Development of Field-Shaping Electrode Configurations for High-Resolution Semiconductor Radiation Detectors for Nuclear Sciences, Forensics, and Safeguards

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Outline

• Goals & Objectives
• Approach
• Relevance to DOE-NP, others applications, and opportunities for training of new workforce
• State-of-the art implementations
• Challenges and limitations
• Status
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  – Characterization
  – Readout
• Summary & Outlook
Goal and Objective

- High-resolution semiconductor detectors are widely used in basic and applied research and many other fields, not the least recently in mapping and monitoring releases of radioactive materials from the Dai-ichi NPP
- Semiconductor detectors provide excellent energy resolution, efficiency, and –along with segmentation – ~mm position resolution in 3D
- Two recent developments illustrate the potential but also limitation in the implementation of advanced concepts, particularly related to the non-contact surfaces:
  - Segmentation of contact for position-sensitive detection, etc.
  - Point-contact geometries for low-noise applications, etc.
- Limitations due to imperfect electrical contact and non-contact surfaces
- Goal of this project is to better understand current and to develop improved processes and technologies to enhance performance and reliability in the operation of advanced semiconductor implementations
  - Evaluate experimentally and theoretically detector fabrication processes, electrical contacts, and surfaces resulting in better and more reliable performance of advanced contact configurations
Uniqueness and Opportunities

• **LBNL’s Semiconductor Detector Laboratory** reflect many years of experience in fabricating semiconductor detectors such as Si, Ge, and CZT
  – E.g. Amorphous contact and passivation technologies, segmentation and readout schemes, point contact configuration, coplanar-grid CZTs to minimize impact of incomplete charge collection of holes, …
  – Established fabrication and characterization processes

• Opportunity now for revisiting earlier studies to improve:
  – Basic understanding in operation of detectors by including bulk and surface properties (e.g. electrical contacts and non-contact surfaces)
  – Understanding of fabrication processes and their impact on detector properties
  – Fabrication and operation of detectors
Approach – Basic Timeline

• Year 1
  – Initially, focus on HPGe detector technologies
  – Define and establish baseline in terms of detector fabrication, theory and modeling as well as characterization
  – Establish tools and processes to perform work

• Year 2
  – Perform systematic evaluation of detector and contact fabrication processes
  – Refine characterization and contact/surface models

• Year 3
  – Apply improved concepts to segmented HPGe detectors and point contact detectors
  – Evaluate improved concepts for other semiconductor detectors
Relevance for Nuclear Physics, Applications and Training

- **Nuclear Physics**
  - Segmentation: Gamma-ray tracking/imaging
  - Point contacts: Ultra-low noise/threshold - Physics of weakly interacting particles (neutrinos, WIMPS, etc…)

- **Other Applications**
  - Monitoring/response/nuclear forensics – e.g. Fukushima (detection, identification, quantification, imaging)
  - Safeguards and Nonproliferation
  - Homeland security
  - Astrophysics
  - …

- **Training**
  - Coupling to UC Berkeley (Nuclear engineering/physics) – Quinn Looker (PhD student), Micah Folsom, Anagha Iyengar
  - Junior researcher – Paul Barton, Anders Priest
Examples of State-of-the Art - 1
Orthogonal Strip Detectors

Developed for gamma astronomy, NCT
S. Boggs, et al., SSL UCB
37 strips each side, 2 mm strip pitch
a-Ge/HPGe/a-Si
< 1pA / strip @ 82 K

Cs-137 spectra
1200 V
2 μs shaping
Examples of State-of-the Art - II
Orthogonal Strip Detector Instruments

S. Boggs, et al.
UCB Space Sciences Laboratory
Gamma-ray astronomy

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Examples of State-of-the Art – III
Fine-Pitched Strip Detectors

1024 strips, 50 µm pitch, 5 mm length
1 mm thick detector
~ 30 pA / strip @ V_b = 55 V, T >100 K

Developed for time-resolved x-ray absorption spectroscopy
J. Headspith, et al., Daresbury Lab
Examples of State-of-the Art – IV
Point Contact Detector - Concept

Detector cross-section

N-type shaped field point-contact detector

P-type version

Benefits

• Large detector volume (~140 cm³, 0.75 kg) → high efficiency

• Low capacitance (~1 pF)
  → extremely low electronic noise
  → extremely low energy threshold

• Interaction site number discrimination
  → event rejection (e.g., Majorana experiment, neutrinoless double-beta decay in ⁷⁶Ge)

Fabricated for Majorana test system

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Amorphous Si:

- Effective electron blocking point contact
  - Low electron injection at contact
- Back surface passivation
  - Low surface leakage
  - Excellent spectroscopic performance
  - Stability with time, cycling, or environment appears to be a problem

Full depletion values:

- $V_d = 3100$ V
- $C_d = 0.9$ pF
- $I_d \sim 2$ pA
Examples of State-of-the Art – VI
Point Contact Detector – LBNL Fabrication

Spectroscopic performance

- Co-60/Cs-137 source
- Bias voltage: 3200 V
- Shaping time: 8 µs

- 1.77 keV FWHM @1.17 MeV
- 1.92 keV FWHM @1.33 MeV
- 0.54 keV FWHM pulser

Ballistic deficit, charge collection broadening

Gamma energy (keV)

- 1333
- 1173
- 662
- 60

Electronic noise

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Examples of State-of-the-Art – VII
Point Contact Detector – Mini-PPC

