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A semiconductor radiation imaging pixel detector for space radiation dosimetry

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ABSTRACT

Progress in the development of high-performance semiconductor radiation imaging pixel detectors based on technologies developed for use in high-energy physics applications has enabled the development of a completely new generation of compact low-power active dosimeters and area monitors for use in space radiation environments. Such detectors can provide real-time information concerning radiation exposure, along with detailed analysis of the individual particles incident on the active medium. Recent results from the deployment of detectors based on the Timepix from the CERN-based Medipix2 Collaboration on the International Space Station (ISS) are reviewed, along with a glimpse of developments to come. Preliminary results from Orion MPCV Exploration Flight Test 1 are also presented.

1. Introduction

The radiation environment in space is very different from that typically experienced here on Earth. It is generally dominated by energetic protons and heavier charged particles. The presence of these incident charged particles with a high Linear Energy Transfer (LET), together with the reduction or lack of atmospheric and geomagnetic shielding, results in substantially higher dose rates. Additionally, the radiation characteristics determining the biological consequences differ from radiation exposure scenarios encountered on Earth. Experience with human exposures to space-like radiation environments is very limited and there is still a significant uncertainty in the potential effects and the associated risks posed by such exposures (Durante and Cucinotta, 2011; Durante, 2014; Kennedy, 2014).

Given that we do not yet possess the necessary detailed understanding of all of the potential effects of radiation within the body, the present strategy for space radiation monitoring is to design systems that harness the latest technologies to characterize the detailed nature of the radiation field impinging on space travelers as accurately as possible. Active devices not only detect the presence of incident radiation in real-time, but provide the data regarding its nature essentially immediately. Current technology enables us to provide compact, low-power active area monitors that can characterize the radiation field in unprecedented detail. The ultimate purpose is to provide devices that can thoroughly measure the details of the actual radiation field incident on each individual crew member on a particle-by-particle basis in real-time. Even with the limitations of the current devices employing single sensor-layers with low-power embedded processors, we can distill a significant amount of detailed real-time information regarding the local charged particle radiation environment as reported here.

The evolution of the radiation detection techniques used in space started with passive detectors such as TLDs (Thermoluminescent dosimeter) (Pradhan, 1981) and emulsions. The advantage of such techniques is that they will measure the integrated quantities such as absorbed dose or fluence during the mission without power or maintenance requirements. However, the readout of such devices is cumbersome and typically requires well-trained person-

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nel and a dedicated laboratory. Thus, passive detectors cannot be used for alarming nor real-time environmental monitoring. The need to characterize the radiation environment in the immediate vicinity of crew members in real-time has led to the development of active monitoring devices. Commonly used active devices employ tissue equivalent gas, scintillation materials, or semiconductors. Tissue equivalent devices such as the Tissue Equivalent Proportional Counter (TEPC) (Rossi and Rosenzweig, 1955a) use active media whose response to incident radiation is similar to that of tissue. The advantage is that theoretically, no corrections are necessary and its measured values of the absorbed dose would not require any further conversions. The disadvantage is that most simple TEPCs are devices where only the energy deposited in a fixed volume by incident particles is measured. No additional information is available, such as the path length of the particles on a track-by-track basis. The interpretation of such data is complex, because different particles can give the same response, and conversely, the same particle can provide different responses. There have been recent attempts to provide complex TEPCs that combine Time-Projection-Chamber technology with a tissue equivalent chamber gases to provide increased information on a track-by track basis. While such improvements are potentially very useful, the complexity and size of these devices present significant challenges (Kishimoto et al., 2013). Silicon-based devices typically have consisted of telescope-like systems, where the coincidence of multiple monolithic detectors is utilized. These devices tend to be larger and more complex, and require significant power. Also, silicon has different response characteristics with respect to ionizing radiation when compared with tissue. Therefore, the measurements made with silicon-based devices require obtaining enough information to enable the conversion of the data to reflect the effects in tissue or water. The latest silicon-based devices offer the promise of providing more information about the radiation environment, namely details allowing derivation of the charge and energy spectra of incident radiation on a track-by-track basis. Once that information is available, one can use existing radiation transport codes to predict the detailed nature of the radiation exposure to various organs and tissues throughout the body and using the most appropriate parameterizations of biological detriment. Finally, in cases where immediate dosimetry estimates are needed, the track-by-track absorbed dose in water can also be determined by using particle- and energy-dependent conversion factors between the sensor material and water (Guatelli et al., 2008).

