Micro-Fabricated Solid-State Radiation Detectors for Active Personal Dosimetry

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Summary

Active radiation dosimetry is important to human health and equipment functionality for space applications outside the protective environment of a space station or vehicle. This is especially true for long duration missions to the moon, where the lack of a magnetic field offers no protection from space radiation to those on extravehicular activities. In order to improve functionality, durability and reliability of radiation dosimeters for future NASA lunar missions, single crystal silicon carbide devices and scintillating fiber detectors are currently being investigated for applications in advanced extravehicular systems. For many years, NASA Glenn Research Center has led significant efforts in silicon carbide semiconductor technology research and instrumentation research for sensor applications under extreme conditions. This report summarizes the technical progress and accomplishments toward characterization of radiation-sensing components for the recommendation of their fitness for advanced dosimetry development.

Symbols and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Alpha (Particle)</td>
</tr>
<tr>
<td>γ</td>
<td>Gamma (Ray)</td>
</tr>
<tr>
<td>ε</td>
<td>Mean Ionization Energy (eV)</td>
</tr>
<tr>
<td>μ</td>
<td>Electron Drift Mobility (cm²/V-s)</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (g/cm³)</td>
</tr>
<tr>
<td>ALARA</td>
<td>As Low As is Reasonably Achievable</td>
</tr>
<tr>
<td>cpm</td>
<td>Counts per minute</td>
</tr>
<tr>
<td>C-V</td>
<td>Capacitance-Voltage</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>E_d</td>
<td>Displacement energy (eV)</td>
</tr>
<tr>
<td>E_g</td>
<td>Minimum Band Gap (eV)</td>
</tr>
<tr>
<td>EIT</td>
<td>Extreme-ultraviolet Imaging Telescope</td>
</tr>
<tr>
<td>EMU</td>
<td>Extravehicular Mobility Unit</td>
</tr>
<tr>
<td>EVA</td>
<td>Extravehicular Activity</td>
</tr>
<tr>
<td>F</td>
<td>Fano factor</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GCR</td>
<td>Galactic Cosmic Radiation</td>
</tr>
<tr>
<td>GRC</td>
<td>Glenn Research Center</td>
</tr>
<tr>
<td>H_0</td>
<td>Peak bin in an energy spectrum</td>
</tr>
<tr>
<td>ICRP</td>
<td>International Commission on Radiological Protection</td>
</tr>
<tr>
<td>I-V</td>
<td>Current-Voltage</td>
</tr>
</tbody>
</table>
Introduction

The current monitoring of the impact of radiation conditions on astronauts and support equipment during Extravehicular Activity (EVA) is limited to post-mission, accumulative information provided by dosimeter badges. Improvements in the basic dosimeter design would provide a valuable tool to improve astronaut safety and provide better awareness of the external situation. This report outlines technology development at NASA Glenn Research Center (GRC) that will lead to a wearable, electronic dosimetry system which would not be adversely affected by radiation with improved sensitivity and detection capability for real-time monitoring of EVA conditions.

Radiation Environment

The primary threat to astronauts from space radiation is high-energy charged particles, such as electrons, protons, alpha and heavier ions, originating from galactic cosmic radiation (GCR), solar particle events (SPE’s) and trapped radiation belts in earth orbit. There is also the added threat of secondary neutrons generated as the space radiation interacts with atmosphere, soil and structural materials (ref. 1).

For lunar exploration missions, the habitats and transfer vehicles are expected to provide shielding from standard background radiation. Unfortunately, the lunar EVA suit is not expected to afford such shielding. For EVA in low earth orbit (LEO), the nominal planned doses are on the order of 0.1 mSv (10 mrem), but actual doses can be up to 10 mSv (1000 mrem) after frequent geomagnetic storms and higher during SPE’s. An 8-hour lunar EVA may see exposures over 1,000 mSv (100 rem), causing acute radiation sickness and increased risk of cancer (ref. 2).

