



Strategies for Radiation Hardness Testing of Power Semiconductor Devices

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Prepared for the
Annual Meeting
sponsored by the American Nuclear Society
San Diego, California, June 5–9, 2005

Prepared under Contract NAS3–00145

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Space Administration

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Abstract - *Plans on the drawing board for future space missions call for much larger power systems than have been flown in the past. These systems would employ much higher voltages and currents to enable more powerful electric propulsion engines and other improvements on what will also be much larger spacecraft. Long term human outposts on the moon and planets would also require high voltage, high current and long life power sources. Only hundreds of watts are produced and controlled on a typical robotic exploration spacecraft today. Megawatt systems are required for tomorrow. Semiconductor devices used to control and convert electrical energy in large space power systems will be exposed to electromagnetic and particle radiation of many types, depending on the trajectory and duration of the mission and on the power source. It is necessary to understand the often very different effects of the radiations on the control and conversion systems. Power semiconductor test strategies that we have developed and employed will be presented, along with selected results. The early results that we have obtained in testing large power semiconductor devices give a good indication of the degradation in electrical performance that can be expected in response to a given dose. We are also able to highlight differences in radiation hardness that may be device or material specific.*

I. INTRODUCTION

Power requirements for future space exploration projects will be dramatically higher than they have been in the past for robotic exploration missions. The Cassini spacecraft which is now visiting Saturn carries three radioisotope thermoelectric generators (RTGs). At the end of its eleven year mission, each of the Cassini RTGs will generate 210 watts of DC electric power at 30 volts¹. In contrast, early planning for a mission to Jupiter and its moons envisions a single power source that would generate 100,000 watts of electric power at more than 300 volts. Electric propulsion systems on such a spacecraft will require up-conversion of the low voltage source, using power semiconductor devices, to several thousand volts. Future permanent outposts in the solar system will require power conversion systems for life support, manufacturing and communications². Semiconductor devices used to control and convert power in these systems would be exposed to neutron and gamma radiation escaping from a power source currently conceived.

Semiconductor devices used in the construction of future space based power conversion systems will

experience exposure to higher levels of natural radiation as well. Beginning an interplanetary journey, a spacecraft encounters energetic trapped particles in the earth's magnetic field. Using electric propulsion would require spending time in these radiation belts as the spacecraft accelerates. Leaving earth's orbit exposes the spacecraft to the solar wind and the galactic cosmic radiation. An encounter with the magnetic field of another planet such as Jupiter brings in another set of energetic trapped particles. Conceptually, these longer duration missions will result in accumulated damage to the semiconductors, and will expose the devices to particles energetic enough to cause sudden failure in a single event. Shields can be designed to reduce exposure, but, because of mass limitations especially on long duration missions, it is desirable to reduce the amount of shielding required. If the effect on operation of the accumulated damage is determined, circuits can be designed to anticipate and mitigate the change in operation. As failure modes are identified, device designs may be modified to increase tolerance to long term exposure and to reduce the likelihood of single event failure. Facilities and test methods have been developed to study these effects.

II. RADIATION ENVIRONMENTS

The natural radiation environments have been monitored for many years. Presently near Earth, the spacecraft³ IMP8, Advanced Composition Explorer(ACE)⁴ and Ulysses monitor our solar radiation environment. Interplanetary probes including Galileo, Cassini-Huygens and Pioneer 10 have carried radiation environment monitors in flybys and orbits of the Jupiter system. Cosmic radiation coming from outside our solar system has been monitored using earth based detectors, devices such as bubble chambers carried aloft by high altitude balloons, and using many space based instruments. Radiation that is produced artificially in communication, power and instrumentation systems has also been measured.

Data from many monitoring efforts has been used extensively to produce mathematical models of the environment near Earth, in interplanetary space and in the vicinity of other planets. The GIRE model⁵, for example, describes the electron radiation environment in the vicinity of Jupiter. The European Space Agency Space Environment Information System⁶ maintains a web site providing links to many other models of natural and artificial radiation environments. Commercial software is also available which allows estimation of the total radiation that an object might experience in any particular orbit.

