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OPERATION
PLUMBBOB

NEVADA TEST SITE
MAY-OCTOBER 1957

Project 6.2a

EFFECT of NUCLEAR RADIATION on SEMICONDUCTOR DEVICES (U)

Issuance date: October 7, 1960

HEADQUARTERS FIELD COMMAND
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EFFECT of NUCLEAR RADIATION on SEMICONDUCTOR DEVICES, (U)

P. H. Haas, Project Officer
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W. V. Behrens

Diamond Ordnance Fuze Laboratories
Washington 25, D. C.
FOREWORD

This report presents the final results of one of the 46 projects comprising the military-effects program of Operation Plumbbob, which included 24 test detonations at the Nevada Test Site in 1957.

For overall Plumbbob military-effects information, the reader is referred to the "Summary Report of the Director, DOD Test Group (Programs 1–9)," ITR-1445, which includes: (1) a description of each detonation, including yield, zero-point location and environment, type of device, ambient atmospheric conditions, etc.; (2) a discussion of project results; (3) a summary of the objectives and results of each project; and (4) a listing of project reports for the military-effects program.
A total of 350 transistors and semiconductor diodes, including germanium and silicon types, were exposed to nuclear detonations. Some of the transistors were operational during exposure as oscillators, amplifiers, and trigger circuits. Radiation levels varied from $10^{14}$ to $10^{16}$ NVT (n/cm$^2$) integral neutron flux, accompanied by gamma radiation between 0.1 and 100,000 r.

The transistors showed a decrease in common-emitter current gain and an increase in collector-diode reverse leakage current. The higher-frequency transistors were less affected by neutron fluxes than were the audio units, and the surface-barrier types were virtually undamaged by the maximum fluxes obtained. Semiconductor diodes showed an increase in forward resistance and a decrease in back resistance, with point-contact types showing much less change than the junction types.

Transistors and diodes in operating equipment suffered permanent damage comparable to those passively exposed. Degradation of performance of this equipment was almost entirely attributable to changes in the semiconductor parameters.

The results obtained are in reasonable agreement with data obtained from pile-type reactors, indicating that total integrated neutron flux is of primary significance, rather than rate of exposure.
CONTENTS

FOREWORD ................................................................................................................. 4
ABSTRACT ..................................................................................................................... 5

EFFECT OF NUCLEAR RADIATION ON SEMICONDUCTOR DEVICES
  Objectives .................................................................................................................. 9
  Background ................................................................................................................. 9
  Theory ........................................................................................................................ 9
  Procedure ................................................................................................................... 10
  Results ....................................................................................................................... 11
  Discussion ................................................................................................................ 13
  Conclusions ............................................................................................................... 18
  Recommendations .................................................................................................. 19

REFERENCES ............................................................................................................. 20

FIGURES
  1 Containers for semiconductor devices for special tests ............................................. 10
  2 Circuit diagrams of transistorized devices ............................................................... 11
  3 Placement of boxes and flux levels ........................................................................ 12
  4 Decrease in beta with neutron bombardment ....................................................... 13
  5 Increase of $I_{o}$ with neutron bombardment ......................................................... 14
  6 Change of forward resistance with neutron bombardment, semiconductor diodes ......................................................................................................................... 14
  7 Change of back resistance with neutron bombardment, semiconductor diodes ......................................................................................................................... 15
  8 Changes in $\beta$ parameters with neutron bombardment, total of twenty-four 2N139 transistors ......................................................................................................... 15

TABLES
  1 Average Values of Beta and $I_{o}$ after Irradiation .................................................. 17
  2 Changes in Minority Carrier Lifetime and Beta with Neutron Bombardment ...... 16
EFFECT of NUCLEAR RADIATION on SEMICONDUCTOR DEVICES

OBJECTIVES

The object of the work described herein was to ascertain the continued effects of neutron, gamma, and electromagnetic radiation upon commercially available transistors and diodes and upon electronic circuits employing these components. Particularly desired was specific information of value to the applications researcher as to the relative radiation susceptibility of the different types of semiconductor devices.

BACKGROUND

The use of nuclear weapons in modern warfare makes necessary the obtaining of information concerning the effects of nuclear radiation upon armaments and equipment. Since many of the armament control circuits either presently utilize semiconductor devices, or may advantageously do so, it is essential to obtain information on the performance of transistors and semiconductor diodes in the environment of a nuclear explosion.

