Detector Design Principles

Ionization (charge separation) Detectors

- Ionization chambers (solid-state and gas)
- Proportional counters
- Avalanche counters
- Geiger-Müller counters
- Cloud/bubble chambers
- Track detectors

Scintillation Detectors

- Phosphorescence counters
- Fluorescence counters (inorganic solid crystal scintillators, organic solid and liquid scintillators)
- Čherenkov counters

Associated Techniques

- Photo sensors and multipliers
- Charged-coupled devices
- Electronic pulse shape analysis
- Processing/acquisition electronics

Detection Of Ionizing Radiation

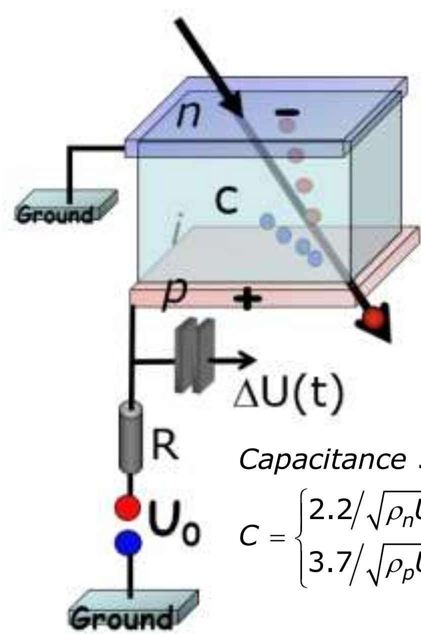
Solid-State Ionization Chambers

Ionization Chambers (Solid-State and Gas Medium)

General principle: Radiation dissipates energy ***E*** via production of electron-ion (e^-, h^+) pairs in a medium enclosed between electrodes (Anode, Cathode). Electronic ***E*** signal picked up at A or C.

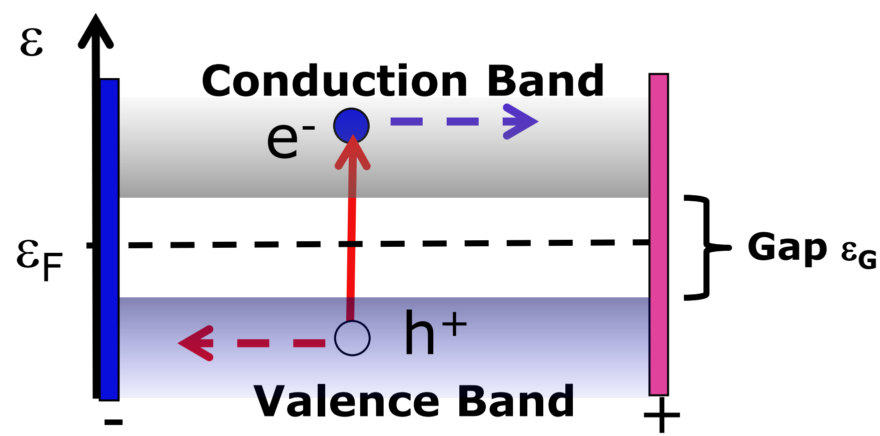
Gas volume between capacitor *C* electrodes.
Energy ***E*** → $\boldsymbol{N}_{\text{ion pairs}} = E/\varepsilon_{ip}$(gas)

Semiconductor *n-, p-, i-types Si, Ge, GaAs,..*
Band structure of solids VB gap CB.



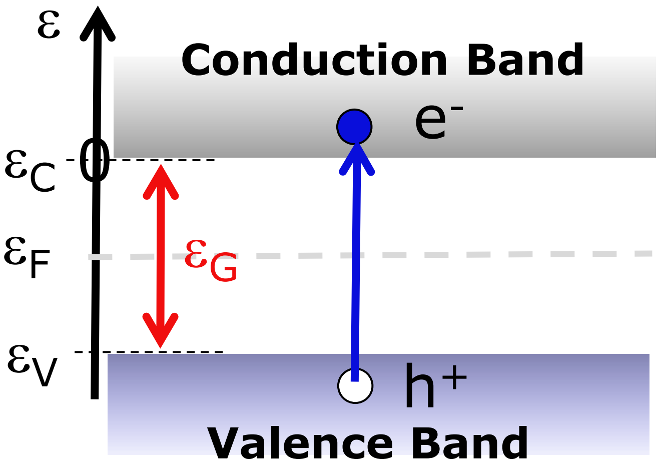
Capacitance Si :

$$C = \begin{cases} 2.2/\sqrt{\rho_n U_0} \;\; pF/mm^2 \\ 3.7/\sqrt{\rho_p U_0} \;\; pF/mm^2 \end{cases}$$



