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Multidirectional Cosmic Ray Ion Detector for Deep Space CubeSats

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ABSTRACT

Understanding the nature of anisotropy of solar energetic protons (SEPs) and galactic cosmic ray (GCR) fluxes in the interplanetary medium is crucial in characterizing time-dependent radiation exposure in interplanetary space for future exploration missions. NASA Glenn Research Center has proposed a CubeSat-based instrument to study solar and cosmic ray ions in lunar orbit or deep space. The objective of Solar Proton Anisotropy and Galactic cosmic ray High Energy Transport Instrument (SPAGHETI) is to provide multi-directional ion data to further understand anisotropies in SEP and GCR flux. The instrument is to be developed using large area detectors fabricated from high density, high purity silicon carbide (SiC) to measure linear energy transfer (LET) of ions. Stacks of these LET detectors are arranged in a CubeSat at orthogonal directions to provide multidirectional measurements. The low-noise, thermally-stable nature of silicon carbide and its radiation tolerance allows the multidirectional array of detector stacks to be packed in a 6U CubeSat without active cooling. A concept involving additional coincidence/anticoincidence detectors and a high energy Cherenkov detector is possible to further expand ion energy range and sensitivity.

INTRODUCTION

Transient heliospheric structures in the interplanetary medium are believed to cause magnetic field variations down to the sub-mHz scale, resulting in anisotropy of solar energetic protons (SEPs) and galactic cosmic ray (GCR) fluxes. The mechanisms that control anisotropy evolution remain poorly understood despite their importance in controlling the propagation of energetic particles and cosmic rays. These transport effects related to charged particle anisotropies are particularly important in the acceleration of SEPs from coronal and interplanetary disturbances.[1]

The manner and extent of the impact of high energy ions on planetary magnetosphere, atmosphere, and surface (space weathering) processes are not systematically known, although GCR ions are suspected to have a role in processes as diverse as space weathering,[2] cloud formation,[3] and magnetospheric shaping.[4]

On bodies lacking strong magnetospheres and true atmospheres, such as the Moon, energetic ions interact directly with the surface, and play an important role in space weathering, redistribution of volatiles, and polymerization of organic materials, through radiation chemistry.

In order to provide a complete understanding of how energetic processes internal and external to the solar system shape magnetospheres, atmospheres, and surfaces, in situ particle observations should include measurements of SEPs and GCR, along with solar wind and plasma. Missions to achieve these measurements would include flexible path orbiters, probes, landers or rovers beyond low Earth orbit (LEO).

SmallSats with mass less than 100 kg (such as CubeSats) are seen to be low-cost platforms ideal for conducting this range of observations either solo or in multiple locations as a swarm. However, current detector technology limits the measurement capability by restrictions of size, power and thermal stability of the SmallSat platform.

DETECTOR DEVELOPMENT

To meet the challenges of low-power, low-noise, multidirectional robust detectors for a wide range of mass and energies, new ion detectors based on wide band gap (WBG) semiconductors are being developed at NASA's Glenn Research Center (GRC) for integration into SmallSat platforms.[5]

As these WBG semiconductor detector technologies advance, more comprehensive (composition, velocity, and direction) in-situ measurements of heavy ions and space plasmas in deep space environments will be made possible on SmallSat platforms.

WBG LET Detectors

The application of silicon carbide (SiC) as Linear Energy Transfer (LET) detectors is based on the material's wide band gap and high displacement energy. These properties give several advantages over silicon-based detectors. Sensors and electronic devices made from SiC have much better resistance to radiation damage from energetic charged particles that can form defects in the semiconductor.[6] The wide band gap nature of SiC also allows measurements made by the detectors to be unaffected by thermal drift due to sun/shade transitions.

