Large-area Si(Li) Detectors for the GAPS Antarctic Balloon Program

Kerstin Perez on behalf of the GAPS Si(Li) team

CPAD Instrumentation Frontier Workshop
GAPS: Novel detection of rare cosmic antinuclei

Time-of-flight system measures velocity and dE/dx

Si(Li) tracker acts as:
- **target** to slow and capture an incoming antiparticle


GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)

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Illustration credit: A. Lowell (UCSD)
GAPS: Novel detection of rare cosmic antinuclei

A rare event search for antideuterons: a dark matter signature with essentially zero conventional astrophysical background


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• *target* to slow and capture an incoming antiparticle into an exotic atom
• *X–ray spectrometer* to measure the decay X–rays
• *particle tracker* to measure the resulting dE/dX, stopping depth, and annihilation products

Requires technique with low–energy (E<0.25 GeV/n) range, large geometric acceptance, high background rejection

Illustration credit: A. Lowell (UCSD)
Si(Li) detectors are key to GAPS science goals

Plastic scintillator TOF
• high-speed trigger and veto
  ➢ < 500 ps timing resolution

Si(Li) tracker
1. X-ray identification
2. dE/dx
3. stopping depth
4. particle multiplicity, vertex reconstruction
5. >10 m² of active area
  ➢ >1000 detectors, 2.5 mm thick, 4” diameter
  ➢ 4 keV (FWHM) energy resolution for X-rays
Si(Li) design principles

- **Active area** totaling >10 m²
  - 10-cm diameter detectors

- **Absorption efficiency** to capture d̄ up to 0.25 GeV/n

- **Escape fraction and efficiency** for X-rays
  - 2.5 mm thickness, >90% active volume

- **Tracking efficiency** for incoming antinuclei and outgoing annihilation products
  - 8 strips per detector

- **Energy resolution** < 4 keV to distinguish X-rays from different antinuclei
  - Leakage current < 5 nA/strip

Key challenges:
- **High operating temperature**: -35 to -45°C
- **Large area, but low leakage current**
- **Power limited** by long-duration flight
- **Need to develop low-cost, high-yield fabrication process**

Solution: *Lithium-drifted* Si detectors

- Li ions compensate impurities in boron-doped Si, creating *extended* charge-free regions
- Rugged techniques, first developed in 1950s-1960s

- Typical Si detectors: reverse bias produces *thin* intrinsic region at interface of p-type and n-type doped regions

K. Perez – MIT
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- Active area totaling \( >10 \text{ m}^2 \)
  - 10-cm diameter detectors

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K. Perez – MIT
GAPS Si(Li) Development Team
Lithium-drifted Si detector fabrication

1. High-quality floating-zone (B doped) $p$-type substrate developed by SUMCO Corp. specifically for GAPS

Crystal orientation: $(1-1-1) \pm 1^\circ$

Bulk ingot lifetime: $> 400 \mu s$

Resistivity: 800-2000 $\Omega$-cm

O impurity: $< 2 \times 10^{16}$ atoms cm$^{-3}$

C impurity: $< 2 \times 10^{16}$ atoms cm$^{-3}$
Lithium-drifted Si detector fabrication

1. High-quality floating-zone (B doped) p-type substrate developed by SUMCO Corp. specifically for GAPS

2. Evaporate and diffuse n+ Li layer

Key aspects of Li:
1. Li is easily ionized in Si, donates electrons → n-type layer
2. High mobility in Si → mobile positive Li ion

Example: prototype fabrication facility
Lithium-drifted Si detector fabrication

1. High-quality floating-zone (B doped) $p$-type substrate developed by SUMCO Corp. specifically for GAPS

2. Evaporate and diffuse $n+$ Li layer

3. Top-hat structure to control Li drift (UIG), evaporate Au/Ni electrodes

Example: prototype fabrication facility

Commercial thermal evaporator for Au/Ni

Ultrasonic impact grinder
Lithium-drifted Si detector fabrication

1. High-quality floating-zone (B doped) $p$-type substrate developed by SUMCO Corp. specifically for GAPS

2. Evaporate and diffuse $n^+$ Li layer

3. Top-hat structure to control Li drift (UIG), evaporate Au/Ni electrodes

4. Drift Li through wafer

Mobile positive Li ions compensate impurities in boron-doped Si, creating extended charge-free regions

- high temperature: ~110 C
- constant voltage: ~500 V
- long time: ~90 hrs for 2.5mm

Example drift of 1.7mm-thick Si(Li)
Lithium-drifted Si detector fabrication

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2. Evaporate and diffuse $n$+ Li layer

3. Top-hat structure to control Li drift (UIG), evaporate Au/Ni electrodes

4. Drift Li through wafer

5. Cut guard ring grooves, strips (UIG).
Validated low-cost technique with prototype Si(Li)

- Prototype Si(Li) detectors: 5-cm diameter, 1-1.75 mm thick

- **Low-cost** fabrication scheme developed to achieve required 4 keV energy resolution at relatively high operating temperature of -40 C

- Total cost ~few hundred dollars in materials

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Perez et al. NIM A905 12-21 (2018)
Prototype Si(Li): key diagnostics

- Capacitance scales with intrinsic region width, and is used to determine the proper operating bias

- Leakage current is main contributor to energy resolution
- For bulk-current dominated, decreases with temperature as \( I \sim \exp\{-E_g/2kT\} \)

