$ is the average minority carrier transit time across the base layer. Because the average transit time is inversely proportional to the grounded base cutoff frequency of the transistor (f_a), high frequency response devices are damaged less by base layer minority carrier lifetime reduction than low frequency ones. The behavior of grounded emitter current gain, β , ($\beta = \frac{\alpha}{1-\alpha}$)⁷ is of more interest to circuit designers than α . The change and rate of change of β as a function of flux are dependent upon the value of β as well as the transit time and damage constant. Typical performance of β as a function of radiation and initial gain is shown for a transistor code in Figure 1. Note that at the same flux level, the change in gain for high gain units is much larger than that for the low gain units. A comparison of the measured changes in β as a function of radiation for different frequency response transistors is shown in Figure 2. Although these curves are typical of the behavior of silicon transistors, unit to unit variations as well as variations caused by circuit bias levels must be expected.

Figure 1. Typical Spread of Current Gain Versus Radiation for a Single Transistor Code

Figure 2. Current Gain of Typical Silicon Transistors Versus Neutron Exposure

Minority carrier lifetime reduction in a transistor also causes an increase of junction leakage current but this change generally is small for radiation levels at which β is significantly altered. Specific circuits, however, may be adversely affected by the increase of leakage current.

Transistors with very short base layer transit times or transistors whose performance does not depend upon minority carrier lifetime, such as the field effect transistor, may fail, not because of lifetime changes but as a result of conductivity alterations caused by irradiation. This failure mode, therefore, places an upper limit on the usefulness of semiconductor devices in a radiation environment. Conductivity changes cause failure only in the least sensitive devices and, therefore, most electronic systems fail at significantly lower flux levels because of minority carrier lifetime reduction. The methods of analysis and prediction discussed are, however, equally applicable to either mode of failure.

In addition to creating lattice defects, ionizing radiation can excite electrons from the valence band into the conduction band and thereby create hole-electron pairs which are free to participate in conduction processes. This has the effect of increasing junction leakage current in semiconductors during irradiation. In transistors, however, the leakage currents may be amplified by the current gain. For a typical power transistor with a wide base, long diffusion length in the collector, large area and high current gain, the steady state value of collector current caused by a constant source of ionizing radiation can be as large as ten microamperes for an exposure rate of 10 rads/second. At the same exposure level a small area, high speed transistor of the type used in logic circuits may have a leakage current of about 6 millimicroamperes. In general, these leakages are not large when compared to the normal operating currents but may be significant for a specific application.

Intense pulses of ionizing radiation, such as those created by a nuclear weapon, cause transient currents in components which introduce temporary spurious signals into the system. These transients may result in system malfunction. The effects considered in this paper are those caused by permanent component alterations which may cause permanent degradation of system performance. The transient behavior of electronic components and systems is not included in this paper.

Although radiation induced changes of transistor surface properties have been observed many times, they have received inadequate attention. However, interest in these changes has increased because of new radiation environments, such as the Van Allen belt and the environment associated with nuclear propulsion systems. In recent experiments, when normally biased transistors were exposed for long periods of time to low dose rates of CO^{60} gamma radiation, significant changes in leakage currents (I_{CO}) and current gains occurred.⁸ Furthermore, these changes were strongly dependent on: transistor bias potentials, the gas used to fill the transistor cases and the surface treatment the transistors had received during fabrication. Although the observed changes apparently are a function of the gamma dose, there is evidence that at very low gamma dose rates the changes are not proportionally as large as at high dose rates. This indicates that some recovery or annealing processes occur. It has been assumed that the damage to the transistors results from surface effects caused by the interaction of gas, surface contaminants, ionizing radiation and electric fields.

As one would expect from a surface problem, large variations in test results are observed between units of the same type made by the same manufacturer. Larger differences can be expected from manufacturer to manufacturer because of variations in surface processing. Consistent with the assumed

damage mode, the data generally indicate that transistors in evacuated cases and planar units are least affected by ionizing radiation.