Astronauts need to be aware of potentially hazardous conditions in their immediate area on EVA before a health and hardware risk arises. These conditions would include fluctuations of the local radiation field due to changes in the space radiation field and unknown variations in the local surface composition. Should undue exposure occur, knowledge of the dynamic intensity conditions during the exposure will allow more precise diagnostic assessment of the potential health risk to the exposed individual (ref. 3).
**Dosimetry Issues**

The traditional position of the radiological protection community to keep radiation exposures “as low as is reasonably achievable” (ALARA) has been instituted into established practices. These ALARA practices are based on recommendations of the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP), and implemented into Department of Energy (DOE) regulations. Active dosimeters are addressed in Article 513 of the DOE Standard “Radiological Control” (DOE-STD-1098-99) for the DOE and its contractors as the guideline for compliance with Title 10 of the Code of Federal Regulations, Part 835 (10 CFR 835) on “Occupational Radiation Protection.” Specifically, the Standard states (ref. 4): “DOE encourages the use of electronic dosimeters for entry into high radiation areas or when planned doses greater than 100 mrem [1 mSv] in 1 work day are expected. An electronic dosimeter provides an early warning of elevated exposure through the use of alarm set points at specified dose rates or integrated doses.”

In light of ALARA practices, active personal dosimetry is specifically recommended for EVA (refs. 5 and 6). The current Man-Systems Integration Standards (NASA-STD-3000) calls for the active monitoring of radiation dosage during an entire mission, and includes either active or passive measurements for each crewmember on EVA (ref. 5). Currently this is satisfied using passive dosimeters consisting of Thermo-luminescent Detectors (TLD’s), Optically Stimulated Luminescence (OSL) detectors and CR-39 track-etch detectors (refs. 6 and 7).

However, the recommendation of the Radiation Dosimetry Working Group at NASA Johnson Space Center (JSC) is that even though the current passive dosimetry fulfills the requirements for crew health and safety, “a small active dosimeter should be developed to monitor individual astronaut exposures during EVA” (ref. 6). Further, the NCRP specifically recommends active electronic personal dosimeters for a measurement package for low earth orbit operations. The council goes on to recommend that “active dosimeters should be used inside and outside of the spacecraft…even carried on the astronaut’s person, including during EVA” (ref. 8).

Radiation dosimetry is critical to EVA operations and dosimetry instrumentation is a recognized technology gap and challenge for human space exploration in general (ref. 9). Advanced technology development for instrumentation and dosimetry for space radiation health applications is specifically called for by NASA (ref. 10). Present radiation environment monitoring is inadequate with the existing architecture beyond earth’s ionosphere (ref. 11). Reliance on current monitoring systems using solar observations in predicting SPE’s (such as X-Ray flare observations, as shown in figure 1) during flight or surface operations beyond earth orbit is not considered acceptable to allow time for crew members to reach shielded locations (ref. 13). Radiation exposure to humans is a critical issue for exploration missions and its monitoring is a technology development priority for advanced EVA systems (ref. 14).

For lunar surface missions, the warning of radiation events is considered a part of medical operations countermeasures architecture (ref. 15). A real-time radiation monitor for operations external of any habitat is needed for reducing this risk for human space exploration (ref. 16). Defining the radiation environment during lunar EVA is seen as a technology challenge.

Figure 1.—The X-Ray Flare of November 4, 2003, the largest on record, as seen on the sun in the 195Å emission line by the Extreme-ultraviolet Imaging Telescope (EIT) on the Solar & Heliospheric Observatory (SOHO) (ref. 12). X-Ray Flares may be indicators of impending SPE’s.
challenges that can be met by hand-held or suit mounted radiation environment sensors (ref. 11). Further, EVA suit dosimetry for astronauts is recognized as a radiation protection strategy for lunar missions (ref. 17).

Solid State Detector Technology

Astronauts need to be aware of potentially hazardous conditions in their immediate area on EVA before a health and hardware risk arises. Real-time feedback of personal dosimeter information regarding astronaut conditions is currently not available. Real-time dosimeters based on silicon electronics could provide real-time information but silicon (Si) lacks the desired sensitivity (ref. 7) and is itself affected by radiation, decreasing the effectiveness of this technology. Improvements in the basic dosimeter design would provide a valuable tool to improve astronaut safety and instrument reliability by providing better awareness of the external situation.

The utilization of a solid detection medium for radiation detection has advantages over gas ionization detectors since the densities of the medium interacting with radiation can be as high as 1000 times of that for gas detectors. Scintillators allow efficient detection of ionizing radiation over a large surface area with a fairly linear output with energy, but the low number of photoelectrons generated in a particle interaction limit energy resolution due to statistical fluctuations. Semiconductor detectors allow a greater energy resolution by generating electron-hole pairs in particle interactions similar to gas ionization detectors, but with compact sizes limited to a postage stamp or smaller (ref. 18).