Ionization lifts e^- up to CB, leaves hole h^+ in VB → free charge carriers, produce Δ ***U(t)~E***.

Particles and Holes in Pure Semi-Conductors



$$e^- : f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

$$h^+ : f_h(\varepsilon) = \left[1 + \exp\left(\frac{-\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

Small gaps ε_G (Ge) → high thermal currents. Reduce by cooling.

Fermi gas of electrons (and holes)
Fermion statistics @ temperature ***T***:

n_e, n_h = # of occupied e^- or h^+ states

$f_e, f_h \le 1$ occupation numbers

$$n_e(\varepsilon) = \frac{(2m)^{2/3} V}{2\pi^2 \hbar^3} \sqrt{\varepsilon} \cdot f_e(\varepsilon) \quad V = volume$$

$$n_h(\varepsilon) = \frac{(2m)^{2/3} V}{2\pi^2 \hbar^3} \sqrt{|\varepsilon|} \cdot f_h(\varepsilon) \quad n_e = n_h !!$$

$$\varepsilon_F = \varepsilon_C - \varepsilon_G/2 = -\varepsilon_G/2 \quad for\ \varepsilon_C := 0$$

$$f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon - \varepsilon_F}{kT}\right)\right]^{-1}$$

$$\xrightarrow[kT \approx 25meV \ll \varepsilon_G]{} \exp\left(-\frac{\varepsilon + \varepsilon_G/2}{kT}\right)$$

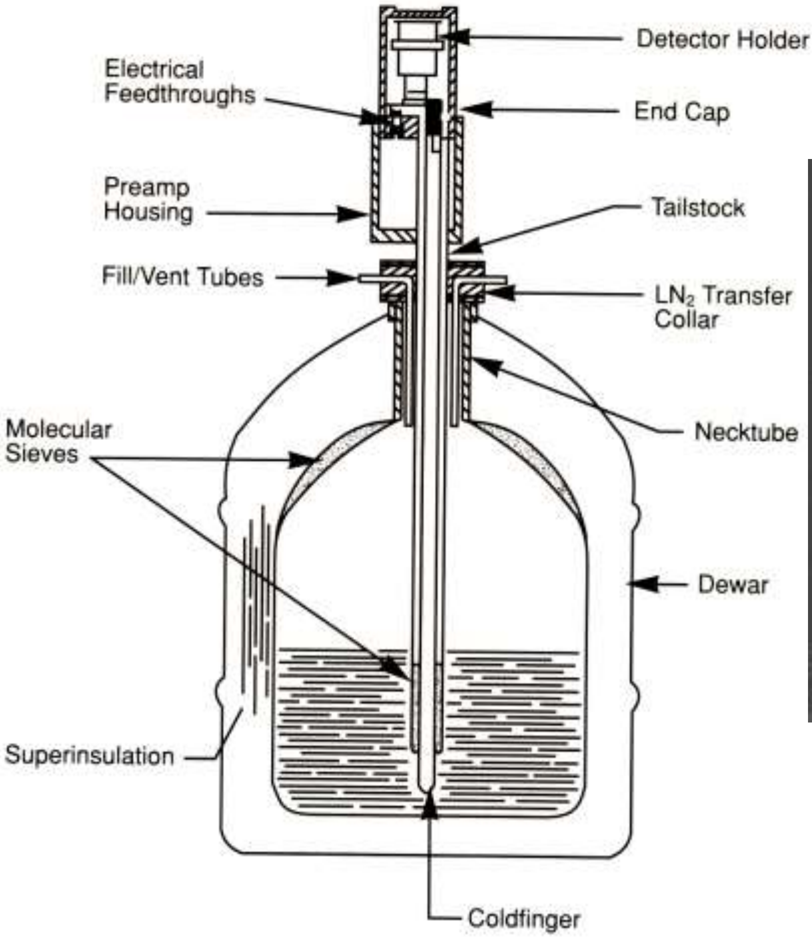
$$\left\langle n_e^2 \right\rangle = \left\langle n_e n_h \right\rangle = \left(\frac{(2m)^{2/3} V}{2\pi^2 \hbar^3}\right)^2 \left\langle \varepsilon \right\rangle \exp\left(-\frac{\varepsilon_G}{kT}\right)$$