Although the damage mechanism is not yet well understood and the data are very limited, an estimation of the problem can be made from the data.⁹ After exposure of 10^4 rads, the observed grounded emitter current gains for silicon mesa transistors were from 0.1 to 3.0 of the initial gain with many units in the 0.5 to 0.8 range. Silicon planar transistors have been tested to 10^5 rads and the observed current gains were as low as 0.4 of the initial value with many units in the 0.6 to 0.8 range. On the other hand, carefully processed mesa transistors in evacuated cases have been tested to 10^5 rads with no significant changes. If the transistors are exposed to sufficiently high ionizing radiation doses at low dose rates, surface effects may be a major damage mechanism to electronic systems.

The most important effects of radiation on transistor performance are those caused by minority carrier lifetime reduction, conductivity changes and surface alterations. Circuit degradation caused by minority carrier lifetime reduction and conductivity changes can be predicted by using the techniques presented in the following discussion. The significance of surface effects is discussed later in this paper.

Circuit Evaluation

The performance of circuits or systems in a nuclear environment can be predicted analytically or determined experimentally. The most economical and reasonable approach is one which utilizes the advantages of both techniques, since both techniques have limitations. For purposes of discussion and evaluation, the advantages and limitations of analytic and experimental methods for determining radiation sensitivity are considered separately.

Analytic Methods

The analytical techniques for predicting the radiation level at which a circuit will fail must include the following processes.

1. Equations describing circuit performance as a function of component parameters must be determined.
2. Variation of component performance as a function of radiation must be established.
3. Circuit equations and component performance must then be combined in a suitable way to yield circuit performance.

Difficulties are encountered in executing each of the above steps. Equations describing the performance of linear circuits are simple and can be written quickly. For switching and other nonlinear circuits, however, the equations are often complicated and require considerable time and skill to write. Furthermore, the effects of approximations, which must be made often, are difficult to evaluate.

Degradation and alteration of transistor parameters can only be determined by exposing representative samples of the devices to appropriate radiation levels and by measuring the parameters of interest at suitable bias levels. Care must be exercised when selecting samples to insure they are representative of the device type. In order to make this selection manufacturing distributions of the parameters must be known. In general, thousands of measurements are required to adequately define transistor parameters of interest in most circuits over the range of neutron and bias levels for which the device is useful.

Of the three steps listed above, the last one is the most difficult to accomplish. Whereas linear equations are solved easily, the nonlinear equations encountered are generally algebraic forms which cannot be solved analytically and, therefore, numerical techniques must be used. Even when the equations can be solved and transistor performance data are available, reasonable statistical techniques do not exist for determining circuit performance if several transistor parameters are involved which are related in a nonlinear way. Under these circumstances the behavior of the circuit can be determined by three different approaches. The first is the use of Monte Carlo techniques. Sets of transistor parameters are picked in a random way from a group representing the unirradiated population of devices. The equations are solved using the values of transistor parameters appropriate to the set of transistors chosen at different flux levels. This process must be repeated many times in order to determine the statistical performance of the circuit. The second method requires establishing the sensitivity of the equations to the various transistor parameters. In general, current gain changes the most with radiation and has the greatest effect upon circuit performance. For many circuits, therefore, change in performance can be, to a good approximation, totally attributed to changes in transistor current gain. If the circuit investigated is of this type, circuit equations can be expressed as a function of one transistor parameter, i.e., current gain, and circuit performance can then be determined by any one of several statistical techniques. Closed analytic forms for the statistical performance of the circuit usually cannot be found and, again, numerical techniques are most practical for obtaining predictions. The preceding two methods yield circuit performance distributions. Probability of failure at a radiation level can be determined from

these distributions and from the circuit performance requirements. A third method of predicting performance, which is quite useful, determines the end points of the distribution. If the equations are solved for "worst case" and "best case" transistor data, the "sure safe" and "sure failure" radiation levels are obtained.

