Semiconductor detectors

An introduction to
semiconductor detector physics
as applied to particle physics

Contents

4 lectures – can’t cover much of a huge field

- Introduction
- Fundamentals of operation
- The micro-strip detector
- Radiation hardness issues

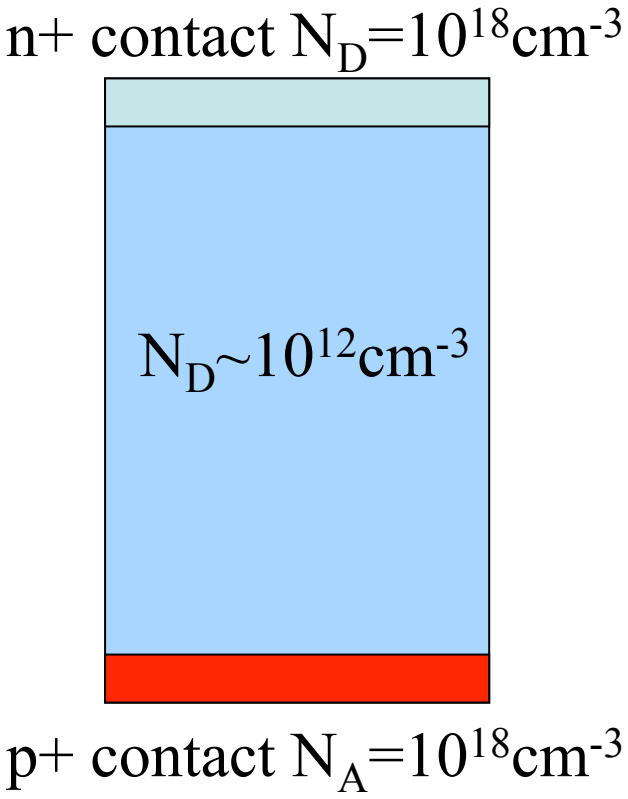
Lecture 2 – lots of details

- Simple diode theory
- Fabrication
- Energy deposition
- Signal formation

Detector = p-i-n diode

- Near intrinsic bulk
- Highly doped contacts
- Apply bias (-ve on p^+ contact)
  - Deplete bulk
  - High electric field
- Radiation creates carriers
  - signal quanta
- Carriers swept out by field
  - Induce current in external circuit

