Semiconductor Radiation Detectors

22.104 Spring 2002

Outline

- Basic materials
- Electronic Properties
- Detector Efficiency
- Energy Resolution
- Noise
- Limitations

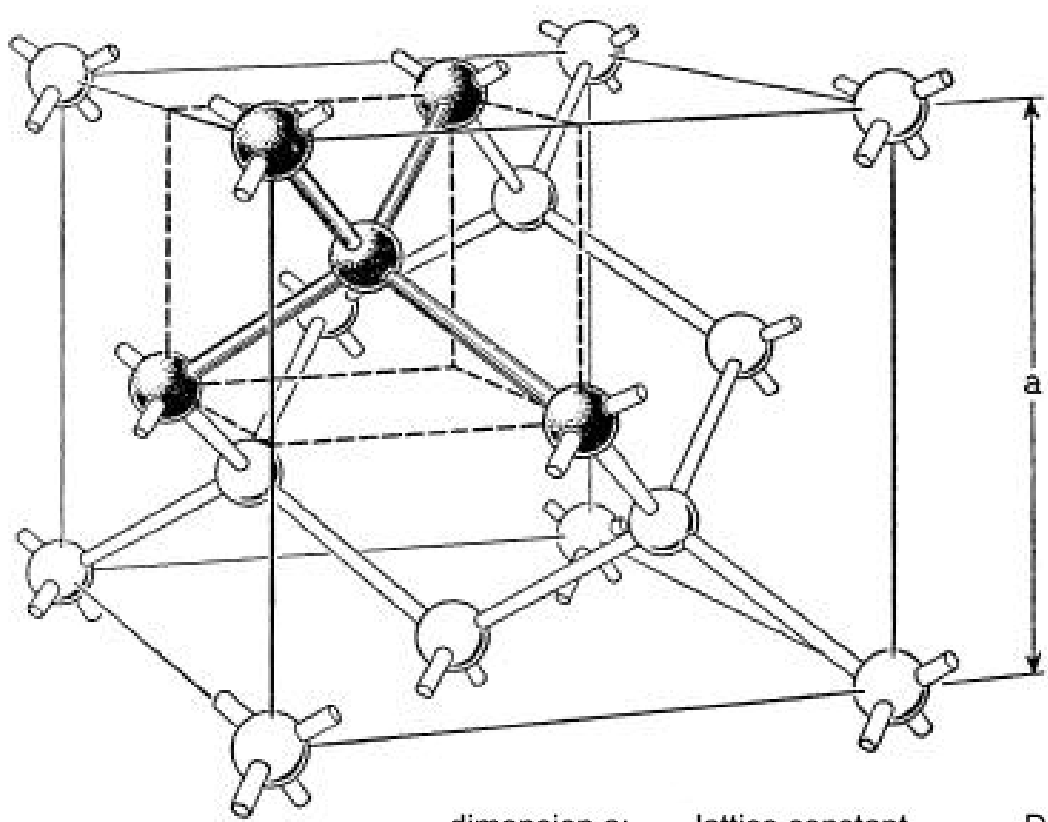
General Issues

- Sensitivity
- Detector Response
- Energy Resolution
- Response Function
- Response Time
- Detector Efficiency
- Dead Time

