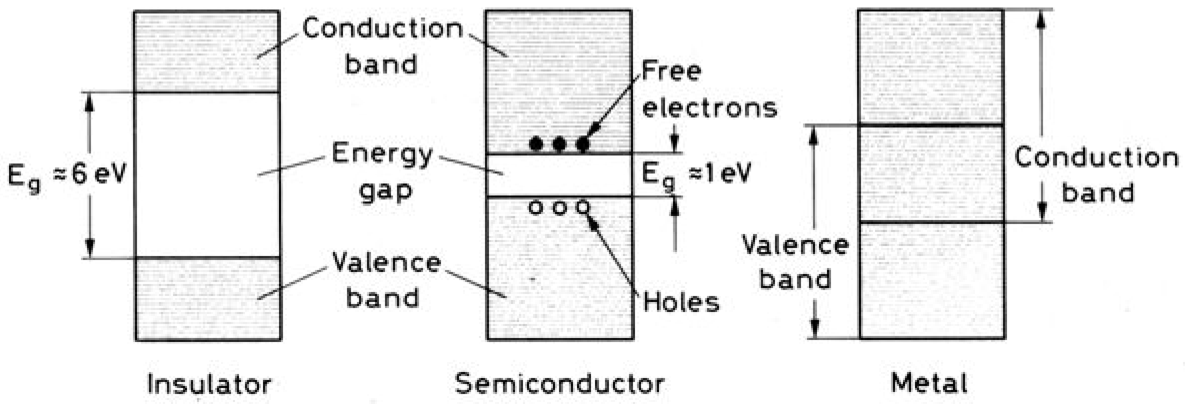
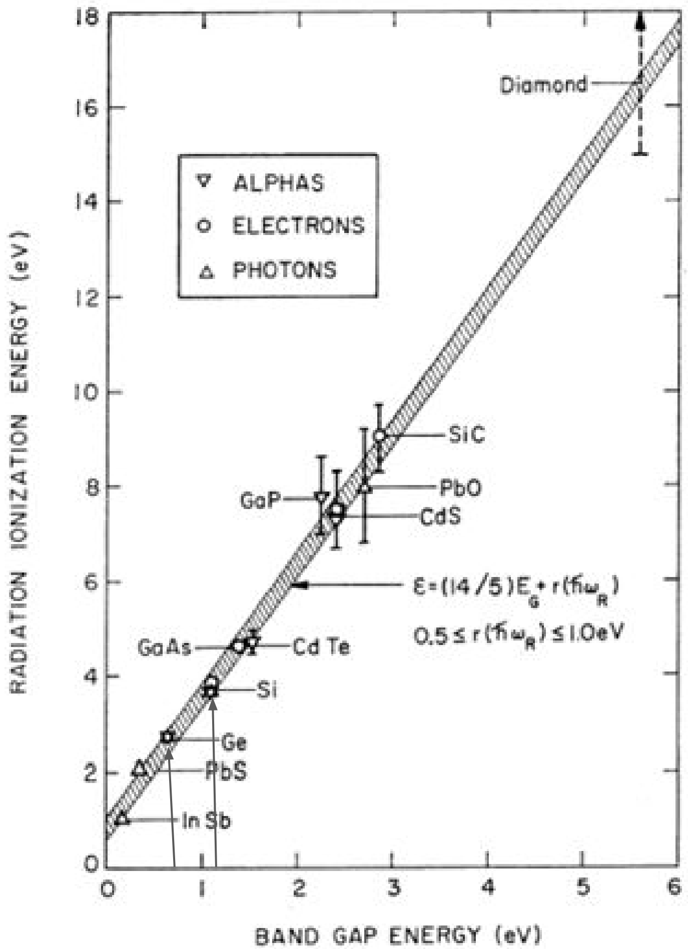
Semiconductor (Ionization) Detectors

Bandgap & Ionization Energy

	Mean Ioniz. En. W [eV]	Density [g/cm³]	Fano Factor
Gases	30	7 – 50x10⁻⁴	0.1-0.2 (ionization vs. excitation)
Si	3.62	2.33	~0.10 (ionization vs. phonons)
Ge	2.96	5.32	~0.10 (ionization vs. phonons)

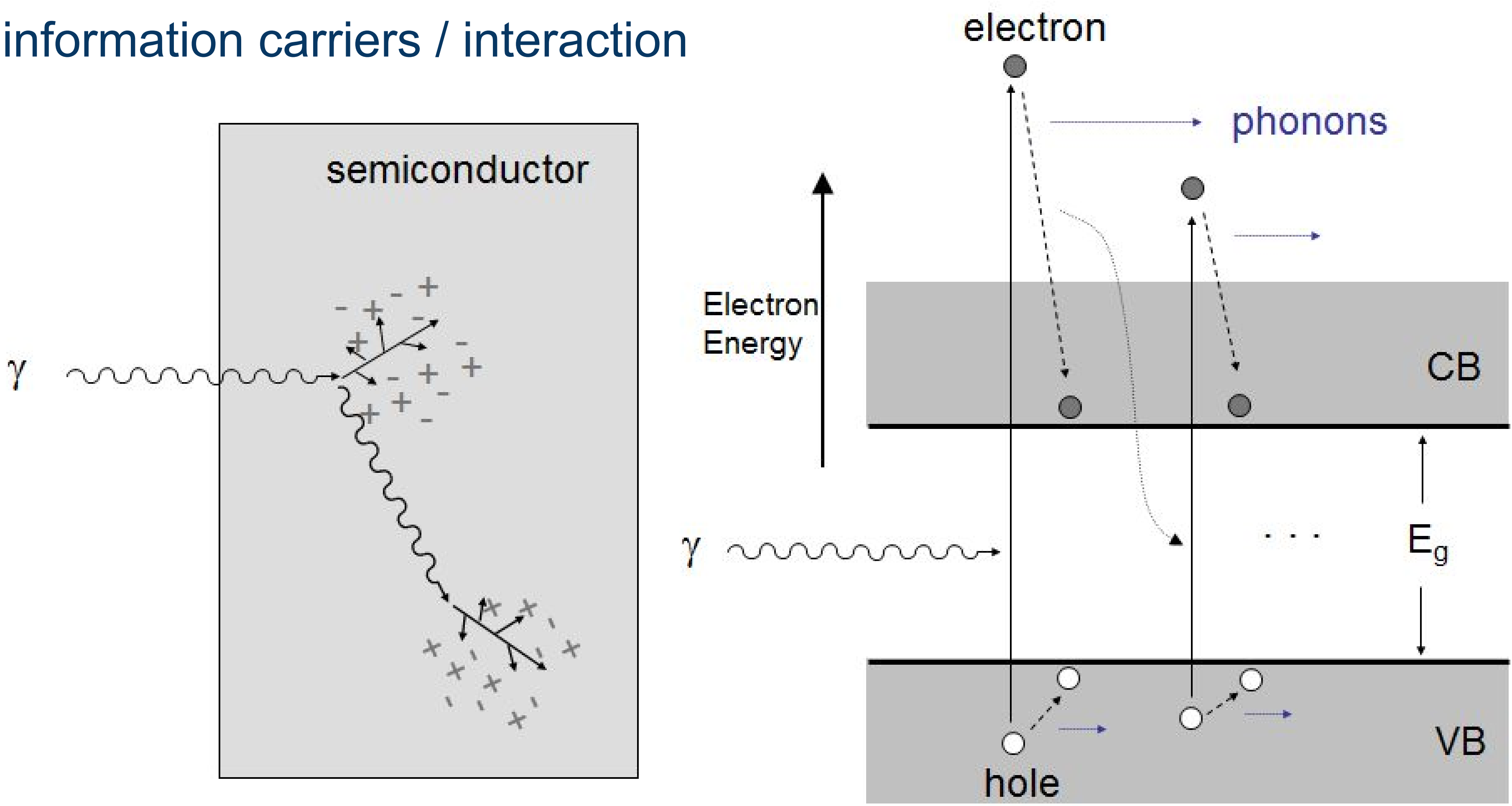




Example: Ge bandgap ~ 0.7 eV; Ge mean ionization energy = 2.96 eV → ~ 4x phonon production per e/h pair.