$\Rightarrow$ signal

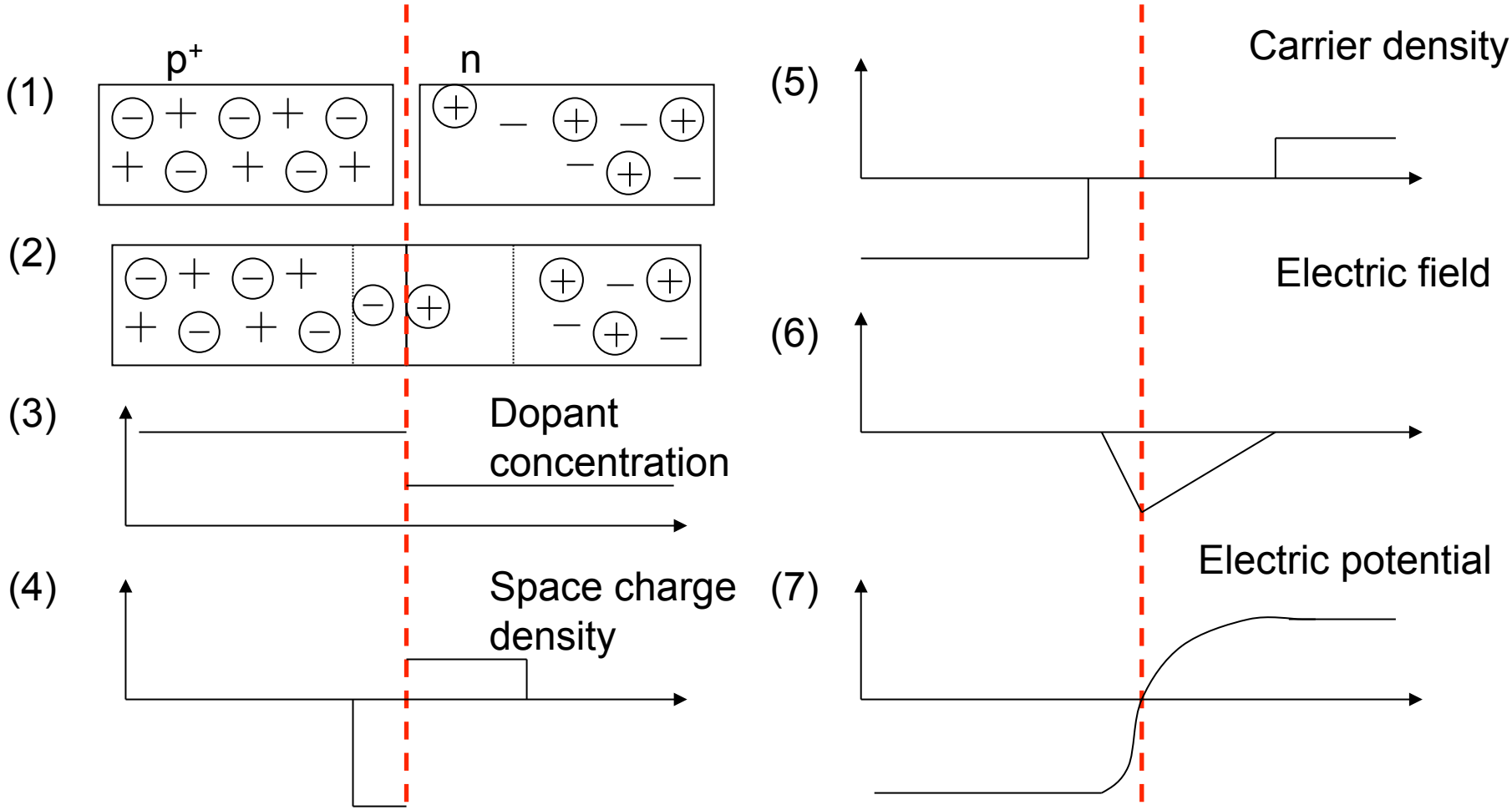


Why a diode?

- Signal from MIP = 23k e/h pairs for 300μm device
- Intrinsic carrier concentration
  - $n_i = 1.5 \times 10^{10} cm^{-3}$
  - Si area = $1cm^2$, thickness=300μm $\Rightarrow 4.5 \times 10^8$ electrons
  - 4 orders > signal
- Need to deplete device of free carriers
- Want large thickness (300μm) and low bias

  But no current!
  - Use v.v. low doped, pure, defect free material
  - p^+ rectifying (blocking) contact

p-n junction


(1)
p+
n
(2)
(3)
Dopant
concentration
(4)
Space charge
density
(5)
Carrier density
Electric field
(6)
(7)
Electric potential

p-n junction

1) Take your samples – these are neutral but doped samples: p^+ and n^-
2) Bring together – free carriers move
   - o two forces drift and diffusion
   - o In stable state

   $J_{diffusion}$ (concentration density) = J_{drift} (e-field)
3) p^+ area has higher doping concentration (in this case) than the n region
4) Fixed charge region with no free carriers

p-n junction

5) Depleted of free carriers
   - o Called space charge region or depletion region
   - o Total charge in p side = charge in n side
   - o Due to different doping levels physical depth of space charge region larger in n side than p side. The thickness of the region is know as the depletion width, W.
   - o Use n- (near intrinsic) $\Rightarrow$ very asymmetric junction

6) Electric field due to fixed charge

$$\frac{dE}{dx} = \frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$$

7) Potential difference across device
   - o Constant in neutral regions.
   - o Potential across device is known as the built in potential (0.7V in silicon)

Resistivity and mobility

- Carrier DRIFT velocity and E-field:

$$v = \mu E$$

$\mu_n = 1350 cm^2V^{-1}s^{-1}$: $\mu_p = 480 cm^2V^{-1}s^{-1}$

- Resistivity $$\rho = \frac{1}{q(\mu_n n + \mu_p p)}$$

  - p-type material $$\rho = \frac{1}{q\mu_p N_D}$$

  - n-type material $$\rho = \frac{1}{q\mu N_A}$$

Depletion width

- Depletion Width depends upon Doping Density:

$$W = \sqrt{\frac{2\varepsilon V}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

- For a given thickness, Full Depletion Voltage is:

$$V_{fd} = \frac{qN_D W^2}{2\varepsilon}$$

- W = 300μm, $N_D \sim 5\text{x}10^{12}\text{cm}^{-3}$: V_{fd} = 100V

Reverse Current

- Diffusion current
  - From generation at edge of depletion region
  - Negligible for a fully depleted detector
- Generation current
  - From generation in the depletion region
  - Reduced by using material pure and defect free
    - high lifetime
  - Must keep temperature low & controlled

$$j_{gen} = \frac{1}{2} q \frac{n_i}{\tau_0} W$$

$$n_i^2 = N_C N_V \exp\left(-\frac{E_g}{kT}\right)$$

$$j_{gen} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right) \qquad j_{gen} \times 2 \; for \; \Delta T = 8K$$