Basic Materials

- Ge
- Si
- CdTe
- HgI
- CdZnTe

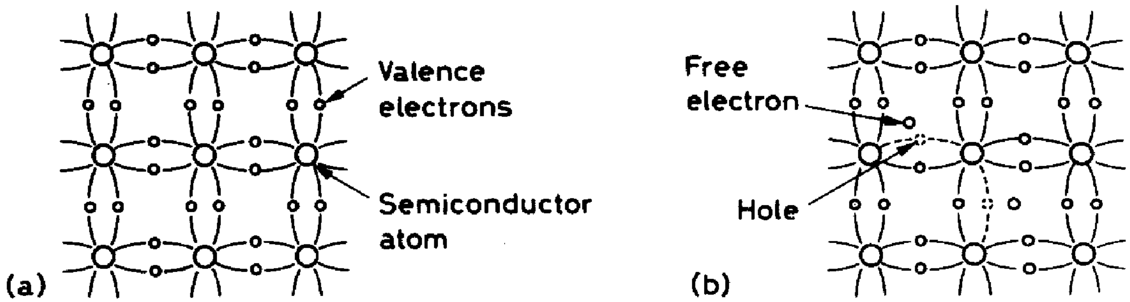
Crystal Structure of Ge and Si



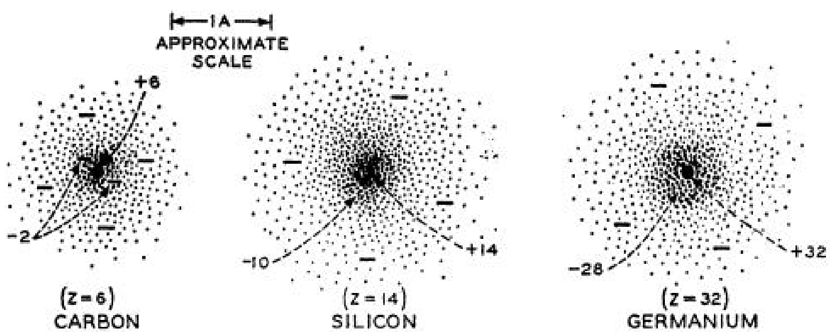
dimension a: lattice constant

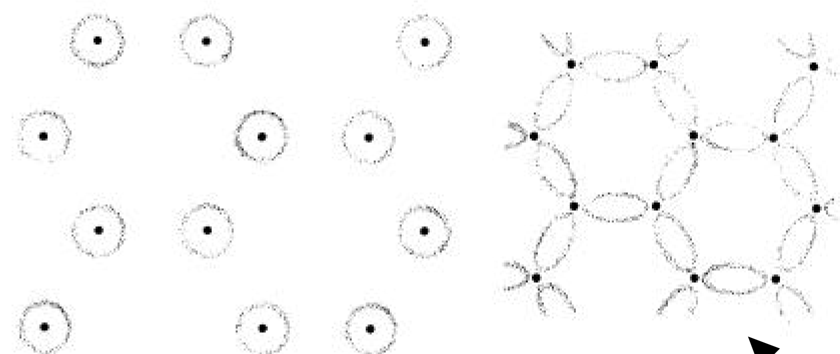
Diamond:	3.56 Å
Ge:	5.65 Å
Si:	5.43 Å

Electronic Structure



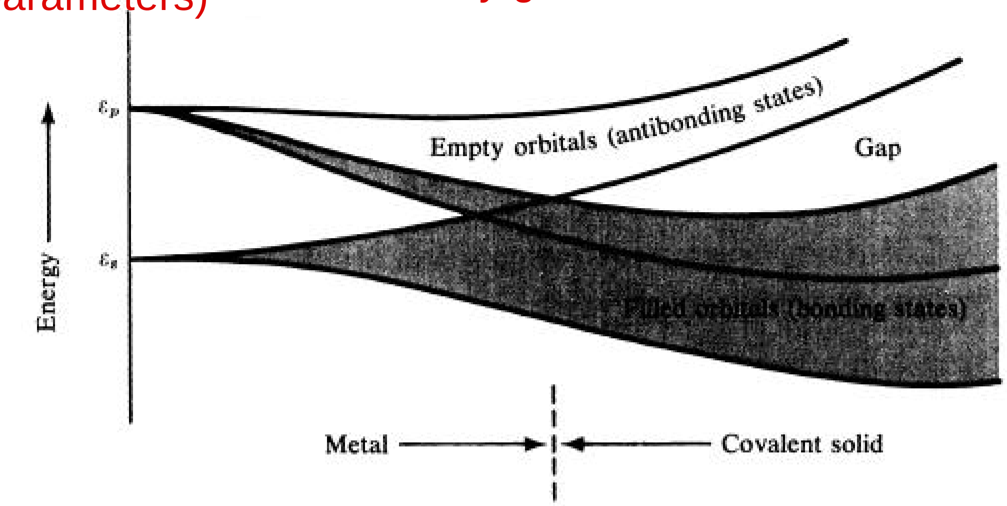
Energy band structure



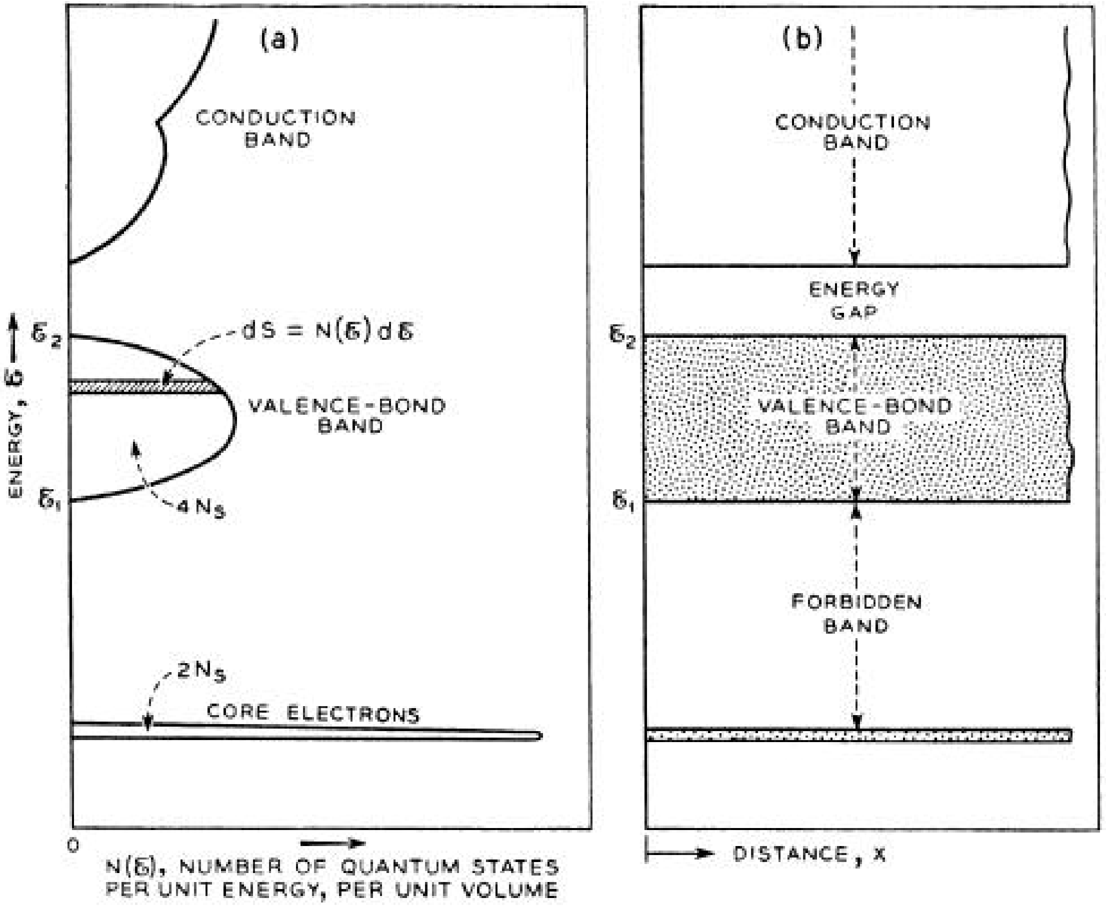


Wavefunctions of atoms
(comparable to lattice parameters)