Semiconductor Radiation Detectors

Micro-electro-mechanical-system (MEMS) based devices fabricated from silicon carbide (SiC) to conduct low-noise neutron and alpha particle spectrometry have been reported outside of the context of personal dosimetry (ref. 19). SiC has a wide bandgap energy and high displacement energy, so SiC sensors and electronic devices have much better resistance to radiation damage from energetic charged particles that can form electron-hole pairs in the semiconductor (ref. 20). Micro-fabricated SiC dosimeters can be small enough to be integrated into EVA pressure suits or other surfaces which need to be monitored for radiation dosages at multiple points.

As a charge particle passes through a semiconductor, many electron-hole pairs are produced as the particle loses energy. The amount of energy required to create one electron-hole pair is the ionization energy ($\epsilon$) of the semiconductor. The ionization energies for semiconductors are typically on the order of electron volts (eV), where for gas ionization detectors are tens of electron volts. The number of electron-hole pairs is simply the energy lost (E) divided by the ionization energy. As in gas ionization detectors, the fluctuation of counting electron-hole pairs is smaller than would be expected for pure Poisson statistics, so the variance is adjusted by the Fano factor (F), which then is a direct indication of the energy resolution of the detector. Also, thermal noise of the detector is based on the rate of electron-hole pairs generated due to the band gap of the semiconductor ($E_g$). The electron drift mobility ($\mu$) will affect the diffusion of electrons in the semiconductor, also a significant indicator of the noise of the detector (ref. 18). The density ($\rho$) of the semiconductor will affect the interaction of radiation with the semiconductor, in both the production of electron-hole pairs as well as radiation damage. The displacement energy ($E_d$) is an indication of sensitivity to semiconductor damage from incoming radiation. These values are given in table 1 for several semiconductors considered for radiation detector applications (refs. 21 and 22). In particular, SiC, gallium nitride (GaN), and diamond are considered to be very rad-hard materials due to their larger displacement energy, and appear to have improved energy resolution over Si from their low Fano factors. The low drift mobility of SiC suggests that this semiconductor has the lowest noise of the wide band-gap semiconductors for radiation detection.
TABLE 1.—PROPERTIES OF SEMICONDUCTORS FOR USE AS RADIATION DETECTORS (REFS. 21 AND 22)

<table>
<thead>
<tr>
<th>Property</th>
<th>Silicon</th>
<th>Germanium</th>
<th>Gallium arsenide</th>
<th>Silicon carbide (SiC)</th>
<th>Gallium nitride (GaN)</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum band gap ($E_g$) [eV]</td>
<td>1.12</td>
<td>0.68</td>
<td>1.42</td>
<td>2.9</td>
<td>3.39</td>
<td>5.48</td>
</tr>
<tr>
<td>Electron drift mobility ($\mu$) [cm²/V-s]</td>
<td>1450</td>
<td>3900</td>
<td>8500</td>
<td>400</td>
<td>1000</td>
<td>1800</td>
</tr>
<tr>
<td>Mean ionization energy ($e$) [eV]</td>
<td>3.63</td>
<td>2.96</td>
<td>4.13</td>
<td>6.88</td>
<td>8.9</td>
<td>12.4</td>
</tr>
<tr>
<td>Fano factor (F)</td>
<td>0.115</td>
<td>0.13</td>
<td>0.10</td>
<td>0.09</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Density ($\rho$) [g/cm³]</td>
<td>2.329</td>
<td>5.323</td>
<td>5.317</td>
<td>3.22</td>
<td>6.15</td>
<td>3.515</td>
</tr>
<tr>
<td>Atomic mass [g/mole]</td>
<td>28.1</td>
<td>72.6</td>
<td>144.6</td>
<td>40.1</td>
<td>83.7</td>
<td>12.0</td>
</tr>
<tr>
<td>Molar density [moles/cm³]</td>
<td>0.0829</td>
<td>0.0733</td>
<td>0.0368</td>
<td>0.0803</td>
<td>0.0735</td>
<td>0.293</td>
</tr>
<tr>
<td>Displacement energy ($E_d$) [eV]</td>
<td>~19</td>
<td>---------</td>
<td>10</td>
<td>28</td>
<td>24</td>
<td>43</td>
</tr>
</tbody>
</table>