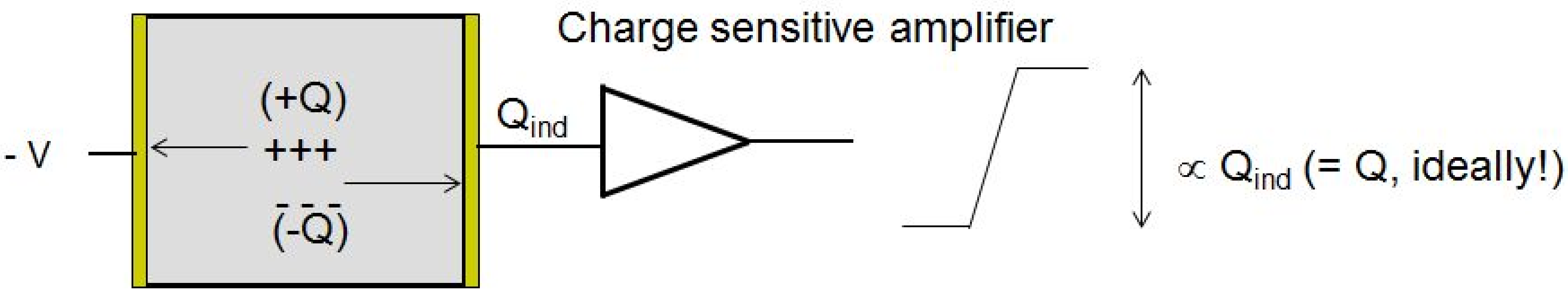
Electron/Hole Pairs: Information Carriers

- Total # of e/h pairs (charge) ∝ energy deposition
- Low mean ionization energy → More information carriers / interaction



Measuring e⁻/h Pairs

- **Challenge**: Measure ionization with high precision (better than 0.1%) in large detector volumes (>~cm^3)
  - E.g. 300 keV energy deposition in Ge → ~10^5 e/h pairs: .1% ~ 100 e/h pairs



- **Requirements**
  - Establish E-field to accelerate charge collection (with low leakage current)
  - Excellent carrier transport
    - High carrier mobility (μ) and lifetime (τ)

Establishing E-Fields with Low Leakage

- Requires material with high resistivity - depends on dopant concentration and carrier mobility $\rho = (eN_D\mu_{maj})^{-1}$
  - Dopant dictates majority carrier (p-type = holes, n-type = e^-)
  - Dopant concentration → total number of available charge carriers
  - Challenge of crystal growth: defects affect carrier mobility
- Truly “pure” material not achievable in practice
  - Properties of Si/Ge determined by minute imbalances of dopant concentrations
  - Compensated material: donor and acceptor impurity concentration equal
    - E.g. Lithium-drifting: Si(Li) & Ge(Li) detectors
- High resistivity can be achieved in some compound semiconductors as well

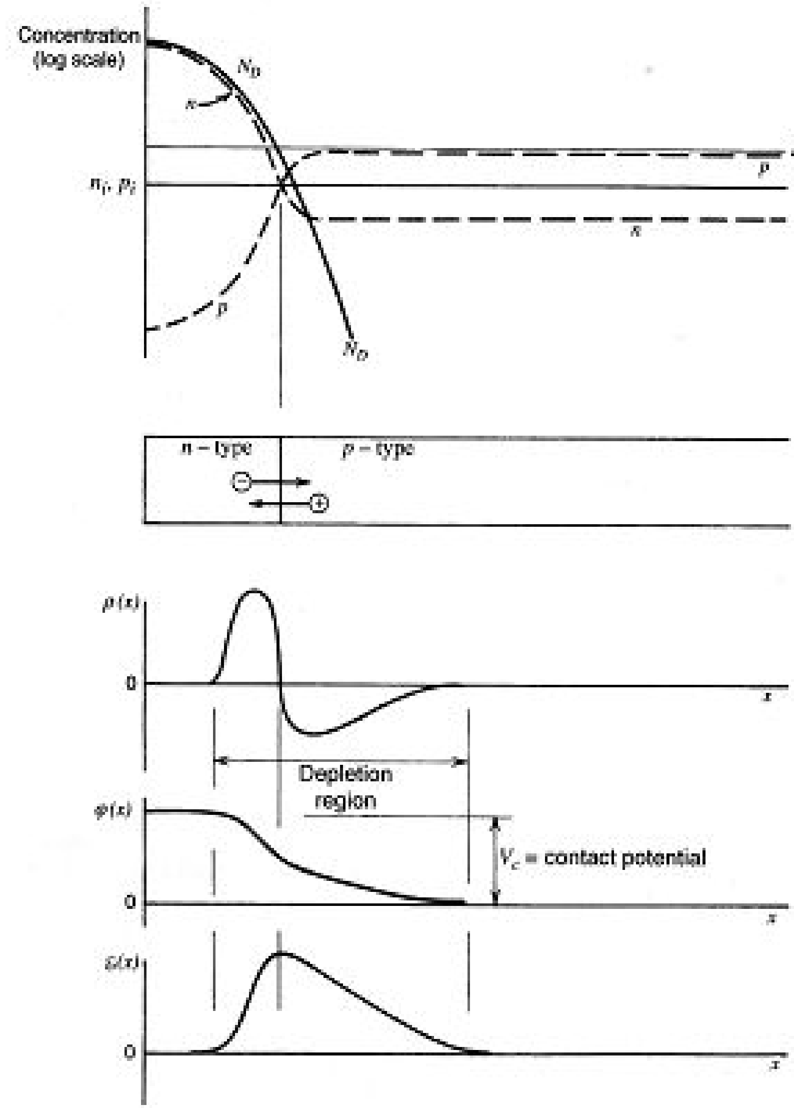
Implementation: Reverse-Biased Diodes

Near-intrinsic bulk (N_D~10^{10}cm^{-3})

Heavily doped thin contacts

$N_A \sim 10^{18}$cm^{-3} $N_D \sim 10^{18}$cm^{-3}

B ~ 3 mm Li ~ 0.5 mm



Apply reverse bias to accentuate contact potential difference

- Attract minority carriers across junction = very low current
- Generate high electric field

