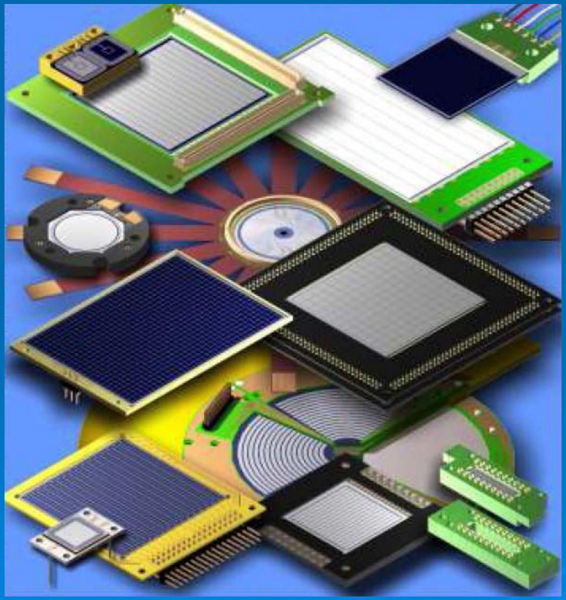
RNC Lecture, (2010) Oct. 8

Semiconductor Detectors

Shunji Nishimura



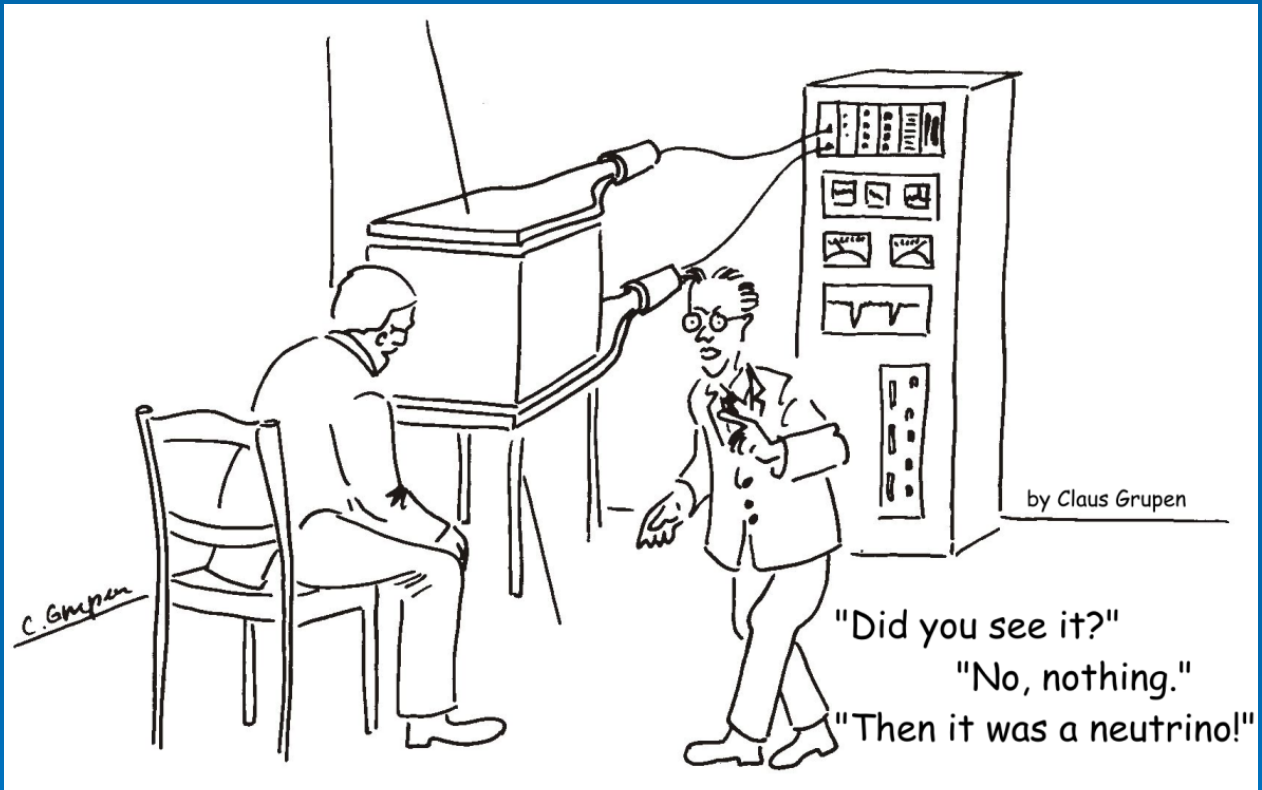
Silicon Detector

Germanium Detector

Outline of this Lecture

- Introduction
  - Detectors General Requirements
  - Why use semiconductor detectors?
- Basic Principles
  - P-type, N-type
  - Depletion layer
  - Type of detectors
- Performance
  - Energy Measurement
  - Position Measurement
  - Timing Measurement
- Electronics
- Operation : How to use?

Design of Experiments



-Big Project

-Small Project

Experimental setup depends

on what you want to measure for your physics

Detectors General Requirements
[Particle Identification]

- what kind of particles?!

Hadrons

proton, neutron, d, t, 3He, …
pion, kaon, …

Photon

Gamma-ray (γ)

Lepton

Electron (β), Muon (μ), Tau(τ)
Neutrino (ν)

- momentum, direction, time, etc..

Kinematics

Requirements for detectors

- **Energy measurement**
  - Energy loss (dE)
  - Total energy (E)
  - Pulse shape
- **Position measurement**
  - (X, Y, Z) → Tracking
  - Bρ → Momentum (p)
- **Timing measurement**
  - Timing (velocity β)
  - High counting rate (dN/dt)
- **Count measurement**
  - Sensitivity to particle (ε)
  - Insensitive to background (S/N)
  - Radiation hardness

There are many types of detectors.

- Scintillation detector (Tamagawa-san)
- Gas detector
- ⇨ Semiconductor detector

→ Is there a perfect detector ?!

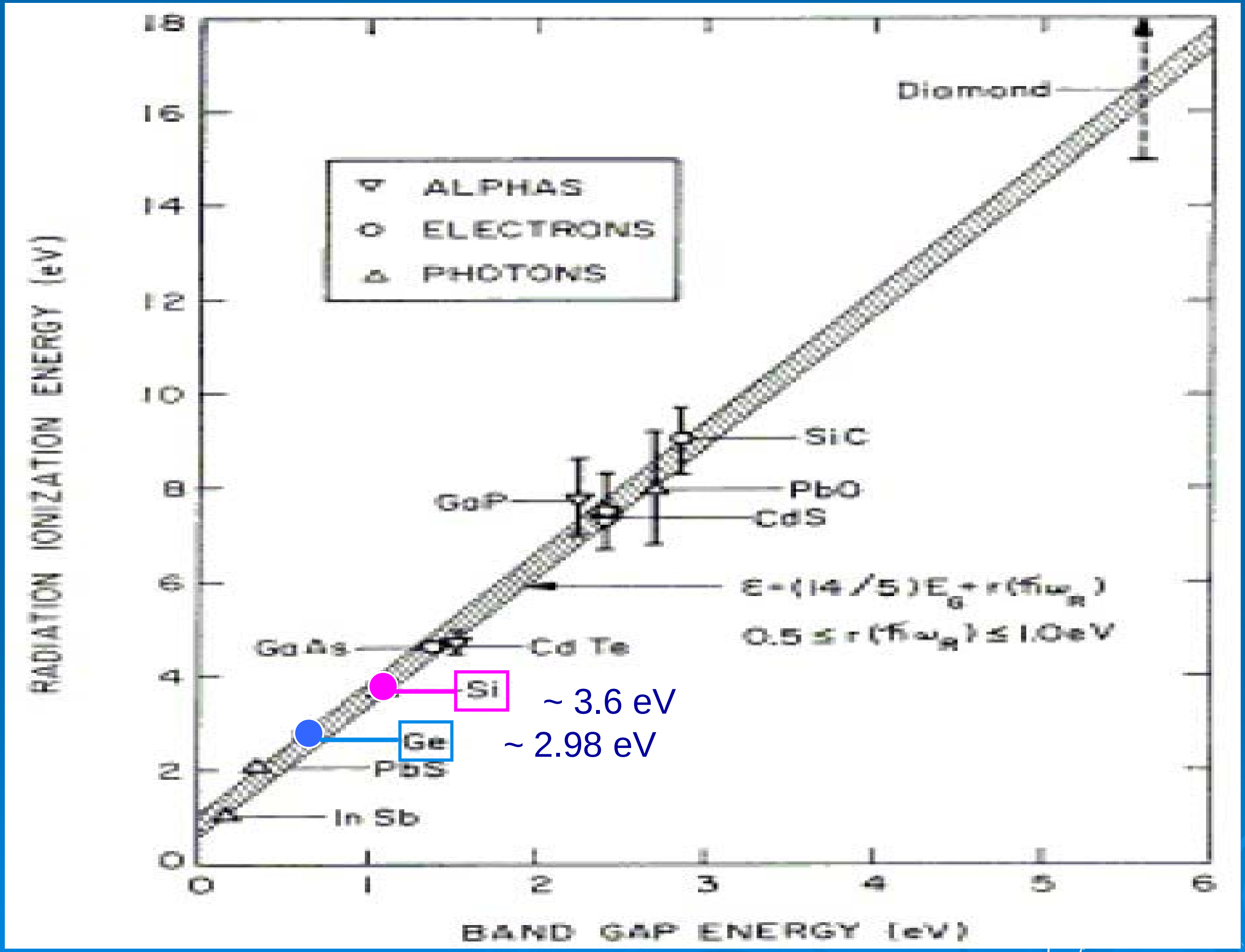
What is the advantage of semiconductor detector?

Characteristics of Semiconductor

- Low ionization energy
  - good signal
- Long mean free path
  - good charge collection efficiency
- High mobility
  - fast charge collection
- Si ... Lower Z = 14
  - low multiple scattering
  - Little cooling
- Ge .. Higher Z = 32
  - higher stopping power
  - Cooling is required.