III. RADIATION SOURCES SUITABLE FOR SIMULATION OF SPACE RADIATION EFFECTS

Damage to power semiconductors occurs when atoms in the semiconductor are displaced, ionized or transmuted. The damage can be accumulated in the bulk crystal, in the insulating oxides and at the interfaces between the crystal and the oxide. Because the space radiation environment is so varied, simulation of damage expected to occur in that environment requires the use of several different radiation sources on earth.

Neutron sources that produce sufficient flux to cause displacement damage in semiconductors are fission reactors and linear accelerators. A mixed field of radiation which consists of neutrons, electrons and gamma radiation is produced in a reactor. The spectrum of neutron energies in a port near the core of a light water fission reactor ranges

from less than an eV to near 15 MeV with an average energy of 2 MeV. Some of the fission neutrons give up energy in a moderator such as water, and reach thermal equilibrium with their surroundings (< 0.2 eV). Mono-energetic neutrons of 2.5 And 14.1 MeV can be produced in a linear accelerator using deuterium and tritium targets and a deuterium source.

Gamma radiation energetic enough to cause ionization of atoms in semiconductors can be found in ⁶⁰Co sources. ⁶⁰Co decays to ⁶⁰Ni in two steps emitting a 1.17 MeV gamma, a 1.33 MeV gamma, and a 315 keV electron. Because the half life of ⁶⁰Co is only 5.3 years, the activity of these sources declines over time and the length of time needed to duplicate a particular exposure increases.

Proton sources producing sufficient energy to simulate space radiation are cyclotrons and linear accelerators. The proton energies are limited to a narrow band set by the tuning the accelerator. Energies in the range from 60 MeV to 200 MeV are commonly used to study ionization and displacement damage. Although protons and neutrons have nearly the same mass, the damage caused by a neutron and a proton of identical energy is not directly comparable because of the charge on the proton. Protons interact with charge in both the nucleus and the electron cloud, while neutrons do not interact with charge. Because they are charged, protons can be trapped in and accelerated by planetary magnetic fields.

Electron radiation sources producing energies from several keV to hundreds of MeV are readily available. Linacs and synchrotrons are used to accelerate electrons. Electrons can be used to study ionization and displacement damage in semiconductor devices. Electrons are also found trapped in planetary magnetic fields.

Heavy Ion Accelerators are can be used to simulate the effects of cosmic radiation on semiconductors. Ions in a range of masses from neon to gold are commonly available. Along the track of the heavy ion through the semiconductor, millions of ionizations occur per centimeter. The ions have ranges in silicon up to several hundred microns. That range is sufficient to allow the ion to

pass completely through the active area of a power semiconductor device.

Power semiconductor devices can be exposed to radiation in any or all of these sources to simulate the exposure which is predicted for a particular mission. Device parameters of interest are measured and recorded prior to exposure to radiation. Power semiconductor devices under test can be operated under load or they can be un-powered during the radiation exposure. The former is defined as functional testing and the latter is defined as characterization testing. We have done characterization testing in air at room temperature and at controlled elevated temperature. Functional testing has been done in air both with and without active temperature control. In our characterization testing, device parameters are measured periodically during the exposure using a high power semiconductor curve tracer wired to the devices in the reactor port. In our functional testing, parameters are recorded continuously while the devices are operated under load in some circuit of interest.

IV. CHARACTERIZATION OF RADIATION SOURCES EMPLOYED IN THIS WORK

We have characterized the radiation environment for irradiation of Si and SiC semiconductor devices in characterization and functional testing vessels in Beam Port 1 (BP1) of the Ohio State University Research Reactor (OSURR). The results that are given below are for the characterization vessel. The results for the functional testing vessel are not greatly different. We have also employed a characterized gamma source at OSU.

For irradiation in a reactor environment, one is most interested in knowing the displacement damage rate (\dot{d}), the average displacement damage energy transferred per second to an atom in the irradiated material. It can be calculated, according to the first formula in Eq. 1,

$$\dot{d} = F_{D,1MeV,mat} \phi_{eq,1MeV,mat}^{Total} = F_{D,1MeV,mat} H_{mat} \phi^{Total} \quad (1)$$

if one knows $\phi_{eq,1MeV,mat}^{Total}$ (the energy integrated 1 MeV equivalent neutron flux), which is defined as