**Scintillating Fiber Detectors**

Common detectors used in spacecraft instrumentation and in accelerator particle physics experiments are scintillating fiber detectors (refs. 23 and 24). The fibers afford flexibility for conforming to novel surfaces and are able to cover surfaces of relatively large volumes. Also, the detectors are typically used in fast triggers to enable particle identification. Such detectors have been used in experiments without failure for many years at a time. The flexibility of a fiber-based dosimeter is an attractive option to allow embedded multidirectional radiation characterization of EVA pressure suits.

The scintillating fibers are organic scintillators, which have the benefit of not needing regular crystalline lattices to form electron-hole pairs as inorganic scintillators require for fluorescence. This benefit allows them to be used as a polycrystalline solid, liquid, vapor or as part of a multicomponent material. The base component of organic scintillators is typically polystyrene or polyvinyltoluene which acts as the primary absorber of radiation. Energy is transferred via a fast (<1 ns) nonradiative dipole-dipole interaction to a fluorescent dye that makes up about 1 percent of the weight of the scintillator. A third dye (called a wave shifter) may be added to absorb and re-emit the light at wavelengths that allow propagation over long distances where optical transmission is an issue. Such two component materials are referred to as binary scintillators and three component materials as ternary scintillators. The fiber themselves are typically between 0.5 and 1 mm diameter total, with a 25 μm thick cladding of acrylic around the scintillating core. Good optical performance using multicladding of multiple layers of acrylic of different index of refraction has been reported. Success using other fibers made of glass and capillaries containing scintillating liquids have been reported (ref. 23).

In use, the fibers are typically mounted side-by-side as a ribbon, either in single or double layer. The fibers are optically coupled to a waveguide block or fiber ribbon (with or without a wave shifter) for readout by a photomultiplier tube (PMT) or a visible light photon counter (VLPC). Current research is ongoing in improving the optical transmission of the scintillators, waveguides and the optical coupling of the components, as well as the development of room-temperature VLPCs for fast photon counting.

**Technology Development at GRC**

Technology development is ongoing at NASA GRC to meet the active dosimetry challenge. We are leveraging our efforts in radiation detection to investigate small and large area scintillating and MEMS devices for sensitivity to radiation and to compare with commercial devices. If these initial results look promising as a path for the design and fabrication of a prototype solid state dosimeter, further testing
would be required in conjunction with other researchers in the space radiation field over the next few years. The long term objective of this effort is to provide a compact, low power active electronic dosimetry system that would not be adversely affected by radiation, with improved sensitivity and detection capability for real-time monitoring of lunar EVA conditions.

**Micro-Fabricated Wide Bandgap Detector Development**

NASA GRC has been leading the world in the development of SiC semiconductor sensors and microelectronics. One recently developed technology is in producing SiC semiconductor surfaces of much higher quality than commercially available. These surfaces have demonstrated advantages over current commercial materials for other sensor applications (ref. 25).

The immediate goal of this technology development effort was to assemble a testing station to test and compare resolution of and sensitivity to energy deposited by alpha (α) particles into Si and SiC diode detectors. The detectors were required to be packaged in a way to allow them to be tested in the station. The electronic properties of the diodes were characterized to allow an understanding of the charge collection capability as detectors. The testing station was designed to allow a range of energies to be tested by varying the distance of the detectors from the α particle source in air using optical mountings. The results of the investigation will dictate future efforts to design and fabricate a personal active dosimeter concept for EVA systems.

**Initial detector packaging**

Six diodes were initially prepared for testing as radiation detectors. The first three (named D1, D2, and D3) were unpackaged SiC Schottky power diodes acquired from Cree, Inc. (Durham, North Carolina). These diodes have respectively a 10 A maximum forward current and 600 V reverse breakdown voltage, 10 A, 1200 V, 6 A, and 600 V. Two unpackaged SiC UV photo sensors (D4 and D5) were also acquired from Cree for radiation detection testing. The sixth diode (D6) was a Hamamastu S3590–02 window-less Si PIN photodiode optimized for radiation detection.