It is necessary to understand the operation of the circuit in order to determine that transistor behavior which constitutes worst case data. For example, worst case data is the behavior of the low-gain transistors for amplifier circuits which must maintain a minimum gain, because transistors with the lowest initial gain generally have the lowest gain at various exposure levels. For those circuits where a change in gain is important, worst case data is associated with the behavior of the high gain transistors because they exhibit the largest change in gain with radiation. For other types of circuits, such as differential amplifiers, worst case requires a high gain transistor in differential configuration with a low gain transistor. In many instances sure safe levels obtained from worst case data are sufficient to indicate whether the circuit must be further investigated. This method can, therefore, be used to minimize the overall effort expended in the analysis of a system.

The analytical approach can be illustrated by using the linear amplifier shown in Figure 3. The set of equations which describe circuit performance and the equivalent circuit from which they were obtained are shown in Figure 4. As an initial step in the analysis, the equations are solved for worst case transistor data to determine if the circuit meets the necessary radiation specifications. The current gain performance of the transistors used in this circuit is shown in Figure 1. Worst case and best case data for this circuit are the transistor parameters corresponding to the lowest and

Figure 3. Four Transistor Linear Amplifier

Figure 4. "h" Parameter Equivalent Circuit and Matrix for the Linear Amplifier

highest values of current gain, respectively, since the criterion of failure for this circuit is its absolute gain. It was determined that the amplifier would not meet manufacturing specifications using worst case transistors which had not been irradiated and, by definition, the amplifier would fail at a zero neutron radiation level. With best case transistors, however, the amplifier would operate properly at about 2×10^{13} NVT. These findings illustrate the failure range of radiation levels often encountered in electronic circuits. The failure range is large for this circuit because the design was originally somewhat marginal and because the initial values of transistor gains extend over a wide range. On the other hand, electronic circuits are often marginal if all of the transistors are worst case and an initial spread of current gains from 30 to 100 is not large when compared to transistor production limits currently accepted by industry.

A numerical study of the circuit matrix indicated that circuit gain changes caused by radiation damage were, for most practical purposes, totally controlled by changes of a single transistor parameter, current gain. Therefore, a Monte Carlo approach was not necessary and the statistical behavior of the circuit was established by methods outlined below.

The density distributions of current gain for the transistor at a particular bias level, before irradiation and at various neutron radiation levels are shown in Figure 5. The initial distribution is essentially Gaussian with the low values removed; however, since most manufacturers select more than one code from a production line, each code has a skewed distribution. Furthermore, radiation alters the distribution and generally causes additional distortions. Because the current gain and damage constant, K , vary as a function of bias level, initial distributions and irradiated distributions must be known for the various bias levels of interest in order to calculate circuit performance. By means of numerical techniques these transistor gain distributions can be used to determine the gain distributions for each transistor stage. By properly combining these to include effects of feedback it is possible to obtain the gain distribution for the circuit and the probability of failure at a given flux level. When this technique was applied to the amplifier previously considered, the gain density functions shown in Figure 6 were obtained. If this calculation is repeated at different flux levels, a failure probability function can be determined as shown in Figure 7. A comparison of the results obtained from worst case analysis and from the statistical treatment is interesting. Worst case analysis predicted that this circuit could fail at zero neutron radiation. The probability of circuit failure at zero flux is about 3×10^{-7} and does not reach significant levels (0.001) until 1×10^{12} NVT. This comparison

illustrates the significance of the skewed gain distributions characteristic of circuits with feedback and shows the conservative nature of the estimates obtained from worst case analysis.

Figure 5. Grounded Emitter Current Gain Density Function at Different Neutron Exposure Levels

Figure 6. Linear Amplifier Gain Density Function

Figure 7. Probability of Failure Versus Neutron Radiation for Linear Amplifier

The sophistication required in an analysis depends to a large degree on the complexity of the circuit. For example, the logic circuit shown in Figure 8 does not require elaborate analysis. The output of the circuit is terminated in "N" identical circuits, where N is the "fan out". The approximate gain required for proper operation is N. If N is 10 and the transistor used in the circuit is the one shown in Figure 1, on a worst case basis the circuit will fail at a flux level of about 5×10^{13} NVT. Furthermore, because only one transistor is involved, the probability of failure can be worked out very quickly by using the data shown in Figure 5.

