Large-area Si(Li) Detectors for X-ray Spectrometry and Particle Tracking for the GAPS Experiment

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Abstract-Large-area lithium-drifted silicon (Si(Li)) detectors, operable 150°C above liquid nitrogen temperature, have been developed for the General Antiparticle Spectrometer (GAPS) balloon mission and will form the first such system to operate in space. These 10 cm-diameter, 2.5 mm-thick multi-strip detectors have been verified in the lab to provide <4 keV FWHM energy resolution for X-rays as well as tracking capability for charged particles, while operating in conditions (\sim -40C and \sim 1 Pa) achievable on a long-duration balloon mission with a large detector payload. These characteristics enable the GAPS silicon tracker system to identify cosmic antinuclei via a novel technique based on exotic atom formation, de-excitation, and annihilation. Production and large-scale calibration of ~ 1000 detectors has begun for the first GAPS flight, scheduled for late 2021. The detectors developed for GAPS may also have other applications, for example in heavy nuclei identification.

I. INTRODUCTION

The first lithium-drifted silicon (Si(Li)) [1], [2] detectors to satisfy the unique geometric, performance, and production requirements of the General Antiparticle Spectrometer (GAPS) experiment have been produced and their performance validated and understood. GAPS is designed to detect lowenergy (<0.25 GeV/n) cosmic antinuclei, in particular rare antideuterons that could be signatures of dark matter, using a novel exotic atom-based particle identification scheme on three Antarctic balloon missions (\sim 3 months total exposure) [3], [4]. In this contribution, we present the X-ray energy resolution and particle track reconstruction capabilities of the GAPS Si(Li) detectors.

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II. REQUIREMENTS AND SPECIFICATIONS

The GAPS instrument consists of a plastic scintillator timeof-flight (TOF) surrounding a tracker composed of ~ 1000 Si(Li) detectors arranged in 10 planes. A cosmic antinucleus first traverses the TOF, which measures velocity and energy deposition and is the basis of the system trigger. The particle then loses energy as it moves through the Si(Li) tracker, where it is eventually captured by a silicon nucleus, forming an exotic atom in an excited state. Particle identification is based on the de-excitation X-rays and hadronic annihilation products of the exotic atom in the tracker, as well as dE/dx and stopping depth information. The Si(Li) system is critical to the success of the GAPS experiment as it serves as the target for the incoming low-energy antinucleus, measuring its energy deposition and stopping depth in the instrument, and capturing the antinucleus into an exotic atom; the spectrometer for X-rays from the deexcitation of the exotic atom; and the tracker for the products of the nuclear annihilation. The detectors must provide the large geometric acceptance needed for a rare-event search and operate with a low-power readout. Since the large instrument size precludes the use of a cryostat or pressure vessel, the detectors are designed to operate at flight pressures and at temperatures \sim -40°C, achievable using an oscillating heat pipe system [5] for cooling. Since the GAPS design calls for > 1000detectors, a low-cost fabrication method with high yield is also required.

The GAPS Si(Li) fabrication method, which has a yield > 90%, was developed in collaboration with Shimadzu Corporation [6], [7], [8] and is based on a silicon substrate developed in collaboration with SUMCO Corporation. The materials cost per detector is ~\$500. The geometry for the GAPS flight detectors is shown in Fig. 1. The 2.5 mm depth is thick enough to stop a 0.25 GeV/n antinucleus in <10 layers, but thin enough to provide high escape fractions for 20-100 keV de-excitation X-rays. With a diameter of 10 cm, ~1000 devices are needed to fill the ten 1.6 m ×1.6 m planes of the tracker.

An energy resolution of $\lesssim 4$ keV FWHM in the 20-100 keV range is required for discrimination between de-excitation Xrays of different exotic atom species and is thus fundamental to the GAPS particle identification scheme. At the same time, the readout electronics must operate on a limited power budget to be compatible with GAPS' balloon nature. In light of the limited power for readout electronics, the Si(Li) system can reach the required energy resolution by controlling detector leakage current and capacitance, two of the dominant detector-related noise sources as discussed in section III-C. The low leakage current is achieved at relative high temperatures $(\sim -40^{\circ}\text{C})$ by implementing a thin undrifted layer on the detector's p-side and a guard ring structure (Fig. 1) that limits surface leakage current in the detector's active area [8]. The capacitance and leakage current are further controlled by segmenting the detectors into strips, which also improves spatial resolution for particle tracking. With 8 strips per detector, the per-strip capacitance of ~ 40 pF is sufficiently low that the required energy resolution can be achieved with a low-power application-specific integrated circuit (ASIC). The ASIC power of $\leq 10 \,\mathrm{mW}$ per channel is low enough to read out 8 channels for each of > 1000 Si(Li) detectors while staying within the overall 110W power budget for readout electronics, and a custom ASIC will be used for Si(Li) detector readout during flight [9], [10].

Detectors that meet these requirements may also be suitable for other applications, e.g., identification of heavy nuclei at rare isotope facilities such as the National Superconducting Cyclotron Lab or Facility for Rare Isotope Beams [11], [12]. A few GAPS detectors would provide sufficient stopping power for relevant nuclei, and fine spatial resolution is not required.