Depletion, Electric Fields, Capacitance

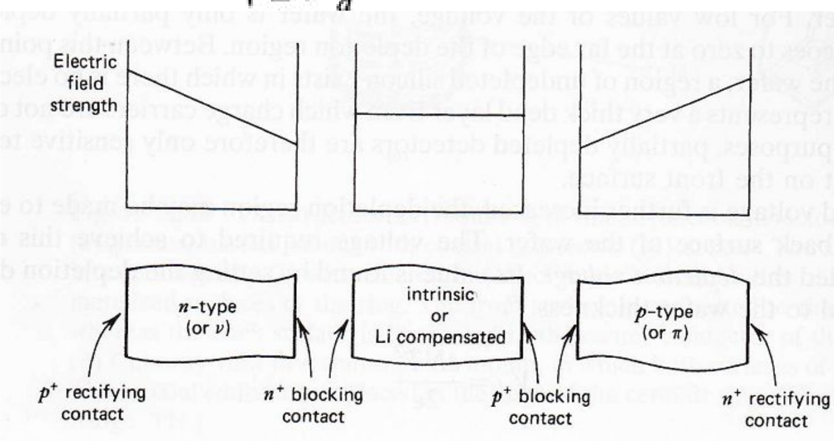
- Example: Planar detector

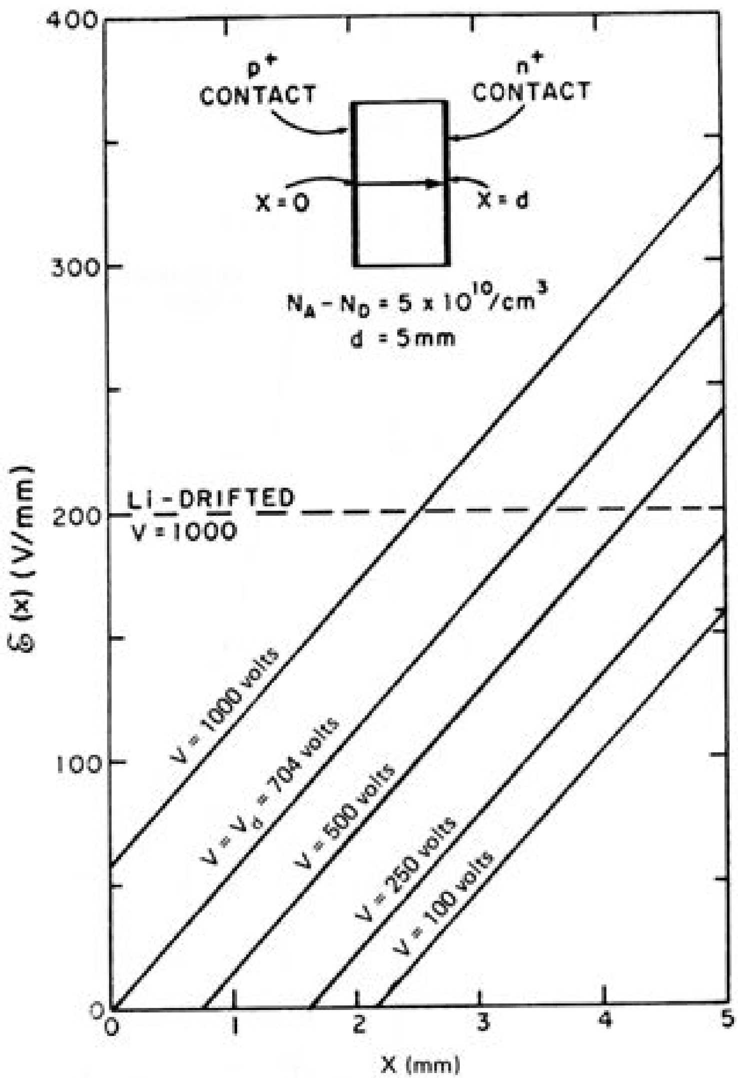
Electric field: $-\mathscr{E}(x)=\frac{V}{d}+\frac{\rho}{\varepsilon}\left(\frac{d}{2}-x\right)$

Depletion voltage: $V_d=\frac{\rho d^2}{2\varepsilon}$ ρ = charge dens. = (*eN*)

Capacitance per unit area: $C=\sqrt{\frac{\varepsilon\rho}{2V}}$

$= \text{constant} = \sqrt{\frac{\varepsilon\rho}{2V_d}}$ for $V > V_d$





Signal Formation - Shockley-Ramo

- Measure current signal induced at electrode due to carrier motion
- Weighting field & potential: convenient constructs for computing induced charge & current

$$i_{ind}(t) = \frac{dQ_{ind}}{dt} = -q\frac{dV_w(P)}{dt} = -q\frac{dV_w(P)}{d\vec{l}} \bullet \frac{d\vec{l}}{dt} \qquad \vec{v} = \frac{d\vec{l}}{dt}$$

$$i_{ind}(t) = q\,\vec{E}_w(P) \bullet \vec{v}(P(t))$$

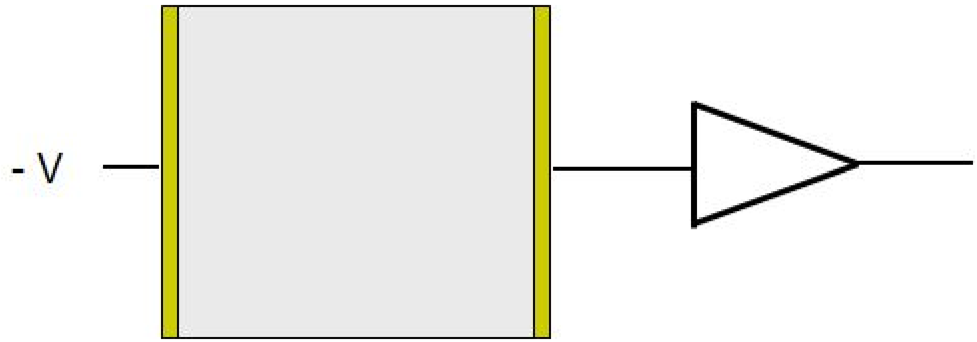
N.B. e^- & holes drift in opposite direction: induce signals of same sign!

$$Q_{ind}(t) = \int i\,dt = q\int \vec{E}_w \bullet d\vec{l} = q\left(V_w(P_0) - V_w(P_t)\right)$$

$\vec{v} = \mu(E)\vec{E}$ Carrier velocity determined by **electric field** → compute via **Poisson** equation (with space charge) in the detector

$\vec{V}_w(P)$ Coupling determined by **weighting potential** → compute via **Laplace** equation (ignore space charge) according to S/R

Example: Planar Detector w/ Perfect Charge Transport



Charge carriers with ***different*** mobilities

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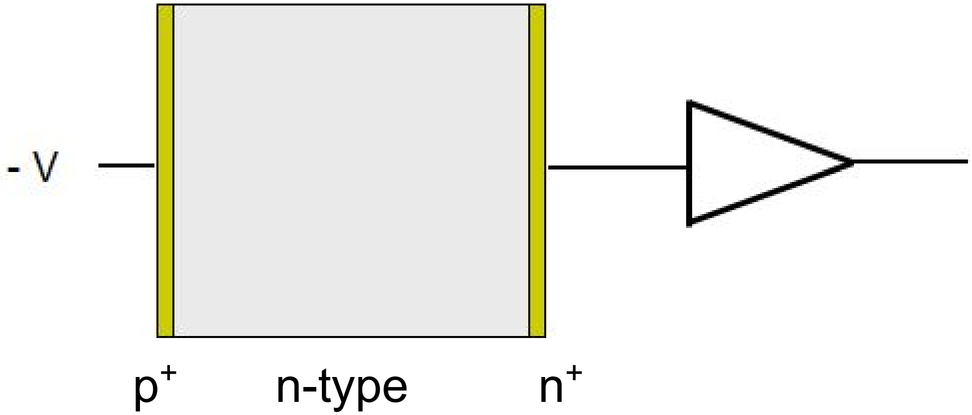

