Germanium Detectors

Greg Hackman
Generic Electronic Radiation Detector

- Radiation (slanted arrow) passes through matter
  - (this is a charged particle)
- Collisions create charged-particle pairs (e.g. free electrons, ions)
- Electric field sweeps up free charge to contacts
- Transient electric current pulse amplified & processed

- What is the grey stuff?
  - Gas
  - Semiconductor diode
What’s special about HPGe?

- High Purity Germanium (HPGe)
- Good tradeoff between energy resolution and efficiency
Applications of Ge

- **Nuclear Physics and Chemistry**
  - Excited levels within nuclear system -- i.e., nuclear structure
  - Lifetimes (rather than by beta counting)
  - Nuclear reaction rates

- **Astronomy**
  - Gamma-ray sky surveys for supernova residues
    - 1809 keV line from $^{26}$Al decay

- **Radiological Assaying**
  - Unique gamma-ray signatures from many common activities
    - 1460 keV -> $^{40}$K beta decay
    - 2614 keV -> $^{208}$Bi beta decay, daughter of $^{232}$Th
    - 375/413 keV -> $^{239}$Pu (!)
  - Used for a Weapons Testing Verification just offsite here at TRIUMF

- **Neutrinoless double-beta decay**
  - Ge enriched in $^{76}$Ge as source and detector
  - $^{76}$Ge->$^{76}$Se+2e-. Q-value 2039 keV
Job for an HPGe: The Shape of $^{10}$Be

- Conventional wisdom: $^{10}$Be $0^+_gs$, $2^+_1$ prolate ($M_{22}>0$)
- AV18 alone: $2^+_1$ oblate, $2^+_2$ prolate
- Include IL2 3-body forces: $2^+_1$ prolate, $2^+_2$ oblate
- Bonn NCSM: $2^+_1$ prolate without 3-body forces
It’s a football
Job for an HPGe: finding trace “peacekeeper” radioactive isotopes

What is the best detector for a hand-held Identifier?

Gamma-Ray Spectra of Natural Background

HPGe: best combination of resolution and efficiency
Job for an HPGe: Galactic Structure

- HPGe in Space
- Look for gamma rays from centre of galaxy
  - 1809 keV from $^{26}\text{Al}$
- COMPTEL, INTEGRAL
Job for an HPGe: Galactic Structure
Making High-Purity Germanium

- Crystal grown by “pulling” from molten Ge
  - Czochralski technique
  - Seed crystal slowly withdrawn
  - Ge freezes to seed as single crystal
    - Diameters up to ~11 cm achievable, but rare
    - 5-8 cm reasonable
  - At phase interface, impurities “frozen out”, collect in liquid
  - In practice, “top” of crystal purer than “bottom”
- “Zone Refining”
  - Pass through microwave oven
  - Melt “zone” migrates impurities one more time
- Resulting crystals: $10^{10}$ impurities per cm$^3$
Typical Ge configuration: Closed-End Coaxial

- Machining after crystal formation
  - Right cylinder
  - Hole drilled partway through centre
  - Typical dimensions: \( R_o = 2-7 \text{ cm} \), \( \ell = 4-12 \text{ cm} \), \( r_i = 0.5 \text{ cm} \), \( x = 1 \text{ cm} \)
- Contacts formed on outer (reddish) surface (except top, as shown) and inner core (blueish)
  - n+ contact: drifted Li (~0.1 cm)
  - p+ contact: implanted boron (2 µm)
- Placement of contact depends on bulk
  - If bulk is slightly p-type: Li on outside
    - Thicker dead area on larger surface
    - Lower efficiency for very low-energy photons
  - If bulk is slightly n-type: Li on core
  - N- vs. P-type decision based on two factors:
    - Price (p-type cheaper)
    - Neutron damage (n-type more resistant, easier to fix)
Typical Ge configuration: Cooling and Efficiency Specification

- Cryogenic cooling
  - Reduces leakage current
  - HPGe CANNOT be used at room temperature
- Typical cooling with LN2
  - Remote reservoir
  - Cooling rod
  - Vacuum cryovessel
    - 1 or more crystals per cooling unit
- Modern mechanical cooling now marketable
  - Still expensive

- Efficiency depends on:
  - Gamma-ray energy
  - Distance and orientation of source with respect to detector
  - Shape and total volume of HPGe minus dead layers
  - Cryostat material (Be, C-fibre windows are common)

- Photopeak efficiency $\epsilon_{pp}$ probability that for an incident photon, total energy is absorbed and detected
  - Does not include incident photon energy is measured

- Peak to Total: Ratio of Photopeak to non-Photopeak counts in spectrum
HPGe Efficiency Standard