When they get closer, discrete levels shift to form energy bands



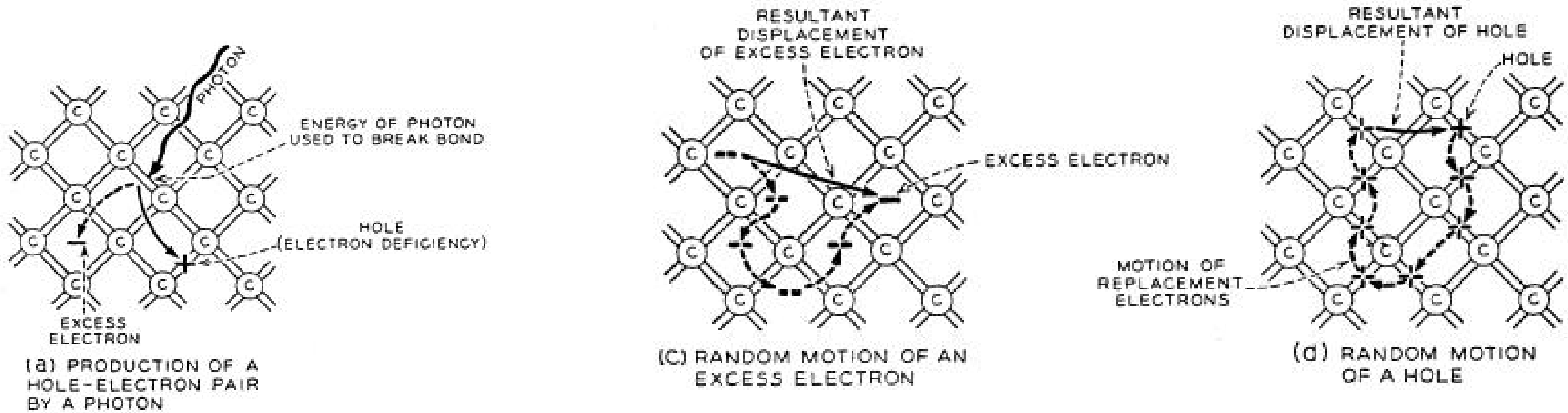
Energy Band Structure



Ge and Si Properties

	Si	Ge
Atomic number Z	14	32
Atomic weight A	28.1	72.6
Density [g/cm^2]	2.33	5.32
Dielectric constant (relative)	12	16
Intrinsic resistivity (300 K) [Ωcm]	230000	45
Energy gap (300 K) [eV]	1.1	0.7
Energy gap (0 K) [eV]	1.21	0.785
Electron mobility (300 K) [cm^2/Vs]	1350	3900
Hole mobility (300 K) [cm^2/Vs]	480	1900

Interaction with radiation



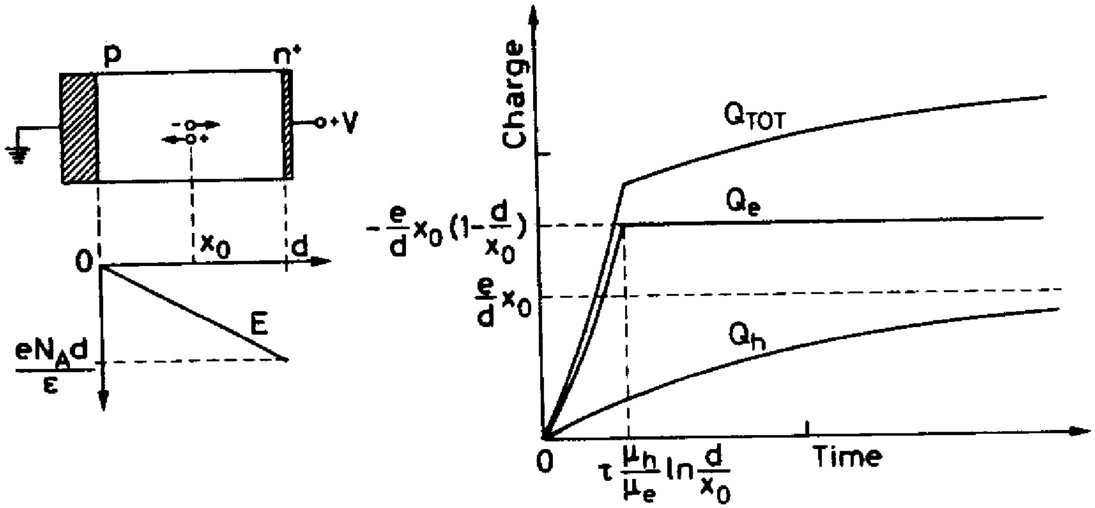
If a field is applied, no current flows since electrons can't pick up energy as there are no higher energy states in the valence band.

BUT

If a bond is broken, then this moves an electron into the conduction band and leaves a "hole" in the valence band.

Both the "hole" and the electron can now move under the influence of the field.