The diodes were electrically interconnected to a ceramic printed circuit board using conductive epoxy. These diodes were electrically interconnected to the printed circuit board with gold wires using thermal sonic wirebonding. Figure 2 shows the five SiC diodes mounted on the circuit board, and figure 3 gives a schematic of the connections of the diodes.
Detector characterization

The diodes were first characterized electrically to determine the parameters to be used for radiation response testing. These basic characterizations in dark conditions include current-voltage (I-V) under both forward and reverse bias, and capacitance-voltage (C-V) under reverse (and zero) bias. Examples of the I-V and C-V data curves for these diodes are shown in figures 4 and 5. The I-V characterizations provide information about the leakage current of the devices under high voltage bias, and the C-V characterizations determine the configuration of the preamplifier for optimized charge sensing. A summary of the characteristics at various biasing voltages is shown in table 2.

<table>
<thead>
<tr>
<th>Detector active area</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.17 mm$^2$</td>
<td>6.25 mm$^2$</td>
<td>4.0 mm$^2$</td>
<td>0.45 mm$^2$</td>
<td>0.83 mm$^2$</td>
<td>100 mm$^2$</td>
<td></td>
</tr>
<tr>
<td>Current at 0 V bias</td>
<td>5.55 pA</td>
<td>1.28 pA</td>
<td>−0.21 pA</td>
<td>−0.81 pA</td>
<td>0.70 pA</td>
<td>−2.61 nA</td>
</tr>
<tr>
<td>Current at −5 V bias</td>
<td>−5.38 pA</td>
<td>−5.20 pA</td>
<td>−9.07 pA</td>
<td>−18.7 mA</td>
<td>−17.8 mA</td>
<td>−2.78 nA</td>
</tr>
<tr>
<td>Current at −20 V bias</td>
<td>−11.4 pA</td>
<td>−9.69 pA</td>
<td>−14.4 pA</td>
<td>----------</td>
<td>----------</td>
<td>−3.22 nA</td>
</tr>
<tr>
<td>Capacitance at 0 V bias</td>
<td>0.400 nF</td>
<td>0.833 nF</td>
<td>0.629 nF</td>
<td>0.0109 nF</td>
<td>0.0108 nF</td>
<td>0.532 nF</td>
</tr>
<tr>
<td>Capacitance at −5 V bias</td>
<td>0.188 nF</td>
<td>0.408 nF</td>
<td>0.295 nF</td>
<td>0.0073 nF</td>
<td>0.0075 nF</td>
<td>0.116 nF</td>
</tr>
<tr>
<td>Capacitance at −20 V bias</td>
<td>0.107 nF</td>
<td>0.230 nF</td>
<td>0.167 nF</td>
<td>0.0051 nF</td>
<td>0.0055 nF</td>
<td>0.0724 nF</td>
</tr>
</tbody>
</table>
Testing station assembly

The testing station consists of an optical mount with three degrees of freedom and a charge preamplifier in a dark box, with bulkhead unions in the box rear to allow coaxial cable connections to processing electronics and biasing sources, as shown in figures 6 and 7. The optical mount holds the detectors and a charge sensitive preamplifier at a fixed position from the sources. This position can be adjusted to allow a variety of energies to be examined. As the charged particle loses energy in the detectors, a charge pulse is generated that is converted to a voltage pulse by the charge sensitive preamplifier. This voltage pulse height is proportional to the charge collected by the preamplifier, and thus proportional to the energy lost by the particle in the detector. The output signal from the preamplifier is connected to the digital pulse processor through the BNC connectors on the wall of the box. The digital pulse processor converts the pulses to a digital signal, and shapes the pulses for analysis in a multichannel analyzer (MCA). The MCA assigns a “bin” to each pulse that is directly proportional to the voltage height of the pulse input into the digital pulse processor. Therefore, the bin assignment of a pulse is directly proportional to the energy deposited in the detector. The digital pulse processor is directly connected with the computer for data collection and analysis. An attenuator is placed between the preamplifier and the digital pulse processor to reduce the output of the Si detector to voltage levels that can be managed by the processor. The attenuator was not necessary for the SiC detectors. The pulses could be observed with an oscilloscope at various points of the signal processing for troubleshooting. A schematic is shown in figure 8.
Figure 6.—Testing fixture with \textsuperscript{239}Pu source.