- **Standard candle**: $^{60}$Co gamma ray source 25 cm from front of CRYOSTAT
  - Oriented in front of any entry window
- Efficiency defined as photopeak counts from 1332 keV gamma ray, relative to relative to a 3 in x3 in NaI(Tl) cylinder
- 100% = 1.2x10^{-3} absolute
  - A 100% HPGe would be about 9 cm x 9 cm
- Peak-to-total: ratio of counts in 1332 and 1173 keV gamma rays versus total counts
  - Continuum from escaping energy
    - Compton scattering out of Ge
    - Annihilation photons escaping Ge
    - etc
  - Manufacturers typically specify a lower limit of 150 keV for summing “total” counts
  - Typical values 15% to 25%
Two typical HPGe detectors (here at TRIUMF)

- Single-crystal p-type
- 80% relative to NaI
- Used mainly for ISAC-I decay spectroscopy

- TIGRESS Clovers
- Four-crystal n-type, 40% each
  - 8 segments on outer contact
- ISAC-II in-beam spectroscopy
Typical Ge configuration: Depletion, Bias, Readout

- Depletion voltage can be estimated from impurity concentration, assume infinite coaxial “capacitor” with dielectric
  - \( V_d = \left( \frac{Ne}{2\varepsilon} \right) \left[ r_i^2 \ln \left( \frac{R_o}{r_i} \right) - \left( \frac{1}{2} \right) (R_o^2 - r_i^2) \right] \)
  - \( N=(Na-Nd)=\text{net density of “electronically active” impurities (acceptors minus donors)} \)
  - \( \varepsilon = \text{permittivity (}\varepsilon/\varepsilon_0=16.7 \text{ for HPGe)} \)
  - \( V_d \text{ typically } 1000 \text{ V to } 4000 \text{ V in readily available detectors} \)
- Typically operate HPGe as high as possible – 500 to 2000 V above depletion
  - About 2000 V/cm field -- Surprisingly uniform
- Charge-sensitive preamplifiers
  - Integrates induced current
  - Can place front-end FET and feedback network in cryostat to improve resolution
Electron and Hole Drift

- At low fields and LN$_2$ temperatures: mobility of electrons in Ge is $\sim 40,000$ (cm/s)/(V/cm), holes slower
  - at 2000 V/cm in a $(R_0$-$r_i)=2$ cm crystal, implies collection times on order of 25 ns
- BUT: At 2000 V/cm, drift velocity of holes and electrons are NOT proportional to field
  - Saturation velocity approx. $10^7$ cm/s
  - Collection time $\sim 200$ ns
- And both direction and speed depend on direction relative to crystal axis
  - 15% difference from $<100>$ to $<111>$
- Recombination lifetime of minority carriers $\sim 1$ ms – great
- Imperfections in crystal lattice trap charge carriers
  - Tail on low-energy side of photopeak
TIGRESS Prototype Centre contact risetimes

- Centre contact rise time results for 662keV interactions
  FRONT contacts, ns

T30  T60  T90
Neutron Damage

- Neutron flux creates charge trapping centres
  - Nuclear scattering can dislodge Ge from crystal lattice site
- Consequence: incomplete charge collection
  - Poor resolution
  - Low-energy tails
- Threshold for measurable effect depends on size, type.
  - “Large” p-type (70%): $1 \times 10^7$ neutrons/cm$^2$
  - “Large” n-type: $1 \times 10^9$ neutrons/cm$^2$
  - Smaller detectors less susceptible
- Recoverable by annealing
  - P-type: weeks
  - N-type: days
  - Annealing may cause Li to drift, causing efficiency loss
    - Worse for p-type
- Effect often does not appear until bias removed and reapplied
  - Deliberately damaged and annealed n-type detector
  - $3 \times 10^9$ neutrons/cm$^2$ dose

![Graphs](image.png)

A. Prior to experiment.
B. Immediately after the experiment.
C. A month later before annealing.
D. After annealing.

1332keV $^{60}$Co photo-peak
Position dependence of collected charge profile

- Consider core contact, n-type detector
  - positive voltage on Li inner core
  - \( R_o - r_i \approx 2.5 \text{ cm} \)
  - \( v_e \approx 10^7 \text{ cm/s}, \ v_h \approx 0.75 \times 10^7 \text{ cm/s} \)
  - Space charge plus operating overvoltage results in nearly constant E-field for drift
  - But Ramo weighting \( E_w \) field for core proportional to \( 1/r \)

- Energy losses near core (A)
  - Electrons reach core immediately
  - Holes drift for 270 ns
  - Initial charge buildup on core (induced current) large since \( E_w \) large
  - Rate of charge buildup decreases