Recently, modern semiconductor detector systems widely used in elementary particle physics have been adapted for use in space radiation monitoring and dosimetry applications. The goal is to use highly miniaturized radiation imaging pixel detectors as a single layer combination tracking and energy measuring device to identify each incident particle's charge and energy on a track-by-track basis. The Timepix-based detectors discussed here are the most recent addition to the available detector technologies for use as space radiation area monitors. The remainder of this paper focuses on the Timepix, and the results from Timepix-based Radiation Environment Monitor (REM) units in operation on-board the International Space Station (ISS), as well as on the recent Exploration Flight Test 1 (EFT-1) mission of the new Orion Multi-Purpose Crew Vehicle (MPCV), and the Hybrid Electronic Radiation Assessor (HERA) which is being developed for Exploration Mission 1 (EM-1), Exploration Mission 2 (EM-2), and beyond.

2. Timepix-based radiation imaging detectors from the Medipix2 Collaboration

The Medipix2 Collaboration, based at the European Organization for Nuclear Research (CERN), has developed a number of radiation imaging pixel detector large-scale integrated circuits including the Timepix "chip" (Campbell, 2010). These chips are intended to be used as a part of hybrid detectors when attached to an accompanying sensor. The Timepix chips contain 256 × 256 pixels, each 55 μm on a side, providing an effective area of the chip that is 1982 cm^2 (Llopart et al., 2002, 2007; Ballabriga et al., 2010). The full chip is 16.120 × 14.111 mm, which includes a service area on one side of the chip that contains 127 input/output wire-bond pads for control, readout and power. Each pixel contains the circuitry within its footprint to digitize the output. As such, unlike CCDs and the CMOS pixel detectors in digital cameras, only digital data is transferred out of the pixels. The input to each pixel is through a conducting solder pad on the upper surface of the chip.

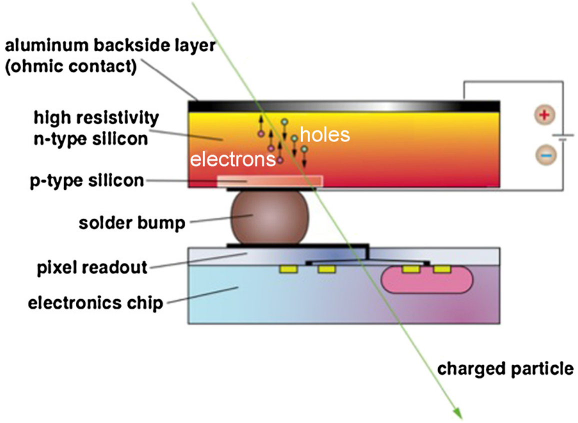

Fig. 1. Timepix Hybrid Assembly. Each pixel in the underlying chip is connected to a bulk semiconductor sensor through a solder-bump as shown. The bulk sensor volume is separated from the sensor's ohmic contact with an opposite polarity doped implant to allow the formation of a p–n junction in the sensor for each pixel. (Courtesy of the Medipix2 Collaboration.)

To fabricate a charged particle detector employing a Timepix, one must attach a semiconductor sensor to the top surface of the pixels as shown in Fig. 1. Different sensor materials may be used for various applications, but for charged particle detection, silicon is the semiconductor of choice. Sensors with thicknesses from 50 μm to 1.0 mm have been fabricated, with 300 and 500 μm thick sensors used on the NASA Timepix-based detection systems. The sensors are fabricated so that the bulk volume is doped as either p-type or n-type, with opposite doping implants on the lower surface. The REM units employ bulk n-type sensors. The implants are in contact with conducting solder pads on the lower surface of the sensor, which allows the p–n junction to be reverse-biased to deplete the sensor volume of free charge carriers. The sensor is attached to the Timepix chip using the FlipChip® solder-bump technology (Riley, 2000). The bias voltage also serves to collect any free electron–hole pairs created by the passage of charged particles in the sensor volume. The presence of free charges in the sensor volume causes image charges to form on the sensor's solder pad. The return path for the bias voltage runs through the solder bump and the pixel's analog front-end circuitry. This current is amplified and shaped by the pixel's analog front-end circuitry. The current flow created in the front-end electronics is generally proportional to the energy deposited in the sensor volume that is collected by the pixel, and the digital portion of each pixel digitizes that value for readout. The digital section of each pixel can be set to function as a charge-summing Wilkinson-type Analog-to-Digital-Converter (ADC) using the Time-Over-Threshold (TOT) technique where the time is referenced to an external clock signal with a maximum frequency of 100 MHz. The clock frequency used on the ISS REM, BIRD, and HERA units is 10 MHz.

The Timepix is controlled by providing discrete inputs to the internal Digital-to-Analog-Converters (DACs) to set various working parameters such as the input threshold to suppress noise. In