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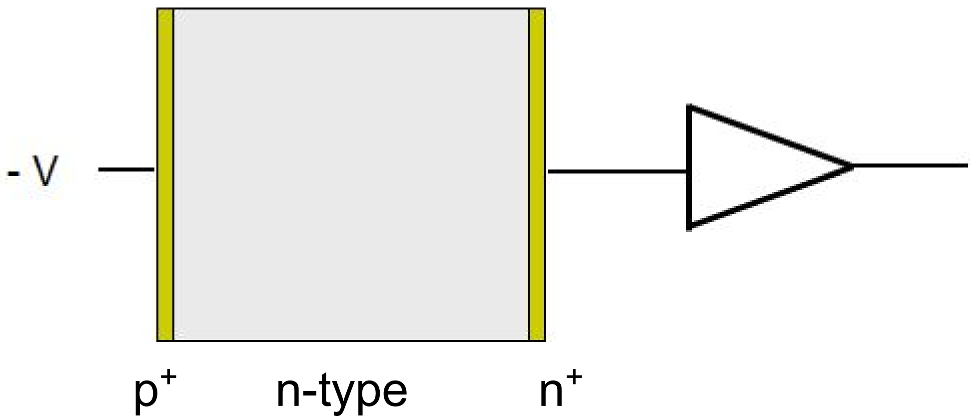

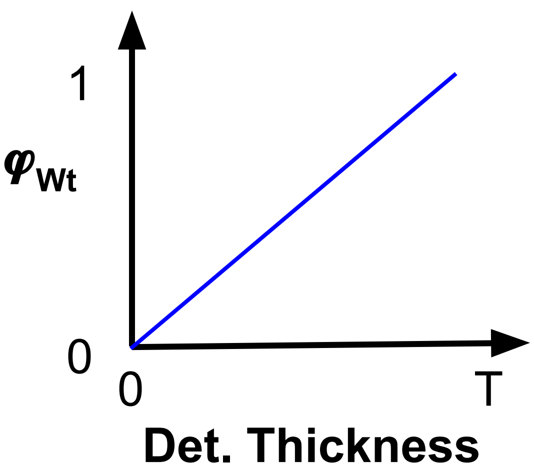

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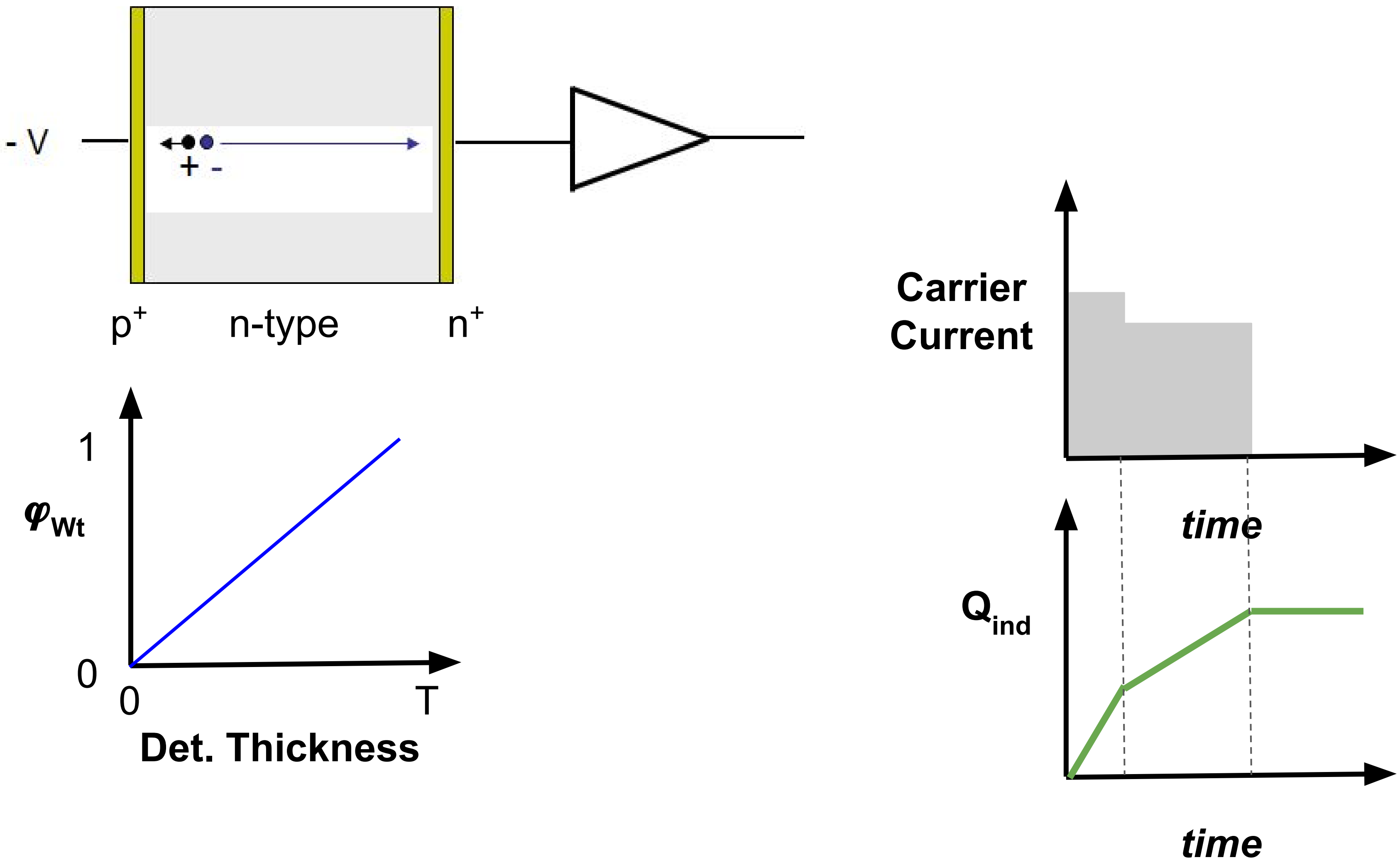

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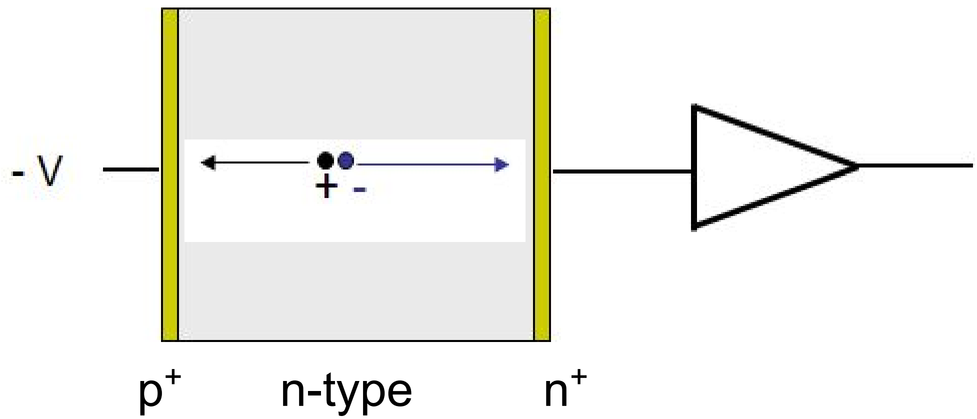