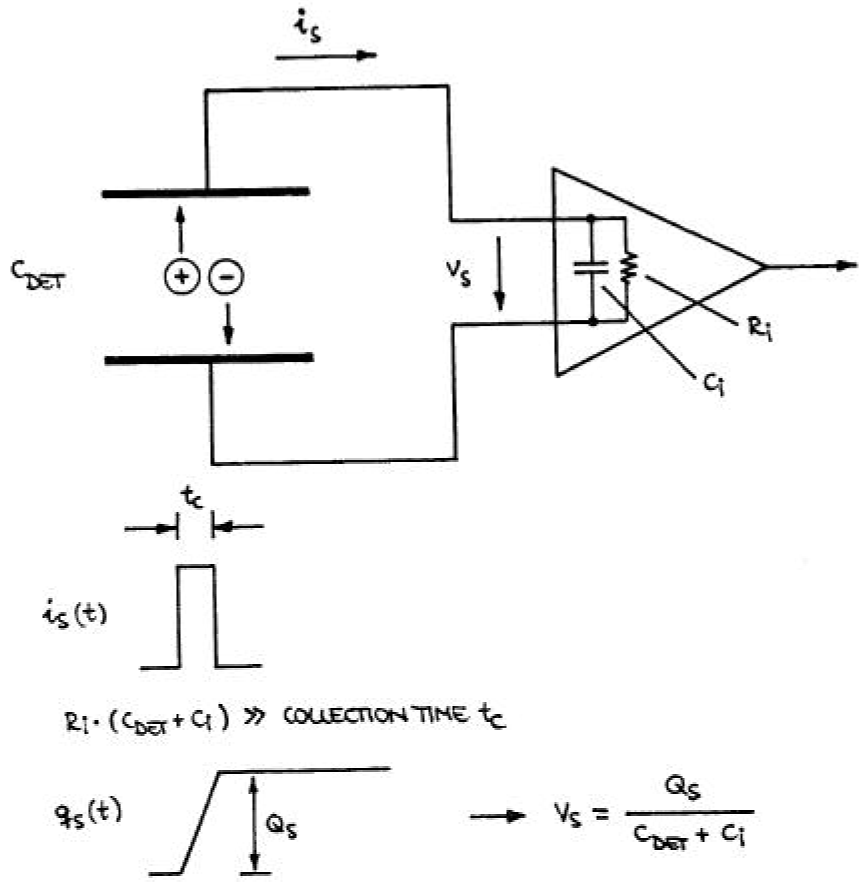
Time Development of Signals



Semiconductor Detectors

- **Semiconductor detectors are *Ionization Chambers***
  - **Detection volume with electric field**
  - **Energy deposited**
    - **+ and – charge pairs**
  - **Charges move in field**
    - **Current in external circuit**
- **Detection medium can be:**
  - **Solid**
  - **Liquid**
  - **Gas**

Electronic Signal Development



Relevant Material Properties

	gas	liquid	solid
density	low	moderate	high
atomic number Z	low	moderate	moderate
ionization energy ε_i	moderate	moderate	low
signal speed	moderate	moderate	fast

Desirable Material Properties

low ionization energy ⇒ 1. increased charge yield dq/dE

2. superior resolution

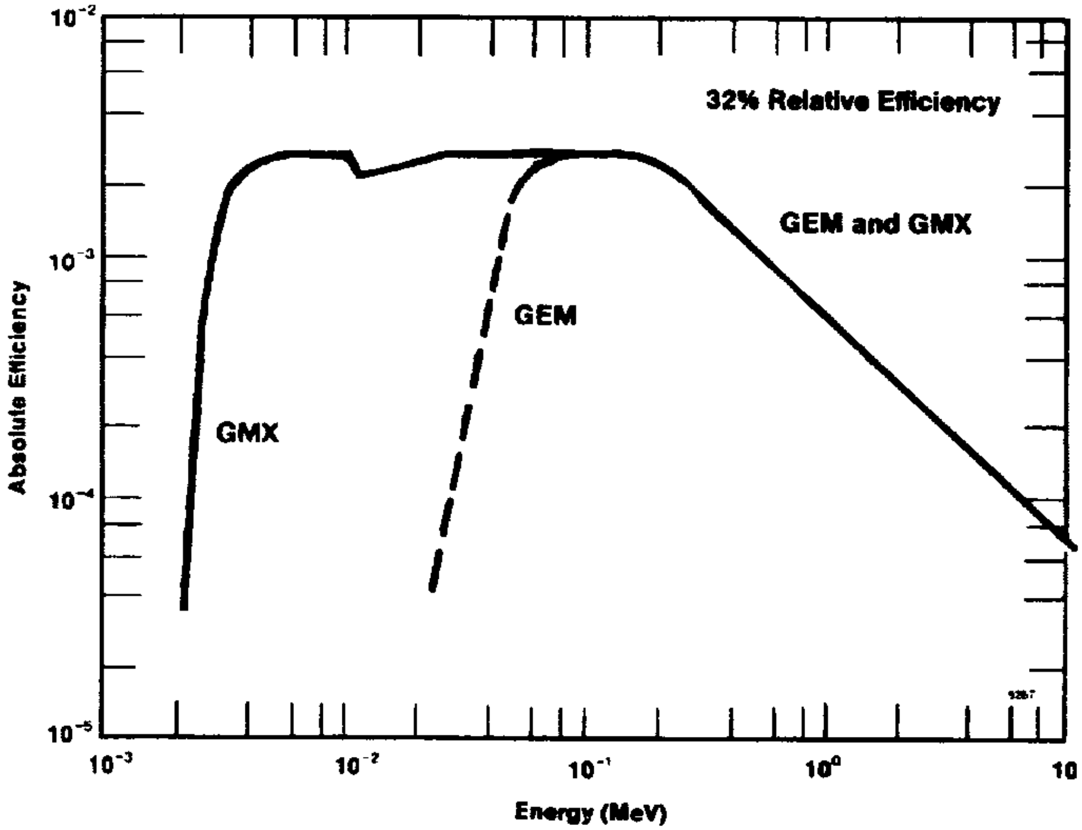
$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_i}} \propto \sqrt{\varepsilon_i}$$