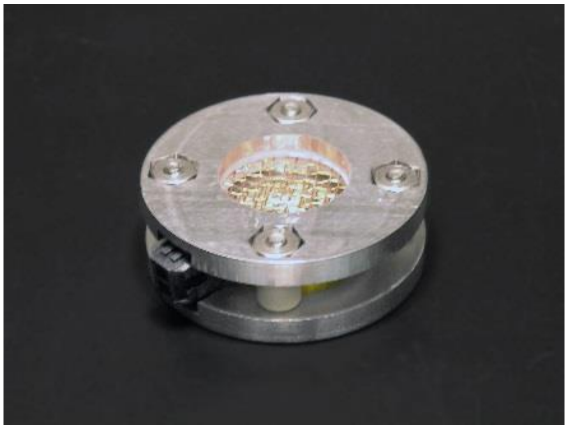

Figure 1: Large area (2 cm²) SiC radiation detectors fabricated and assembled

Micro-electro-mechanical-system (MEMS) based devices fabricated from silicon carbide (SiC) for the purpose of conducting low-noise neutron and alpha particle spectrometry have been reported in the context of reactor core monitoring.[7] A low power, low mass space radiation detector prototype system using a SiC Schottky power diode was developed at GRC for dosimetry use during future lunar missions.[8] Recently two large area (200 mm²) SiC radiation detectors based on High Purity Semi-Insulating (HPSI) SiC were fabricated and demonstrated as proof-of-concept devices, shown in Figure 1.

A bench check of the capacitance and leakage current of the HPSI SiC detectors revealed that they had electrical characteristics comparable to much smaller silicon PIN diode detectors (with 2% of the active detection volume of these SiC detectors). The detector capacitances averaged 65±5 pF, with leakage currents of 4.5 nA at 100V corresponding to an estimated carrier concentration of 1.24×10^4 cm^{-3}.

Exposure of the detectors to alpha sources revealed significant sensitivity to external electromagnetic interference (EMI), which was traced to the leads between the detector and charge amplifier. The gamma spectrum of the sources was seen in the background noise of the detectors at high gain (550×) on the multichannel analyzer (MCA). Blocking the background in the MCA software, an alpha signal was seen at low gain (3.10×).

The recorded spectra with background and peaks labeled are seen in Figures 2 and 3. The peak widths are seen on average to reflect dE/E = 0.20. These peaks were greatly affected by EMI, energy spreading due to the wide 5 cm² sources, and the air gap between the detector and source.

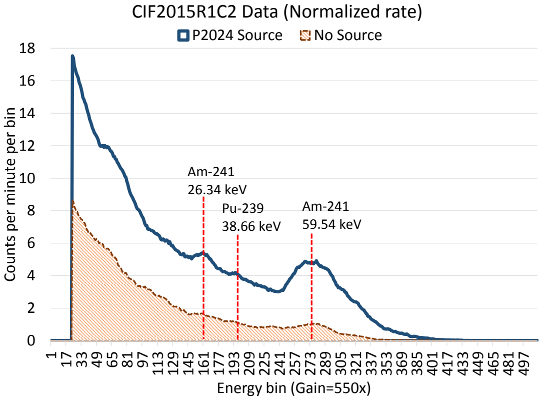

Figure 2: Reaction of a large area SiC LET detector to gamma rays emitted from Pu-239 source.

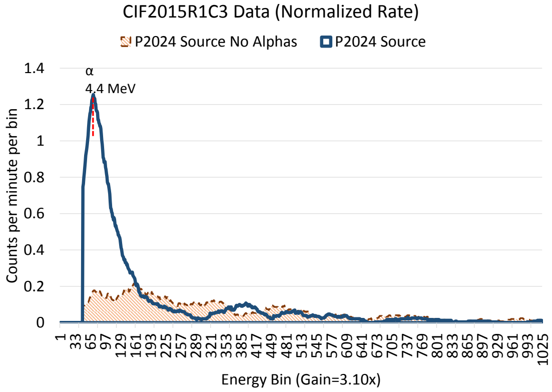

Figure 3: Reaction of a large area SiC LET detector to alpha particles emitted from a Pu-239 source.

CUBESAT APPLICATION

Taking advantage of WBG semiconductor technology demonstrated as proof-of-concept in the lab, the Solar Proton Anisotropy and Galactic cosmic ray High Energy Transport Instrument (SPAGHETI) was conceived to meet the challenges for understanding variations in the anisotropy mechanisms in the interplanetary medium on a Small Sat platform. The

SPAGHETI CubeSat would be a multidirectional detector system specifically designed to monitor solar protons and cosmic ray ions from six directions simultaneously. A conceptual illustration is shown in Figure 4.

Figure 4: Proposed SPAGHETI 6U deep-space CubeSat

The complete instrument was envisioned as a 6U (1U×2U×3U) CubeSat system that contained six detector packages mounted at various places in the frame constructed from stacks of SiC LET detectors. The detectors stacks would be arranged in a CubeSat at orthogonal directions to provide multidirectional measurements.