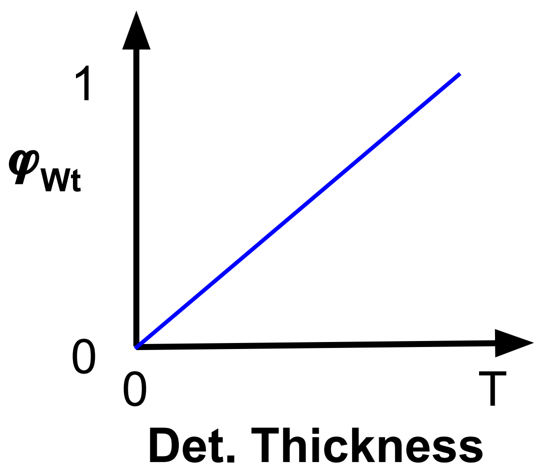

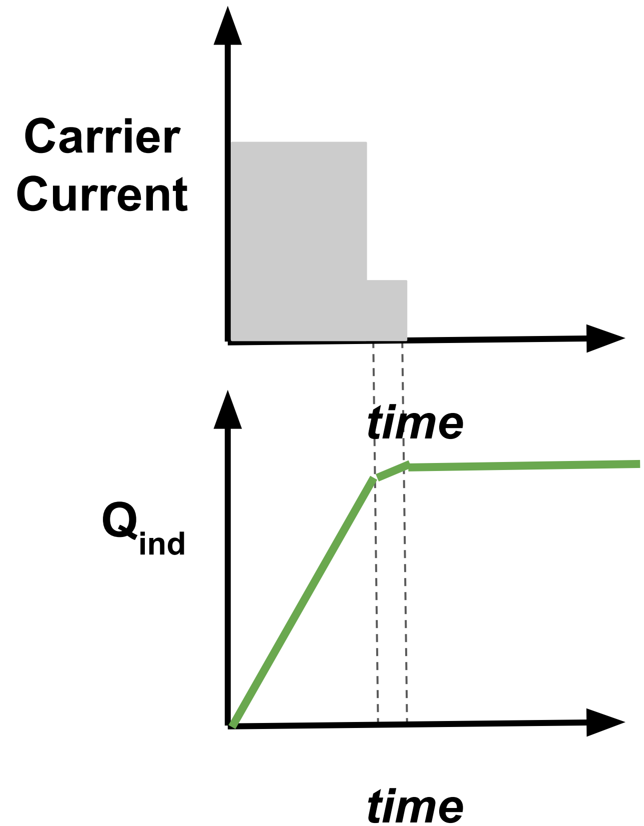

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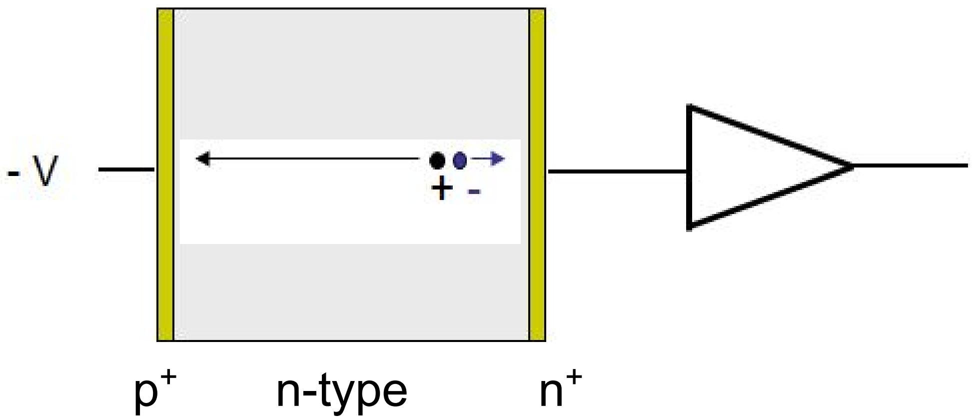