$$\phi_{eq,1MeV,mat}^{Total} = \int_0^{\infty} \frac{F_{D,mat}(E)}{F_{D,1MeV,mat}} \phi(E) dE \quad , \quad (2)$$

and $F_{D,mat}(E=1MeV)$ (the displacement damage kerma factor, evaluated at 1 MeV) for Si and SiC. Alternatively, since $\phi_{eq,1MeV,mat}^{Total}$ is related to ϕ^{Total} (the energy integrated neutron flux), which is defined as

$$\phi^{Total} = \int_0^{\infty} \phi(E) dE \quad , \quad (3)$$

through the definition of the hardness factor (H_{mat}),

$$H_{mat} = \phi_{eq,1MeV,mat}^{Total} / \phi^{Total} \quad , \quad (4)$$

\dot{d} can be calculated with a knowledge of ϕ^{Total} , the material hardness parameter (H_{mat}), and $F_{D,mat}(E=1MeV)$, according to the second formula in Eqn 1. It is for this reason that H_{mat} is oftentimes presented by others, and it is why we present H_{mat} here.

The values of $F_{D,mat}(E)$ that were used in our calculations are given in Fig. 1.

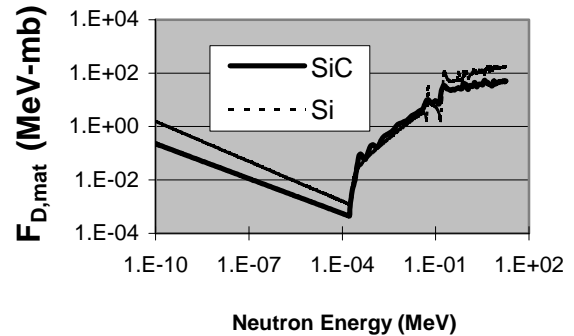


Fig. 1. The displacement damage kerma factors (damage functions) for Si ($F_{D,Si}(E)$) and SiC ($F_{D,SiC}(E)$): logarithmic scales are used for the ordinate and for the abscissa.^{9,10}

We used the method of multiple foil activation, and the SAND-II neutron energy spectrum deconvolution code to determine the energy dependent neutron flux ($\phi(E)$) at four locations (Positions 1, 2, 3 and 4) in the characterization vessel. Irradiation positions 3 and 4 are equidistant from and closest to the reactor core. Positions 1 and 2 are also equidistant from the core, but are located several inches further away.

The results of our measurements and calculations are presented in Table 1 for 50 kW operation (approximately 10% of full power). We have developed the mathematical infrastructure whereby we can quantify the radiation exposure of Si and SiC semiconductor devices in terms that are technically precise and relevant to the observed

radiation effect. There is good agreement in the measurements between positions 3 and 4, and reasonably good agreement between positions 1 and 2. Radiation decreases over the distance between the near and far position pairs by about a factor of two.

Table I: $\phi_{eq,1MeV,Si}^{Total}$, H_{Si} , \dot{d}_{Si} , $\phi_{eq,1MeV,SiC}^{Total}$, H_{SiC} and \dot{d}_{SiC} for Positions 1, 2, 3 and 4

	Position 1	Position 2	Position 3	Position 4
$\phi_{eq,1MeV,Si}^{Total}$ (neutrons $cm^{-2}s^{-1}$)	3.34×10^{10}	3.07×10^{10}	6.03×10^{10}	6.03×10^{10}
$\phi_{eq,1MeV,SiC}^{Total}$ (neutrons $cm^{-2}s^{-1}$)	4.01×10^{10}	3.69×10^{10}	7.21×10^{10}	7.20×10^{10}
H_{Si}	0.545	0.530	0.550	0.554
H_{SiC}	0.655	0.637	0.657	0.661
\dot{d}_{Si} (n $cm^{-2}s^{-1}$)(MeV-mb)	3.17×10^{12}	2.92×10^{12}	5.73×10^{12}	5.73×10^{12}
\dot{d}_{SiC} (n $cm^{-2}s^{-1}$)(MeV-mb)	1.14×10^{12}	1.05×10^{12}	2.05×10^{12}	2.05×10^{12}

The gamma irradiator at Ohio State consists of a six inch inside diameter tube which is surrounded by pins of ^{60}Co . The dose rate profile in the irradiator was measured in January of 2002 using ceric-cerous liquid dosimeters⁷. The dosimeters were spaced out on a frame and lowered into the test area. As seen in Fig. 2, the maximum dose rate in water at the time of the calibration was 1.98 kGy/hr at 8 inches above the bottom of the irradiator. At the time of this writing the dose rate has decreased and is now calculated to be 1.30 kGy/hr.