high field in detection volume

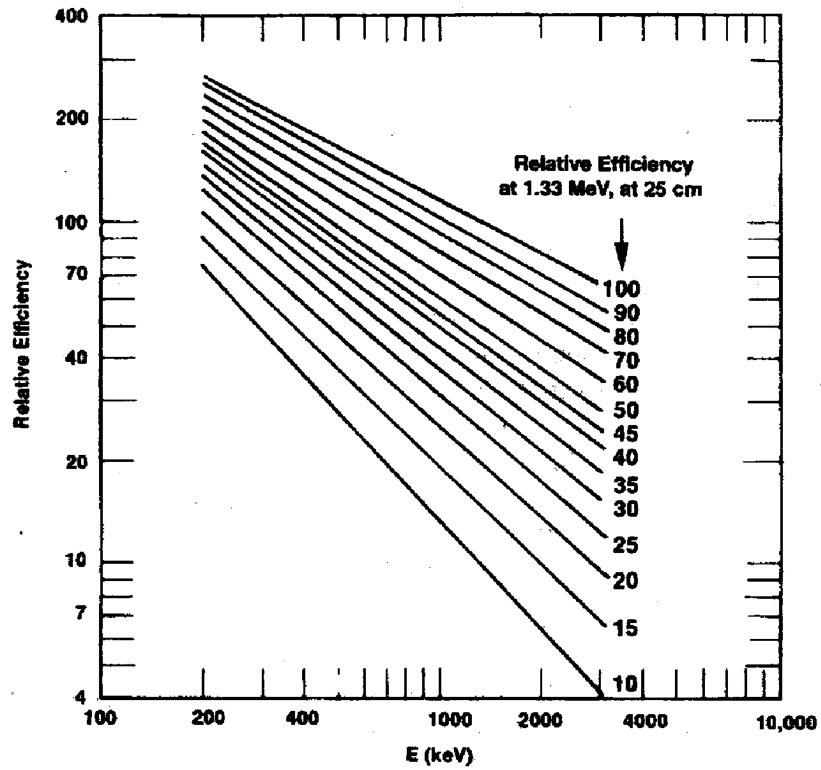
⇒ 1. fast response

2. improved charge collection efficiency (reduced trapping)