$$\left\langle n_e \right\rangle_{rms} \sim \exp\left(-\frac{\varepsilon_G}{2kT}\right) \propto \textit{noise generating conductivity at } T$$

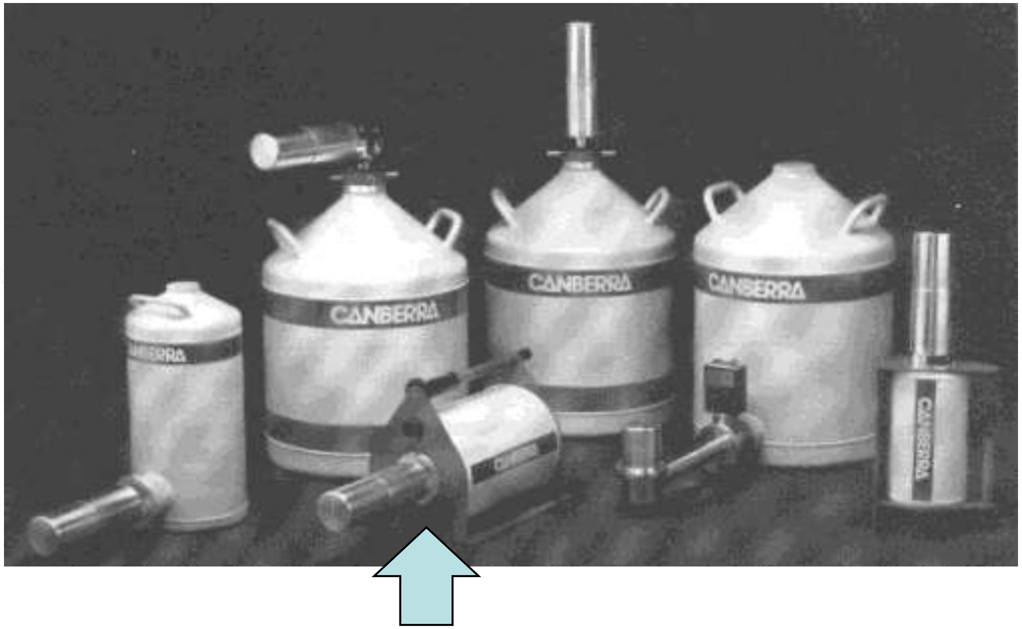
Hyper-Pure Germanium (HpGe) γ–ray Detectors

Hyper-pure Ge detectors for γ-rays: High σ_{photo} , small gap → high efficiency & high resolution. Cool to -77°C (LN_2) because of small gap E_G.

Ge Cryostate (Canberra)