Preliminary high-intensity, short-duration neutron-irradiation tests were made in 1956 (Reference 1) using the Los Alamos Scientific Laboratory’s Godiva pulse reactor as a neutron source. The choice of semiconductor devices and the design of electronic circuitry exposed during Operation Plumbbob were made as indicated by the results of the Godiva test.

THEORY

Since the operation of semiconductor devices depends upon carrier movement through a well-ordered crystal lattice, it should be expected that particle bombardment of the crystal would disrupt its orderly arrangement and thereby cause device performance to deteriorate. In addition, the accompanying gamma rays were expected to cause ionization of matter (grease, potting compound, etc.) in contact with the crystal, resulting in surface effects detrimental to transistor action.

Decrease in the common-emitter forward current gain (beta) of transistors as a result of continuous low-level neutron radiation over a long period of time has been measured by others (References 2 and 3). Since the loss of beta has been attributed primarily to a decrease in minority carrier lifetime (References 3 and 4), it was expected that this would be of less proportional importance for high-frequency units, wherein the minority carriers diffuse through a thinner base region.

An increase in collector diode backward leakage current ($I_{o3}$) of radiated transistors has also been measured by investigators using continuously operated reactors (References 2 and 3). This degradation has been attributed to a combination of surface effects at the collector-base junction, together with changes in bulk characteristics of the semiconductor that tend to destroy the barrier. The former effects, that of conductances shunting the collector-base barrier, have been considered to result (References 2 and 4) primarily from exposure to gamma radiation and are reported to vary considerably with the type of grease or filling compounds surrounding the
crescents, whereas the effects of the other isotope were attributed principally to neutron irradiation.

PROCEDURE

The semiconductor devices under test were placed between sponge rubber pads and contained in aluminum cans. The cans were packed with sawdust insulation and placed inside a heavy marine plywood box. The physical test objects were positioned at various distances from the ground-zero point of the nuclear detonation, and at various depths in the ground in such a manner that exposure to neutrons may vary from 10 to about 10^3 neutrons per square centimeter XAT, and gamma radiation from less than 1 to 1000. Gold foil was included in each can to act as an indicator of the relative intensity of neutron irradiation.

Figure 1 is a photograph of the containers for the transistors and diodes exposed.

Semiconductor devices in both the passive and active states were exposed; however, monitor-
unit was powered by a single battery. Each self-powered oscillator-amplifier combination was contained in an aluminum can. Similarly, the trigger circuits and the transistorized power supplies were also each contained in individual aluminum cans and powered by self-contained batteries.

The checking of the transistors' forward current gain (beta) and collector diode back leakage current ($I_{leak}$) was done with a laboratory-type beta checker. An ac-vacuum-tube voltmeter was used to monitor the outputs of the oscillators and amplifiers. The trigger circuits were self-monitoring by the use of small squibs, which ignited at a predetermined current level. Monitoring of the outputs of the dc-to-dc high-voltage power supplies was accomplished by using a high-impedance electrostatic voltmeter.

The measurements indicated above were taken and recorded before exposure to the radiation and were repeated again afterwards. In every case, after-exposure recovery of the equipment and its monitoring were accomplished before the self-contained batteries had run down enough to cause consequential error.

Data from several types of detectors, placed at various distances from ground zero as part of Project 2.3, provided a means for computing the total integrated neutron flux (NVT) levels. These values correlated well with relative values obtained from the gold-foil detectors placed inside the boxes.

A total of 293 transistors and 60 semiconductor diodes were irradiated in these tests; of these, 43 transistors were in the operating state during irradiation. Three samples each of representative types of commercially available transistors were exposed to the selected levels of nuclear radiation. A few of the less-available types were tested in smaller quantities.

Figure 2 shows the placement of the boxes containing the semiconductors and semiconductor devices relative to Shot Pescolla. The one box exposed to Shot Hood was buried 4 inches below the ground at 800 feet from ground zero.

RESULTS

The permanent performance capabilities of these particular transistorized devices were only slightly affected by exposure (under operating conditions) to atomic radiation up to $2.9 \times 10^{15}$.
NVT and $3.3 \times 10^4 \text{ r}$. As was experienced in the preliminary tests, component damage was manifested only in the semiconductor devices.