Figure 8. Typical Logic Circuit Used in Electronic Systems

Experimental Methods

The experimental methods of determining and predicting the radiation level for failure can generally be classified into two groups: laboratory methods and nuclear testing. In this report nuclear testing is defined as the process of exposing a complete circuit or system to nuclear radiation.

Laboratory Methods -- An approach which the author has found useful in determining the effects of radiation on a complex electronic system consists of substituting groups of pre-irradiated transistors into the circuits and then measuring circuit performance in the laboratory. The groups are composed of transistors which have been irradiated to progressively higher radiation levels and are, essentially, a "library" of radiation degraded transistors. The parameter important to circuit operation for each group of transistors is adjusted by irradiation to correspond to the worst case value observed at a given flux level in prior component tests. In order to test the four stage amplifier previously discussed, for example, groups of four transistors are irradiated until their current gains equal the lowest observed gain at various flux levels as shown in Figure 1. When this library of transistors is used in the circuit, transistor gain and, consequently, the flux level at which failure occurs can be determined. This experimental technique, therefore, yields the worst case failure level and does not give probability distributions. Notwithstanding the limitations of worst case determinations,

this approach is particularly useful for screening circuits and subsystems to determine those areas most sensitive to radiation. It is invaluable for testing circuits with complex interactions which are extremely difficult to analyze.

Marginal circuits identified by the above technique can be analysed to gain a better understanding of their performance. From a practical viewpoint, circuits often do not require a complete analysis and can be improved significantly with minor design modifications.

If this concept of using pre-irradiated transistors is applied during the design phase of an electronic system, the failure levels will be known when the design is complete. Furthermore, improvements in the radiation level at which a circuit fails generally can be made during the design phase at little or no expense to schedules or overall system performance.

The advantages of the experimental approach are illustrated by a study of a power inverter in which voltage regulation is achieved by a nonlinear magnetic system which senses the output voltage and appropriately adjusts the input voltage. Analysis of this power supply is difficult and time consuming because it contains four nonlinear elements: a magnetic voltage regulator, a square loop frequency regulator, a nonlinear power transformer and two transistor switches. Transistors of the type used in this inverter were irradiated with neutrons and the graph of current gain versus radiation obtained was similar to that shown in Figure 1. Pairs of transistors were then irradiated until their current gains equaled the lowest observed gain for several flux levels along the curve. This library of transistors was used to determine the minimum transistor current gain required for proper operation of the power inverter and the corresponding minimum flux level at which failure could occur. Failure occurred because the magnetic regulator caused excessive loading of the inverter during the startup phase of operation; the output voltage, switching waveshape and frequency were all significantly altered. This example illustrates a complex failure mechanism resulting from interactions of nonlinear components which is extremely difficult to predict analytically. Once the mode of failure was established, however, circuit modifications required to improve performance were obvious.

It is possible to perform a Monte Carlo substitution of pre-irradiated transistors in a system and thereby determine probability of failure. For those systems using many transistors, the number of pre-irradiated transistors and the time required to make the substitutions and measurements are prohibitive. This approach, therefore, is not considered practical for most applications.

Nuclear Testing -- The effects of a radiation environment are seldom considered during the design phase of a system and only after the design is completed are any serious efforts made to establish these effects. Then the designer often requests an irradiation of his entire system to determine its sensitivity. This is an unreasonable approach because information so obtained applies only to the specific system tested. Results of the test cannot be used with reasonable confidence to predict the performance of other similar systems because radiation induced component changes are a function of the initial component parameters and because changes in system performance depend on component changes as well as the interactions between components. The large variations normally encountered in transistor parameters prevent, therefore, a few observations on a specific system from being a reasonable basis for predicting radiation performance of similar systems. The amplifier shown in Figure 3 illustrates this problem. The range of neutron flux over which the unit could possibly fail is about thirteen orders of magnitude. Generally, a system composed of many circuits with complicated interactions often has wide limits of failure.