Capacitance

- Capacitance is due to movement of charge in the junction
- Fully depleted detector capacitance defined by geometric capacitance
- Strip detector more complex
  - Inter-strip capacitance dominates

$$C = \frac{dQ}{dV} = \sqrt{\frac{q\varepsilon N_A N_D}{2(N_A + N_D)V}} = \sqrt{\frac{q\varepsilon N_D}{2V}} = \sqrt{\frac{\varepsilon}{2\mu\rho V}} = \frac{\varepsilon}{W}$$

Noise

- Depends upon detector capacitance and reverse current
- Depends upon electronics design
- Function of signal shaping time
- Lower capacitance $\Rightarrow$ lower noise
- Faster electronics $\Rightarrow$ noise contribution from reverse current less significant

Noise

$$ENC_{tot}^{\ 2} = ENC_{pa}^{\ 2} + ENC_i^2 + ENC_R^{\ 2}$$

- Pre-amp noise
  - ENC_{pa} = A + B. C_{load}
  - Typically 100-500e
- Shot noise $$ENC_i = \frac{e}{q}\sqrt{\frac{qI_l\tau_s}{4}}$$ For CR-RC shaping
- Thermal noise $$ENC_R = \frac{e}{q}\sqrt{\frac{\tau_s kT}{2R_b}}$$

Fabrication

- Use very pure material
  - High resistivity
    - Low bias to deplete device
      - Easy of operation, away from breakdown, charge spreading for better position resolution
  - Low defect concentration
    - No extra current sources
    - No trapping of charge carriers
- Planar fabrication techniques
  - Make p-i-n diode
  - pattern of implants define type of detector (pixel/strip)
  - extra guard rings used to control surface leakage currents
  - metallisation structure effects E-field mag $\Rightarrow$ limits max bias

Fabrication stages

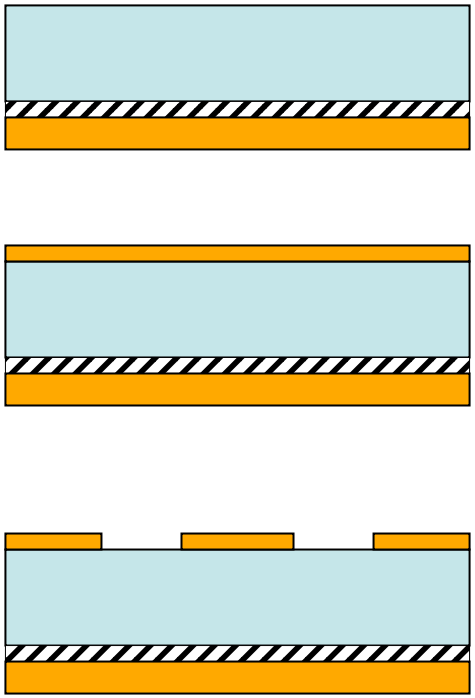
- Stages
  - dopants to create p- & n-type regions
  - passivation to end surface dangling bonds and protect semiconductor surface
  - metallisation to make electrical contact





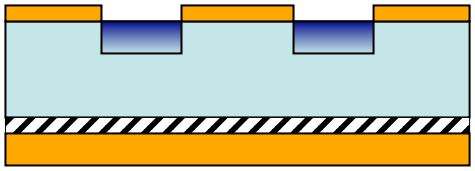
- Starting material
  - Usually n-
- Phosphorous diffusion
  - P doped poly n+ Si

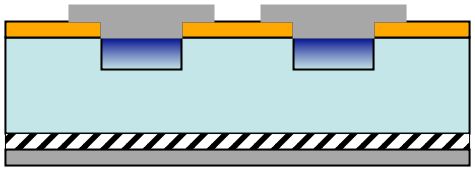
Fabrication stages



- Deposit SiO_2
- Grow thermal oxide on top layer
- Photolithography + etching of SiO_2
  - Define eventual electrode pattern

Fabrication stages





- Form p^+ implants
  - Boron doping
  - thermal anneal/Activation
- Removal of back SiO_2
- Al metallisation + patterning to form contacts

Fabrication

- Tricks for low leakage currents
  - low temperature processing
    - simple, cheap
    - marginal activation of implants, can’t use IC tech
  - gettering
    - very effective at removal of contaminants
    - complex

Energy Deposition

- Charge particles
  - Bethe-Bloch
  - Bragg Peak
- Not covered
  - Neutrons
  - Gamma Rays
    - Rayleigh scattering, Photo-electric effect, Compton scattering, Pair production

