Inorganic scintillators are appropriate for nuclear γ-ray spectroscopy due to their high stopping power and light yields, both of which contribute directly into excellent detection efficiency. Maximizing science return, however, depends not only on γ-ray detection but also on spectroscopic performance. Our goal is to optimize these factors to produce a device capable of meeting science-based spectroscopic performance requirements relevant for astrophysics and planetary science, while simultaneously minimizing size, weight, and power resources (SWaP).

Silicon photomultipliers (SPM) are a viable opto-electronic alternative to traditional scintillator readout schemes. Integrated into a high-resolution spectroscopy system they represent an enabling technology, providing a number of key implementation benefits such as ruggedness, compactness, low mass, insensitivity to magnetic fields, and low bias voltage (~30V) operation. While identified originally to address power challenges, SPMs facilitate the use of low-cost scintillating materials, achieve excellent spectroscopic performance, mitigates implementation complexity, and reduce instrument mass significantly - key benefits that in turn may reduce cost.

Maximizing spectroscopic resolution requires optimization of parameters:
- **Maximize** $N_{\text{photons}}$:
  - Materials with high scintillation light yield
  - Optimize match-photodetector optical spectrum & detection QE
  - Optimize Photon Detection Efficiency (PDE)

- **Minimize** $v(t)$:
  - Reduce sensor gain variations
  - Reduce scintillator non-proportionality
  - Mitigate scintillator crystal inhomogeneities

Optimization, combined with next-generation opto-electronic readout devices provides high-resolution, cost-effective gamma-ray spectroscopy solutions.

### Spectroscopic Performance

Laboratory measurements of prototypes SPM-based spectrometer module utilizing CsI(Tl). Data shown were obtained at room temperature (~23°C) and 10°C using laboratory radiological standards at a bias voltage 24V above breakdown. Resolution is anticipated to improve by ~20-25% at a bias voltage 4V above breakdown, with a corresponding increase in noise - impact to spectroscopic resolution under study.

- **SPM** @ 662 keV
  - Dark Count: -4kHz @ 23°C
  - Dark Count: -0.9kHz @ 10°C

All performance results validated/ duplicated with analytic model of SPM functionality.

### Spectroscopic Optimization

The SPM is a novel, high gain, single photon sensitive sensor based on a summed parallel array of identical and independent Geiger-mode avalanche photodiodes and quenching resistor combined into elements called microcells. SPM detectors are manufactured using standard CMOS technology which results in highly uniform breakdown characteristics.

Each microcell is:
- Structured as a p-n diode
- Provides low-noise amplification of single photoelectrons (~10(5) gain)
- Biased above the breakdown voltage with no current flow
- Photon initiates avalanche breakdown

In general, the maximum obtainable energy resolution (FWHM) can be parameterized as

$$\Delta E = \frac{E}{\sqrt{N_{\text{photons}}}}$$

where $N_{\text{photons}}$ is the photoyield of the sensor used to detect scintillation photons, and $v(t)$ is the variance in sensor time ($1\text{fs}$).

### Silicon Photomultiplier (SPM)

**Prototype Array**

Based on Sera’s SPMArray4

SPM detectors are manufactured using standard CMOS technology which results in highly uniform microcell breakdown characteristics, typically within ±0.1%. Such a small breakdown range is significant since it simplifies the electronics requirements for biasing large numbers of detectors. Response uniformity is also good, variations are less than ±10% max/min, within ±0.06V. Such a small breakdown range is significant since it results in highly uniform microcell breakdown characteristics, typically within ±0.1%.

- **Total Irradiation Does (TID) Test**
  - *Dark Voltage: 8V*
  - *Temperature: 20°C*

- **Displacement Damage (DD) Test**
  - *Dark Voltage: 6V*

### Radiation Tolerance

**Front-End Electronics** - Leverage Proven Space-Qualified FEE Implementation Approaches
- **Module Design, Assembly, and Thermal Modeling** - Evaluation of Passive & Active Cooling Approaches, Inform Assembly Design
- **Additional Radiation Tolerance Testing** - Derive Impact to Spectroscopic Performance
- **Instrument Performance & Simulation** - GEANT-based Spectrometer Module Simulation, Incorporate into Full Instrument Model(s)

**References for presented work available upon request**

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