If a circuit is exposed to very high radiation levels before it fails and if the radiation performance of the transistors is known, a sure safe radiation level for similar circuits can be predicted. Because the transistor gain distributions do not overlap, it is obvious that if a circuit using the transistors shown in Figure 5 survived a radiation exposure of 5×10^{13} NVT, all similar circuits would survive an exposure of 5×10^{12} NVT. If this circuit failed at 3×10^{13} NVT, however, it is impossible to guarantee that all similar circuits would operate properly prior to irradiation. Because this method of testing is not sensitive to the true performance of the circuit, it lacks the accuracy usually required and is not useful for most applications.

It is not practical, therefore, to test most semiconductor electronic systems in a nuclear environment in order to predict or verify performance. On the other hand, the negative aspect of test results is valuable. If a system fails when tested, it is obvious that the radiation requirements have not been met.

The aforementioned limitations of testing are not unusual. They were discussed because of the common practice of irradiating one or two systems and then claiming radiation performance solely on the basis of the tests.

Variations in the performance of components initially and as a function of flux, cause the major difficulties in predicting system performance in

a radiation environment. If transistors can be selected with the same initial current gain and rate of degradation, the problem of determining and predicting performance is minimized as follows: the probability study required in the analytic approach is unnecessary; the laboratory technique of substituting pre-irradiated transistors and measuring performance yields failure level instead of worst case failure level; nuclear testing also measures failure level and predictions based upon nuclear testing are possible. The radiation degradation of transistors generally can be predicted by using nondestructive electrical measurements if the radiation performance of transistors of a particular code and manufacturer is known. The equation of α as a function of radiation shows that the change of current gain for transistors with the same α_0 and t is practically identical for a given set of bias conditions. In general, good correlation between performance of devices of the same code made by different manufacturers should not be expected because they often use different device geometries, material composition and processing techniques. In many applications, gain and transit time selection would make the cost of a system prohibitive; however, it may be practical if only one or two systems are built or if the electronic system is a small fraction of the total system cost. In principle, this approach is not unusual but is simply another method of controlling system performance through control of component performance.

Estimation of System Failure Level

The methods previously discussed permit accurate determination of failure levels and probability of failure but are time consuming and costly. To determine or guarantee performance of a system specifically designed to withstand a given neutron environment and, in particular, if this environment is near the limits of the state of the art, these methods are, virtually, the only suitable approaches and must be applied to the entire system. On the other hand, it is often necessary to estimate the neutron failure level for systems not designed to survive a neutron environment. In general, such systems have a few circuits which fail at much lower exposure levels than the other circuits within the system. By identifying these circuits and their failure levels, the system failure level can be determined with minimum effort.

Those circuits most sensitive to radiation can be identified in several ways. There is a high probability they can be found by system irradiation. Although this is the most expensive, it is the approach requiring the least skill and understanding of the problem. Generally, the most economical method involves reviewing the component performance in conjunction with circuit performance and system requirements.

No unambiguous rules for identifying the most sensitive circuits can be stated because different systems require different approaches. Most systems not designed for a radiation environment contain low frequency response transistors which are relatively sensitive to radiation damage. Power circuits often contain these devices because low frequency power transistors are much more common and less expensive than those with high frequency response. Circuits without feedback should also be suspect as they are the most sensitive to small changes of transistor gain. Finally those circuits whose performance cannot be degraded appreciably without significantly affecting system operation should be investigated.

After the circuits most likely to fail have been identified, any one or a combination of the methods previously discussed can be used to determine their radiation failure levels. It should be recognized: (1) this technique of estimating system failure levels does not guarantee great accuracy of prediction and (2) a thorough investigation (such as the statistical analysis described) of the most sensitive circuits is not warranted because only the most probable system behavior has been considered and little is known about failures which have a low probability of occurring. Therefore, this method of estimating system behavior is useful only when approximate failure levels are required and a high degree of assurance regarding behavior is not required. Notwithstanding these limitations, this very practical and economical approach is of value for many types of systems.