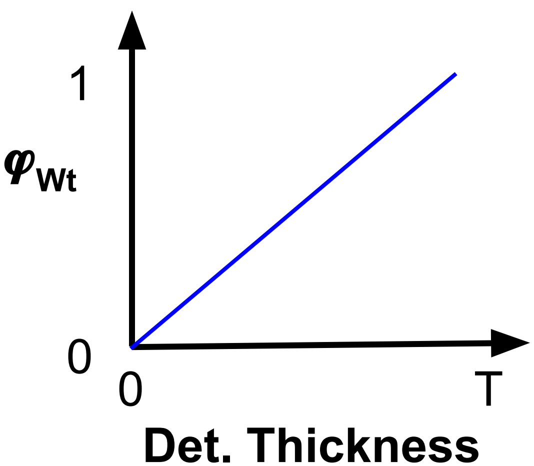

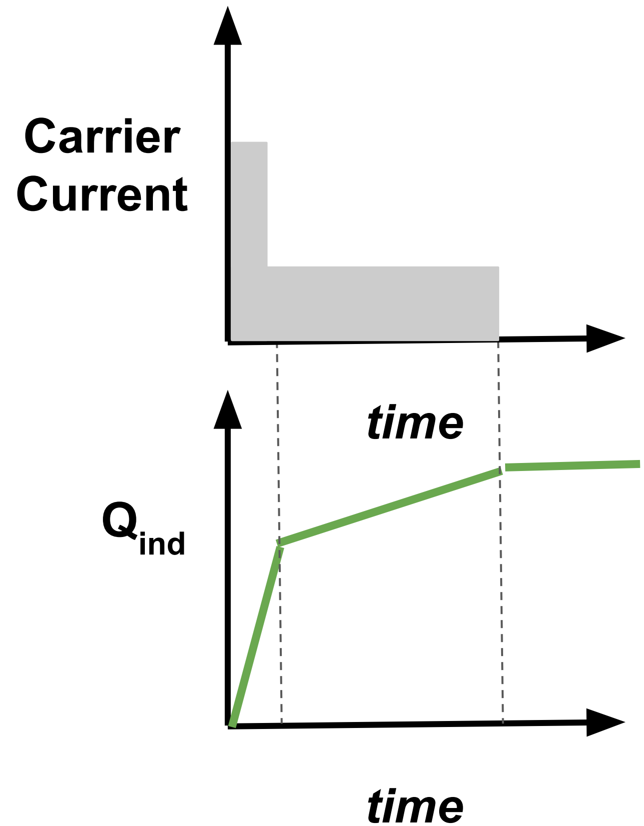

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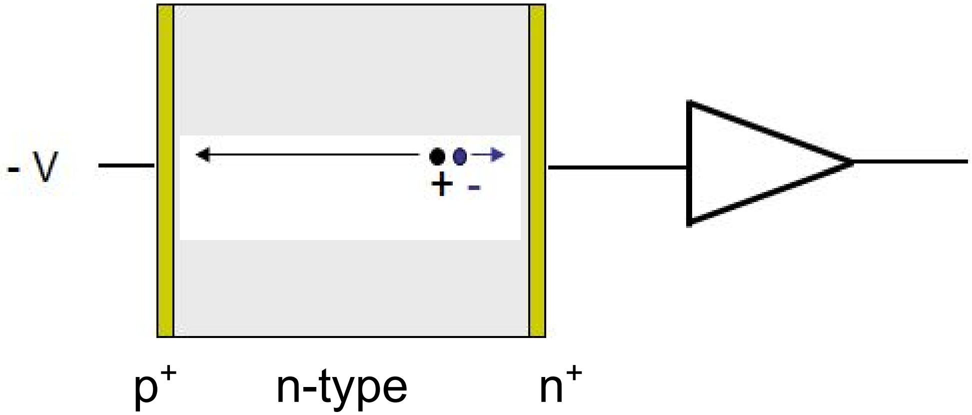
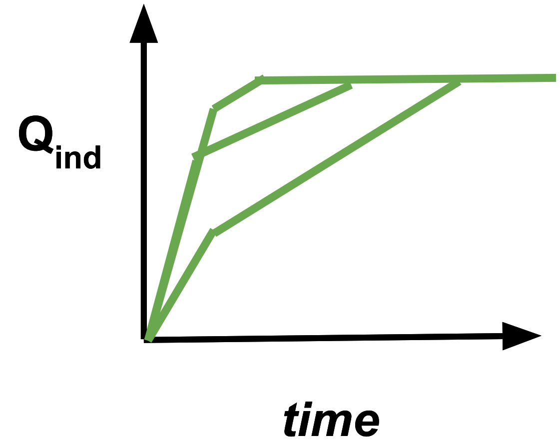
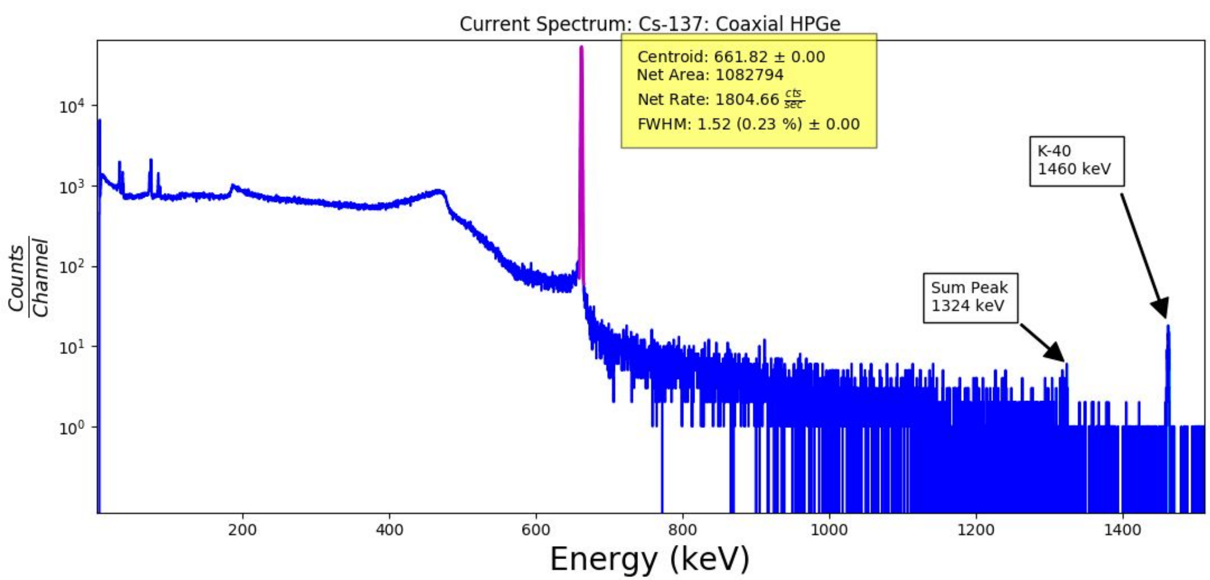
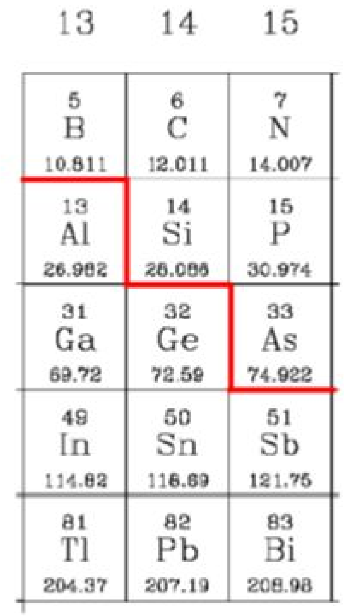






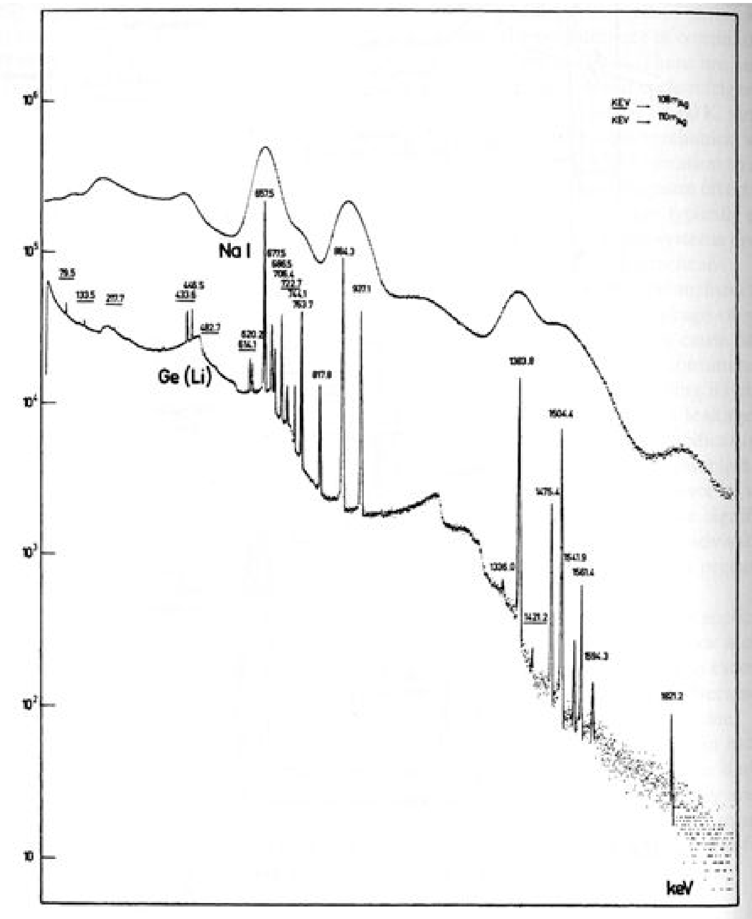
High-Purity Germanium (HPGe) Detectors

- Ge vs. Si detectors:
  - Smaller band gap than Si (0.7 vs 1.1 eV)
  - Higher density (5.32 vs. 2.33 g/cm^3) and higher Z (32 vs. 14)
  - Lower impurity (10^9 vs 10^{12} cm^{-3}) allows much larger volumes to be depleted
- 1962: Pell (LBL) produces first compensated Ge(Li) detector
  - Drawbacks: limited volume, must **always** be kept at LN_2 temperatures
- 1970’s: HPGe replaces Ge(Li)
  - Improved purity (zone refining), improved crystal growth methods (Czochralski process)
- 1990’s: Large-volume HPGe
  - >800 cm^3
  - Impurity conc O(10^9 cm^{-3}) = purest commercially available material on earth!



General Remarks

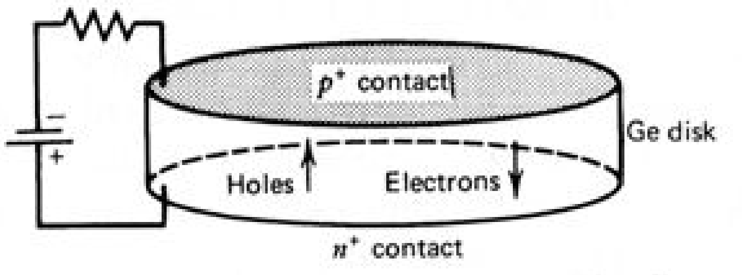
- HPGe and Si detectors are the “gold-standard” in many applications such as electron spectroscopy (Si) and gamma-ray spectroscopy (HPGe)
  - Excellent energy resolution
    - Statistics of charge-carrier production
  - High density (solid state)
  - Excellent charge carrier collection properties
    - High mobility and lifetimes for both electrons and holes
  - Very good timing characteristics
    - Design dependent, but influenced by high carrier mobility



