# Detection Of Ionizing Radiation

# Agenda

- Detection of ionizing radiation (photons and charged particles)
  - Solid-state detectors (Ge, Si)
  - Gas amplification detectors (Ionization chamber, proportional counter, Geiger counter)

Reading: Knoll Ch.12.I-12.IV

- Phenomenological model of matter ionization by particles
  - Electronic stopping
  - Bethe-Bloch Formula
  - Examples
  - Range and specific ionization
  - Stopping power curves, energy loss in thin foils

Reading: Knoll Ch. 6.I-6.V

- Spurious response of gas counters to photons

# Detector Design Principles

## Ionization (charge separation) Detectors

- Ionization chambers (solid-state and gas)
- Gas Amplification Dets
  - Proportional counters
  - Avalanche counters
  - Geiger-Müller counters
- Cloud/bubble chambers
- Solid track detectors

## Scintillation Detectors

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

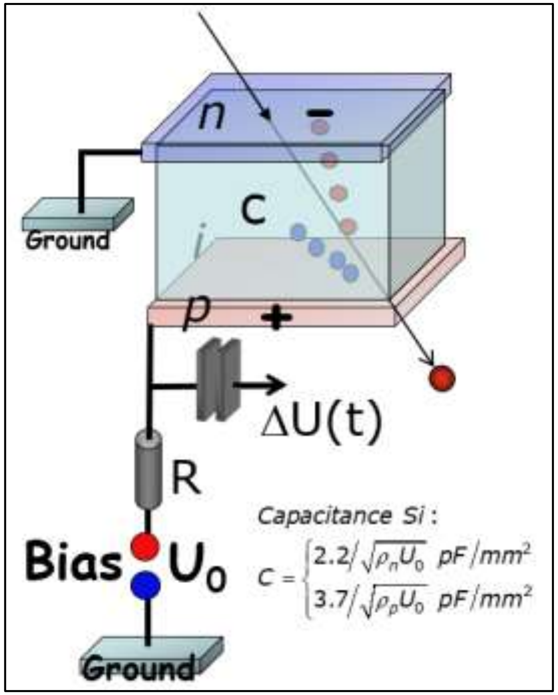
## Associated Techniques

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

# 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.

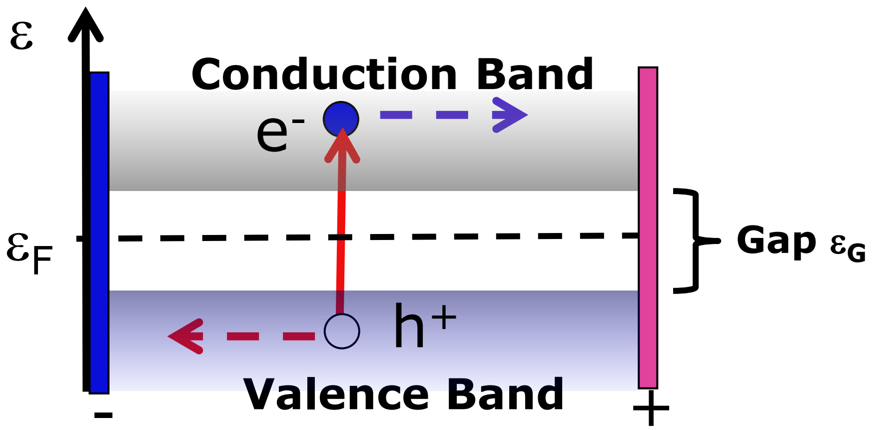
Gas volume between capacitor *C* electrodes.
Energy ***E*** → $\boldsymbol{N}_{\text{ion pairs}}=E/\varepsilon_{ip}$(gas)



Capacitance Si :