Figure 7.—Experimental testing apparatus.
For this effort, four sources of $^{239}$Pu with $\alpha$ particle activities of $1.05 \times 10^3$ counts per minute (cpm), $1.16 \times 10^4$ cpm, $1.16 \times 10^5$ cpm, and $1.22 \times 10^6$ cpm and one source of $^{241}$Am with an activity of 0.2 microcurie ($7.4 \text{ kBq}$ or $4.44 \times 10^5$ cpm) were acquired from the NASA GRC Radiation Safety Office. The circular areas of the $^{239}$Pu sources are 615 mm² and the $^{241}$Am source 3 mm², and all count rates were reported over a solid angle of $2\pi$ sr. The $^{239}$Pu sources emit $\alpha$ particles of 5.155 MeV (73.3 percent), 5.143 MeV (15.1 percent) and 5.105 MeV (11.5 percent) and $\gamma$ rays of 51.6 keV with a half-life of 24,000 years (ref. 18). The $^{241}$Am source emits $\alpha$ particles of 5.486 MeV (85.2 percent) and 5.443 MeV (12.8 percent) and gamma ($\gamma$) rays of 59.5 keV with a half-life of 433 years (ref. 18). The safety permit for using and storing these radioactive materials in the testing lab was submitted and approved to use these sources for detector testing.

**Initial testing**

The Si detector D6 was first tested for reaction to $\alpha$ particles with 0 V bias at 13, 25, and 34 mm distances using the $1.22 \times 10^6$ cpm $^{239}$Pu source to allow the best statistics. Also, the energy spectrum for $\alpha$ particles in air at these distances and 1 mm were modeled using TRIM calculations (ref. 26), and the peaks are shown in figure 9, and summarized in table 3. The pulse height spectrum from D6 exposed to the $^{239}$Pu source is shown in figure 10. The resulting distribution was disappointing as the noise levels were 30 percent of the full scale. Only the 2.2 and 3.8 MeV peaks were visible, and had widths approximately equivalent to the noise level. The noise of the system also prevented any peaks from being detected with the SiC detectors D1, D2, D3, D4, and D5.

![Diagram of detector signal processing.](image)

**TABLE 3—SUMMARY OF TRIM PREDICTIONS OF ENERGY PEAKS AND WIDTHS OF $\alpha$ PARTICLES FROM $^{239}$Pu AT VARIOUS DISTANCES IN AIR**

<table>
<thead>
<tr>
<th>Distance in air (mm)</th>
<th>Peak energy (MeV)</th>
<th>FWHM energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.05</td>
<td>0.02</td>
</tr>
<tr>
<td>13</td>
<td>3.81</td>
<td>0.08</td>
</tr>
<tr>
<td>25</td>
<td>2.22</td>
<td>0.13</td>
</tr>
<tr>
<td>35</td>
<td>0.17</td>
<td>0.13</td>
</tr>
</tbody>
</table>
To reduce electronic noise from the detectors, the packaging of the diodes was redesigned to have a shielded outside housing with a coaxial connection instead of the wires to screw terminal connections. The duplicate diodes for D1, D2, D3, and D6 were mounted with conductive epoxy on BNC connectors as shown in figure 11. The epoxy formed a 0.8 mm² spot for the wire connection on the surface of D1, D2, and D3, which reduced the active area of the detector. The epoxy spot size also excluded the mounting of D4 and D5 with this method. The new packaged detectors are referred to as D1b, D2b, D3b, and D6b.

**Detector package redesign**

To reduce electronic noise from the detectors, the packaging of the diodes was redesigned to have a shielded outside housing with a coaxial connection instead of the wires to screw terminal connections. The duplicate diodes for D1, D2, D3, and D6 were mounted with conductive epoxy on BNC connectors as shown in figure 11. The epoxy formed a 0.8 mm² spot for the wire connection on the surface of D1, D2, and D3, which reduced the active area of the detector. The epoxy spot size also excluded the mounting of D4 and D5 with this method. The new packaged detectors are referred to as D1b, D2b, D3b, and D6b.
The SiC detector D2b and the Si detector D6b, the two largest area detectors of the lot, were tested for response to $\alpha$ particles with 0 V bias, –4 V bias, and –20V bias at a fixed 1 mm distance from the $1.22 \times 10^6$ cpm $^{239}\text{Pu}$ source. Again, the high cpm source was chosen to obtain the best statistics. The close proximity of the detectors to the sources compared to the large area of the source removes the need for solid angle corrections. The resulting energy spectra are given in figure 12 for D2b and figure 13 for D6b. Future tests will include D1b and D3b as warranted.