Ag-108m & Ag-110m. Knoll 12.4

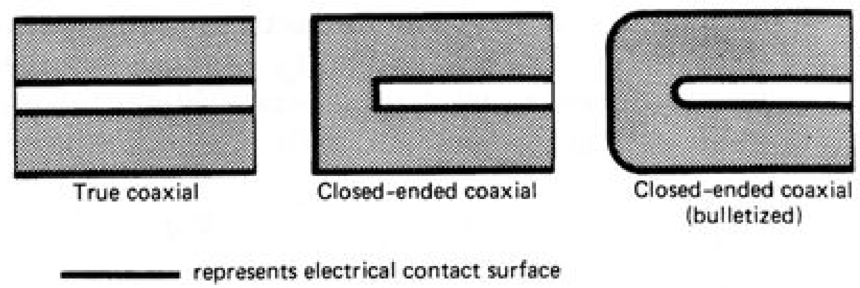
HPGe Detector Configurations

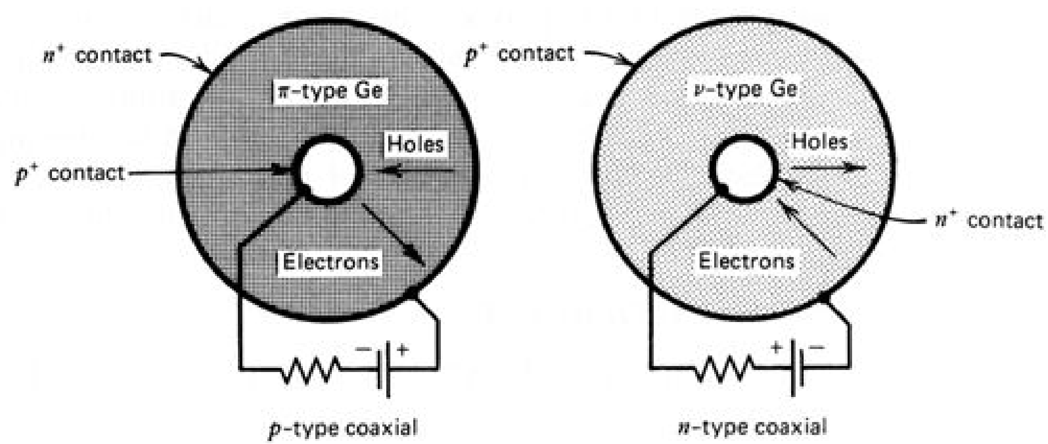
- Planar configuration
  - Limited volume



- Bulk material can be n-type or p-type
- Traditional contacts
  - n^+ by Li diffusion (~O(100μm) thick)
  - p^+ by boron implantation (<1μm thick)
- Modern contacts: amorphous semiconductor (e.g. α-Ge)
  - Blocking contact for both carrier types

- Coaxial detectors
  - Large volume

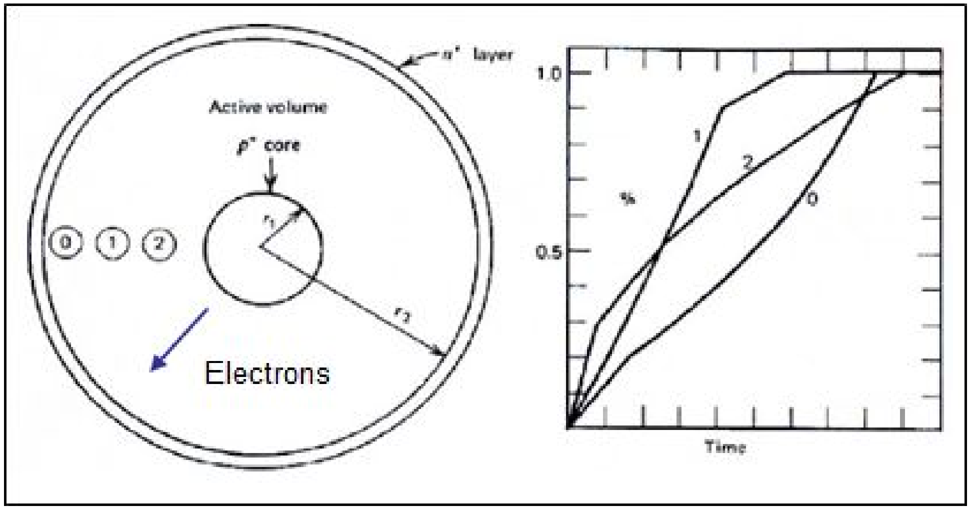




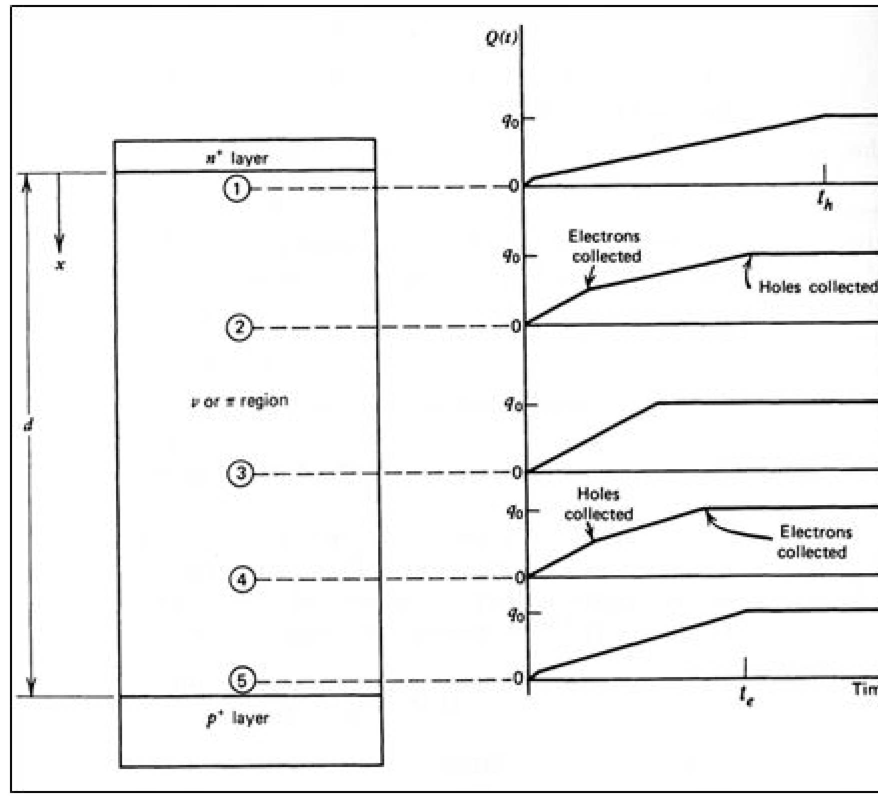
Signal Shapes in HPGe Detectors

- Signal induction process → Signal shape depends on interaction position!