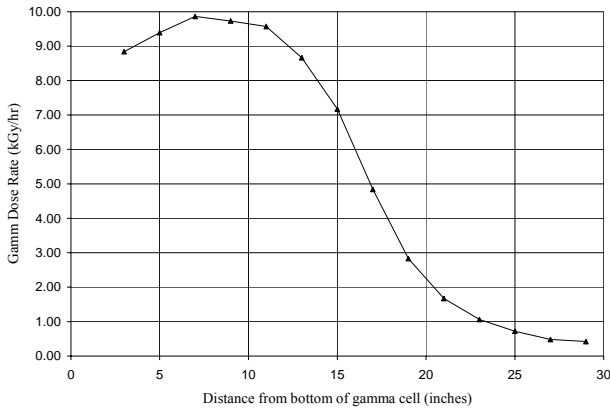


Fig. 2. Gamma dose curve in ^{60}Co irradiator.

V. RESULTS

Several examples of radiation damage in power semiconductor devices are presented here.

Radiation induced charging of the gate oxide in a large power MOSFET is illustrated in Fig. 3. The gate threshold voltage falls in response to gamma irradiation in both the ^{60}Co source and in response to the reactor gamma dose. It is thought that the gate voltage shift is the result of hole trapping in the gate oxide and at the interfaces between the semiconductor layers⁸. In the case of gamma radiation, the ionization appears to be caused by Compton scattered electrons. To investigate this possibility, we exposed the gate oxide of the same large power MOSFET to an electron beam in an SEM. The gate threshold shift of the MOSFET in the SEM had an onset near 20 keV. This is an electron energy that could reasonably be the produced during Compton scattering of electrons by the 1.2 and 1.3 MeV ^{60}Co gamma rays.

The forward on resistance of silicon power devices increases with exposure to neutron fluence, Fig. 5. The damage mechanism is thought to be the creation of broken bonds and trap states for carriers as the neutrons displace atoms from their lattice sites. Forward voltage drop in junction devices increases because of this change. The forward IV curves shown in Fig. 6 were recorded in real time as displacement damage accumulated in a large silicon pn junction power diode.