Detector	Ionization energy I (eV)	Energy resolution @ 5MeV $2.35/\sqrt{(5x10^6/I)}$
Scintillation	100 ~ 500	1.1 ~ 2.4 %
Gas	30	0.6 %
Semiconductor	3	0.2%

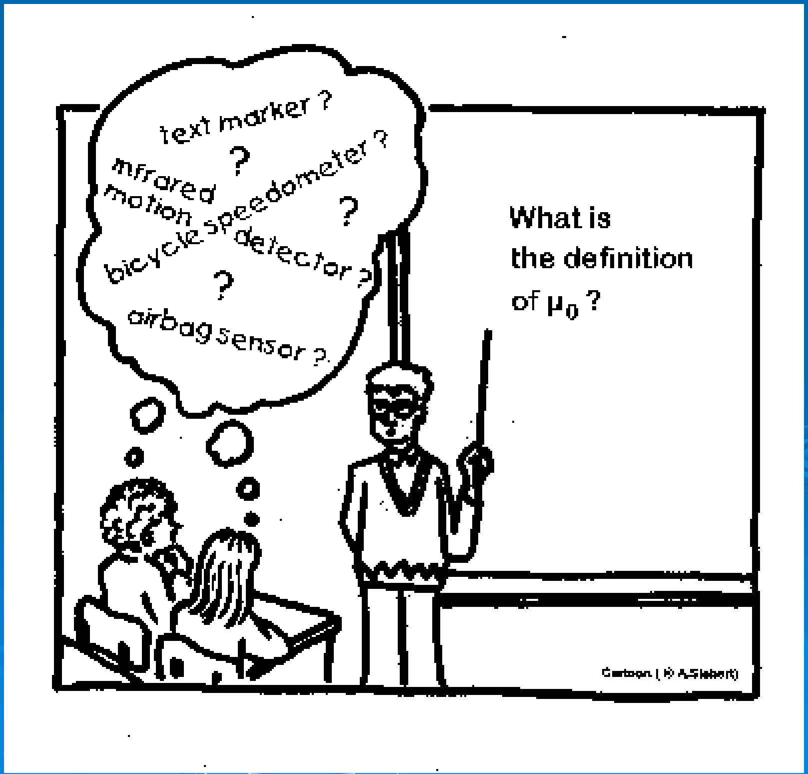
Energy required for creation of an electron-hole pair



Silicon:
The basic ingredients are ridiculously cheap

C.A.Klein, J. Applied Physics 38 (1968) 2029.

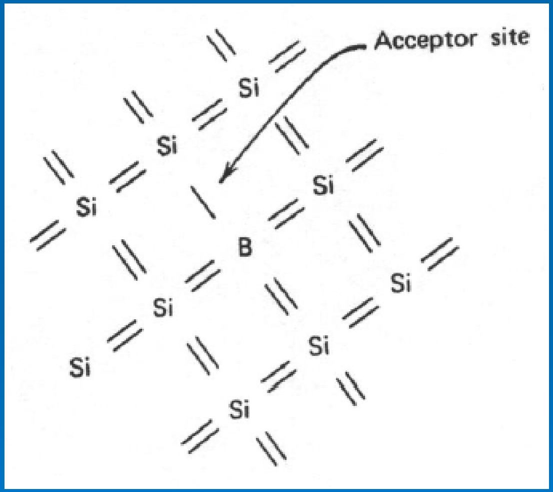
Basic Principles



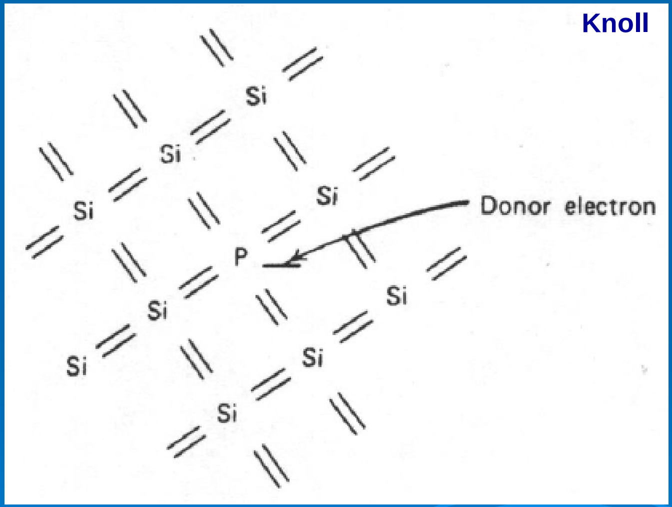
Basic Principles

[To dope the silicon with impurities]

Boron doping (p-type)
holes are majority carriers

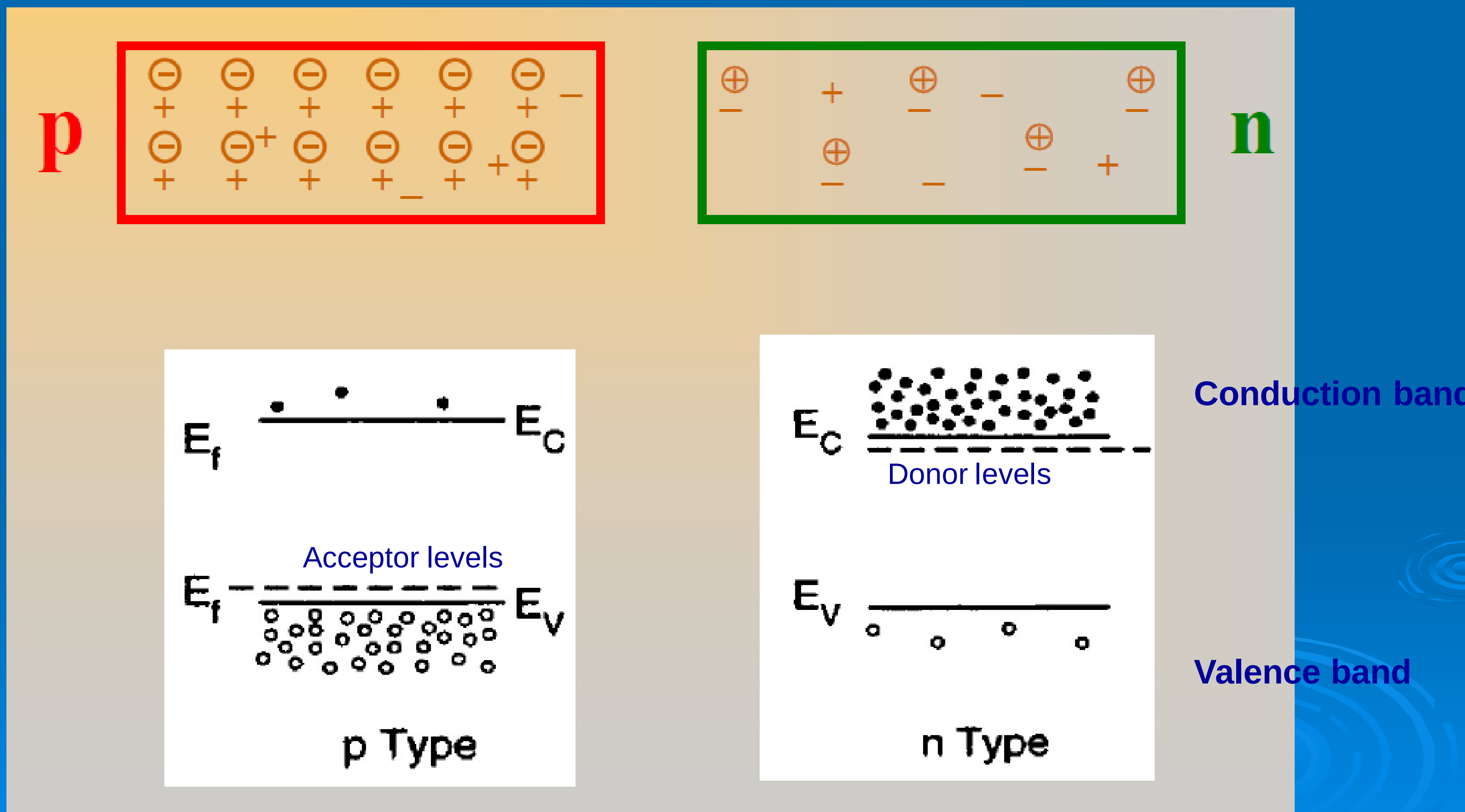


Phosphorus doping (n-type)
electrons are majority carriers



Basic Principles

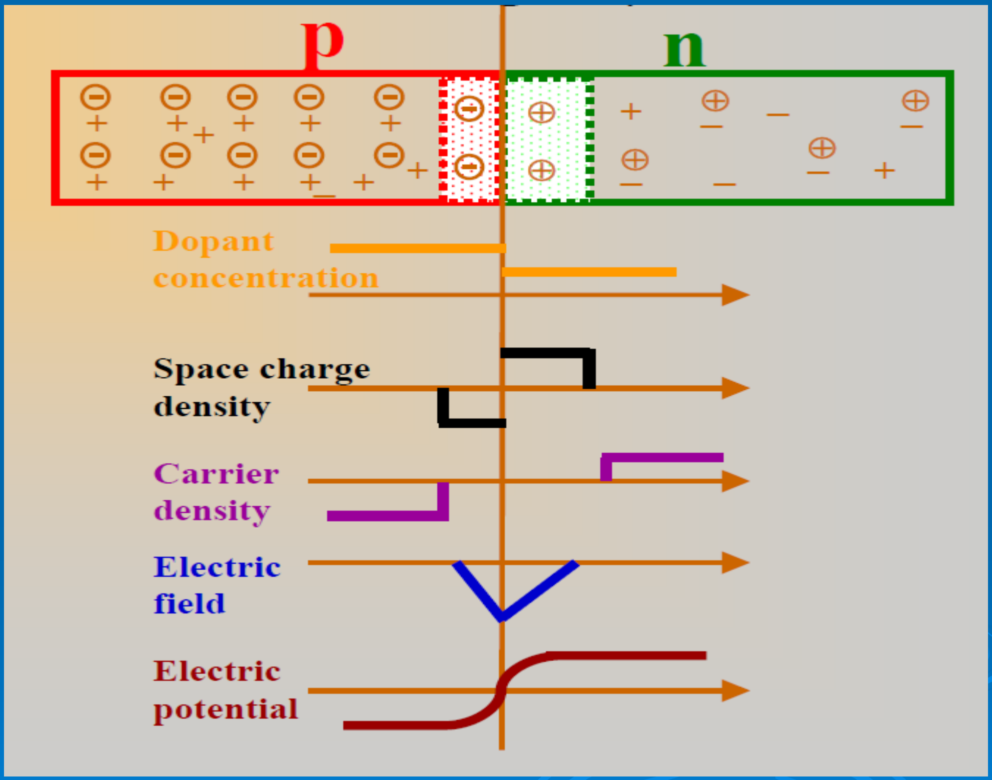
- Now we can construct a p-n junction



P. Collins (CERN)

Basic Principles

Now for the magic part !