A summary of the characteristics of the detectors is given in table 4. The peak bin ($H_o$) was found using an average of the product of the cpm with the bin number, and then dividing by the average cpm for the range. The bin range was selected around the visible peak structure, which varied from 400 to 1200 bins depending on the data set. Once $H_o$ was located, the peak cpm was found by averaging the counts of 40 bins on either side of the peak bin. The half maximum of the peak cpm was used to determine the noise floor and the full width half maximum (FWHM) values. The resolution of the system is determined by dividing the FWHM by $H_o$ (ref. 18). The integrated cpm was determined by summing the cpm of the bins at FWHM from either side of the peak, such that the total width of the bins summed was twice FWHM.

From the data in table 4, the Si detector had a higher noise floor than the SiC detector, and also the Si detector had the high signal output. The signal-to-noise ratio is on average over a factor of two greater for

| TABLE 4.—SUMMARY OF DATA ON BNC PACKAGED DETECTORS |
|-------------------|---|---|---|---|---|---|---|
| Detector          | 2b | 2b | 2b | 6b | 6b | 6b | 6b |
| Bias              | 0  | –4 V| –20 V| 0  | –4 V| –20 V|
| 5 MeV peak bin    | 4087| 5201| 6396| 18910| 24268| 25384|
| 5 MeV peak cpm    | 4.75| 8.40| 7.41| 199| 212| 213|
| Noise floor bin   | 814| 491| 328| 1464| 932| 644|
| (1/2 peak cpm)    |   |   |   |   |   |   |
| Signal to noise   | 5.0| 10.6| 19.5| 12.9| 26.0| 39.4|
| FWHM (bins)       | 658| 810| 852| 1952| 3312| 3400|
| Resolution        | 16%| 16%| 13%| 10%| 14%| 13%|
| 5 MeV integrated cpm (99%) | 3518| 7534| 6847| 95093| 171166| 173988|
| 5 MeV cpm/mm²     | 646| 1382| 1256| 951| 1712| 1740|
Figure 12.—Response of D2b SiC Schottky diode to 5 MeV $\alpha$ particles at different bias voltages.

Figure 13.—Response of D6b Si PIN diode to 5 MeV $\alpha$ particles at different bias voltages.
the silicon detector than the SiC detector. However, the resolutions of the two detectors are the same to ±2.3 percent, which can be reasonably attributed to statistical variation, and may be more of a reflection of the signal processing. The integrated cpm for the Si diode is larger due to the larger area, and the integrated cpm per area is also greater with the Si diode may be due to the fact that D6b was a PIN diode optimized for radiation detection, and D2b is a non-optimized Schottky diode. The energy spectrum using the Si detector in figure 13 also shows a “tail” from losses due to the electrons diffusing through the semiconductor which was not seen in the SiC detector in figure 12. As can be seen in table 1, SiC has lower electron diffusion than Si to which the lack of tails can be attributed.

**Thin Film Coated Scintillating Detectors**

In other activities, NASA GRC is attempting to verify claims (refs. 27 to 30) of nuclear energy in sonoluminescence (shown in fig. 14) using a thin film coated scintillation detector fabricated at NASA GRC (ref. 31). The detector consists of a coated scintillator connected to a photomultiplier tube (PMT) module with fiber optics. The scintillator generates a pulse of light when interacting with an ionizing particle. The coating is selected to function as either an attenuator or a convertor to allow radiation to react with the scintillator, and also to prevent the sonoluminescence light from generating false readings. The detection of reaction products will allow verification of power generation in sonoluminescence. Figure 15 shows a prototype detector that has been tested using background radiation. The concept of utilizing fiber optic detectors for limited volume spaces could be applied to EVA suits.