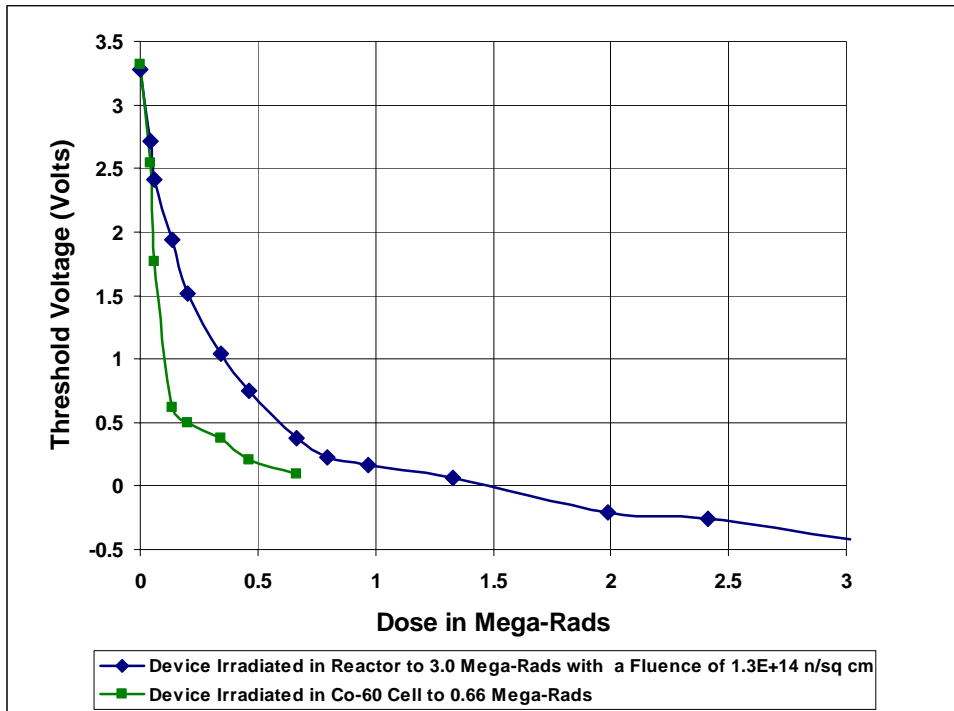


Fig. 3. MOSFET threshold shift due to gamma radiation

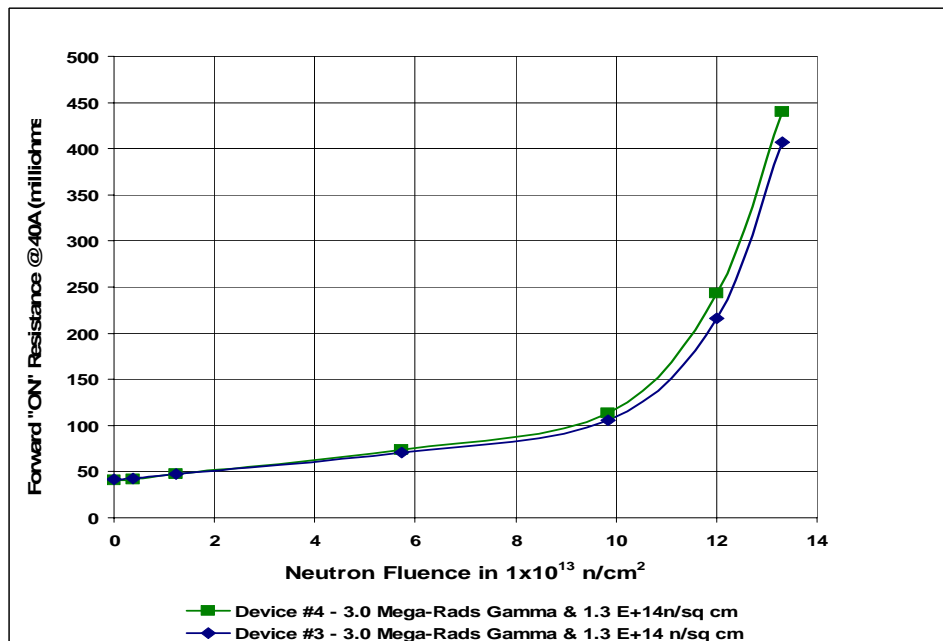


Fig. 4 MOSFET R_{on} shift due to neutron irradiation.

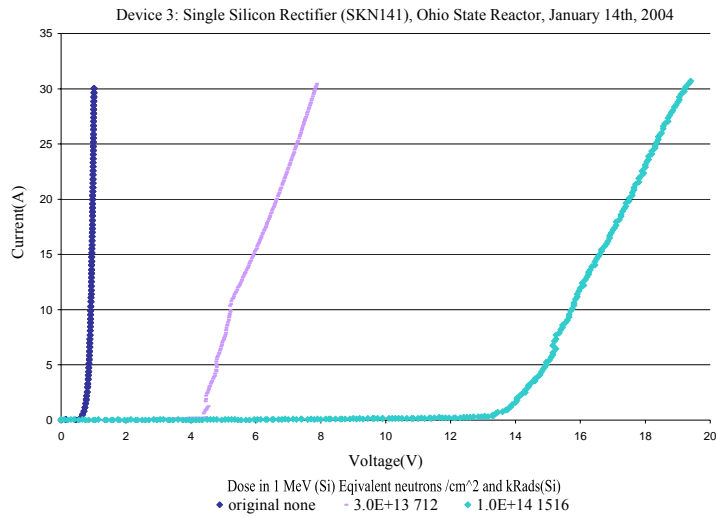


Fig. 5. Silicon PN junction power rectifier exposed to reactor mixed field radiation.