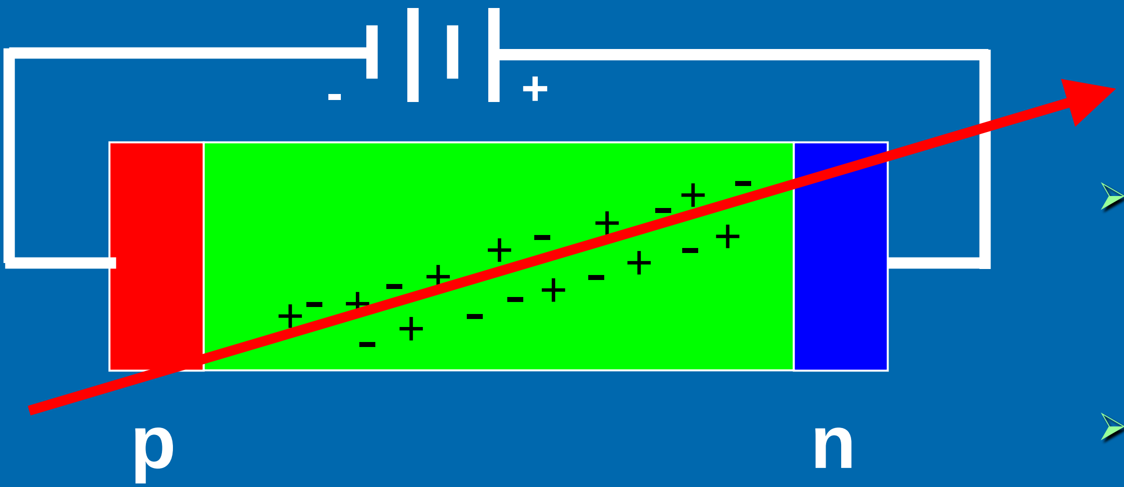


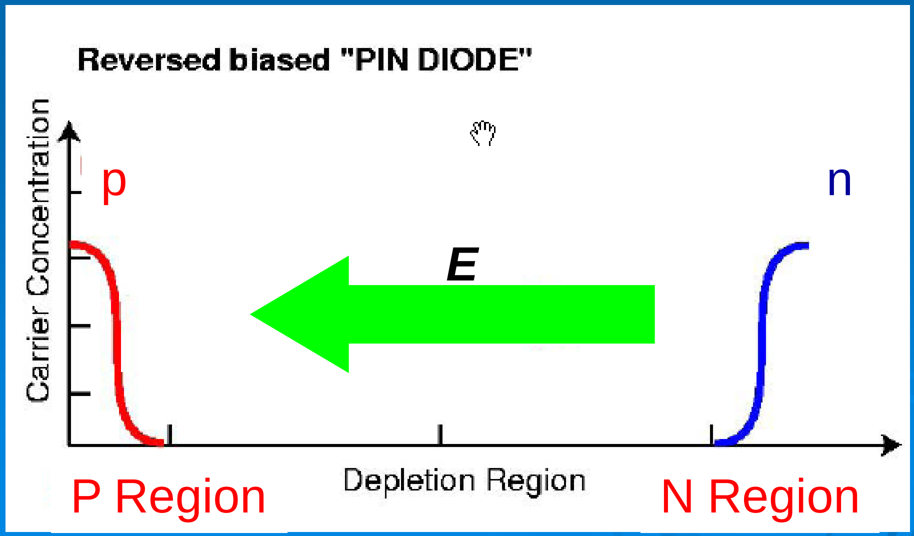
P. Collins (CERN)

When brought together to form a junction, the majority diffuse carriers across the junction. The migration leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region. The electric field set up in the region prevents further migration of carriers.

Basic Principles

[Semiconductor structure]





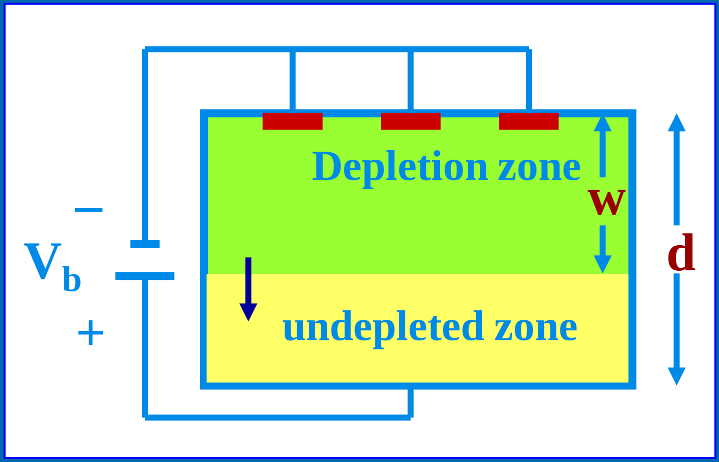
- **Use ionization signal left behind by charged particle passage.**
- **Ionization produces electron(e)-ion(h) pairs, use electric field to drift the e and h to the oppositely charged electrodes.**
- **Si needs 3.6eV to produce one e-h pair.**

Depletion zone

- Depletion zone

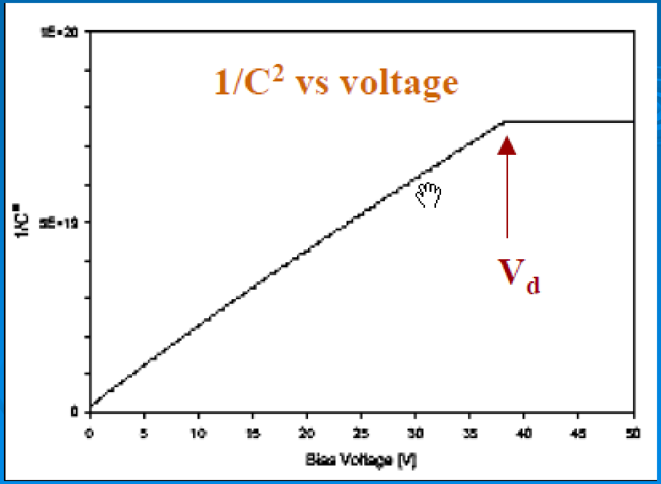
$$w = \sqrt{2\varepsilon\rho\mu V_b}$$

where $\rho = 1/q\mu N$ for doped materiel and N is the doping concentration (q is always the charge of the electron)



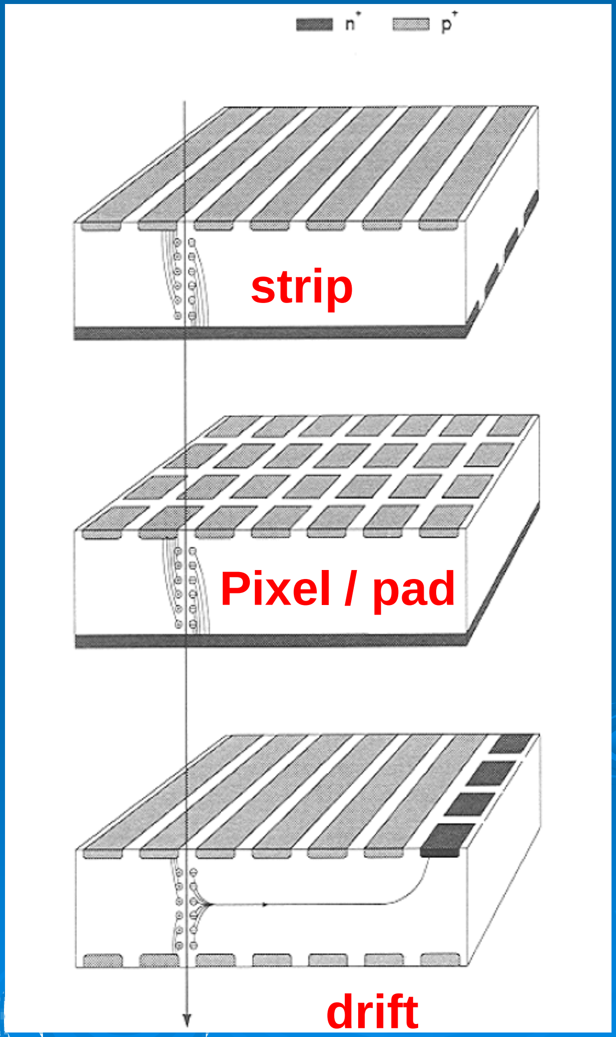
- The voltage needed to completely deplete a device of thickness d is called the depletion voltage, V_d

$$V_d = d^2 / (2\varepsilon\rho\mu)$$



Types of Silicon detectors

- Strip devices
  - High precision
  - Large active area
  - Single-sided or Double-sided
- Pixel devices
  - True 2-D measurement
  - Small areas, but high track density
- Pad devices
  (Big pixels / wide strips)
  - Pre-shower and calorimeters
- Drift devices