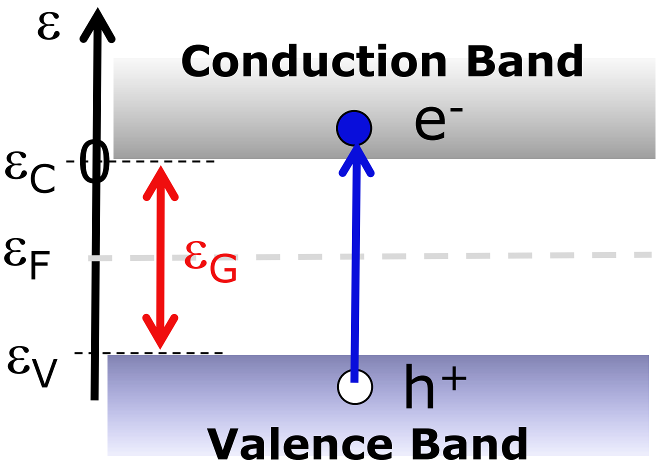
$$C=\begin{cases}2.2/\sqrt{\rho_n U_0}\ pF/mm^2\\ 3.7/\sqrt{\rho_p U_0}\ pF/mm^2\end{cases}$$

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



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

# Particles and Holes in Hyper Pure Semi-Conductors



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

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

$f_e, f_h \leq 1$ occupation numbers

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

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

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

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

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

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

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

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

Small gaps $\varepsilon_G$ (Ge) → high thermal currents. Reduce by cooling.

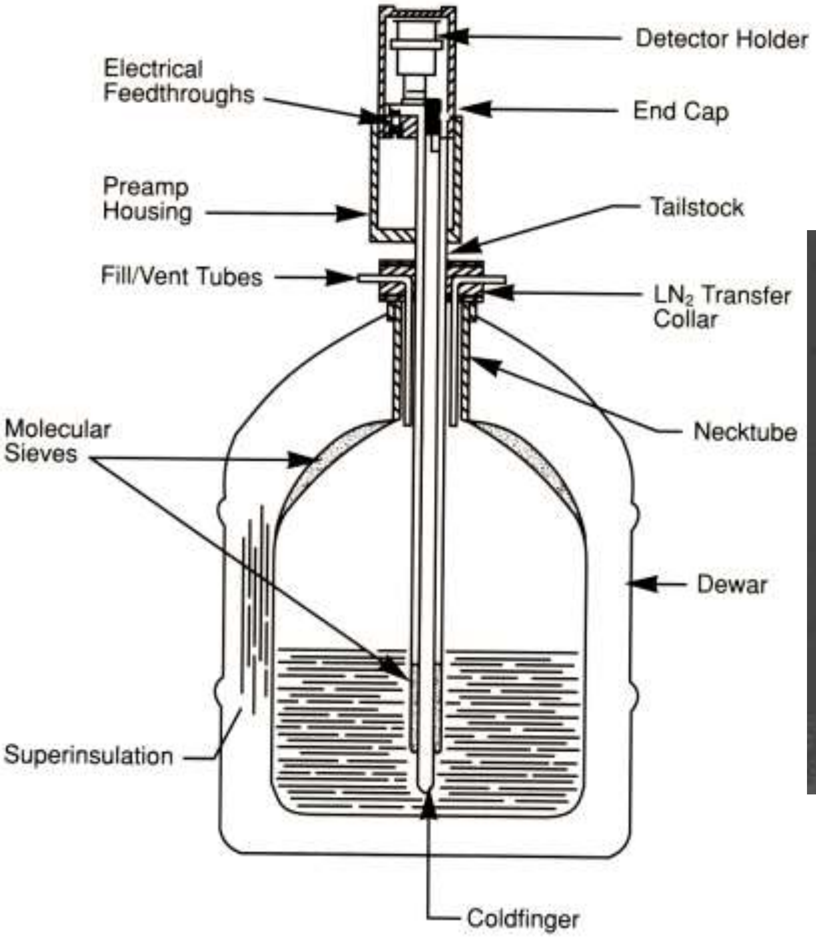
$$\boxed{\langle n_e \rangle_{rms} \sim \exp\left(-\frac{\varepsilon_G}{2kT}\right)} \quad \propto$$