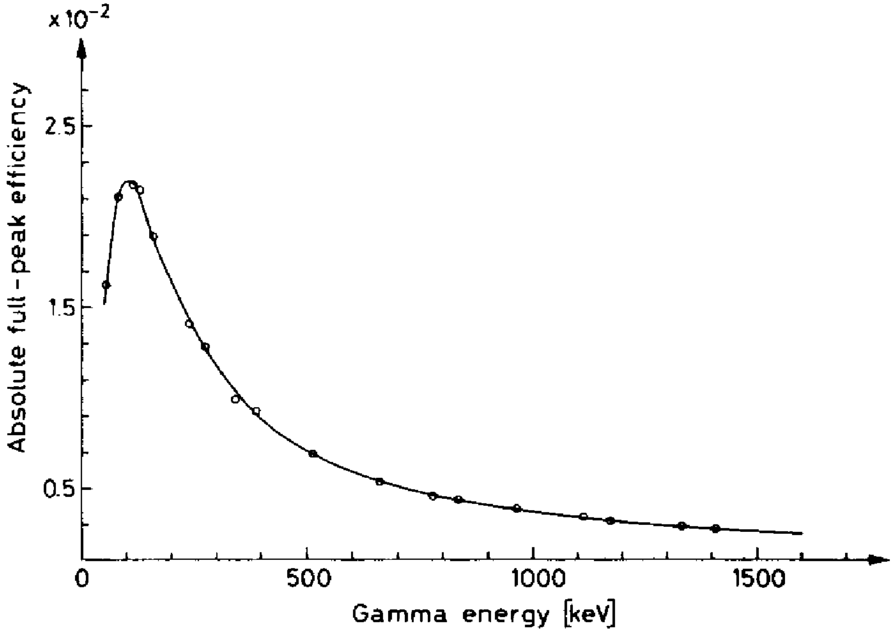
Absolute Efficiency



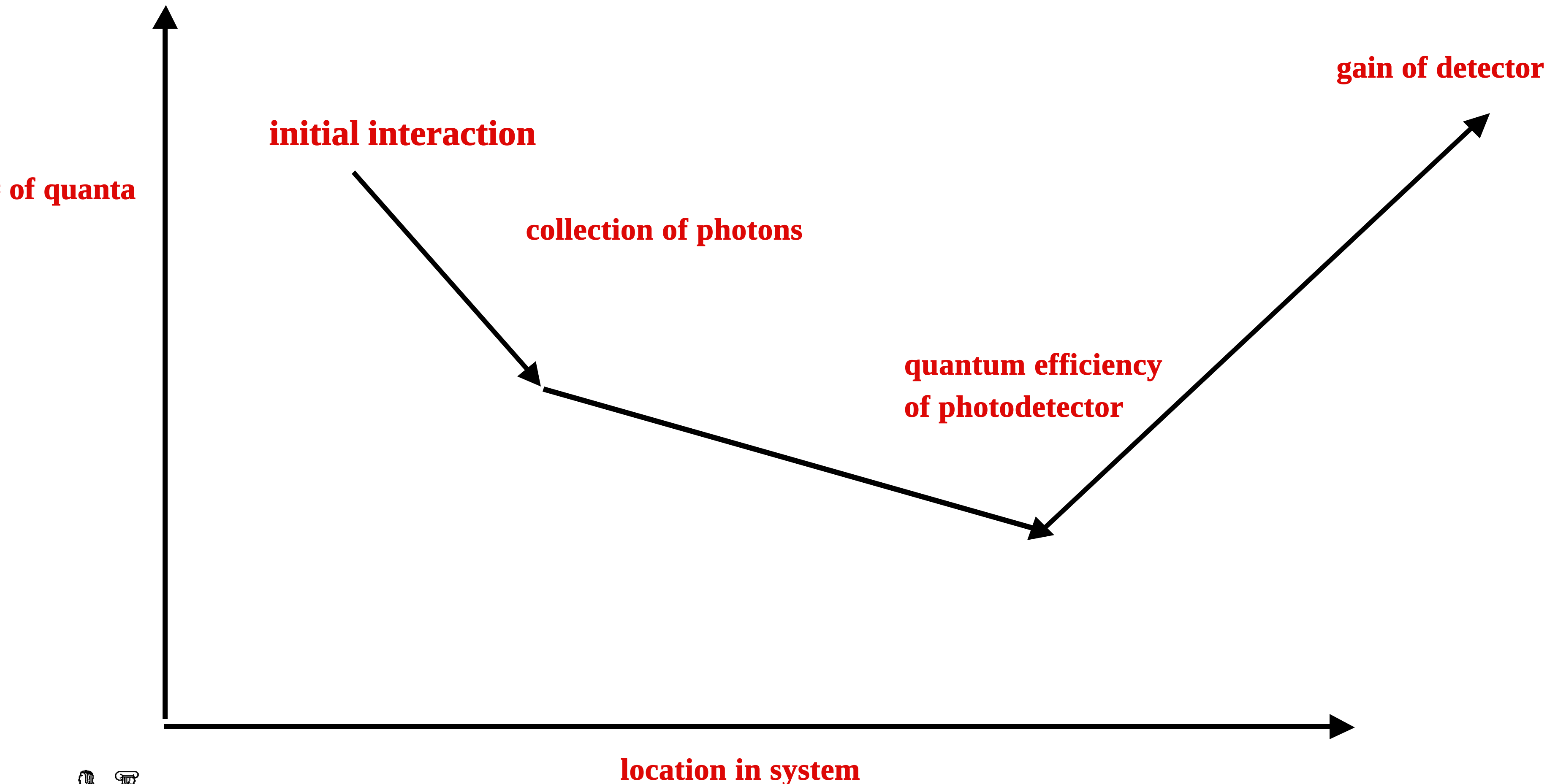
Relative Efficiency



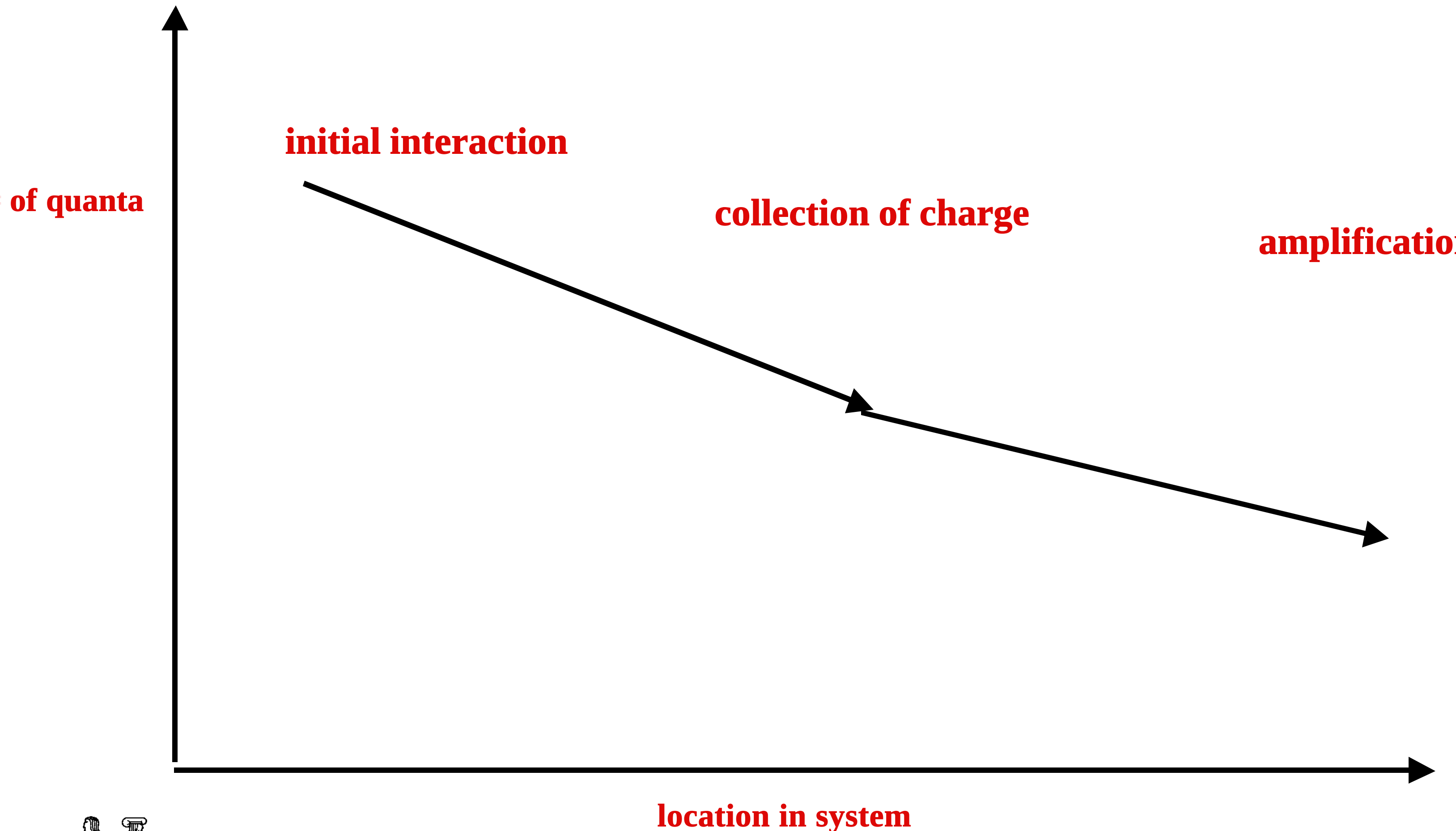
Absolute Efficiency vs Energy



Energy resolution and "quantum sinks" for Scintillators