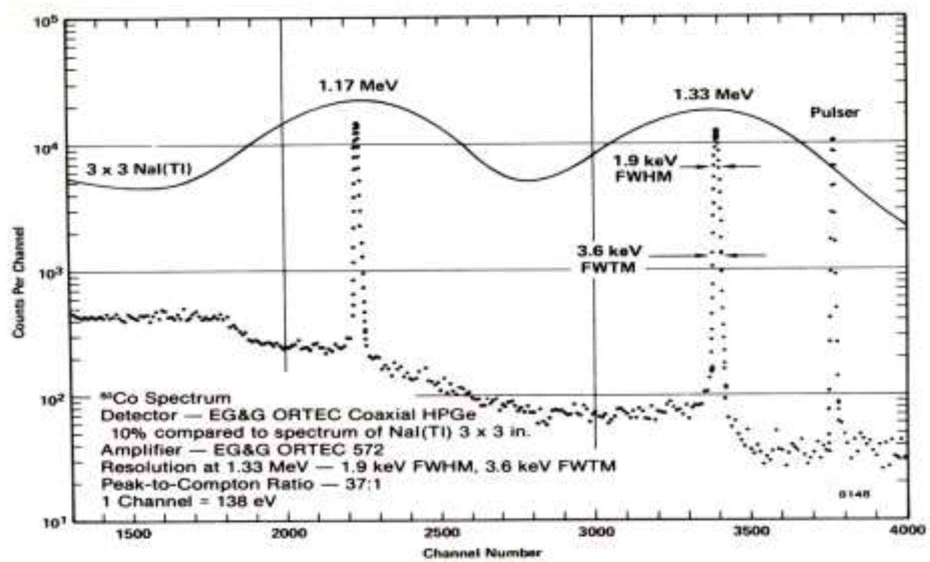


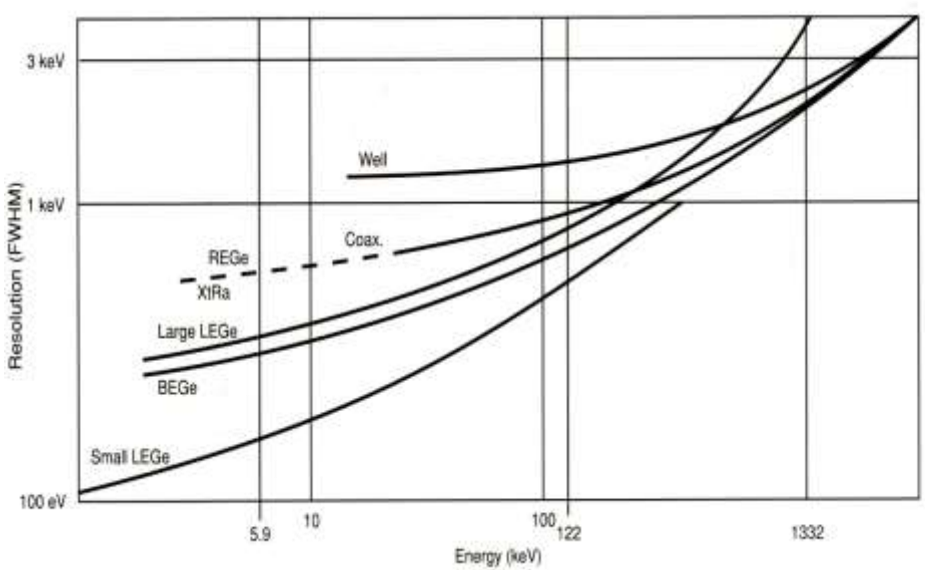
Ge cryostate geometries (Canberra)



Type used in large numbers in NP arrays with anti-Compton shield detectors.