LMFE + Mini-PPC detector

7/22/09
LMFE - mini PPC
M0XTEK MX-11
Vb = 2.6 V, Id = 6 mA

85 eV FWHM
50 eV FWHM

Optimized LMFE w/o detector

8/25/09
LMFE - mini PPC
M0XTEK MX11r
Vd = 2.6 V, Id = 4 mA

55 eV FWHM
35 eV FWHM

Results by Paul Luke @ LBNL

➤ ≤ 50 eV noise (≤ 100 eV threshold) with 1 kg Ge detectors?
Status – Challenges and Limitations
All is not perfect: Strip detectors

<table>
<thead>
<tr>
<th>Detector characteristics</th>
<th>Primary performance measures affected</th>
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| Inter-contact charge collection          | Intrinsic resolution (pulse-height deficits)  
Efficiency (event loss)  
Sensitivity (background event increase) |
| Bulk leakage                             | Electronic noise (shot noise)                                                                         |
| Inter-contact impedance                  | Electronic noise (thermal noise)                                                                     |
| Surface channels                         | Efficiency (event loss)  
Sensitivity (background event increase)                                                              |
| Stability with temperature and vacuum cycling | Degraded performance                                                                                 |
| Immunity to high voltage breakdown      | Yield, lifetime, reliability                                                                          |

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Status – Challenges and Limitations
Same issues impact other geometries

Challenges

• Charge collection
  ➢ Charge trapping
  ➢ Collection to back surface

• Leakage current
  ➢ Contact injection
  ➢ Back surface conduction

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Status – Challenges and Limitations
Charge sharing and associated charge loss

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Status – Challenges and Limitations
Temperature cycling stability ...

Electron injection at a-Ge contact increases with T cycling
Electron injection at a-Si contact decreases with T cycling
Process reproducibility and robustness?

Possibly impacted by many process parameters: pre-deposition treatment, gas mixture, pressure, temperature, thickness, target impurities, ...

Physical mechanism?

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Status – Challenges and Limitations
And more … E.g. Surface Channels

Observations:

• Depends on side processing (sputter recipe and pre-sputter treatment), impurity concentration, and typeness, W.L. Hansen, E.E. Haller, G.S. Hubbard, IEEE TNS 27, 247 (1980)

• Reduced surface channels at low T

• Sometimes leads to edge strips with substantial leakage current

• Strong channel appears to be the source of large leakage currents and detector breakdown failure

• Incomplete coating of sides has led to detector failure

• NCT a-Ge/Ge(p)/a-Si configuration suffers more from this than a-Ge/Ge(p)/a-Ge configuration (~ same side coating?)

• High impurity p-type HPGe material suffers more from this than low impurity based on results from NCT detectors

Reproducibility? Impact of geometry, T cycling, ...
Status – Detector Fabrication I

- Fabrication of small test detectors
  - Mechanical crystal preparation
  - Sputtering and thermal evaporation film deposition
- Confirmed results of previous studies

Guard ring device in test cryostat

Test device geometry
Preliminary Results

- a-Ge/p-type/a-Si device
  - Lower leakage current
  - Leakage decreases with T cycle

- a-Ge/p-type/a-Ge device
  - Leakage slightly increases with T cycle
Future – Detector Fabrication

- Systematic study of detector fabrication processes
  - Multi-detector cryostat (temperature variable)
  - Change process with regard to
    - Surface treatment
    - Sputter process (gas composition, pressure, temperature, ...)

Modular Design
- Many small detectors of various geometries
- Larger detectors also possible

Essential for testing process parameters at an acceptable rate
Status – Detector Characterization
Signal response – Linear 1D/ 2D scan

• Need to understand position-dependent response of new detector configurations

• Collimated scanning takes time
  – Direct tradeoff between resolution and time
  – Collimated coincidence scanning takes even more time
Positions of Ge detector, $^{22}$Na source, and scintillator are known and fixed.
- Source emits positrons
  - Short positron range
  - Annihilation leads to collinear, oppositely oriented 511-keV gamma rays

Domingo-Pardo, NIM, 643, 79 (2011)

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Status – Detector Characterization
Signal response – 3D coincidence scan

- Combined perpendicular data sets give defined volume
- Some prior knowledge of Ge detector response is required
- Assumes unique position-dependent response
- Similar pulses from two cones assumed to be same location
- Average waveform gives expected position-dependent response

Domingo-Pardo, NIM, 643, 79 (2011)
In order to develop and evaluate the low noise performance of point contact detectors, a low-mass and ultra-low noise front-end is being refined (similar to MAJORANA Low-Mass Front-End)

- Fused Silica (7 x 16 x 0.25 mm³)
- Ti/Au Traces (evaporated)
- a-Ge:H₂ (sputtered)
- Gate Pin to Detector Feedback Resistor (20 GΩ)
- Parasitic Pulser Capacitance
- Parasitic Feedback Capacitance (0.1 pF)
- Source Drain Pulser Feedback / Output
A rapid test environment for temperature-dependent testing of LMFE performance.

Future:
Design for 60x60 mm point contact detector to be fabricated with low-noise readout and improved fabrication process.
Summary & Outlook

• Summary
  – Detector fabrication baseline established
    • Production and characterization of small (and large) HPGe detectors initiated
  – Multi-detector cryostat is being built
  – Detector characterization system available and upgrade being built
  – Modeling and simulation environment established
  – Detector readout development ongoing

• Outlook
  – Systematic measurements and improvements in the fabrication of HPGe detectors including theoretical studies on contacts and surfaces
  – Large detector demonstration to come later …