The detector stacks used low-power large-area LET detectors fabricated from high-density, high-purity silicon carbide (SiC). The detectors would measure the energy deposited by ions passing through them. Stacks of these LET detectors were to be separated by an ion moderator to allow energy and ion species resolution.

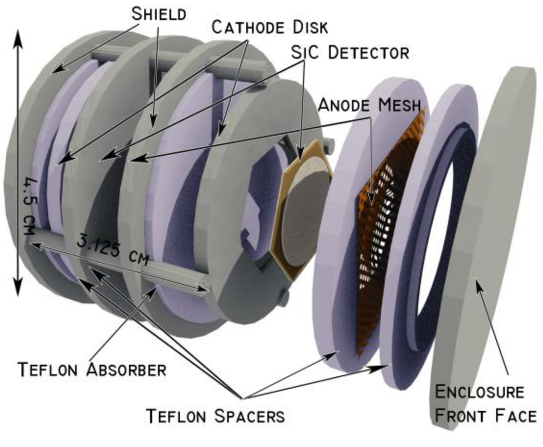

Figure 5: SPAGHETI Detector stack containing SiC LET detectors

Each detector stack would be constructed to be directionally sensitive with an 80° field of view and a geometric factor of 0.84 cm²·sr. A schematic of the detector stack construction is shown in Figure 5. Two pair of detectors would be placed back-to-back and oriented along the +/- X and +/- Y directional axes rotated 45° to the long axis of the CubeSat. A third pair of detector stacks is placed at either end of the CubeSat.

The small spacing of the detectors gave each stack a large geometric factor in order to allow the adequate statistical sampling. The low-noise, thermally stable nature of SiC and its radiation tolerance allows a multidirectional array of detector stacks to be packed in a small volume without active cooling. The placement of the detector stacks in the SPAGHETI 6U CubeSat bus is shown in Figure 6.

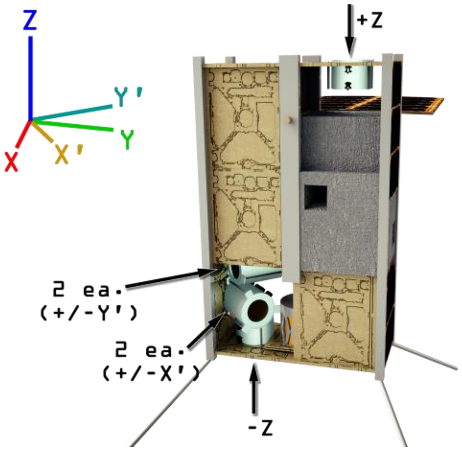

Figure 6: Placement of LET detector stacks in the SPAGHETI deep-space 6U CubeSat bus.

Operation

The SPAGHETI 6U CubeSat bus would have the appropriate attitude, guidance, navigation, and control (GNC), and command and data handling (C&DH) hardware, communication system, and solar electric power arrays to produce 72 W continuously to support operation in a deep-space environment. A propulsion system could be integrated into the CubeSat to allow the insertion of the instrument from an as-deployed heliocentric orbit from a trans-lunar launch to, for example, a lunar orbit for data collection.

The general concept for each radiation detector stack is that of a directional coincidence counter. A pulse is generated by a traversing ion in one or both of the detectors in the stack. A charge amplification circuit for each detector stack will detect the pulse height and actively compare the arrival times between the two LET detectors. If two pulses are found to arrive simultaneously, two signals proportional to the pulse height would be transmitted to a central field-programmable gate array (FPGA) circuit for data handling.

The charge amplification circuits and common FPGA circuit would be located on a central event processor circuit board that will be mounted in the CubeSat. All detectors stacks would interface with the event processor, which in turn would interface with the CubeSat C&DH system. A high through-put X-band communication system designed for deep space CubeSat missions would allow data download to mission operations center during line-of-sight periods.

FUTURE OPTIONS

The fully-integrated application concept for the various WBS semiconductor detector technologies under development at GRC is a Compact Full-field Ion Detector System (CFIDS).[5,9] The CFIDS is comprised of a central spherical Cherenkov detector surrounded by a dozen detector stacks of LET detectors as well as coincidence and anticoincidence detectors for data triggering and rejection of signals during processing. In contrast, SPAGHETI had only six detector stacks without anticoincidence detectors or a Cherenkov detector. The addition of these other detectors and stacks will allow cleaner signal and wider energy range detection than what is anticipated by SPAGHETI.