The IV plot in fig. 6 shows the effect of neutron displacement damage as it accumulates in a silicon PN junction power rectifier. Measurements of the diode forward IV characteristic were made prior to irradiation, at an accumulated damage dose of $3.0 \text{ E}+13$ and at a dose of $1.0 \text{ E}+14$ one MeV silicon equivalent neutrons per square centimeter. Fig. 7 presents the forward IV change that occurred in a silicon carbide Schottky diode. These two devices were mounted in position three of the test fixture in

two different reactor runs. The IV measurements were made on the silicon carbide Schottky at $2.0 \text{ E}+12$, at $1.3 \text{ E}+14$ and $1.8 \text{ E}+14$ one MeV silicon equivalent neutrons per square centimeter. The forward voltage drop at 10 amps in the silicon carbide part increased by one volt while the forward voltage drop of the silicon junction diode at the same current increased by 15 volts over a similar range of radiation exposure.

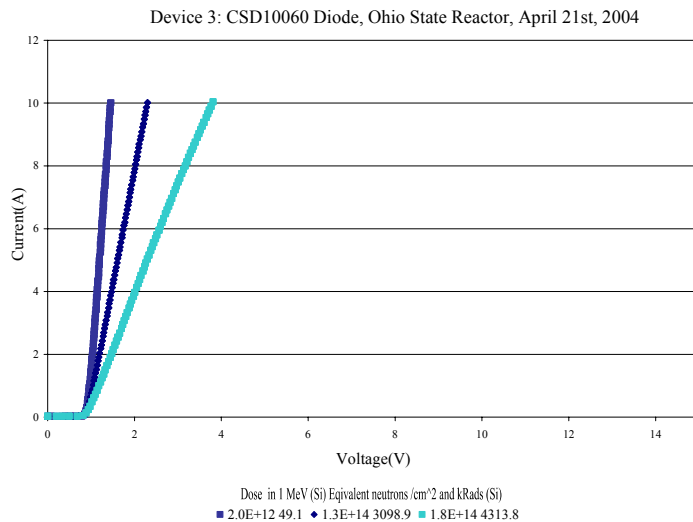


Fig. 6. Silicon Carbide Schottky power rectifier exposed to mixed field radiation.