- Well-functioning detector (TD0048) is >90% depleted by ~1000 V/cm (150V bias for these 1.5 mm detectors)

- Achieve < 0.5 nA/cm², necessary for required energy resolution performance
- Scales with temperature as expected

Perez et al. NIM A905 12-21 (2018)
Rapid, successful development of flight detectors

Partnered with Shimadzu Corp., a commercial producer of Si(Li) detectors with over 40 years of experience

Conventional Si(Li) for X-ray spectrometry:
- Small diameter < 1 cm
- Low operation temperature (Liquid nitrogen temperature)

Commercial products:
~10 mm diameter
~3 mm thick
Rapid, successful development of flight detectors

Partnered with Shimadzu Corp., a commercial producer of Si(Li) detectors with over 40 years of experience.

Commercial products:
- ~10 mm diameter,
- ~3 mm thick

5 cm wafer diameter,
- 2.5 mm thick

Feasible flight design!
Both 4–strip and 8–strip validated (8–strip default)
Suppressing leakage current: 

(1) Guard ring geometry and surface preparation

**Guard ring** structure prevents surface leakage current from entering readout circuit e.g. Goulding NIM 12 249-262 (1962)

Chemical etching of grooves:
- Removes surface impurities
- Smooths surface
- Sets proper surface state (lightly n-type)

→ **Proper groove surface treatment** ensures electrical isolation of detector regions, in particular the guard ring

![Graphs showing leakage current vs. bias voltage and etching time](image)

“**It would be no exaggeration to say that the least understood and most time-consuming aspect of semiconductor devices is the behavior of the region where a junction intersects the surface of the crystal.**” – F.S. Goulding (1963)
Suppressing leakage current:
(2) Optimized drifting process

**Typical Si(Li):**
Au p-side contact prevents charge injection into intrinsic detector region

**Shimadzu development:**
Un-drifted p-side layer suppresses leakage current

**Un-drifted p-side layer suppresses leakage current**
- GAPS Si(Li) only for X-rays >20 keV
- No need for thin p-side “window” in conventional Si(Li)
  → Un-drifted layer does not affect anti-nuclei identification

![Graph showing leakage current vs. bias voltage](graph.png)
Basic 8-strip performance meets requirements

- Uniform characteristics across all strips
- Leakage is far below the 0.5 nA/cm² requirement to provide <4 keV (FWHM) energy resolution
- Capacitance indicates detector is fully depleted by our operating bias of 250 V
- Depletion corresponds to ~95% of detector thickness

Sample 8-strip Shimadzu detector
T = -35°C

Demonstrate required energy resolution

- Energy resolution is measured at MIT using a custom low-noise, discrete-component preamplifier and flowing liquid N2 cooling system
- Same preamplifier design will be used for flight detector calibration

- Demonstrate <4 keV FWHM energy resolution and <1% energy linearity using $^{241}$Am 59.5 keV and $^{109}$Cd 88 keV X-rays

K. Perez – MIT
Energy resolution meets model predictions

- Noise model combines detector characteristics with pulse shaping and readout characteristics to describe final energy resolution performance.

\[ ENC^2 = \left(2qI_{leak} + \frac{4kT}{R_p}\right)F_i\tau \quad \text{Series noise} \]
\[ +4kT(R_s + \frac{1}{g_m})F_v \frac{C_{total}^2}{\tau} \quad \text{Parallel noise} \]
\[ +A_fC_{total}^2F_{\nu f} \quad \text{White noise} \]

\[ FWHM = 2.35\epsilon \frac{ENC}{q} \]

e.g. Goulding, NIM 100 (1972) 493-504; Radeka, BNL (1974)

✓ Our measured energy resolution (FWHM) as a function of pulse peaking time is well-described by this model.

Energy resolution (FWHM) as a function of peaking time for Strip B of the 8-strip Shimadzu detector Sh0077, measured at -39°C and 250V operating bias using the 59.5 keV line of an Am-241 source. The red solid line shows the predicted energy resolution using the noise model with the parameters shown in the insets.
Resolution scales with leakage current and temperature as expected

- Energy resolution scales with **leakage current** as expected from the noise model
- If a detector has one strip with poor leakage current, all other strips will still be useful for X-ray detection

- Energy resolution and leakage current scale with **temperature** as expected
- We will be able to predict energy resolution as a function of in-flight temperature
Production ongoing of >1000 Si(Li) detectors

- Large-area Si(Li) detectors have been developed to meet the unique temperature, power, cost constraints of the GAPS Antarctic balloon experiment
- Demonstrated <4 keV X-ray energy resolution at relatively high temperature of -35 to -45 C
- Evaluating production yield (estimate ~90% based on recent 10 detectors)
- Ongoing production by Shimadzu Corp. of 1100 10-cm diameter, 8-strip Si(Li) detectors, from late 2018 through early 2020

First GAPS flight late 2020

World-leading limit or detection of rare cosmic antideuterons + precision antiproton spectrum at E < 0.25 GeV/n
Backup
A generic **new physics** signature with **essentially zero** conventional astrophysical background

- Probes a variety of dark matter models that evade or complement collider, direct, or other cosmic-ray searches
- GAPS first experiment optimized specifically for low-energy antinuclei signatures
- **First Antarctic flight:** late 2020