Properties of Ge Detectors: Energy Resolution





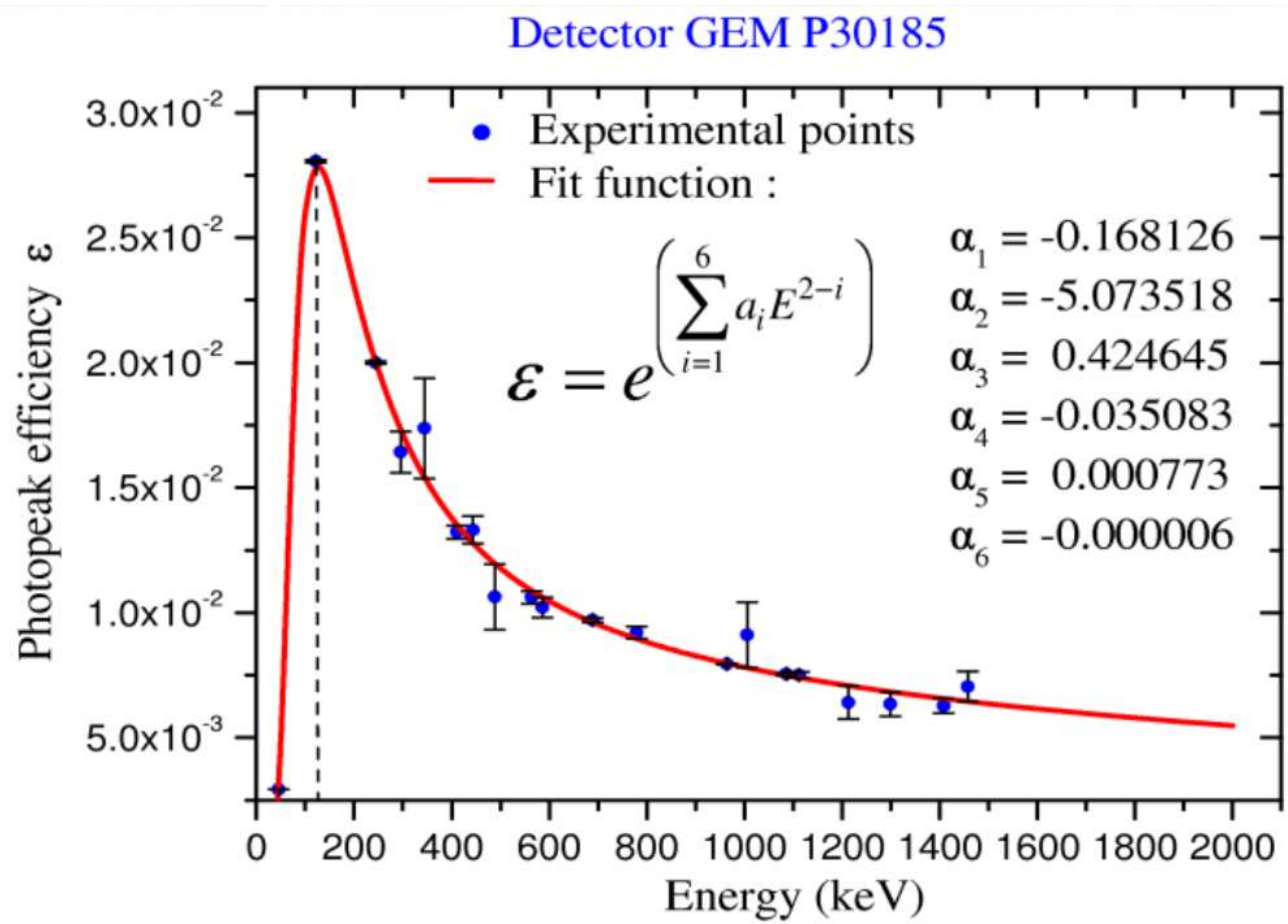
Superior energy resolution, compared to NaI