Coaxial Geometry

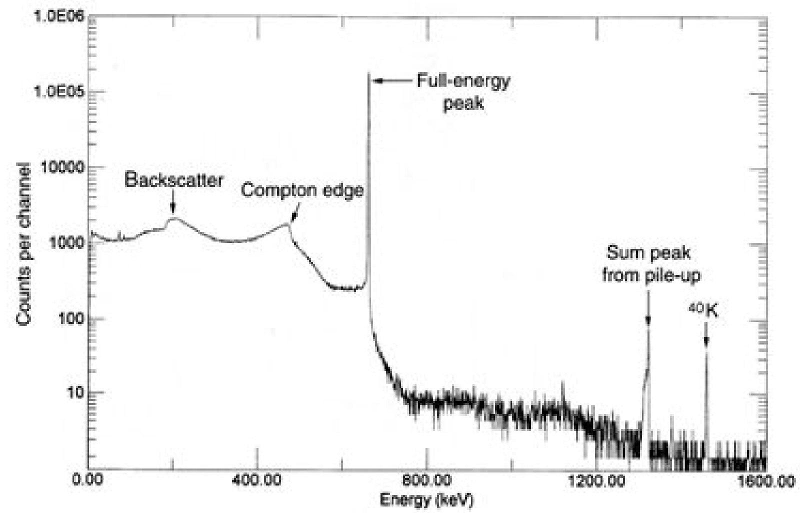


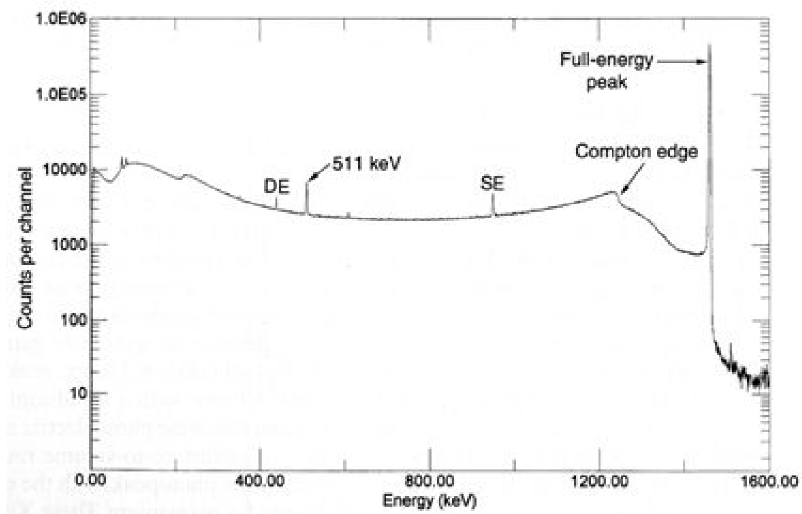
Planar Geometry



Gamma-Ray Energy Spectrum in HPGe

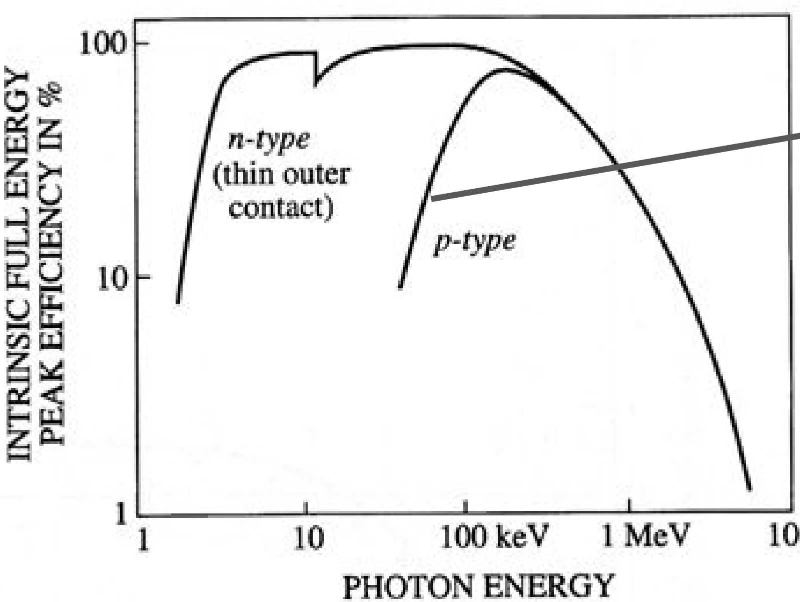
- Features based on various gamma-ray interaction mechanisms (coupled to detector geometry)
  - Full energy peak
    - Last interaction must be PE abs.
  - Features due to Compton scattering
    - Compton continuum, Compton Edge, Compton “valley”
    - Backscatter peak
  - Features from pair production
    - Escape peaks (single, double)
- “Good” coaxial detector
  - Ener. Res. < 0.2% @ > 1 MeV

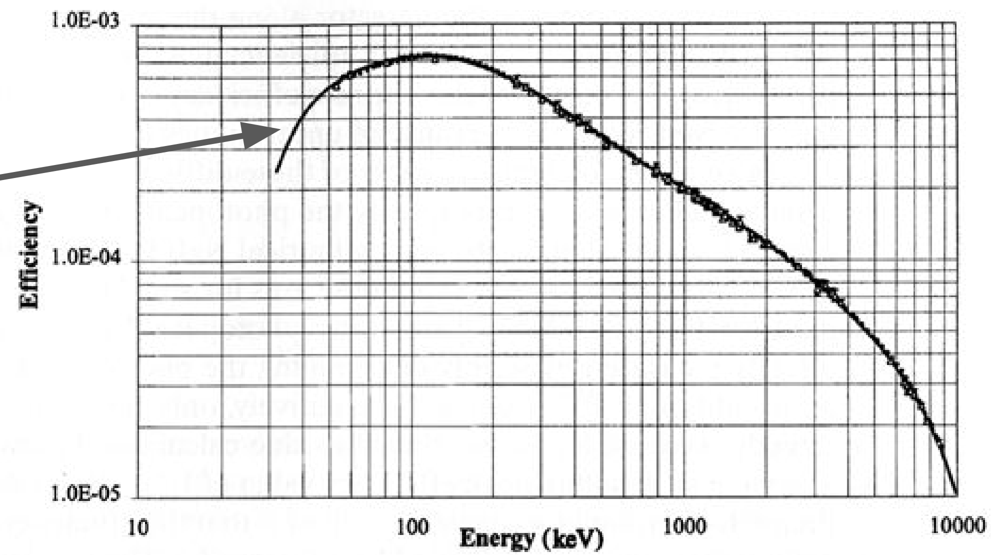




HPGe Detector Efficiency

- Absolute full-energy (peak) efficiency = (Counts in photopeak) / (number of emitted gamma rays)
- Intrinsic full-energy (peak) efficiency = (Counts in photopeak) / (number of emitted gamma rays incident on the detector)
- Relative full-energy (peak) efficiency = efficiency at 1332 keV (^{60}Co source) relative to 3”x3” cylindrical NaI(Tl) crystal at 25 cm distance.



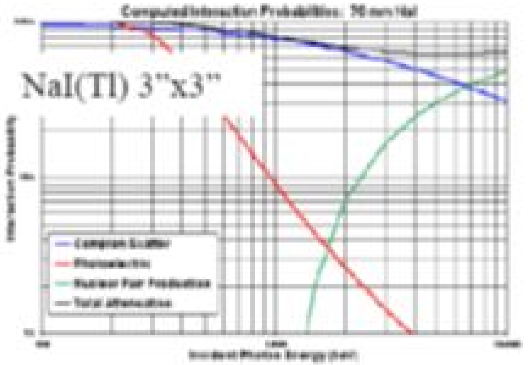


Absolute peak efficiency for 25% p-type HPGe detector at 25 cm distance

Historical Note about HPGe Efficiency

Detector efficiency is often quoted in percent of that for a 3”x3” NaI(Tl) detector (for historical reasons) and generally for the 1332.5 keV line from ^{60}Co.

NaI(Tl) 3"x3"



$$\varepsilon_{geo} = \frac{1}{2}\left(1 - \frac{d}{\sqrt{d^2 + a^2}}\right) \qquad d = 25cm, a = 1.5''$$

$$\varepsilon_{geo} = 5.707x10^{-3}$$

$$\varepsilon_{total}(NaI) = 1.2x10^{-3} \rightarrow \varepsilon_{\text{intrinsic}}(NaI) = 0.210$$