Mass production of large-area lithium-drifted silicon detectors for the GAPS silicon tracker

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Mass-production of large-area lithium-drifted silicon (Si(Li)) detectors has been done for the General Antiparticle Spectrometer (GAPS). GAPS aims for a high-sensitivity observation of cosmic-ray antiparticles, especially antideuterons which are predicted to be a distinct signal of the dark matter. A large-volume silicon tracker plays an essential role in the novel GAPS detection technique, which is based on exotic atom physics. We established a fabrication method for the large-area Si(Li) detector and produced >1000 detectors. In this report, statistical characteristics of the detectors are discussed based on the performance parameters. The results ensure that a silicon tracker with large and high-quality sensitive volume is achieved with our detectors.

1. GAPS experiment

- International collaboration between Japan, US and Italy
- High-sensitivity observation of low-energy antiparticles (p, d, ...) in cosmic-rays
- First flight using NASA long-duration balloon in Antarctica is scheduled in late 2022.
- Novel detection technique based on exotic atom physics
  1. Incident antiparticle forms an excited exotic atom with silicon nucleus.
  2. Characteristic X-rays and annihilation particles (mainly pions) from exotic atom enable an efficient identification of the antiparticle.
- Payload size: H ~4 m × W ~4 m × L ~6 m
- Weight: ~3.5 metric ton

2. Large-area lithium-drifted silicon (Si(Li)) detectors

(M. Kozi et al. (2019) NIM A; F. Rogers et al. (2019) NIM A; N. Saffold et al. (2021) NIM A; K. Perez et al. (2018) NIM A)

The silicon detector was a key development in realizing the novel detection concept. We developed a fabrication method for large-area Si(Li) detectors for the tracker.

- Basic Si(Li) fabrication process
  1. Procuring a boron-doped silicon wafer.
  2. Evaporating/diffusing Li ions onto a side of the wafer to form an n-layer.
  3. Drifting Li ions toward the p-side by applying a bias voltage to the heated wafer.
  4. The thick drifted layer functions as a sensitive layer.

- The GAPS Si(Li) detector features:
  - Large (10 cm) diameter with ~9 cm sensitive area.
  - 2.5 mm thickness with ~90% sensitive layer.
  - Segmentalized into 8 strips with equal area.
  - Energy resolution of <4 keV FWHM (Full Width at Half Maximum) for 20-100 keV X-rays.
  - Relatively high operating temperature (~40°C), which allows use of a low-power cooling system.

3. Mass-production of the large-area Si(Li) detectors

- Rapid mass-production was one of the key issues to construct the large-volume silicon tracker.
- We established a fabrication method and produced >1000 detectors for the first flight.
- Leakage currents (LCs) and capacitances of all strips at room temperature (RT) were measured for all detectors just after each detector was fabricated.
- Very Good detectors are defined using the LCs and capacitances at RT as below. They enable distinct identification of the exotic-atom products during flight.
  - ≥7 strips in 8 strips have LCs ≤ 7 uA at the bias voltage of 250 V. LC of 7 uA at RT corresponds to ≤ 5 nA at the operating temperature (~40°C).
  - All strips and guard ring have LCs ≤ 50 uA at 250 V, or their change ratios are ≤ 0.05 uA/V in the range of 200-300 V.
  - All strips have capacitances between 35 and 42 pF.
  - ~90% detectors in ~1100 detectors were classified as Very Good grade. This high yield rate enables construction of the large-volume silicon tracker.
  - Majority of the detectors failing the Very Good criteria will still function as particle trackers. Detailed grading is now performed based on the measurements at the operating temperature (~40°C).

4. Preliminary results of the statistical study

Fig. A displays the strip LCs and capacitances at RT. The LC is a major factor limiting the energy resolution. The LC distribution has a maximum at ~2 uA, several times smaller than the Very Good criterion at 7 uA. This performance margin will provide high reliability or designing flexibility of the tracker.

Fig. B shows the strip LCs and capacitances of the Very Good detectors, split into each strip position. There is significant dependence of the performance on the position. Especially the variations (FWHMs) in the capacitance are within 38-40 pF (~5%) in all histograms. This indicates that Li ions were very uniformly drifted in all strips and detectors by our custom material and methods. The uniform drifting had been a major issue in previous studies of large-area Si(Li) detectors.

Summary

Mass-production of large-area Si(Li) detectors has been done to construct a large-volume silicon tracker for GAPS. Stable production was performed as scheduled and ~90% of the fabricated detectors meet the criterion imposed from scientific requirements. Distribution of the capacitance indicates that lithium-drifted layers, i.e. sensitive layers, have uniform depths in all detectors. Ongoing investigation analyzing fabrication data along with the performance data will provide further insights into the fabrication process.