Types of Ge-detectors

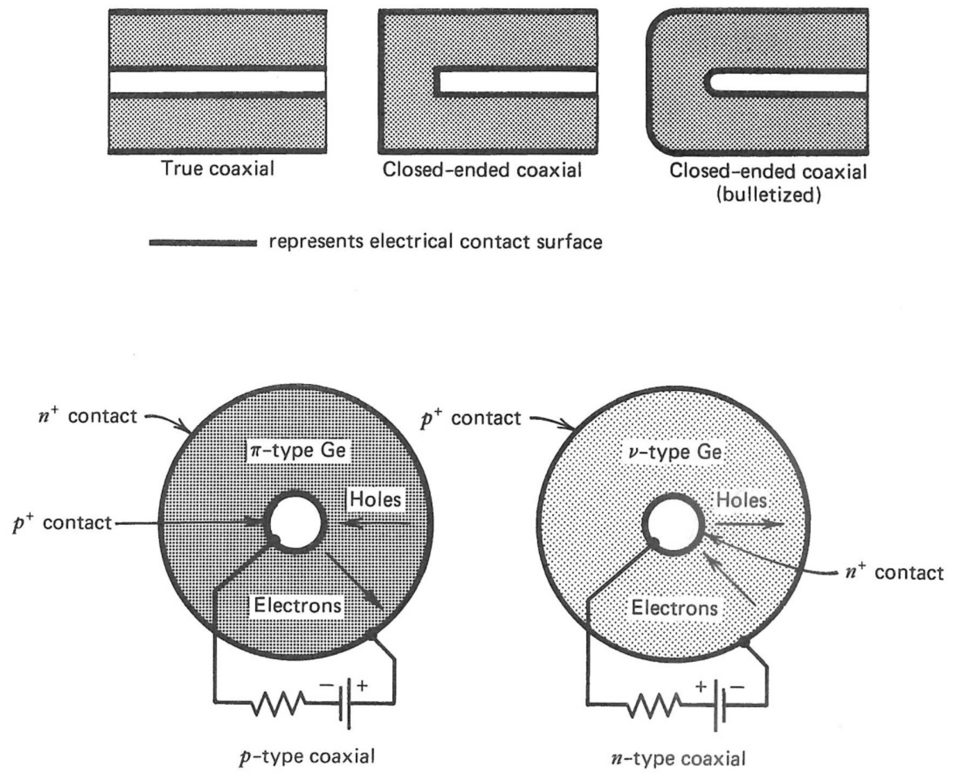
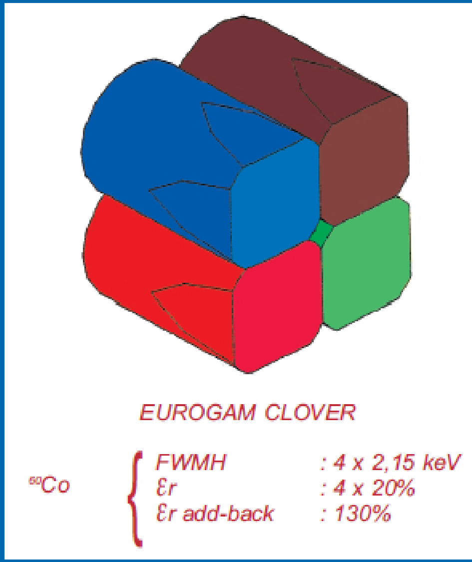


Figure 12.3 At the top are shown the three common shapes of large-volume coaxial detectors. Each represents a cross-sectional view through the axis of a cylindrical crystal. The outer electrode is extended over the flat front (left) surface in both closed-ended cases. Cross sections perpendicular to the cylindrical axis of the crystal are shown at the bottom. The HPGe material may be either high-purity p or n type. The corresponding electrode configurations are shown for each type.

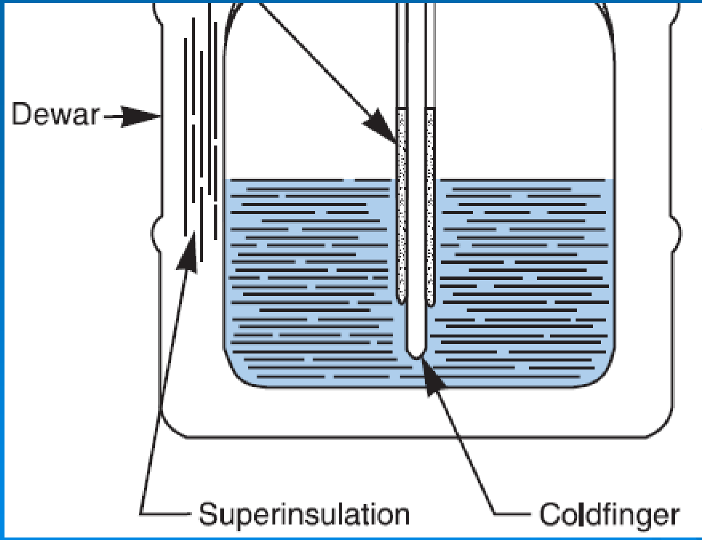
Strip Ge detector

Clover Detector

4 crystals



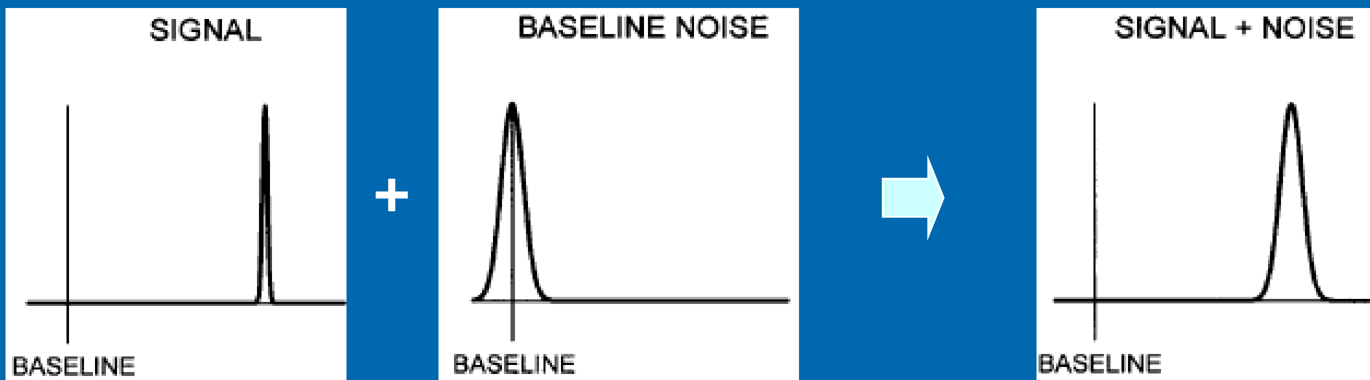
Liquid Nitrogen for cooling



Performance I

Energy Resolution

Energy Resolution



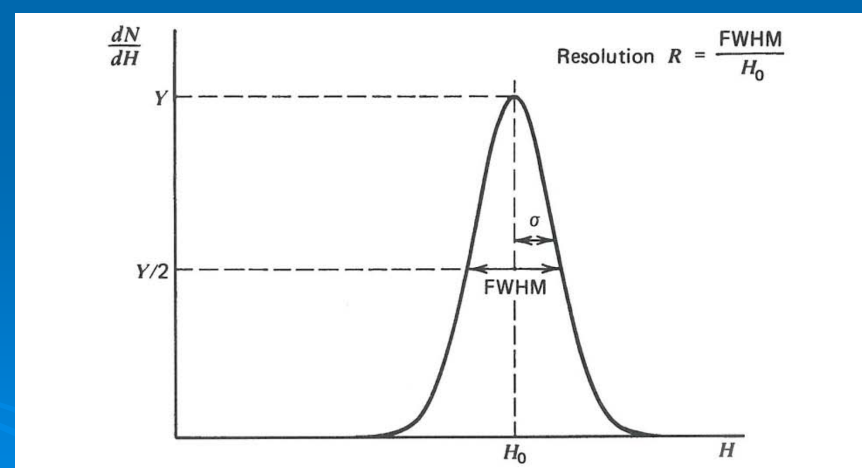


Figure 4.5 Definition of detector resolution. For peaks whose shape is Gaussian with standard deviation σ, the FWHM is given by 2.35σ.

If Signal Variance << Baseline Variance
→ Electronics (baseline) noise
critical for resolution

Energy Resolution : NaI(Tl) vs Ge

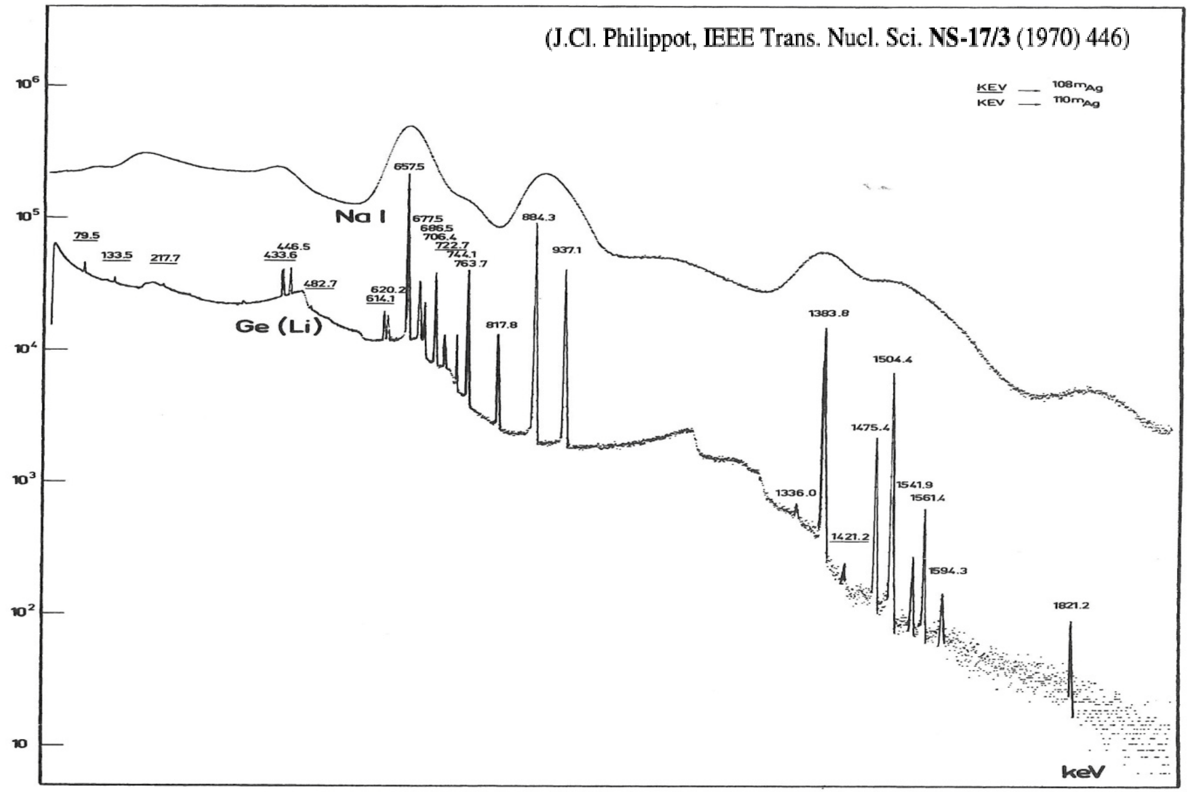
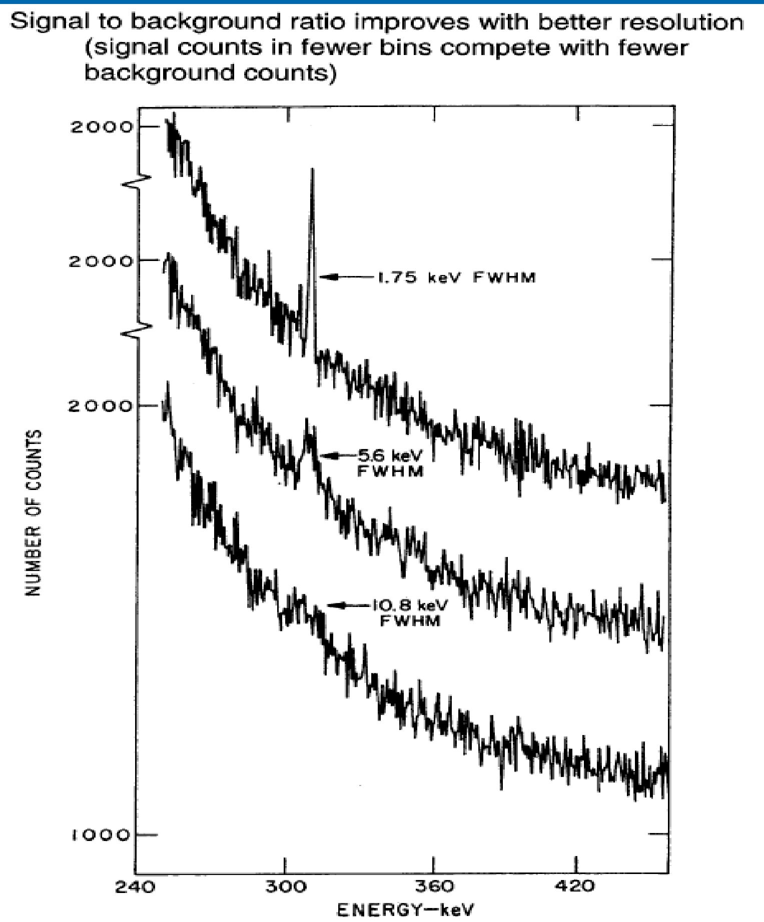