*noise generating conductivity at T*

# Hyperpure (Intrinsic) Ge $\gamma$–ray Detectors

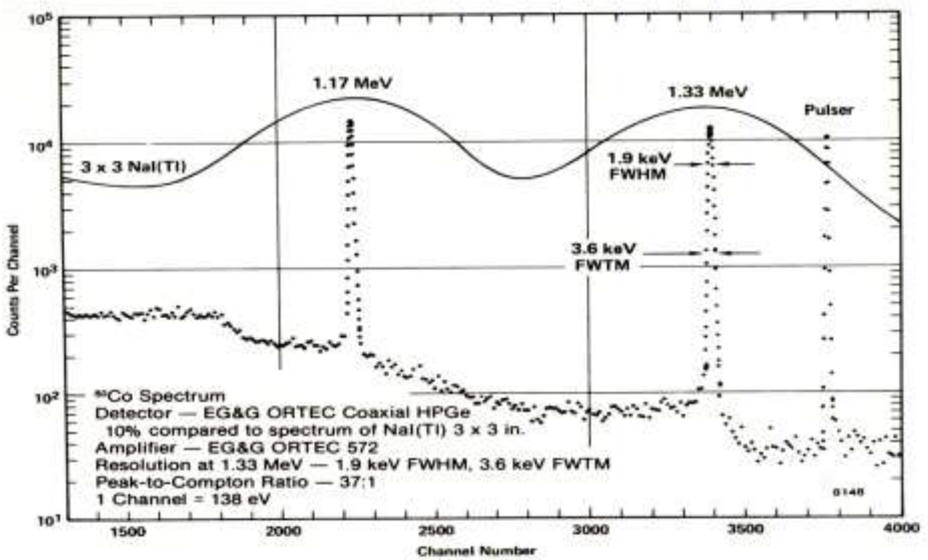
Hyper-pure Ge detectors for $\gamma$-rays use because of small gap $E_G$, cool to -77$^{o}$C ($LN_2$). Simple band structure.