$\Delta E_\gamma \sim 0.5\text{keV} \ @\ E_\gamma = 100\text{keV}$

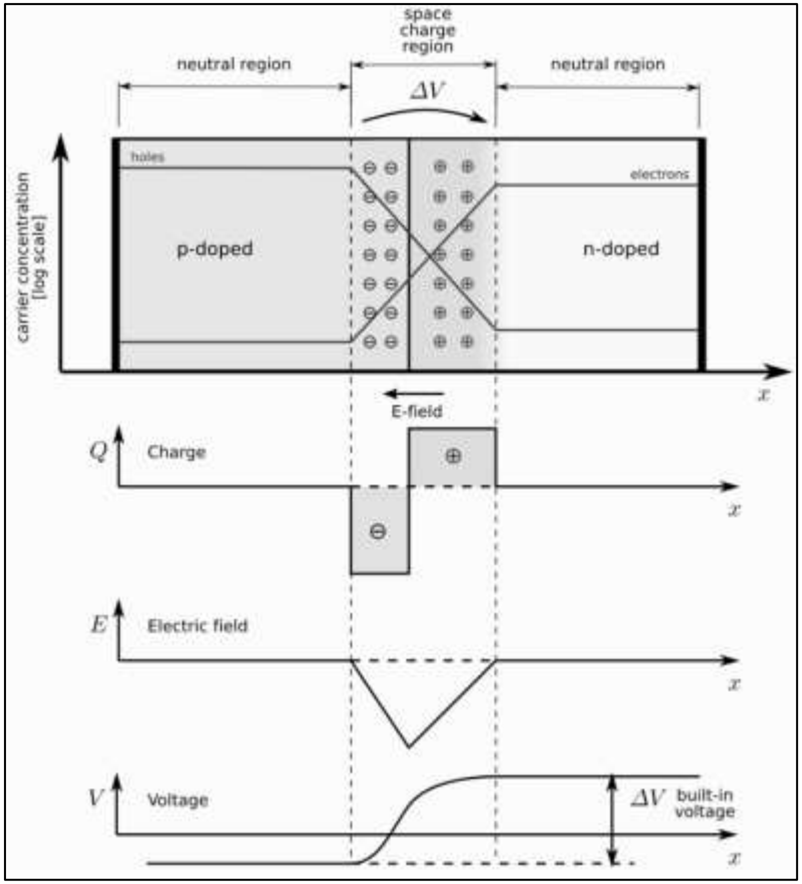
Higher peak/Compton ratios

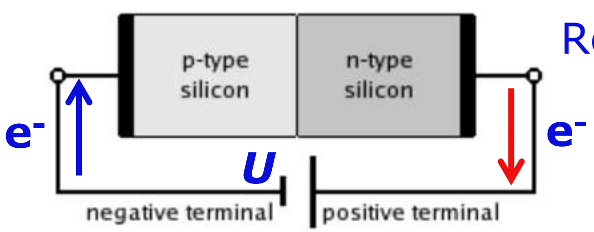
Size=dependent mall detection efficiencies of Ge detectors $\varepsilon \sim 10\%$ →solution: bundle in 4π-arrays *GammaSphere,Greta EuroGam, Tessa,…*

Typical Energy Resolution of a HPGe Detector



Semiconductor Junctions and Barriers





Reverse bias

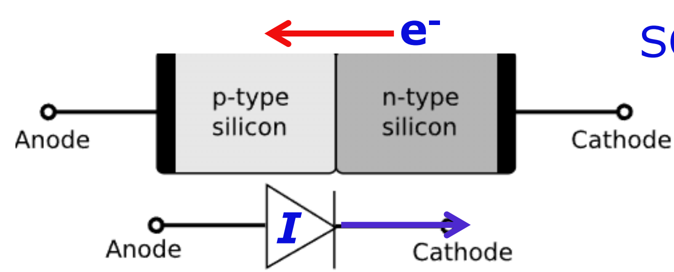
Need detector for rad-induced charges
→ otherwise, no free carriers allowed.

Difficult to make: perfect *i*-type (intrinsic) Si = chemical Group IV.

Trick: Deplete part of combination (SC junction)
n-type Si: by doping with *Li or* Group V e^- donor atoms (*P, Sb, As*),
p-type Si: by doping with Group III e^- acceptor atoms *(B,Al,..)*.

Junctions diffuse donors and acceptors into Si bloc from different ends.
Diffusion at interface → e^-/h^+ annihilation → space charge=zone depleted of carriers

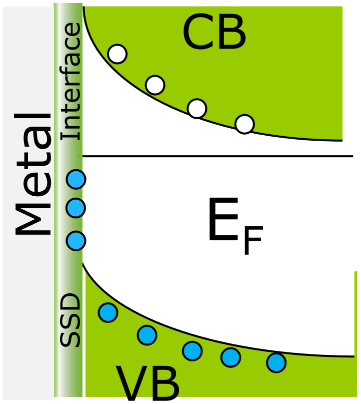
SC Diode



Electrons move easily through the junction *from n to p but not from p to n*, and the reverse is true for holes.