Figure 12.7 Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector. The source was gamma radiation from the decay of ^{108m}Ag and ^{110m}Ag. Energies of peaks are labeled in keV. (From Philippot.[13])

Semiconductor detector

➔ Excellent detector for energy measurement !!

Energy Resolution
[Signal to Background Ratio (S/N)]



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

→ Good Energy Resolution
→ Higher Statistics

We can extract
- precise peak position,
- and find NEW Peaks!!

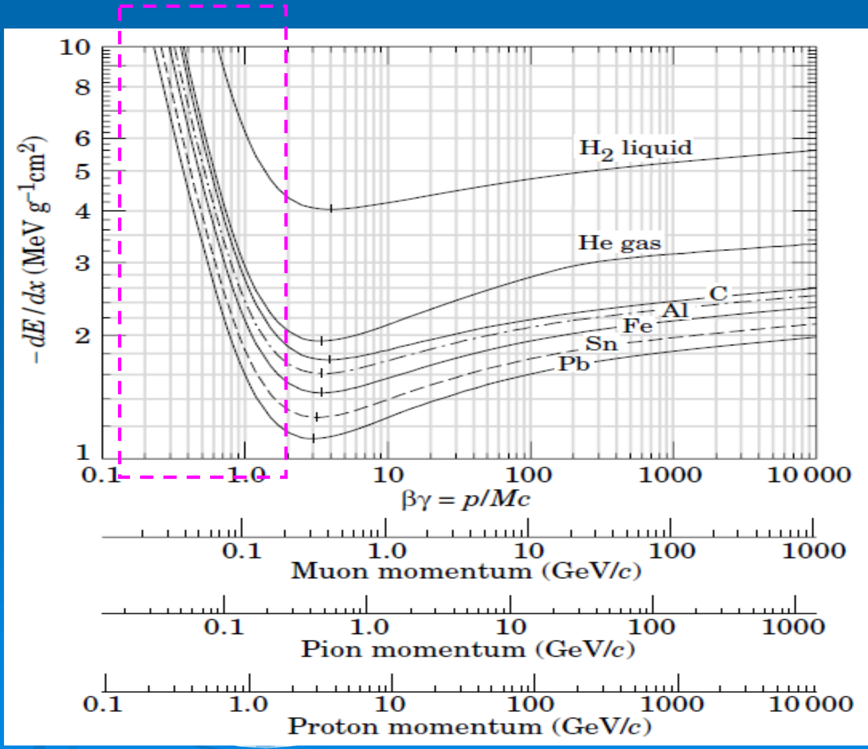
Particle Identification
[Use Difference of Stopping Power]

$$p = m_0 \beta \gamma$$

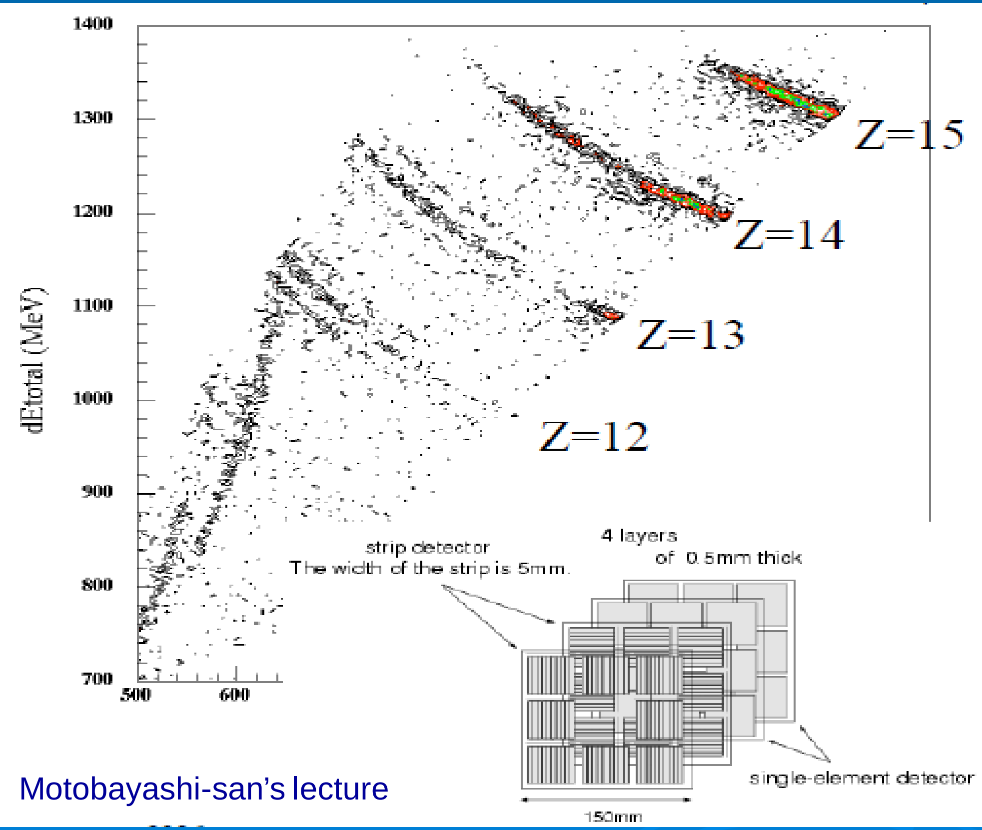
$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2 \gamma^2\right)$$

Knowing p and β gives m

For very low momenta,
we can exploit the bethe-bloch
formula for particle identification



Particle Identification
[dE-E Correlation]



Motobayashi-san's lecture

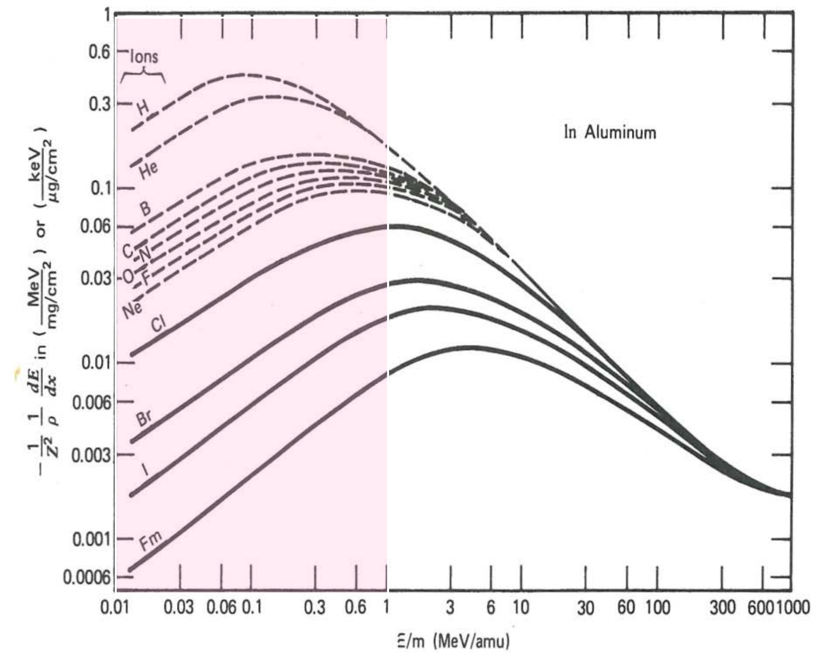


Figure 2.11 Plots showing the specific energy loss of various heavy ions in aluminum. The abscissa is the ion energy divided by its mass, and the ordinate is $-dE/dx$ divided by the density of aluminum and the square of the ion atomic number. Typical fission fragments (e.g., iodine) show a continuously decreasing $-dE/dx$ while slowing from their initial energy (~1 MeV/amu). (From Northcliffe and Schilling.[8])

Multi-layer detectors enable us to identify the particles!

Energy Resolution :

[Temperature Dependence]

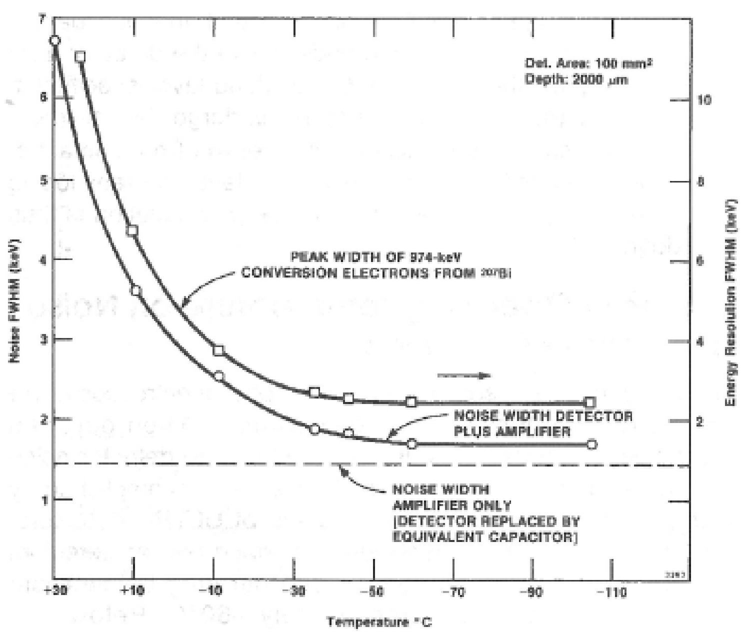


Fig. 9. Detector Noise and Electron Energy Resolution as a Function of Temperature.