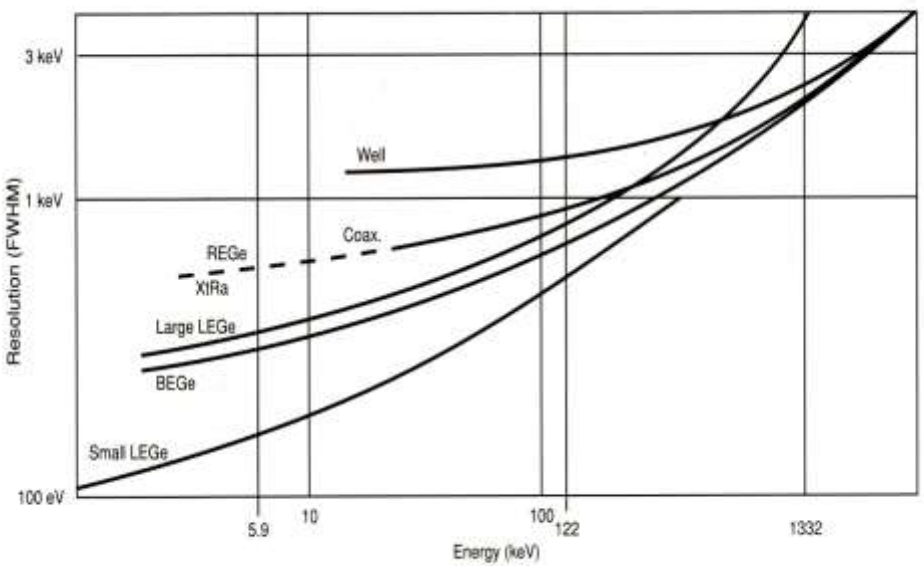
**Ge Cryostate (Canberra)**



**Ge cryostate geometries (Canberra)**

# Properties of Ge Detectors: Energy Resolution





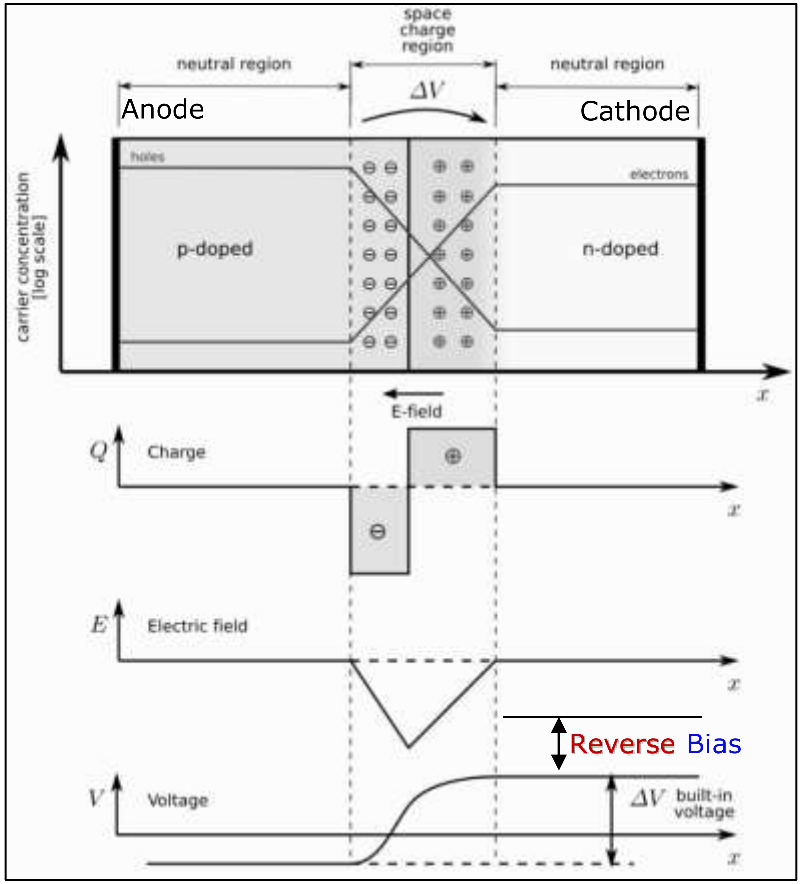
Superior energy resolution, compared to NaI

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

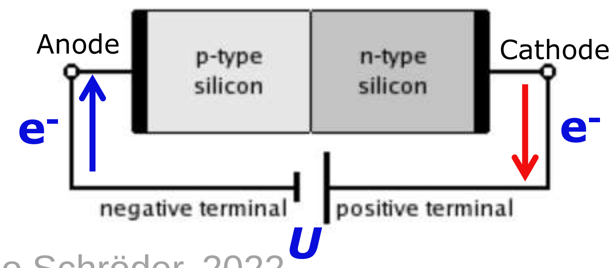
Higher peak/Compton ratios

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

# Alternative: Semiconductor Junctions and Barriers



Reverse Bias: *I≈0*



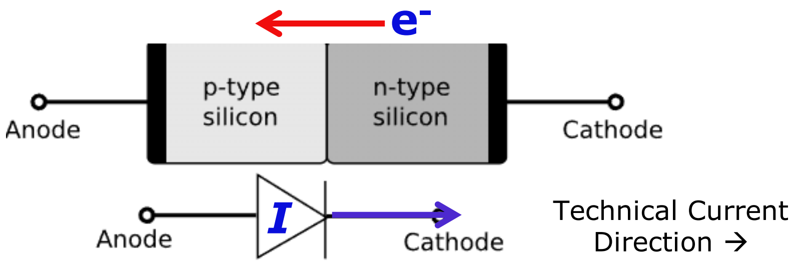
Need detector for rad-induced charges
→ otherwise, no free carriers allowed.