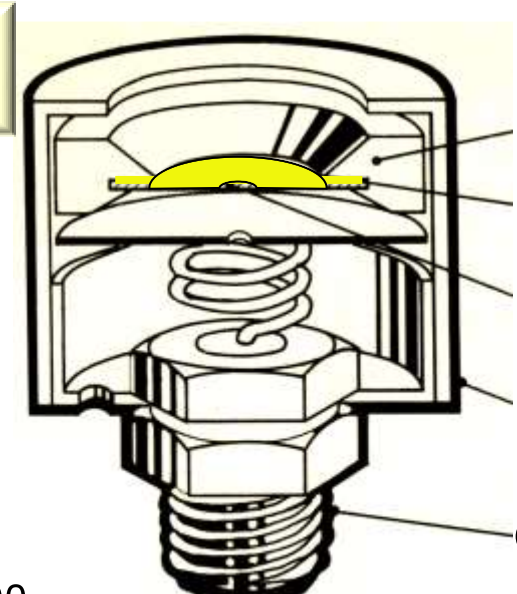
Surface Barrier Detectors

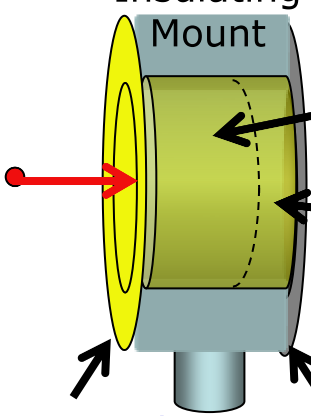
Semiconductor/ Metal Junction



Thin metal film on Si surface produces space charge (SSD surface states) = effective barrier (contact potential) → depleted zone with no free charges. Apply reverse bias to increase depletion depth. Free charge carriers created from incident radiation → ΔV signal

ORTEC HI detector





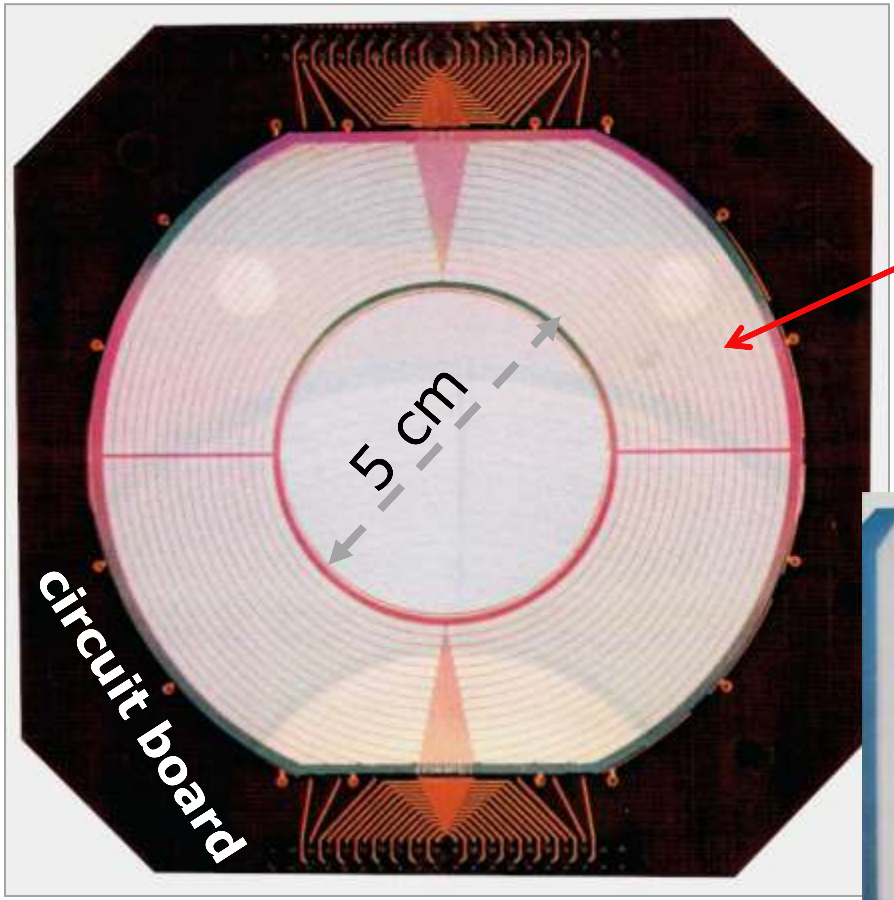
Ground
Front: Au

+Bias
Back: Al

evaporated electrodes

Possible: electrical depletion depth ~ 100μ
dead layer $d_d \leq 1\mu$
$V \sim 0.5V/\mu$
Over-bias reduces d_d

Si-Strip Detectors



Typically (300-500)μ thick.
Fully depleted, thin dead layer.

Annular:
16 bins ("strips") in polar (θ) ,
4 in azimuth (ϕ) (Micron Ltd.)

Rectangular with 7 strips