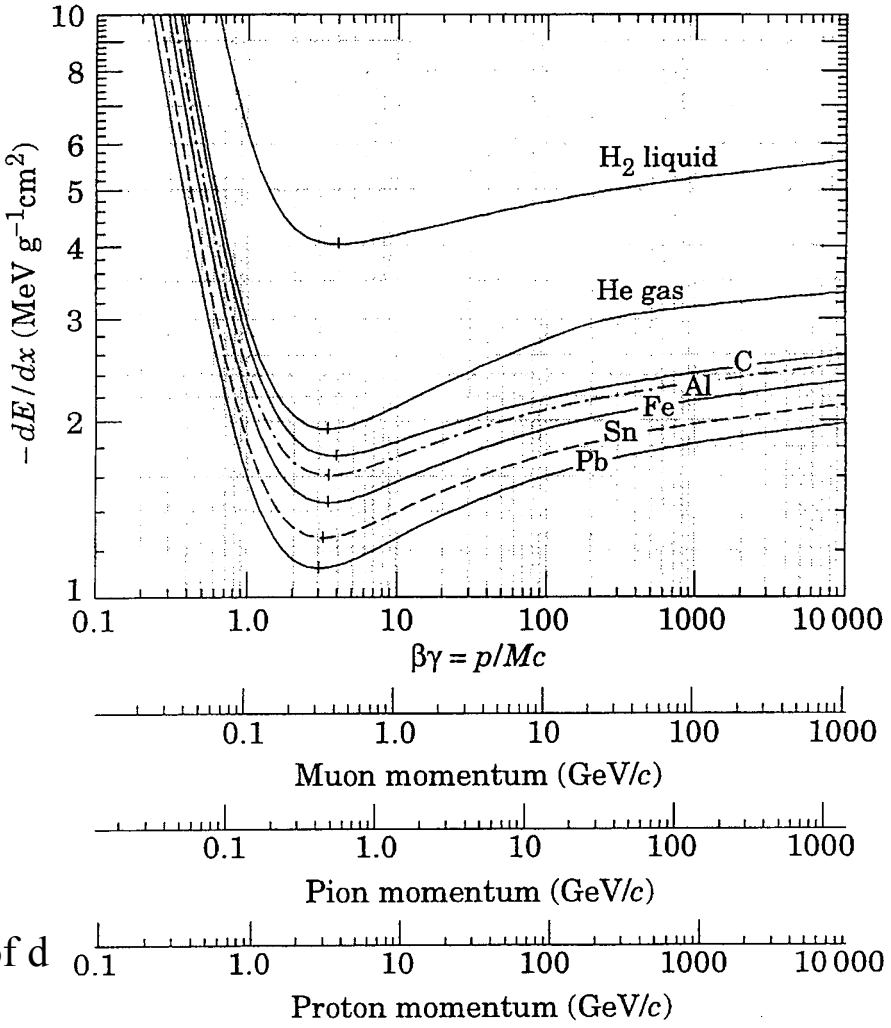
Charge particles

- concentrating on electrons

Bethe-Bloch formula

$$-\frac{dE}{dx} = \frac{4\pi q_e^4}{m_0}\frac{z^2}{v^2}\cdot NZ\cdot\left[\ln\frac{2m_0v^2}{I} - \ln\left(1-\beta^2\right) - \beta^2\right]$$

- At $\beta\gamma \approx 3$, dE/dx minimum independent of absorber (mip)
- Electrons
  - mip @ ~1 MeV
  - E>50 MeV radiative energy loss dominates

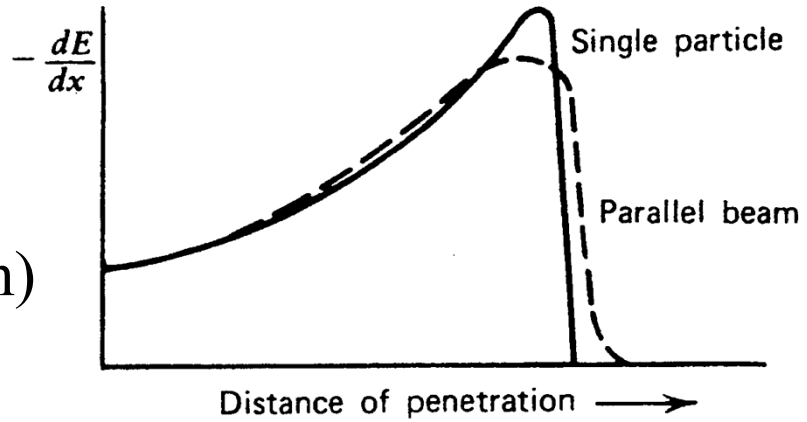


Momentum transferred to a free electron at rest when a charged particle passes at its closest distance, d. integrate over all possible values of d