The oscillator and amplifier units, which utilized the same type of high-frequency transistors for both functions, showed negligible permanent effect from irradiation as intense as $10^{12} \text{ NVT}$ and $150 \text{ r}$. A slightly higher exposure of $2.9 \times 10^{12} \text{ NVT}$ and $3.3 \times 10^5 \text{ r}$ resulted in percentage reductions in the amplifiers' outputs, by type of transistor used, as follows: 2N126, 3.0 percent; 2N114, 7.5 percent; 2N247, 15 percent; and 2N94A, 18 percent. The outputs of the oscillators remained practically unchanged after exposure at the above levels.

Trigger circuits of two types, blocking oscillators, and two transistor switches were exposed in the operational state with indicator squibs connected in the circuits to disclose false triggering. Although inspection of the circuits after recovery showed that no permanent damage to performance resulted from irradiation as high as $1.6 \times 10^{12} \text{ NVT}$ and 900 r, the expended indicator squibs showed that all circuits exposed to fluxes greater than $1.9 \times 10^9 \text{ NVT}$ (with negligible gamma radiation) had been caused to trigger by the nuclear radiation. Two of the blocking oscillator circuits, which were more sensitive than the two-transistor trigger circuits, triggered from exposures of $6.3 \times 10^4$ and $3.2 \times 10^5 \text{ r}$, respectively.

Subsequent checking showed that the batteries powering the two-transistor trigger circuits had run down considerably following the irradiation, whereas similar batteries powering the blocking oscillators remained at nearly original strength.

The results of irradiating the transistorized high-voltage power supplies were somewhat erratic. A unit exposed to $3.6 \times 10^{11} \text{ NVT}$ and 8 r suffered a 19 percent drop in output, whereas a similar one exposed to $1.6 \times 10^{11} \text{ NVT}$ and 900 r had its output decreased by only 2.4 percent (both four days after exposure).

The output of a unit irradiated at $0.8 \times 10^{11} \text{ NVT}$ and negligible gamma was not reduced. Laboratory testing of the supplies approximately 3 weeks after their irradiation showed that all the voltage outputs had recovered to within 2 percent of their pre-exposure values.

A check of semiconductor devices exposed to a nuclear detonation when in the passive state showed that most high-frequency transistors suffered moderate damage from exposure to fluxes of $1.1 \times 10^{11} \text{ NVT}$ (highest flux accurately instrumented) and $8.8 \times 10^4 \text{ r}$. Exceptions to this were the surface-barrier transistors, the characteristics of which were only slightly altered by irradiation at this level. Of the several types of surface-barrier transistors tested, the 2N128 transistors exhibited the highest resistance to radiation damage. The average characteristics of three 2N128 transistors exposed to fluxes of $1.1 \times 10^{11} \text{ NVT}$ and $8.8 \times 10^4 \text{ r}$ indicated a loss in beta of less than 3.2 percent and an increase in $I_{1V}$ of about 70 percent. (Highest $I_{1V}$ was still

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less than 2 μm.) The change of characteristics of the 2N247 drift transistors from irradiation at the 1.1 $\times 10^{14}$ NVT level was somewhat unusual, since the average beta of the transistor dropped only about 30 percent, whereas the average $I_{CE}$ increased to twelve times its pre-exposure level.

Results similar to those above were obtained when the same types of transistors were contained in a two-layer Boral (slow-neutron) shield container inside the regular aluminum housing, and this assembly was exposed to the same neutron and gamma-flux intensity.

Figures 4 and 5 show the decrease in forward current gain (beta) and the increase in reverse collector diode leakage current ($I_{C0}$), respectively, of several of the types of transistors passively exposed. Data showing the effects of radiation on the beta and $I_{C0}$ of each of the transis-

![Figure 4](chart.png)

**Figure 4** Decrease in beta with neutron bombardment.

itors passively exposed appears in Table 1. Both the graphs and the table show normalized values, i.e., the average original value altered by the average percent change. Where several transistors were exposed at a given flux level, the individual deviations from the average change were generally less than 30 percent. The transistors exposed while in operating condition in equipment were affected to approximately the same degree by irradiation as were the same type of passively exposed transistors.

Figures 6 and 7 show the increase in forward resistance and decrease in back resistance, respectively, of several types of semiconductor diodes included among the components passively exposed.

The changes in $I_{C0}$ of the Type 2N139 transistors exposed to nuclear radiation when in the passive state are shown in Figure 8.