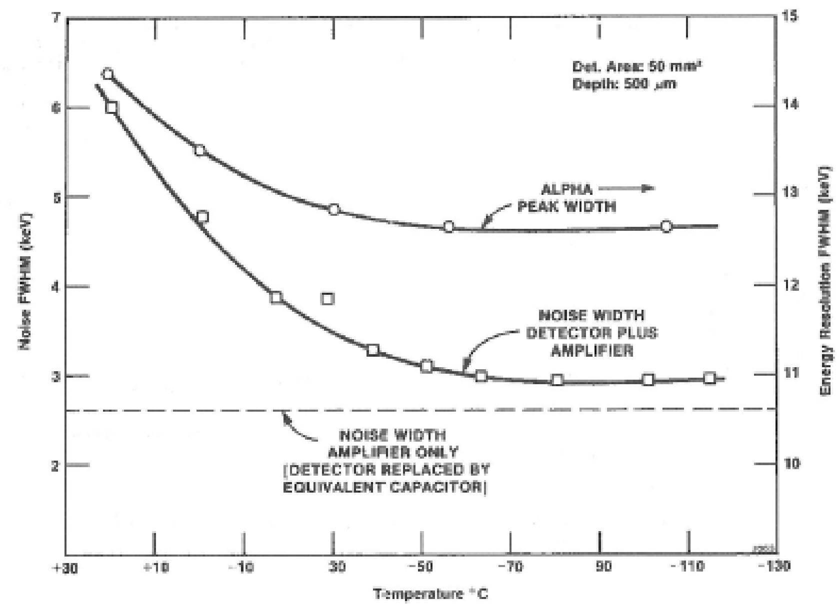
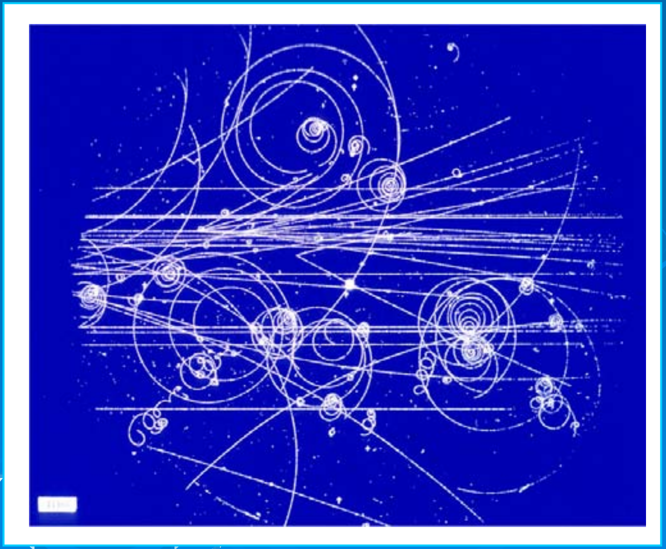


Fig. 8. Detector Noise and Alpha Energy Resolution as a Function of Temperature.

Semiconductor Detectors prefer COOLING !

Performance II

Position Measurement



Bubble chamber (CERN)

Position Measurement

Table 28.1: Typical resolutions and deadtimes of common detectors. Revised September 2003 by R. Kadel (LBNL).

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2 μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2 ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift [7]	~175–450 μm	~ 200 ns	~ 2 μs
Gas Micro Strip [8]	30–40 μm	< 10 ns	—
Resistive Plate chamber [9]	$\lesssim$ 10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	h	h
Silicon pixel	2 μm[i]	h	h

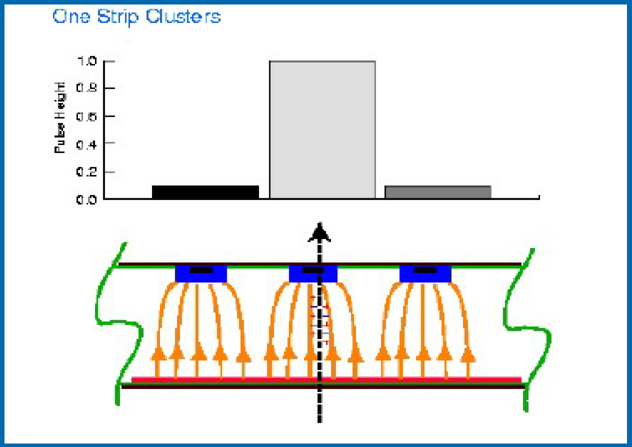
[a] Multiple pulsing time.
[b] 300 μm is for 1 mm pitch.
[c] Delay line cathode readout can give ±150 μm parallel to anode wire.
[d] wirespacing/$\sqrt{12}$.
[e] For two chambers.
[f] n = index of refraction.
[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$ 25 μm) with pulse-height-weighted center finding.
[h] Limited by the readout electronics [10]. (Time resolution of $\leq$ 25 ns is planned for the ATLAS SCT.)
[i] Analog readout of 34 μm pitch, monolithic pixel detectors.

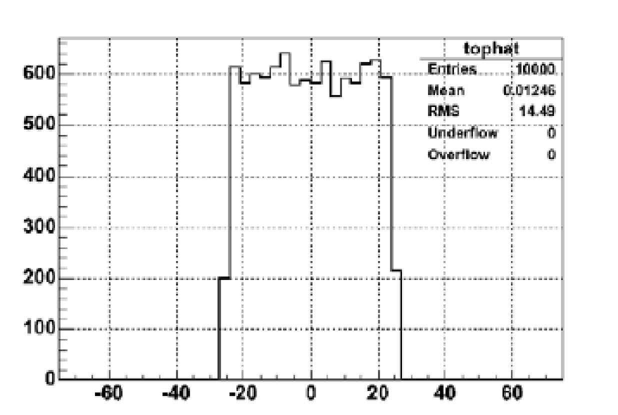
Silicon Detectors

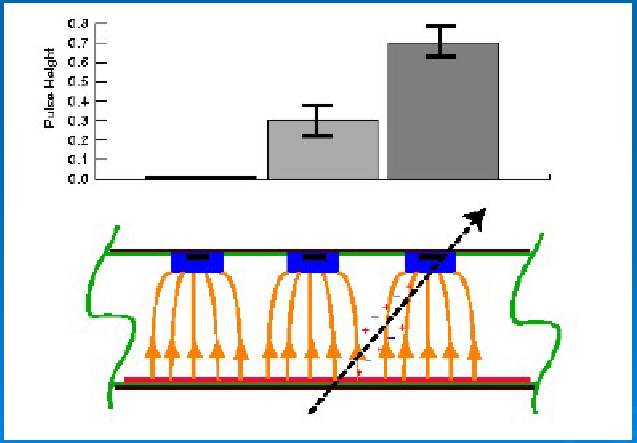
- very good position resolution.
- works under high magnetic field.
- high rates and triggering.

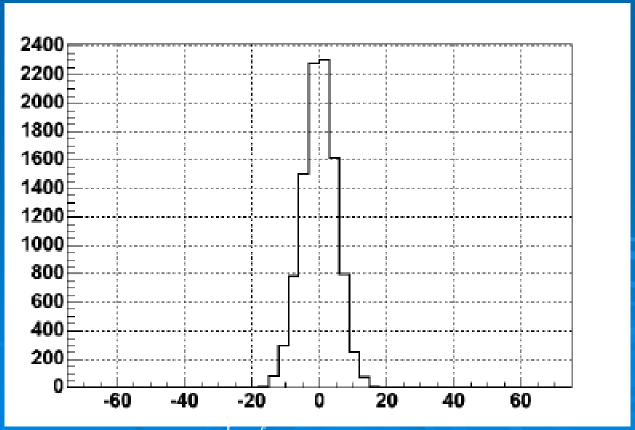
Position Measurement

σ = pitch/√12

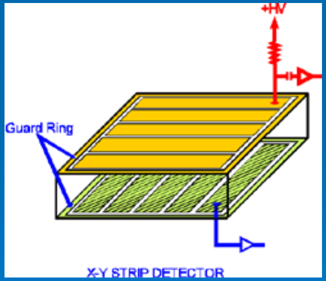








Position Sensitive Ge detectors



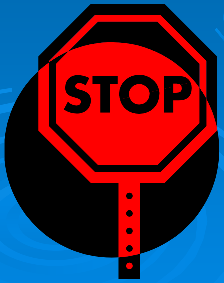
Ge detector array (GRAPE)
CNS, Univ. of Tokyo

Performance III

Timing Measurement

Silicon detector

- Electrons ~10ns/300um
- Holes ~ 25ns/300um



Timing Measurement

2. Nuclear Mass Spectroscopy by Time-of-Flight

Two silicon detectors

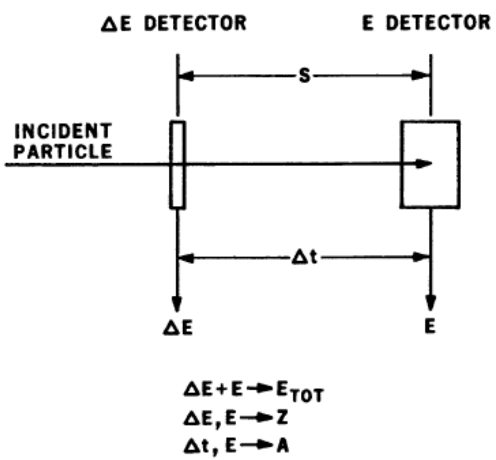
First detector thin, so that particle passes through it (transmission detector)