A design concept for the CFIDS is illustrated in Figure 7. To enable this concept, advancements have been made in radiation detector technology using WBG semiconductor devices.

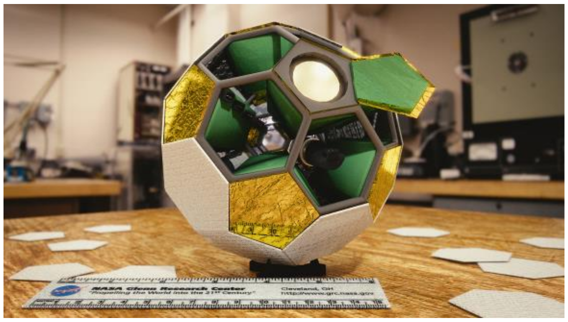

Figure 7: Compact Full-field Ion Detector System (CIFDS) Concept

Solid-State Trigger/Veto Detector

Spacecraft-based trigger and veto detectors are generally comprised of scintillator blocks of plastic or iodide crystal mated to a photomultiplier tube (PMT) or a pixelated avalanche photo detector (APD), also referred to as a silicon photomultiplier (SiPM). The goal is to replace the role of PMTs and SiPMs in these types of detectors with WBG devices, saving on size, weight and required power.

A miniature "paddle style" radiation detector was demonstrated using a gallium phosphide (GaP) photodiode mated to a polyvinyltoluene (PVT) scintillator block as shown in Figure 8. The preliminary results indicate that the improvement in required size and power with the use of the WBG material and, if used with acrylic ribbon scintillators, allows its use in the CFIDS concept.

Figure 8: Miniature scintillation/diode ionizing radiation detector as demonstrated

Solid-State Cherenkov Detector

At the heart of the detector system concept is a spherical Cherenkov detector. Typical Cherenkov detectors are comprised of flat disks or blocks of sapphire or acrylic mounted on photomultiplier tubes. The goal is to replace the role of the relatively large photomultiplier tubes with solid-state devices that do not require temperature control or compensation.

A fast, large area solid-state UV detector based on the WBG semiconductor zinc oxide (ZnO) has been recently developed at GRC. The proof-of-concept detector was fabricated on commercially available bulk single-crystal undoped ZnO. Inter-digitated finger electrodes and contact pads were pattered via photolithography and formed by sputtered silver, as shown in Figure 9. The device tested had an active area of 1 mm by 2 mm (2 mm^2), designed to have a 1 ns response time with 10 V applied bias voltage. In a bridge circuit, the detector would detect small, fast pulses of UV light such as those required for Cherenkov detectors.

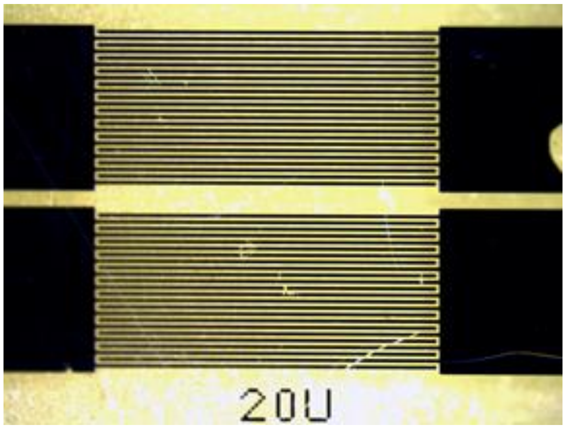

Figure 9: Proof of concept ZnO UV detectors with 20 µm electrode spacing. The sizes of the inter-digitated finger areas are 1 mm by 2 mm.

The ZnO-based detector was demonstrated to be sensitive to UV light at 254 nm, slightly less so at 370 nm, and not sensitive to room lighting (about 430-630 nm). Compared to commercial SiC and GaP detectors tested in parallel, this detector also demonstrated greater sensitivity to UV than the existing devices.

SUMMARY

NASA GRC is leveraging expertise in harsh environment thin films, SiC devices and harsh environment packaging, micro-optics, and space-based instrumentation to advance radiation detector technology. Development of wide band gap semiconductors as radiation detectors holds the promise of improved low-power, robust detectors to enable a compact full-field ion detector system for space science on a CubeSat platform. The proposed SPAGHETI Deep Space CubeSat will apply more advanced SiC radiation detectors to perform multidirectional in-situ studies of SEP and GCR interactions in lunar and interplanetary environments.

Acknowledgments

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