Well defined range

- at end of range specific energy loss increases
- particle slows down
- deposit even more energy per unit distance

Bragg Peak



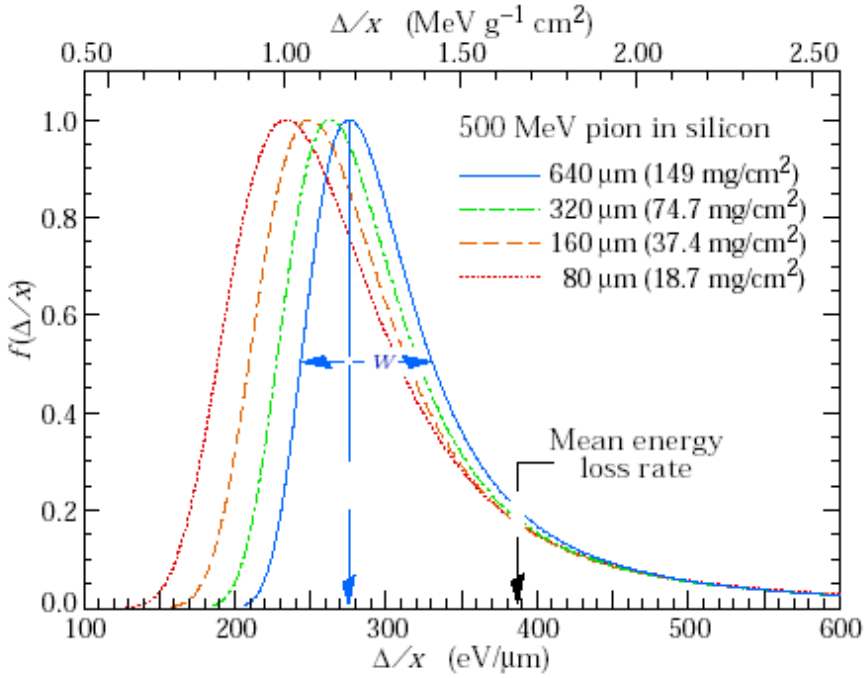
E = 5 MeV in Si:		R (μm)
(increasing charge)	p	220
	α	25
	^{16}O	4.3

Useful when estimating properties of a device

Energy Fluctuation

- Electron range of individual particle has large fluctuation
- Energy loss can vary greatly

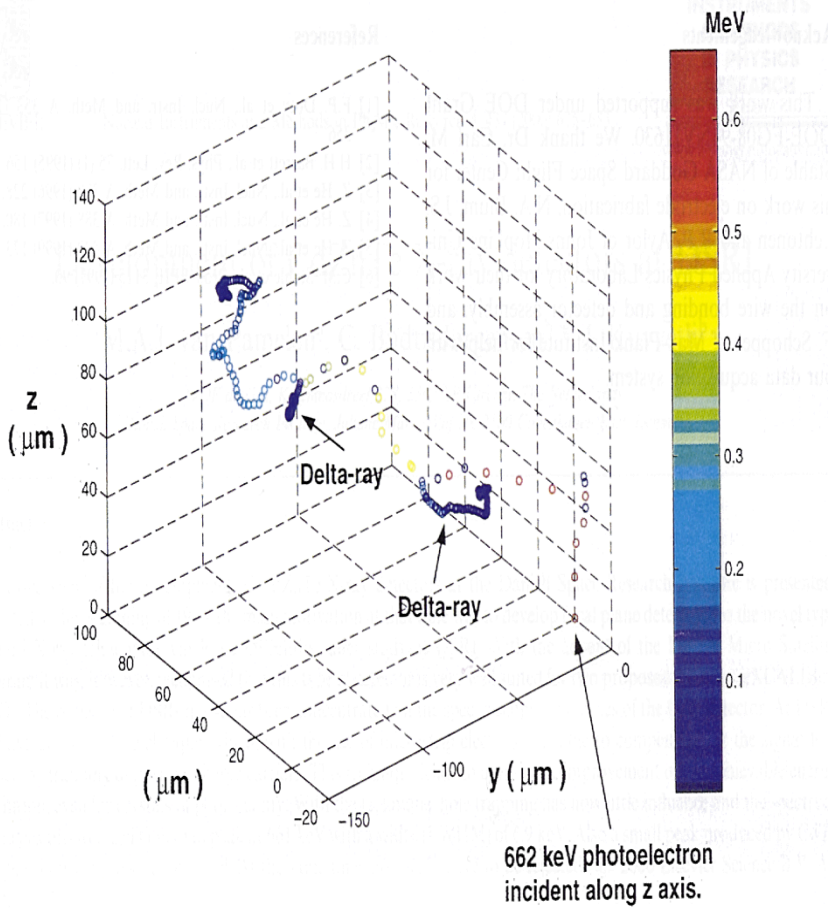
- Landau distribution
  - Close collisions (with bound electrons)
    - rare
    - energy transfer large
    - ejected electron initiates secondary ionisation
    - Delta rays - large spatial extent beyond particle track
  - Enhanced cross-section for K-, L-shells
  - Distance collisions
    - common
    - M shell electrons - free electron gas