⇒ differential energy loss ΔE

Second detector thick enough to stop particle

⇒ Residual energy E

Measure time-of-flight Δt between the two detectors



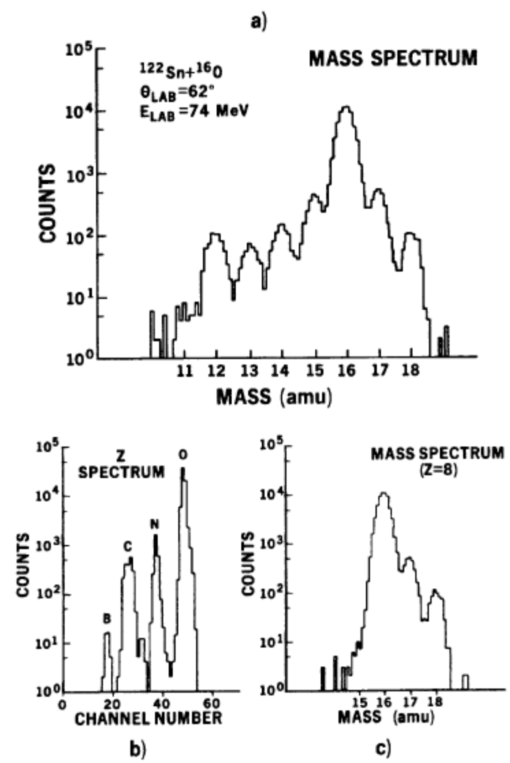
$E_{tot} = \Delta E + E$ $\quad Z \propto \sqrt{\Delta E \cdot E_{tot}}$ $\quad A \propto E \cdot (\Delta t / s)^2$

"Typical" Results

Example 1

Flight path 20 cm, $\Delta t \approx 50$ ps FWHM

$\sigma_t = 21$ ps



(H. Spieler et al., Z. Phys. **A278** (1976) 241)

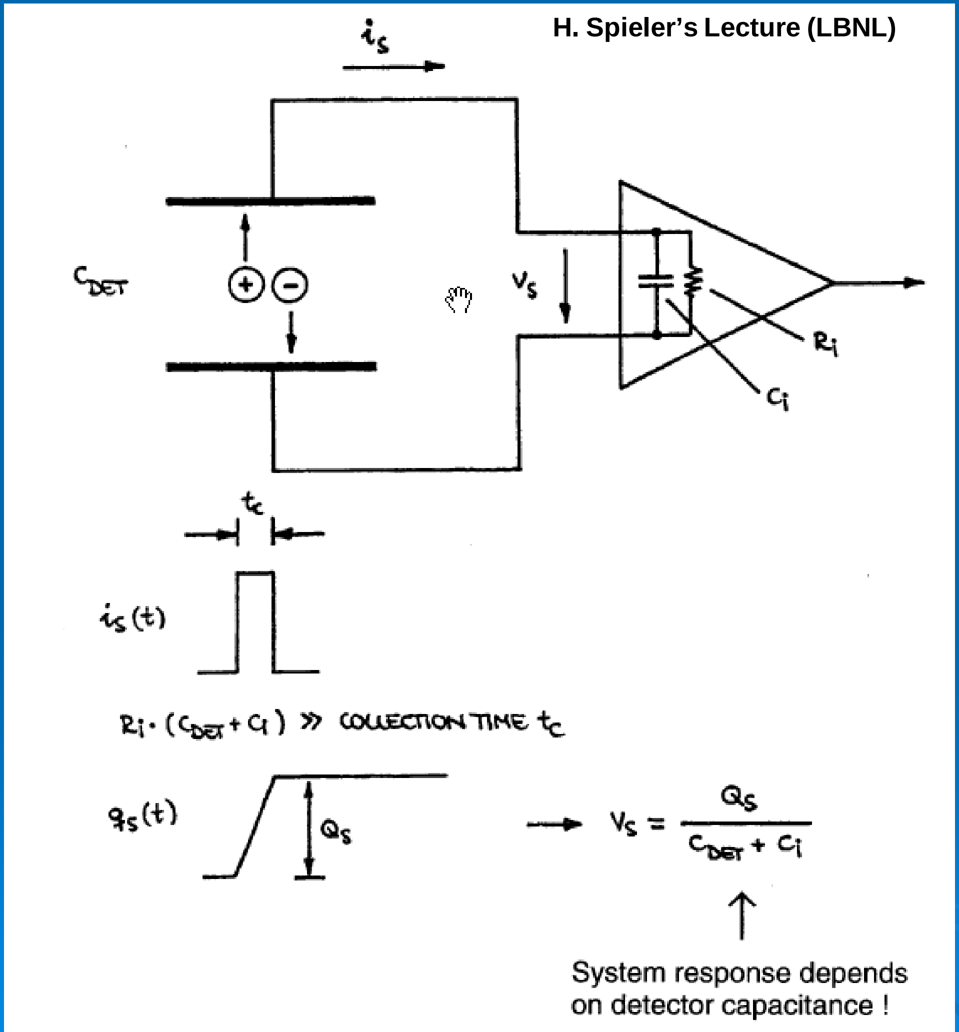
Electronics

Electronics

- Noise is a big issue for Silicon/Ge detectors. At 22000 e- for a 300 um thick silicon sensor, the signal is relatively small. Signal losses can easily occur depending on electronics, stray capacitances, coupling capacitor, frequency etc.

  - Improve energy resolution
  - Allow a low detection threshold

Electronics
[Signal Integration on Input Capacitance]



Energy Deposit ∝ Charge Qd
However,

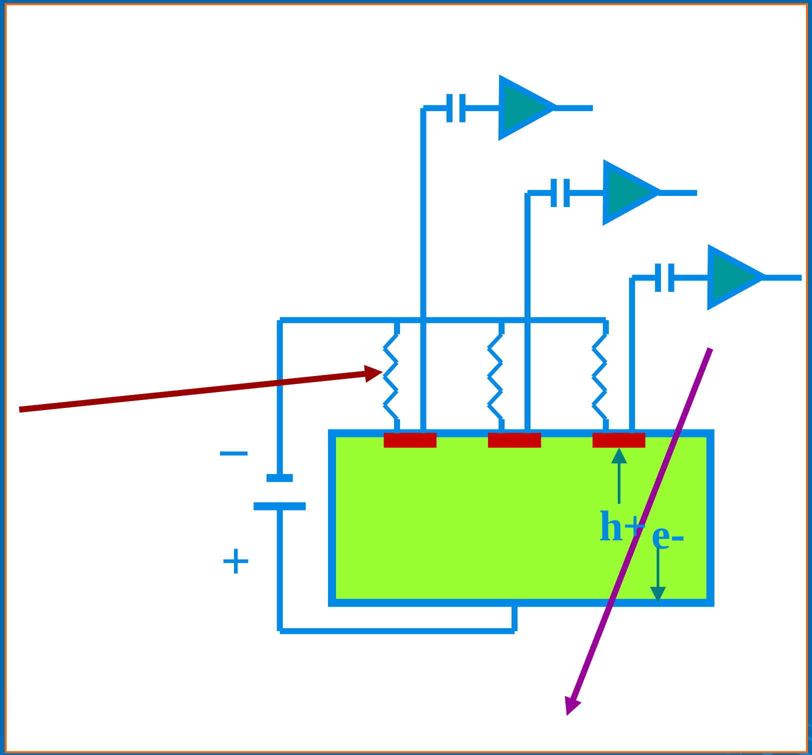
☆Detector capacitance C_{DET} may vary within a system or change with bias voltage.
☆Variation of charge collection in time T_c

Make system whose gain (dV_{out}/dQ_s) is independent of detector capacitance.

Charge sensitive preamp !

Charge Collection

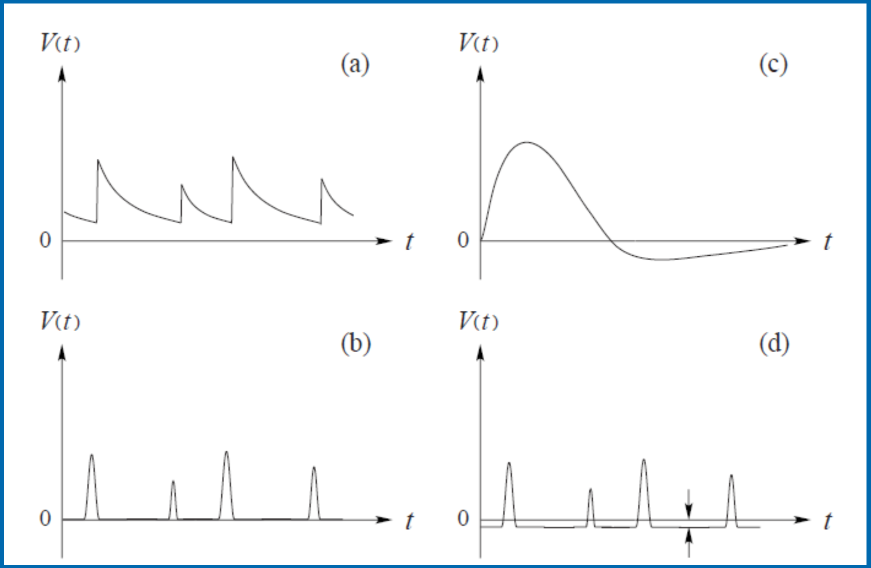
- **Isolation of each strip using high impedance bias connection**
  - **→ Collect / measure charge on each strip**



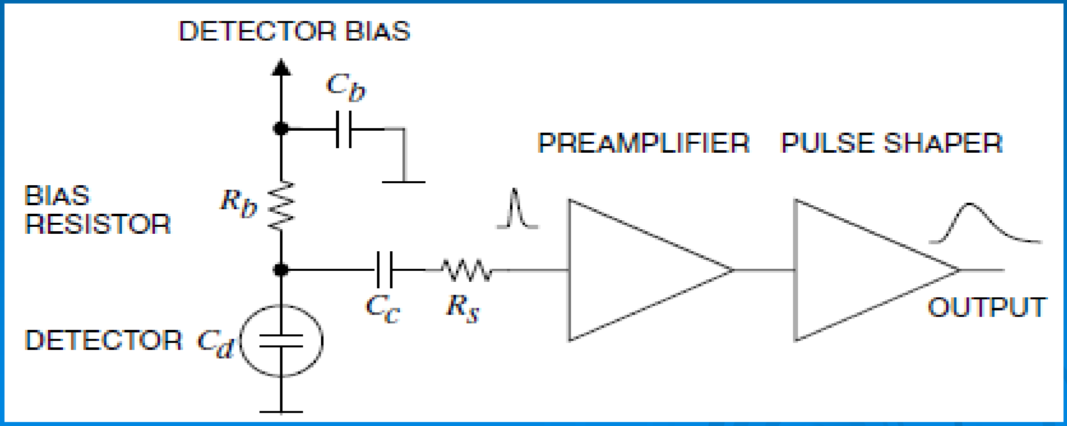
- **AC couple input amplifier (usually)**
  - **→ Avoid large DC input currents**

Signals

- (a) Output of preamp
- (b) Output of shaping amp
- (c) Undershoot
- (d) Base-line shift



The output of preamplifier : rapidly rising step, followed by a slow exponential decay.
Amplitude of the step = energy of the detected radiation
Exponential decay time = feedback resistor in parallel with the feedback capacitor.