III. SI(LI) DETECTOR PERFORMANCE

A. Laboratory Testing Setup

Details of detector preparation and experimental methods are in [13]. In short, the detector's *p*-side is biased at -250 V relative to the guard ring and signal processing electronics. While the ASIC is under development, each strip is read out from the n^+ -side by a discrete-component charge-sensitive preamplifier [14]. Temperature is monitored with a calibrated diode.

Energy resolution in the 20–100 keV range is assessed in an aluminum vacuum chamber at ~1 Pa, with the detector cooled by flowing nitrogen in a closed system. Two γ lines are used, 59.5 keV (²⁴¹Am) and 88.0 keV (¹⁰⁹Cd). Signal from a preamplifier channel is shaped by a Canberra 2020 Spectroscopy Amplifier with variable peaking time and digitized by an Ortec Ametek Easy MCA module.

The cosmic muon measurement is recorded in a nitrogen atmosphere cooled by injecting cold nitrogen. To eliminate non-muon background, coincident hits are required between the corresponding strips of two vertically-stacked detectors. The preamplifier signals are processed by a CAEN N6725 digitizer, enabling coincident triggering. A rough calibration is extrapolated from the 59.5 keV peak of ²⁴¹Am.

B. Tracking Performance

The response of a strip at -40° C to heavy particle tracks is assessed using cosmic muons. The data in the top panel of Fig. 2 show the cosmic muon spectrum obtained by the method in section III-A, which is consistent, given the uncertainty in calibration, with the expected distribution of energy deposition in 2.3 mm of active silicon depth.

Antinuclei in the GAPS energy range are too slow to be MIPs and therefore will deposit more energy as they traverse the detectors. Different energy deposition signatures can be used for identification of incident particles as they slow to stop from up to 0.25 GeV/n. Accordingly, the ASIC is designed to accept signals up to 100 MeV before saturating.

C. Energy Resolution Performance

The response of a GAPS detector strip irradiated by ²⁴¹Am and ¹⁰⁹Cd is shown in the middle panel of Fig. 2. Each monoenergetic line manifests as a Gaussian photopeak and a nearlyflat low-energy tail from Compton scattering from surrounding materials. <4 keV FWHM was achieved at the relatively high temperature of -35° C.

To understand the different noise contributions to the energy resolution, we use the established noise model [15], [1] for a semiconductor read out by a discrete-component preamplifier and shaping electronics:

$$ENC^{2} = \left(2qI + \frac{4kT}{R_{p}}\right)\tau F_{i} + 4kT\left(R_{s} + \frac{\Gamma}{g_{m}}\right)\frac{C^{2}}{\tau}F_{\nu} + A_{f}C^{2}F_{\nu f},$$

$$FWHM = 2.35(\epsilon/q) \times ENC. \tag{1}$$

In (1), q is the electron charge, k is Boltzmann's constant, T is temperature, and ϵ is the ionization energy of silicon. I and C are the leakage current of the strip and total capacitance, the latter having strip, preamplifier, and stray components. The parallel resistance R_p , scaling factor Γ , and transconductance g_m are preamplifier properties while multiple sources may contribute to the series resistance R_s and coefficient of $\frac{1}{f}$ noise A_f . τ is the peaking time of the shaper and F_i , F_{ν} and $F_{\nu f}$ are shaper-dependent coefficients of the different noise terms. Detector contributions to I and C are measured independently.

In the bottom panel of Fig. 2, the energy resolution of the 59.5 keV line is recorded at two temperatures and a range of peaking times for a single detector strip, and (1) is fit to the data using the fitting method detailed in [13]. The energy resolution as a function of τ and T is well-described by the noise model, lending us confidence in predicting energy resolution with different readout electronics or at varying flight temperatures.

IV. CONCLUSIONS

Si(Li) detectors meeting the unique requirements of the GAPS experiment have been produced by Shimadzu Corporation and their tracking and energy resolution performance have been tested and understood in the laboratory setting. In particular, the detectors exceed the requirement of < 4 keV FWHM energy resolution at -40° C, when read out with custom discrete preamplifier electronics in the laboratory setting. In flight, they will be coupled with a custom ASIC for readout. Large-scale production and calibration are underway: since January 2019, the GAPS collaboration has received \sim 70 detectors monthly, and \sim 1000 detectors will operate on the first GAPS flight scheduled for December 2021.

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Fig. 1. Top: Cross-sectional diagram of a GAPS detector (not to scale). Drifting is facilitated by a ~ 1 mm-deep, ~ 3 mm-wide top-hat brim (1). Li ions from the ~ 0.1 mm-thick n^+ Li-diffused layer (2) are drifted through the *p*-type wafer to form a compensated active volume (3). The top hat brim and a 0.1 mm-thick *p*-side remain undrifted (4). The electrical contacts consist of ~ 20 nm Ni (5) and ~ 100 nm Au (6). The ~ 1 mm-wide, ~ 0.3 mm-deep grooves separate the guard ring (7) from the active region (8) and segment the active region into parallel strips of equal area and capacitance. Bottom: Photograph of a GAPS flight detector.



Fig. 2. *Top*: Spectrum of cosmic muons. A Landau distribution (red) fitted to the data describes the fluctuations of energy loss in the detector. *Middle*: Spectrum of 241 Am and 109 Cd around their 59.5 and 88.0 keV peaks, with fits to the photopeak and Compton scattered components. The inset shows the same data in semi-log format to better display the 88.0 keV peak. *Bottom*: Energy resolution at 59.5 keV varies with peaking time at two temperatures. The best fit of (1) is shown in red.

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