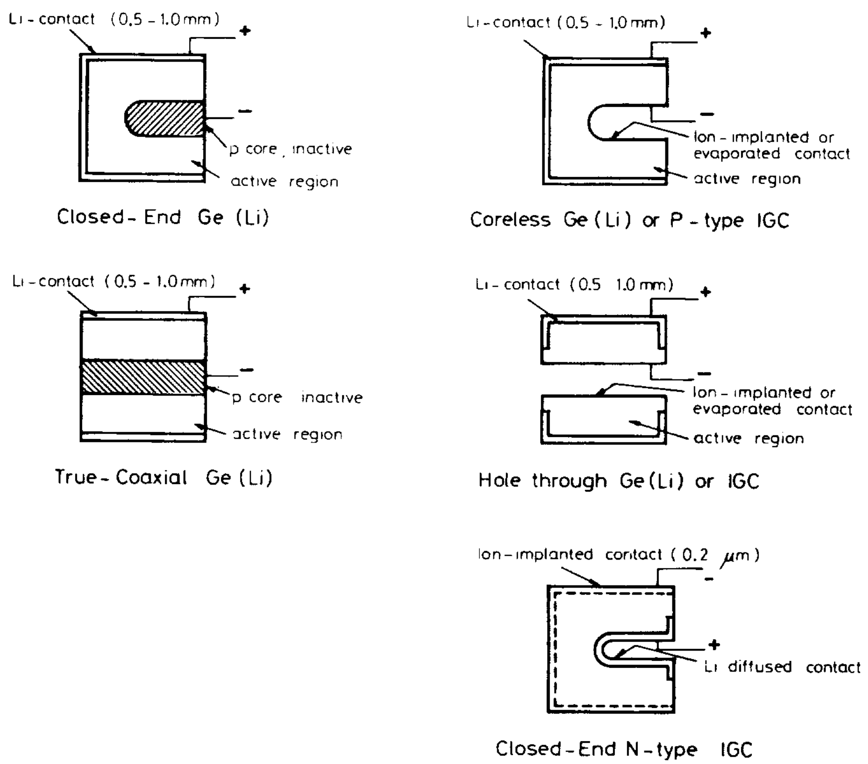
Energy resolution and "quantum sinks" for Semiconductor detectors



Key Properties of Semiconductor Detectors

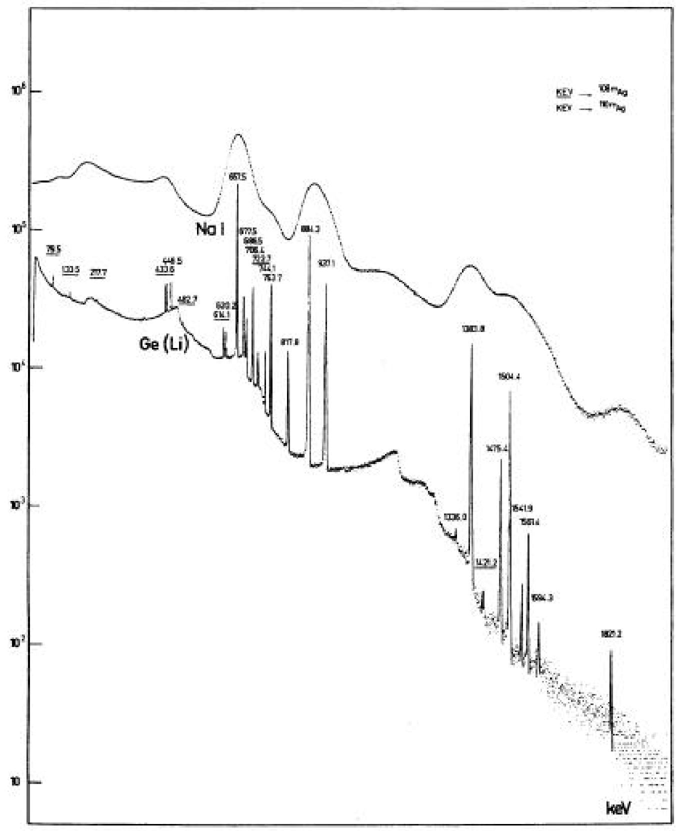
- Excellent Energy Resolution
- Slow Time Response
- Compact