Table 2 lists the measured values of minority carrier lifetime and forward current gains for 2N77 transistors before and after exposure to several intensities of nuclear radiation.

**DISCUSSION**

It is believed that neutron bombardment was responsible for the permanent damage to the semiconductor devices exposed in these tests. Other investigators (References 2 and 3) have found that a gamma dosage of about $10^7$ r was required to reach the threshold of permanent semiconductor damage. Since the maximum gamma dosage received by any component in these tests was less than $10^5$ r, the possibility of permanent damages from gamma radiation is ruled out.

Although it was planned to irradiate the units of operating equipment at levels up to $2 \times 10^{13}$ NVT, the maximum level to which operating units actually were exposed was $2.9 \times 10^{12}$ NVT, a
Figure 5 Increase of $I_{co}$ with neutron bombardment.

Figure 6 Change of forward resistance with neutron bombardment, semiconductor diodes.
Figure 7: Change of back resistance with neutron bombardment, semiconductor diodes.

Figure 8: Changes in h parameters with neutron bombardment, total of twenty-four 2N159 transistors.
It is to be expected that a neutron flux of \(2.9 \cdot 10^{12}\) NVT would only slightly affect the performance of transistorized devices using the high-frequency, thin-base, transistors. As occurred in the preliminary tests, the oscillator outputs were not affected, since the oscillators were designed with a relatively large amount of positive feedback and since the performance of the high-frequency transistors used as oscillators in this test deteriorated only slightly at exposures of \(2.9 \cdot 10^{12}\) NVT and below.

The reduction in output of the amplifiers, which occurred at the maximum exposure level (for active devices) of \(2.9 \cdot 10^{12}\) NVT, was almost directly proportional to the loss in forward current gain of the transistors. As was done in the preliminary tests, the amplifiers were purposely designed to reflect this deterioration. The maximum decrease in output of 18 percent (1.7 db), however, cannot be considered to constitute a device failure, for variances greater than this exist in commercially available transistors and are allowed for in conventional electronic design.

The false triggering of the blocking oscillator and two-transistor switch circuits is believed to be due to transient currents resulting from either the effects of neutron and gamma radiation on the semiconductor devices or the circuit intercepting the radiated electromagnetic field. The results indicate a triggering sensitivity to nuclear radiation of several orders of magnitude greater than that for permanent radiation damage to audio transistors.

The erratic behavior of the high-voltage power supplies may have been due to the combination of the spread of characteristics of the transistors and the fact that this particular design requires a transistor with high forward current gain and a high collector-base resistance at the instant of current cutoff.

Since only one supply was tested at each dosage level, anomalous behavior of the one sample (which would average out for many samples) could be responsible for the incongruous data. When laboratory tests were made, 3 weeks after the exposure, there had been sufficient annealing so that the direct-current output of the damaged unit was almost up to its original value.

The majority of transistors exposed to the nuclear radiation while in the passive state exhibited a decrease in beta and an increase in \(I_{C(sat)}\) to approximately the same degree as was experienced for similar transistors in the preliminary tests. Since those contained in a Boral container were damaged to almost the same degree as were similar units not so contained, it appears that the elimination of low-energy neutrons causes no appreciable change in radiation damage.

The effects of the changes in \(h\) parameters on the performance of conventional transistor amplifiers should be considered. The power gain (P.G.) of a typical grounded-emitter-transistor-amplifier stage is approximated by:

\[
P.G. \approx (h_{ie})^2 \left( \frac{h_{ie}}{h_{ie} + R_L} \right) \frac{R_L}{h_{ie}}
\]

Where:
- \(R_L\): the load resistance
- \(h\) parameters per Institute of Radio Engineers' standards, corresponding to the hybrid parameters for a four-terminal network.
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If one assumes that $R_L$ is considerably smaller than $h_{ie}$, a condition met in most RC coupled transistor amplifiers and in many others, then the power gain equation reduces to:

$$P.G. \quad \frac{R_L}{h_{ie}}$$

Equation 2 indicates that the power gain of an amplifier stage is a function of the transistor parameters $h_{ie}$ and $h_{re}$; however, the variance of the input impedance, $h_{ie}$, of a transistor from irradiation is relatively small in comparison to the change in $h_{re}$, the forward current gain (beta). It follows that the power gain is approximately proportional to $(h_{ie})^2$. The extent of damage to an amplifier stage is thus seen to be a drop in power gain of about 6 dB for each 50-percent decrease in beta of the transistor. Since 40 dB of gain per transistor-amplifier stage is possible with high-gain transistors, a 6-dB loss due to transistor damage might be tolerated in most cases. Variations of this relative magnitude could be reduced considerably by the application of negative feedback, and in addition, the negative feedback, if of the dc type, would increase the circuit stability. High circuit stability is particularly desirable for circuits exposed to nuclear radiation, because of the unavoidable increase in transistor $h_{re}$.