Shaping Time

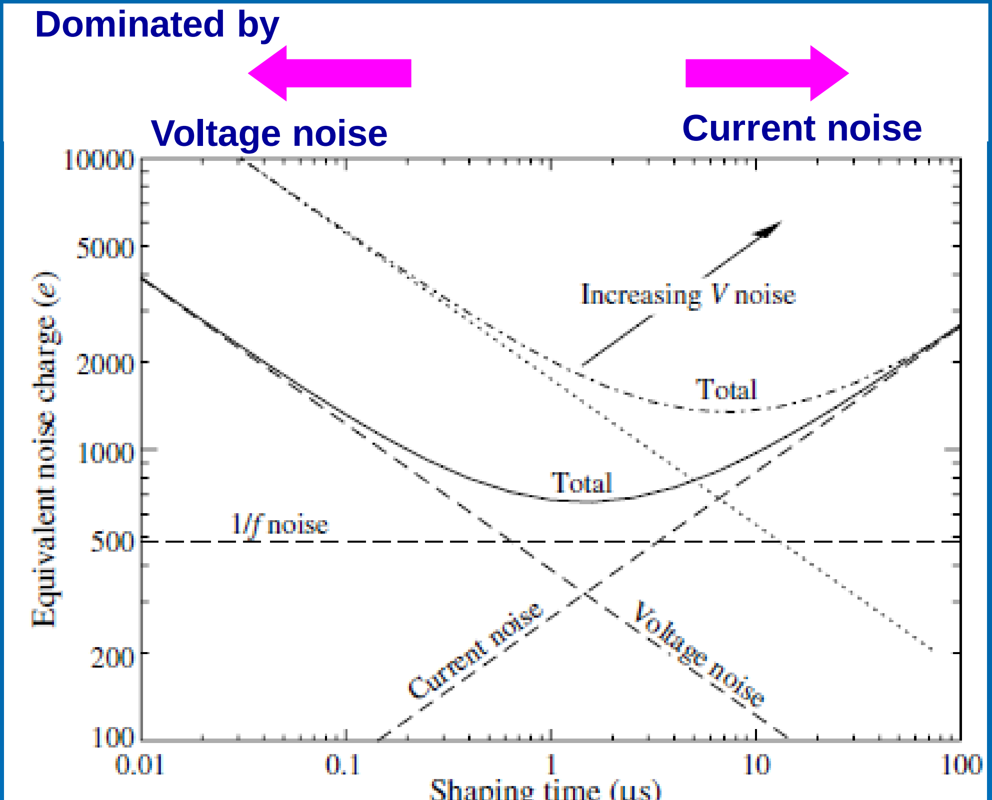
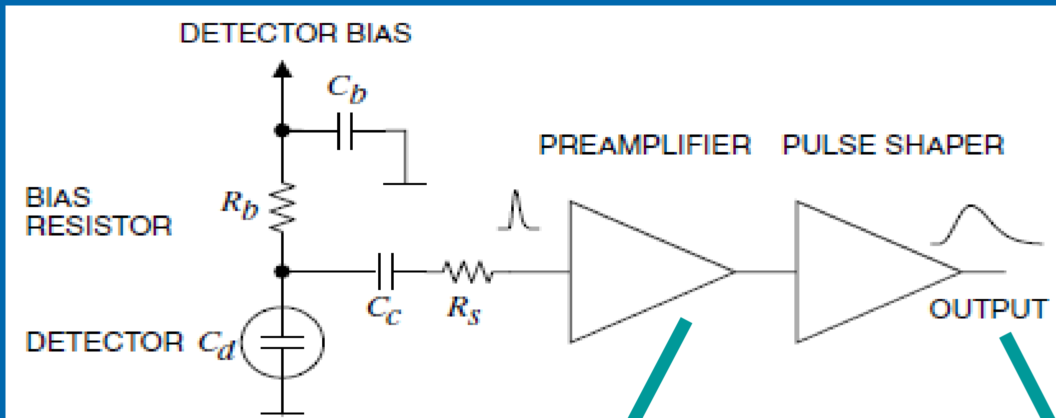


Figure 28.20: Equivalent noise charge *vs* shaping time. Changing the voltage or current noise contribution shifts the noise minimum. Increased voltage noise is shown as an example.

PRL667

Optimization is required in shaping time, ~ 1 μs

Electronics : Pile-up



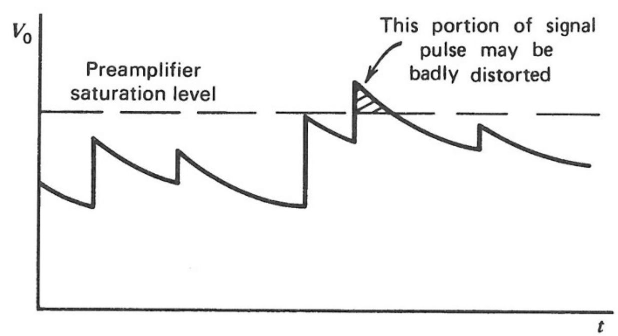
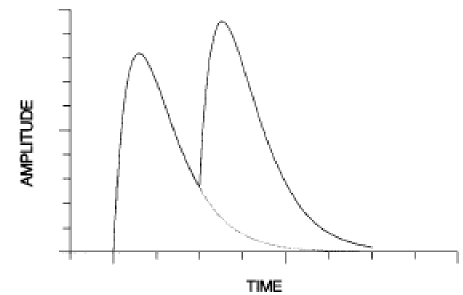
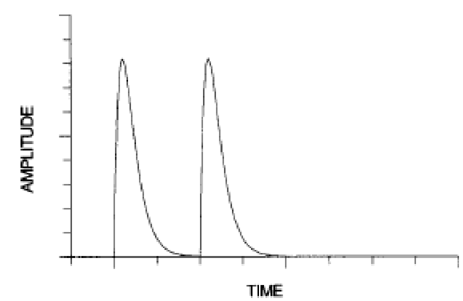


Figure 17.3 The pile-up of pulses within the preamplifier at high rates. If the saturation level of the preamplifier is exceeded, some pulses can be seriously distorted.

Pulse pile-up distorts amplitude measurement

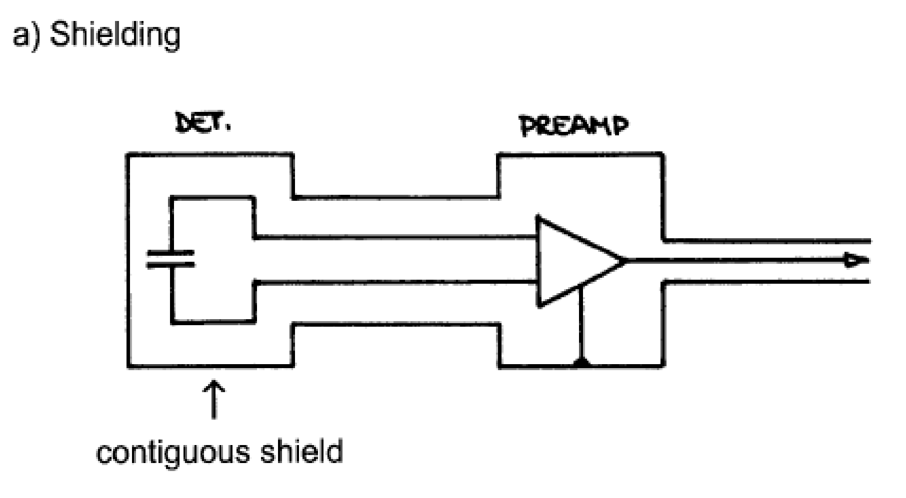


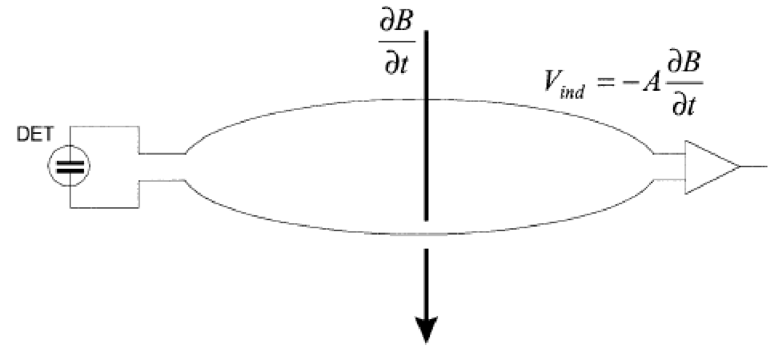
Reducing pulse shaping time to 1/3 eliminates pile-up.



Shielding and Loops

H. Spieler (LBNL)





Clearly, the area A enclosed by any loops should be minimized.

Accomplished by routing signal line and return as a closely spaced pair.

Better yet is a twisted pair, where the voltages induced in successive twists cancel.

Problems occur when alternating detector electrodes are read out at opposite ends – often done because of mechanical constraints.

Operation

How to use them

Operation

DELICATE Devices

- **HV should be increased SLOWLY..**
  - **Check its maximum HV value and Polarity (+/-)**
  - **Check the current in HV module and its signal carefully.**
  - **If something is wrong, stop the operation and investigate the reason.**

- **Shock / vibration may destroy the detector.**
  - **Careful handling.**

- **Silicon detectors**
  - **Only the support frame can be touched.**
  - **Silicon detector hates moisture.**
  - **Sensitive to photons (light) … Operate in dark place.**

- **Ge-detector**
  - **Liquid nitrogen is required to cool the detector down.**

Summary

- Semiconductor detectors based on the simple principle of the p-n junction.
- Si is typically used for charged particle & X-ray
- Ge is used for γ ray spectroscopy.

Friday afternoon, Practical training using Ge detector (by Watanabe-san)

I wish you all the best for enjoying your stay in JAPAN !!

References

- SLAC Lecture
  - http://www-group.slac.stanford.edu/sluo/lectures/Detector-Lectures.html
- Silicon Detector by Paula Collins
  - http://lhcb-doc.web.cern.ch/lhcb-doc/presentations/lectures/CollinsItacuruca03-2nd.pdf
- REVIEW OF PARTICLE PHYSICS, Phys. Letters B 667 (2008).
- EG&G ORTEC, Modular Pulse-Processing Electronics and Semiconductor Radiation Detectors.
- GLENN F. KNOLL, Radiation Detection and Measurement.

End

谢谢。