- Energy loss near outside (B)
  - Holes reach outside immediately
  - Electrons drift for 200 ns
  - Induced current small initially
  - Increases as electrons reach region of high weighting field near core

- BOTTOM LINE: Pulse shapes vary drastically based on location of interaction
  - Multiple interactions: linear sum of currents
  - Time resolution is poor.
Position dependence of induced charge profile

- Implanted contact may be easily segmented by masking during implantation
  - Outer-contact segmentation common in modern (pure research) applications
- Neighboring contacts collect no net charge
- But induced currents give rise to a transient pulse
  - Due to fringing in weighting field
- Charge-carrier generation nearer to contact results in larger transient signal
- Polarity of pulse depend on whether nearer to core or outside
  - Certain locations: induced currents cancel, transient pulses negligible
- Compton cameras and tracking arrays analyse pulse shapes to localize interactions, reconstruct source incoming vector
  - Example here: Compton scattering followed by photoabsorption

- Position sensitivity depends on segment geometry, noise
- 2 mm for single interactions demonstrated in TIGRESS
Addback and Escape Suppression

• If all incoming photon energy is deposited in crystal, you get a high resolution photopeak

• High probability that a Compton scatter or annihilation photon following pair production will escape

• Lost energy has a continuous spectrum

• Becomes a background that can swamp weak lines

• Solutions:
  • Place HPGe detectors in close proximity and add energy loss in each
    – E.g. TIGRESS clover
  • Surround HPGe with less expensive, high density scintillator
    – BGO works well: $X_0=1.1$ cm
    – Veto events with BGO signal in coincidence with HPGe signal
    – Leave entrance hole of course
Addback and Escape Suppression

• TIGRESS HPGe crystal and suppressor scheme
• Suppression: If energy measured in front, side or back scintillators, veto any events in HPGe
Addback and Escape Suppression

- TIGRESS HPGe crystal and suppressor scheme
- Addback: If energy deposited in two crystals, treat as a single incident gamma ray – add energies
- 4x40% crystals in addback mode become effectively a 220% photopeak efficiency detector
$^{60}\text{Co} – \text{Full Suppression}$
$^{60}\text{Co} – \text{Full Suppression}$
Characterising TIGRESS for high energy – R. Kshetri, SFU/TRIUMF

$^{11}\text{Be}$ β decay ($t_{1/2} = 13.8$ s) gives gamma-rays up to 8 MeV
TIGRESS Addback, Suppression

Energy = 7974.73 keV

FWHM (addbk) = 9.48 keV
FWHM (add) = 8.91 keV
Area (Addback) = 6978 (98)
Area (Add) = 3298 (62)
so, Addback factor at 8 MeV = 2.12 (5)
TIGRESS absolute efficiency for $^{12}\text{C}$, $^{10}\text{Be}$ Campaign

- 8 clovers and fixed side & back suppressors
- 12 sets of retractable front shields
- Maximum suppresson configuration
  - Clovers back
  - Suppressors forward
Other Ge configurations

• Planar detectors
  – 5 to 20 mm thick hockey pucks
  – Superior low-energy response
  – Variation: Low-Ax

• Double-Sided Strip HPGe
  – Square, with orthogonal strips on opposite sides
  – Choice for Compton cameras (medical, security imaging)

• Ge(Li)
  – Before HPGe
  – Use heat, electric field to drift Li donors into bulk to compensate acceptor impurities
  – “Freeze” Li in place at operating temperature
  – If these warm up they are destroyed.
Other Ge configurations

- “Drift Chamber” HPGe
- Replace core with “button”
- Induced signal on button only when electrons very close
  - Weighting field proportional to $1/r^2$
- Clean identification of multi-site vs. single-site energy deposition
  - Will be used in Majorana to discriminate neutrinoless double-beta decay from high-energy gamma ray pair production
Up and coming alternatives to HPGe

**Cadmium Zinc Teluride**
- Semiconductor
- Room temperature operation
- About twice the FWHM
- Crystal growth is still challenging
- Holes very slow ($1/10^{th}$ electron) and easily trapped
- Appropriate for imaging applications

**LaBrCe**
- Scintillator
- Room temperature
- About twice the FWHM
- Excellent timing
  - 3 ns light curve
- Patented -> expensive
- Competitive for in-beam spectroscopy
The end
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<tr>
<th>Material Property</th>
<th>Silicon</th>
<th>Germanium</th>
<th>NaI(Tl)</th>
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<td>Type</td>
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<td>Gamma-ray FWHM energy resolution, $^{60}$Co source (1332 keV gamma)</td>
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<tr>
<td>Cooling</td>
<td>Not necessary</td>
<td>Must operate at low temperatures (~95 K)</td>
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