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

**Trick**: to make fully depleted Si→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 → interface → e$^-$/h$^+$ annihilation → space charge= depleted zone

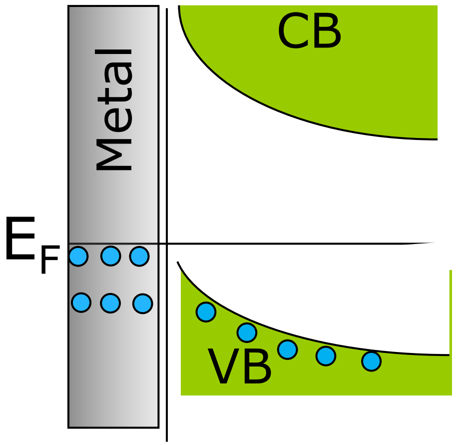
**Semiconductor Diode**



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

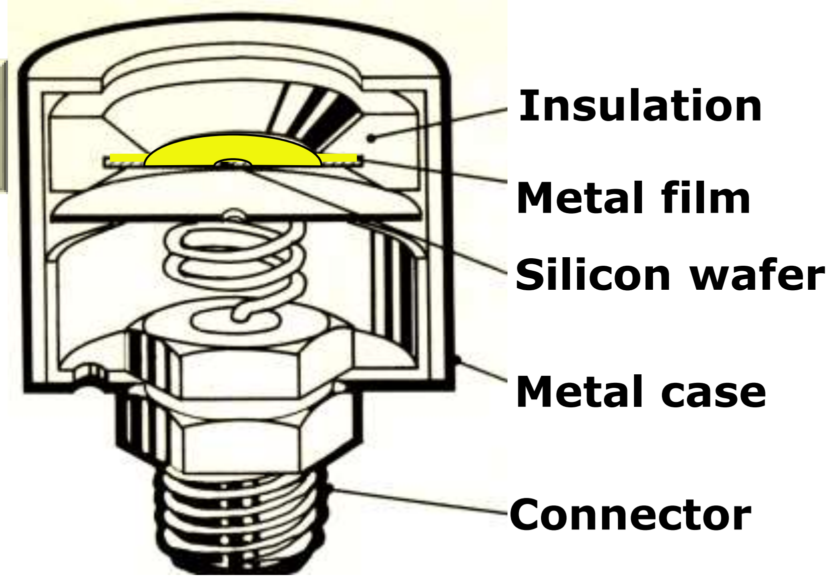
# Surface Barrier Detectors

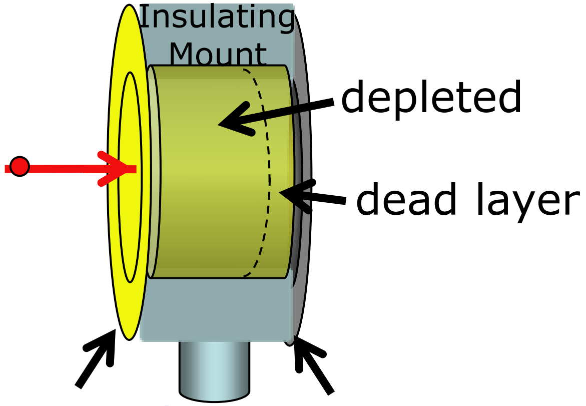
Semiconductor/ Metal Junction



Different Fermi energies adjust to on contact.
Thin metal film on Si surface produces space charge, an effective barrier (contact potential) and depleted zone free of carriers.
Apply reverse bias to increase depletion depth.

ORTEC
HI detector





Ground +Bias
Front: Au Back: Al
evaporated electrodes

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

Used in medium-precision charged-particle spectroscopy (α particles, β particles).

Next:

# Gas Amplification Counters