Significance of Surface Effects -- It is impossible to predict system performance in a radiation environment if component performance is unpredictable. Ionizing radiation induced alterations of surface effects are not well understood and only limited prediction of performance is possible. A screening technique has been developed for separating transistors which are the least sensitive to ionizing radiation effects from those which are the most sensitive.⁴ Screening is accomplished by exposing each device to an ionizing source and measuring the rate of degradation. Only those devices exhibiting a low rate of degradation are used. This is a reasonable approach until the surface problem is understood and/or transistors can be manufactured which are not adversely affected by ionizing radiation. The screening process is not an entirely satisfactory solution, however, because of the cost and the uncertainty that the selection is adequate.

It is not practical to design circuits to accommodate the extreme changes in current gain often caused by radiation induced surface effects. Therefore, the device designers must solve this problem by studying the mechanisms involved, making necessary design modifications and using quality control. Until improved semiconductor

devices are available, carefully selected transistors should be used in those systems designed to operate in an ionizing environment for long periods of time.

Design Techniques for Minimizing Radiation Effects

Although the design techniques for minimizing radiation effects were implicit in the foregoing discussions, they will now be reviewed by considering, separately, the component selection, circuit design and system, design required.

The components used should have a minimum degradation in the radiation environment of interest. For neutron environments, these devices can be chosen on the basis of minority carrier lifetime and frequency response. For an ionizing radiation environment, devices can be selected by screening. Regardless of the environment, device performance must be known in order to design the circuits properly and, therefore, complete measurements of device performance as a function of radiation are required. Furthermore, to insure device uniformity, it is necessary to maintain quality control on the devices. This can be accomplished, generally, by electrical measurements which correlate with radiation behavior and by occasional sample selection and irradiation.

The effects of radiation on a circuit can be minimized by careful design. Transistors operated at low bias levels are degraded more than those operated at higher bias levels because the damage constant, K , is sensitive to injection level. Therefore, transistors should not be operated at low bias levels. Feedback should be used, whenever possible, to minimize the effects of component changes. Pre-irradiated transistors should be used during the circuit design phase in order to estimate the failure level and provide a tool for circuit improvements. In general, designers will find that simple circuits which are fully understood are easier to "harden" than complicated circuits.

Finally, the system should be designed to minimize the performance required of the electronics. Often minor modifications of the system can greatly reduce performance requirements for the electronics.

Summary

Analytical and experimental techniques are available for determining the radiation level at which an electronic circuit or system may fail. The choice of a particular approach for evaluating radiation sensitivity depends upon the complexity of the system, the accuracy required and the facilities available. In general, the most economical approach is one which combines analysis with the use of pre-irradiated transistors. In addition, the negative

aspect of nuclear testing can be used to verify that no failure mechanism has been overlooked.

The analytical approach requires considerable mathematical skill and is time consuming. Extreme care must be exercised in expressing performance in equation form in order to obtain a proper representation of the circuit and, therefore, the analytical method is most easily used for relatively simple circuits. This approach has the advantage of being accurate and providing the probability of failure.

The experimental approach of substituting pre-irradiated transistors has the advantages of being relatively inexpensive, not especially time consuming and requiring only normal design capabilities. It is a very powerful tool when used during the design phase. It has the disadvantage of providing only worst case and best case circuit behavior.

Nuclear testing is not a practical method for predicting or verifying the performance of most electronic circuits or systems. The uncertainties of the test results may be much greater than those experienced for other environments because of the large range of transistor parameters and degradation rates normally encountered. Nuclear testing is of value, however, for those systems with very carefully controlled semiconductors which have consistent and uniform performance.

All prediction techniques require knowledge of the component performance for the environment of interest. This implies measurement of performance as well as quality control of the product.

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