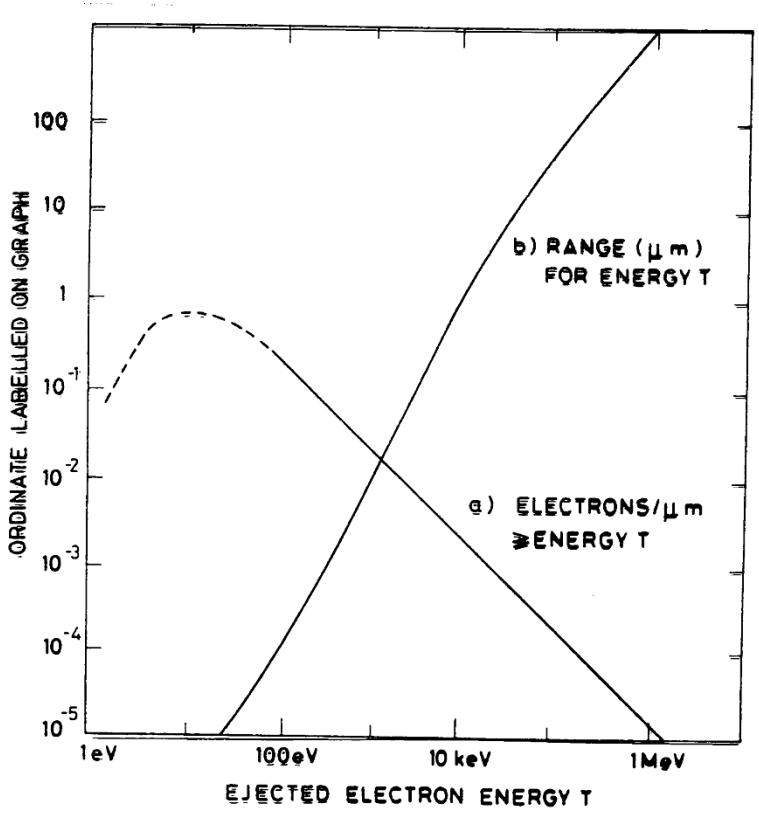


e/h pair creation

- Create electron density oscillation - plasmon
  - requires ~17 eV in Si
- De-excite almost 100% to electron hole pair creation
- Hot carriers cool
  - thermal scattering
  - optical phonon scattering
  - ionisation scattering (if E > 3/4 eV)
- Mean energy to create an e/h pair (W)
  is 3.6 eV in Si (E_g = 1.12 eV $\approx$ 3 x E_g)
- W depends on E_g therefore
  temperature dependent

Delta rays





a) Proability of ejecting an electron with E ≥ T as a function of T
b) Range of electron as a function of energy in silicon