Coaxial Ge Detectors



Importance of Resolution

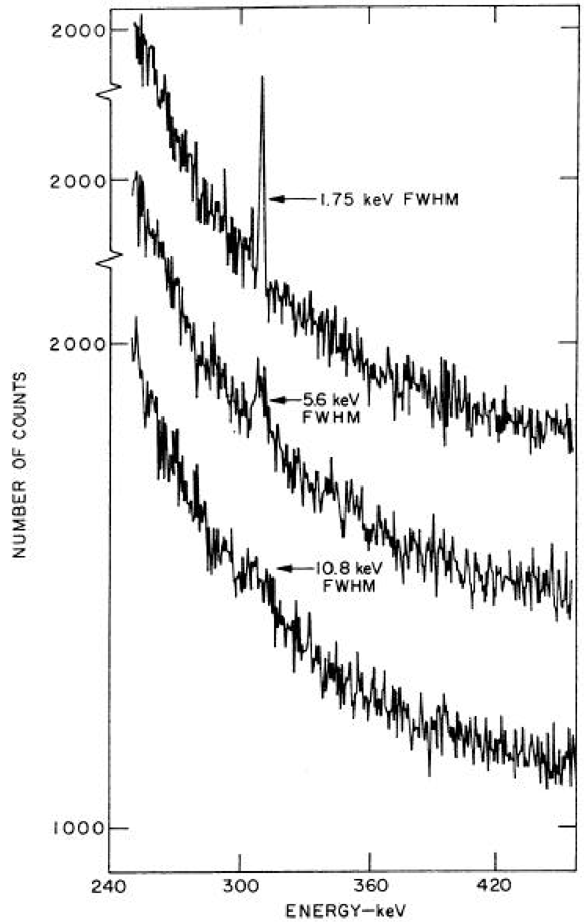
Find structure in spectra



(J.Cl. Philippot, IEEE Trans. Nucl. Sci. **NS-17/3** (1970) 446)

Importance of Resolution

Improve SNR

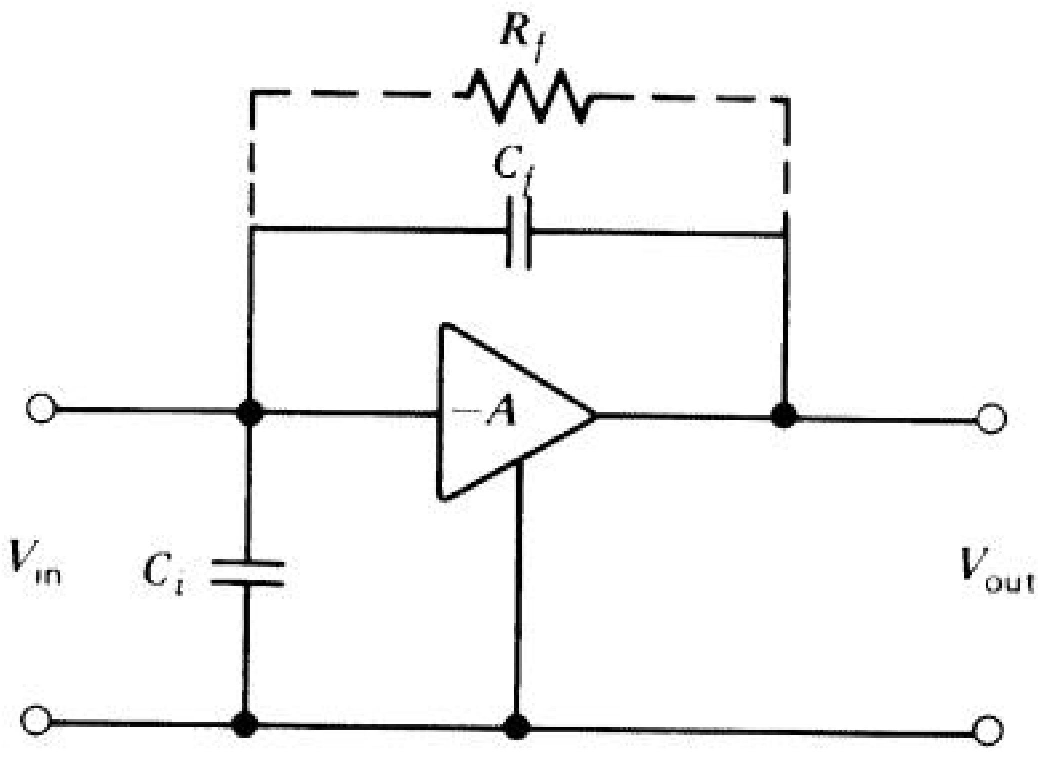


G.A. Armantrout, *et al.*, IEEE Trans. Nucl. Sci. **NS-19/1** (1972) 107

Noise Sources

- Statistical
- Leakage current
- Electronic amplifier
- Trapping
- Ballistic effects

Charge Amplifier

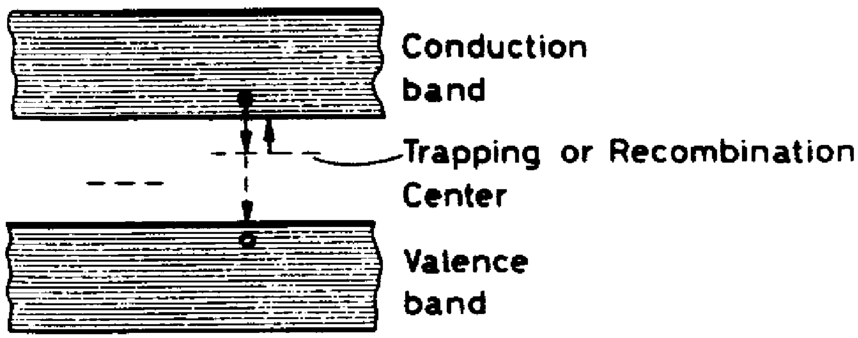


$$V_{out} = Q / C_f$$

$$t = R_f C_f$$

$$Q_{noise} \approx \frac{C_{total} e_{FET}}{\sqrt{t}}$$

Trapping of Charge



Room Temperature Materials

- CdZnTe
- HgI
- Si

Advantages of Room Temperature Detectors

- Compact
- Do not require cryogenics
- Potentially low cost

Limitations of Room Temperature Detectors

- Trapping
- Difficulty in making large detectors
- No industrial production (compared to Si)
- Yields
- Costs

Conclusions

- Semiconductor detectors and technology growing
- Important when combined with modern IC technology
- Attractive performance potential