The analysis above was made using the common-emitter transistor h parameters, since the majority of circuits now employ transistors using the common-emitter connection. Figure 8 shows radiation effects on the transistors' common-base h parameters, the latter being used because they are the more commonly measured classical parameters. For either type of h parameter, the significant changes from irradiation are such as to cause similar performance degradations.

With the exception of a few anomalies, the measured minority carrier lifetimes listed in Table 2 are proportional to the loss of beta of the transistors. Of particular interest are Transistors 1, 2, and 3, which suffered an almost complete loss of beta and also showed extremely short minority carrier lifetimes.

**CONCLUSIONS**

Of the components normally used in electronic circuits, semiconductor devices are the most susceptible to damage by nuclear radiation. In locations where physical survival of electronic equipment from the effects of a nuclear weapon is possible, fast-neutron bombardment alone is believed to be responsible for the permanent damage to semiconductor devices.

By designing circuits to be highly stable (using negative feedback and optimized biasing networks) and by using high-frequency transistors, the transistorized oscillators and amplifiers

18

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of low-power type should still be usable after exposure to neutron fluxes as high as $10^{14}$ NVT. During the nuclear detonation, however, malfunctioning of certain electronic equipment employing semiconductor devices can be expected from exposures as low as $10^3$ NVT, with negligible gamma radiation. It is yet to be determined whether either the neutron flux or the radiated electromagnetic field, or both, were responsible for malfunctioning during detonation.

Permanent damage to transistors from a nuclear detonation consists chiefly of a decrease in forward current gain, beta, and an increase in collector back leakage current, $I_{CQ}$. Therefore, transistorized circuits subject to exposure to a nuclear detonation should be designed to be as self-compensating as possible for changes in these parameters. The designer should avoid circuits with outputs that are proportional to the forward current gain of the transistors.

High-frequency transistors were less susceptible to damage by fast-neutron irradiation than were the audio units. Surface-barrier units underwent an exposure of $1.1 \times 10^{14}$ NVT from a detonation without suffering appreciable damage, whereas audio units were damaged severely by irradiation at this level. Of the surface-barrier transistors tested, Type 2N128 exhibited greatest resistance to radiation damage.

The irradiation of semiconductor diodes at levels up to $1.1 \times 10^{14}$ NVT caused the back resistance of the diodes to decrease in all cases and, in most cases, caused the forward resistance to increase. The behavior of the germanium point-contact Type 1N55A was unusual, since its forward resistance remained fairly constant after irradiation.

The reasonable correlation in measured drop of minority carrier lifetime with loss of beta of irradiated transistors supports the theory that the decrease in beta is caused principally by the minority carrier lifetime decrease.

**RECOMMENDATIONS**

Tests should be made to ascertain and record semiconductor performance during exposure to a nuclear detonation and to ascertain specifically the degree of contribution to semiconductor malfunctioning of gamma, neutron, and electromagnetic field radiation during the explosion.

Functional transistor and diode circuitry should be constructed to be as radiation resistant as possible, and these circuits should be irradiated in operating condition to ascertain and record their performance both during and after exposure.
REFERENCES


MEMORANDUM FOR DISTRIBUTION

SUBJECT: Declassification Review of Operation PLUMBOB Test Reports

The following 101 reports concerning the atmospheric nuclear tests conducted during Operation PLUMBOB in 1957 have been declassified and cleared for open publication/public release:


An additional 13 WTs from PLUMBOB have been re-issued with deletions and are identified with an "EX" after the WT number. These reissued versions are unclassified and approved for open publication. They are:

WT-1410 thru WT-1416, WT-1418, WT-1445, WT-1471, WT-1517, WT-1521, and WT-1541.

This memorandum supersedes the Defense Special Weapons Agency, OPSSI memorandum same subject dated June 13, 1997 and may be cited as the authority to declassify copies of any of the reports listed in the first paragraph above.

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