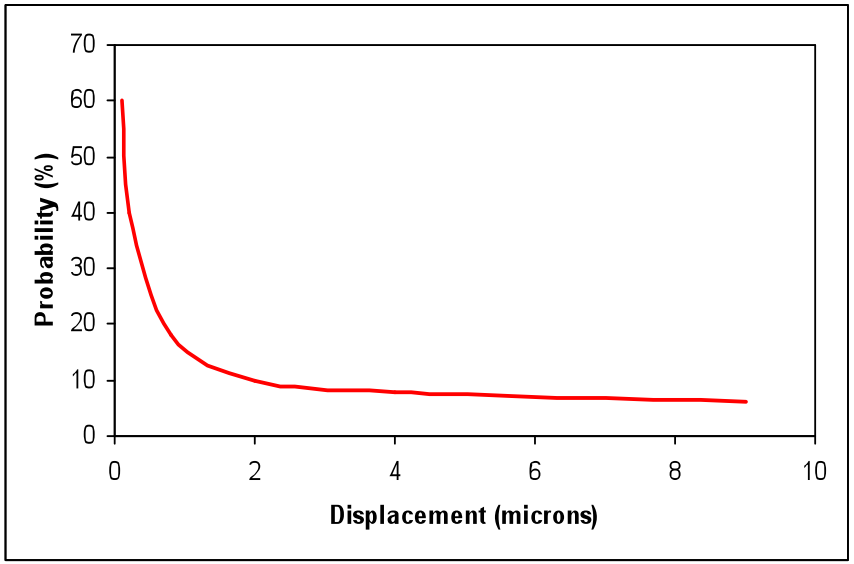
Displacement from δ-electrons

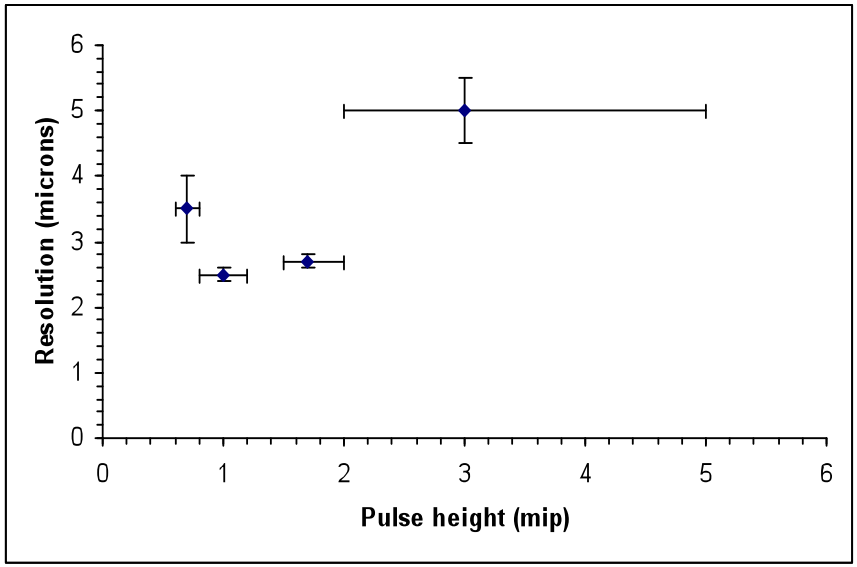
- Estimate the error
  - Assume 20k e/h from track
  - 50keV δ-electron produced perpendicular to track
  - Range 16μm, produces 14k e/h
  - Assume ALL charge created locally 8μm from particle's track