**Fiber optic dosimeter concept**

The current Extravehicular Mobility Unit (EMU) has three major assemblies: The Space Suit Assembly (SSA), the Life Support Subsystem (LSS), and EMU ancillary equipment. An example EMU from STS114 is shown in figure 16. The SSA is the pressure vessel that encloses the astronaut’s torso, limbs, and head. The components of the SSA are covered with Thermal Micrometeoroid Garments (TMG’s) consisting of an outer reflecting layer of puncture- and fire-resistant white “Ortho-Fabric” consisting of a blend of fluropolymer and aromatic polyamide fabrics, five insulating layers of aluminized reinforced polyester film, and an inner lining of polychloroprene-coated nylon ripstop fabric. The purpose of the TMG’s is to provide environmental protection during the course of an EVA (ref. 32). As part of the environmental protection, the insertion of a flexible optical fiber ribbon radiation detection system may be included in the design of a future EMU SSA. An image of this concept is shown in figure 17 with a 12 mm wide, 1 mm thick single layer fiber ribbon and a sample of TMG.

![Figure 14.—Sonoluminescence created at NASA GRC (true color, contrast enhanced).](image1)

![Figure 15.—Fiber optic radiation detector prototype.](image2)
Conclusions and Future Plans

Current monitoring of radiation conditions during LEO EVA is limited to post-mission, accumulative information provided by passive dosimeter badges. Improvements in the basic dosimeter design would provide a valuable tool to improve astronaut safety and equipment reliability, providing better awareness of the external situation. The utilization of a solid detection medium for radiation detection has advantages over gas ionization detectors since the densities of the medium interacting with radiation can be as high as 1000 times that for gas detectors. Scintillators allow efficient detection of ionizing radiation over a large surface area with a fairly linear output with energy, but the low number of photoelectrons generated in a particle interaction limit energy resolution due to statistical fluctuations. Semiconductor detectors allow a greater energy resolution by generating electron-hole pairs in particle interactions similar to gas ionization detectors, but with compact sizes limited to a postage stamp or smaller. Another trade-off in detector selection is that the power for semiconductor detectors needs to be provided at the sensing location, whereas the power for scintillator detectors does not need to be at the sensing location through the use of optical fibers.

Technology development is ongoing at NASA GRC to meet the active dosimetry challenge. An experimental testing system including both hardware and software for radiation sensitivity testing of Schottky diodes and photo detectors in detecting α particles has been designed and built. Commercial SiC Schottky diodes and Si and SiC photo diodes have been electronically characterized to determine the configuration of the front-end electronics to analyze the radiation response. After repackaging the diodes, the room-temperature response of a SiC Schottky diode was compared to a Si PIN diode optimized for radiation detection. The Si PIN diode had only a slightly better signal strength and signal-to-noise ratio, but the SiC diode showed much lower noise. The testing of an optimized SiC diode may improve the signal strength, which will improve the signal to noise ratio. No testing was done at the temperature extremes expected on the lunar surface to determine signal stability of the two semiconductor materials. A concept for utilizing scintillating fiber ribbon for use as a dosimeter was outlined, and further investigations are needed to determine the technologies required to produce a proof-of-concept and compare to the semiconductor devices.

We are leveraging our efforts in radiation detection to investigate small and large area scintillating and MEMS devices for sensitivity to radiation and to compare with commercial devices. If these initial results look promising as a path for the design and fabrication of a prototype solid state dosimeter, further
testing would be required in conjunction with other researchers in the space radiation field over the next few years. The long term objective of this effort is to provide a compact, low power active electronic dosimetry system that would not be adversely affected by radiation, with improved sensitivity and detection capability for real-time monitoring of lunar EVA conditions.

References

12. Image Source/Credit: “X28 flare in EIT 195,” Solar & Heliospheric Observatory (SOHO). SOHO is a project of international cooperation between ESA and NASA.


Active radiation dosimetry is important to human health and equipment functionality for space applications outside the protective environment of a space station or vehicle. This is especially true for long duration missions to the moon, where the lack of a magnetic field offers no protection from space radiation to those on extravehicular activities. In order to improve functionality, durability and reliability of radiation dosimeters for future NASA lunar missions, single crystal silicon carbide devices and scintillating fiber detectors are currently being investigated for applications in advanced extravehicular systems. For many years, NASA Glenn Research Center has led significant efforts in silicon carbide semiconductor technology research and instrumentation research for sensor applications under extreme conditions. This report summarizes the technical progress and accomplishments toward characterization of radiation-sensing components for the recommendation of their fitness for advanced dosimetry development.