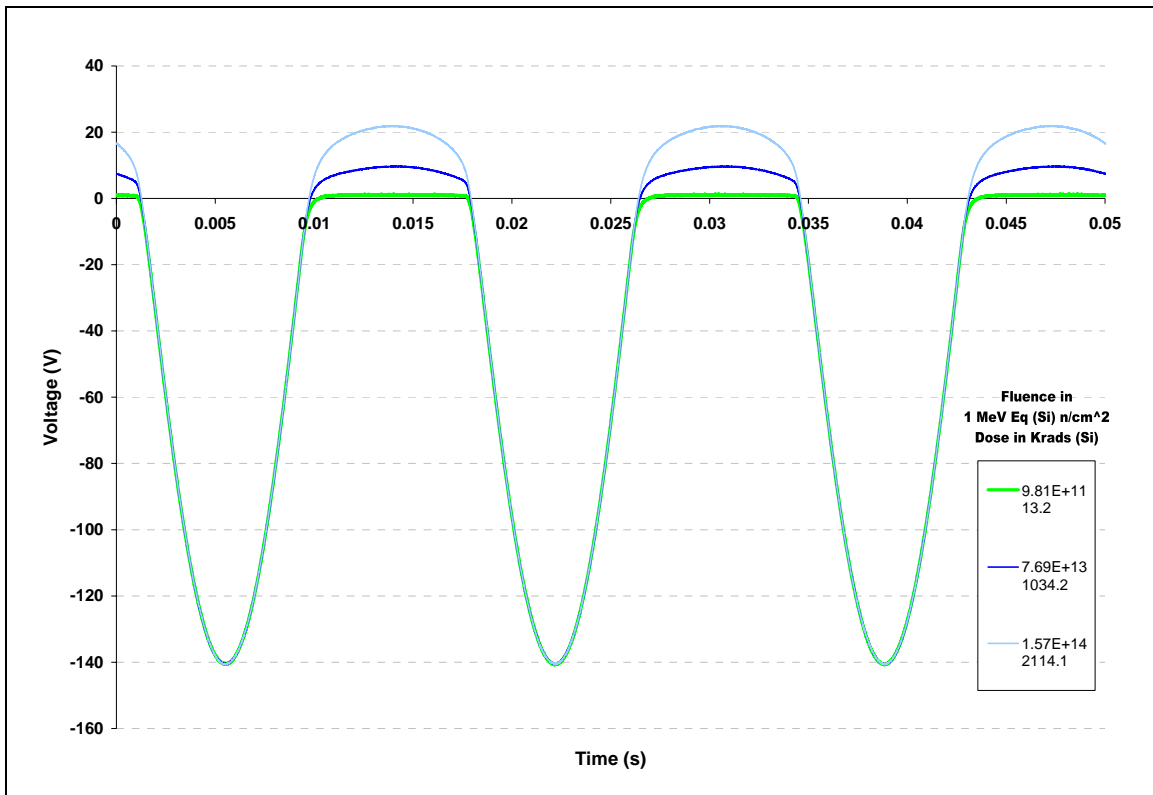


Fig. 7. Silicon power diode operated as a half wave rectifier in mixed field reactor radiation.

Fig. 7 presents the effects of neutron and gamma radiation on a large silicon power diode which was operated under load while being irradiated in a functional test. The temperature of the device was maintained at 20C using a PID controlled water closed loop water chiller/heater. The diode was operated as a half wave rectifier on a 60 Hz sine wave into a 10Ω resistive load. The effect of three levels of radiation are shown in the figure for clarity, but during functional testing the signals are recorded continuously along with the reactor power curve so that damage at any radiation level can be investigated. It can be seen that the forward voltage drop of the diode increased by a factor of 20 at the final level recorded, while the reverse characteristics were unaffected. Functional testing allows visualization of actual effects on circuit operation that are caused by exposure to radiation. These effects can be compared to mathematical models, which may allow better understanding of damage mechanisms and prediction of effects on other more complex circuits. De-rating curves can also be generated from this information for use by the

designers of the electrical power conversion and distribution systems.

VI. CONCLUSION

Semiconductor devices employed in the power control and conversion systems of future nuclear electric spacecraft and in planet based power plants would be exposed to neutron and gamma radiation from the power source. They will also experience natural radiation in planetary magnetic fields, in the solar wind and by exposure to galactic cosmic radiation. Two of the major damage types that all of these sources of radiation produce in semiconductor devices are displacement and ionization. Both types of damage can also be produced using neutrons and gamma radiation on earth. Device parameters can be recorded as the damage is occurring. In a functional test, the devices can be operated under load and changes in circuit operation can be monitored. This information will allow defensive circuit design to mitigate the identified effects of the radiation and will allow for design of shielding to reach minimum mass and adequate effectiveness.

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REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 2005	3. REPORT TYPE AND DATES COVERED Final Contractor Report	
4. TITLE AND SUBTITLE Strategies for Radiation Hardness Testing of Power Semiconductor Devices			5. FUNDING NUMBERS WBS-22-973-80-20 NAS3-00145	
6. AUTHOR(S) Martin O. Patton, Richard D. Harris, Robert G. Rohal, Thomas E. Blue, Andrew C. Kauffman, and Albert J. Frasca				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Analex Corporation 1100 Apollo Drive Brook Park, Ohio 44142			8. PERFORMING ORGANIZATION REPORT NUMBER E-15164	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CR-2005-213807 Paper 1021	
11. SUPPLEMENTARY NOTES Prepared for the Annual Meeting sponsored by the American Nuclear Society, San Diego, California, June 5-9, 2005. Martin O. Patton and Richard D. Harris, Analex Corporation, 1100 Apollo Drive, Brook Park, Ohio 44142, Telephone 216-433-2594, Fax 216-433-8656, m.o.patton@grc.nasa.gov; Robert G. Rohal, Micro Energy Corporation, 3584 Valley Parkway, North Royalton, Ohio 44133; Thomas E. Blue and Andrew C. Kauffman, Ohio State University, 190 N. Oval Mall, Columbus, Ohio 43210-1328; and Albert J. Frasca, Wittenberg University, P.O. Box 720, Springfield, Ohio 45501-0720. Project Manager, James V. Soltis, Power and Electrical Propulsion Division, NASA Glenn Research Center, organization code RPE, 216-433-5444.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 76 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
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14. SUBJECT TERMS Semiconductor devices			15. NUMBER OF PAGES 14	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