$$\Delta = \frac{20k \times 0\mu m + 14k \times 8\mu m}{20k + 14k} = 3.3\mu m$$

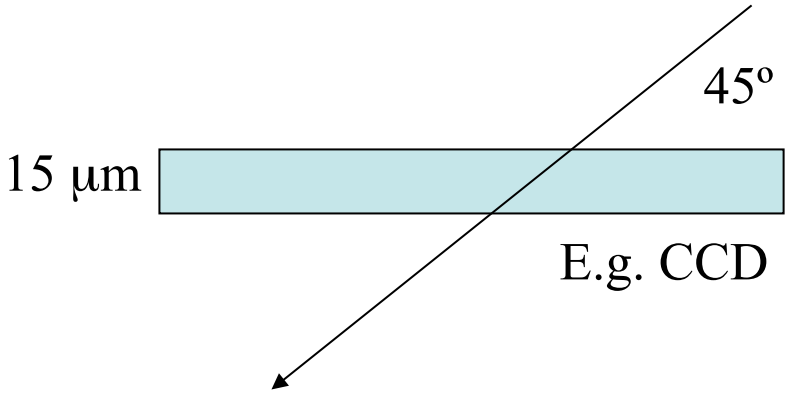
Consequences of d-electrons

- Centroid displacement
- Resolution as function of pulse height

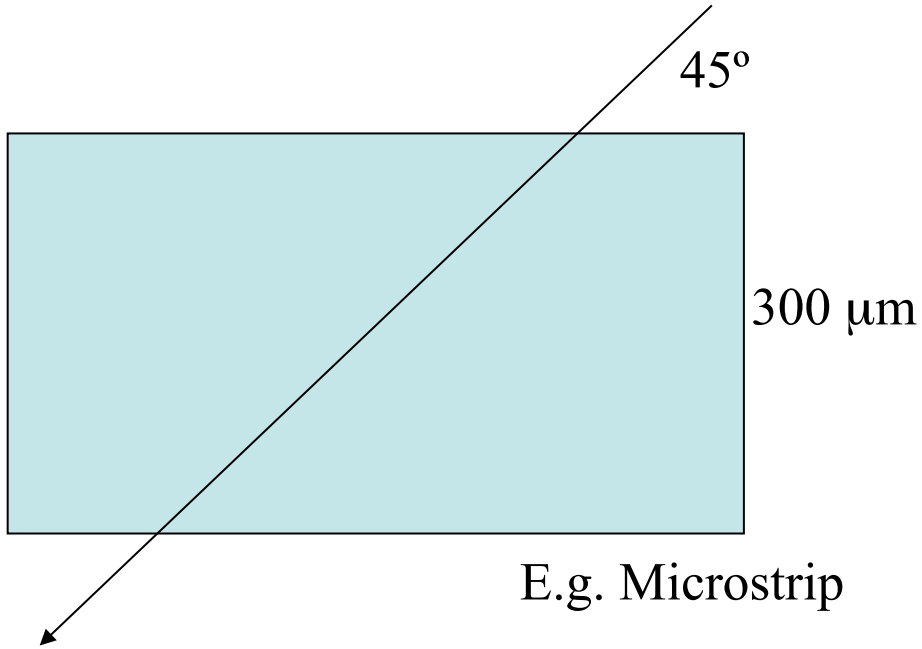




Consequence of δ-electrons



Most probable E loss = 3.6keV
10% prob^{y} of 5keV δ
pulls track up by 4 μm

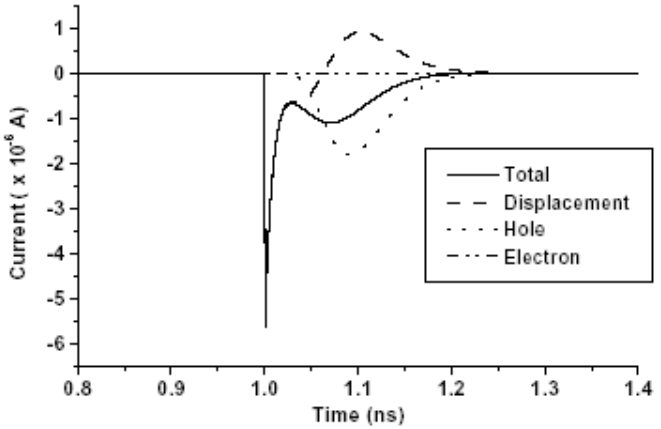


Most probable E loss = 72keV
10% prob^{y} of 100keV δ
pulls track up by 87 μm

Signal formation

- Signal due to the motion of charge carriers inside the detector volume & the carriers crossing the electrode
  - Displacement current due to change in electrostatics (c.f. Maxwell's equations)

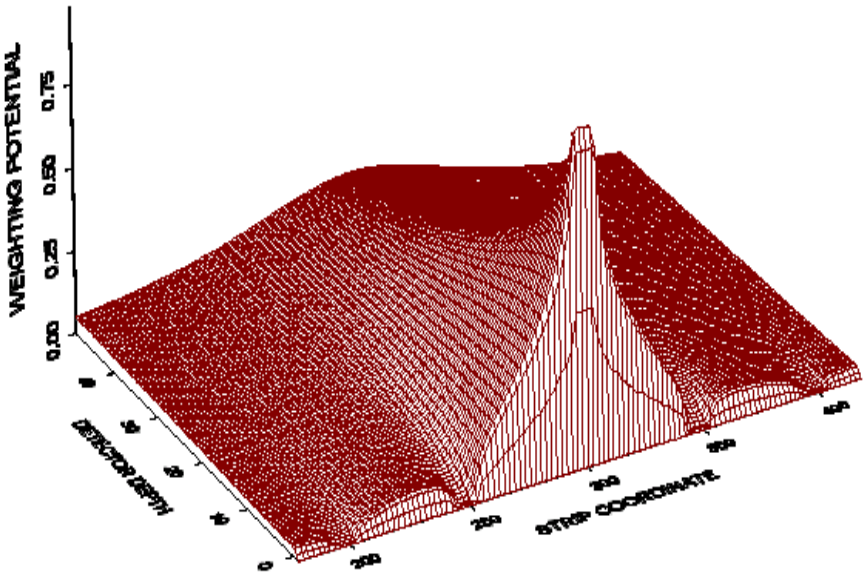
- Material polarised due to charge introduction
- Induced current due to motion of the charge carriers
- See a signal as soon as carriers move



Signal

- Simple diode
  - Signal generated equally from movement through entire thickness
- Strip/pixel detector
  - Almost all signal due to carrier movement near the sense electrode (strips/pixels)
  - Make sure device is depleted under strips/pixels

    If not:
    - Signal small
    - Spread over many strips



Currents induced by electron motion.
Simon Ramo

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