Basic Semiconductor Detector

Requirement:
Large sensitive region ...

We know:

$$d \approx x_p \approx \sqrt{\frac{2\epsilon U}{e N_A}}$$

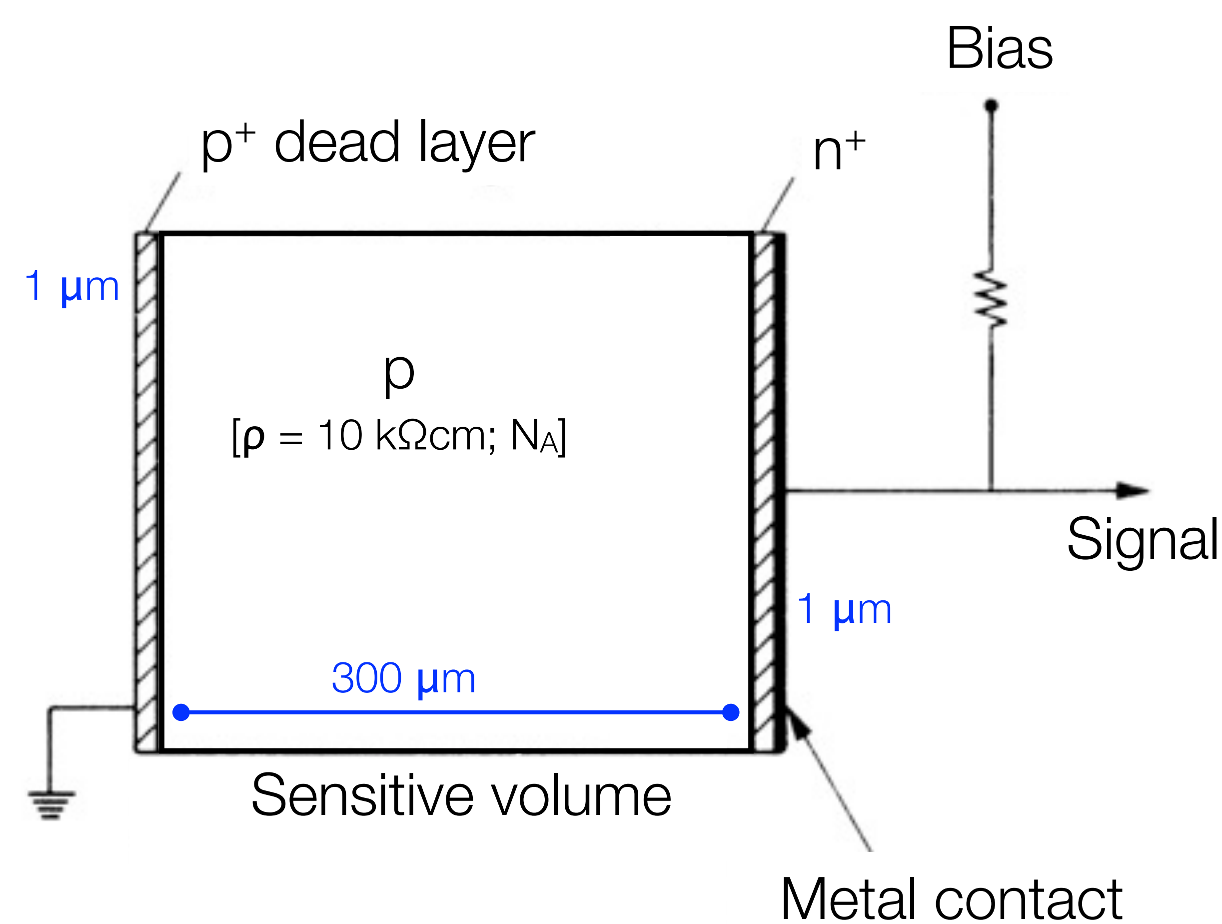
Typical: $N_A = 10^{15}/\text{cm}^3$
n^+ region highly doped: $N_D \gg N_A$

$$U = \frac{e}{2\epsilon} N_A d^2$$
$$= 100\ \text{V}$$

Electric field:

$$E = \frac{U}{d} = \frac{100\ \text{V}}{300 \cdot 10^{-6}\ \text{m}} \approx 3 \cdot 10^5\ \frac{\text{V}}{\text{m}}$$

[Safe. Breakdown limit at 10^7 V/m]



n^+ and p^+ needed to
allow metallic contacts ...
[High doping = small depletion zone]

Bias voltage supplied
through series resistor ...

Pulse Shape Estimate

Electric pulse arises from induction ...

Movement of electron from x ➛ x+dx
yields change in potential energy:

$$dW = e\,dU = e|\vec{E}|dx = e\frac{U_B}{d}dx$$

also: $$dW = dQ\,U_B$$

[dQ = charge collected by capacitor]

Thus:

$$dQ = \frac{e\,dx}{d}$$

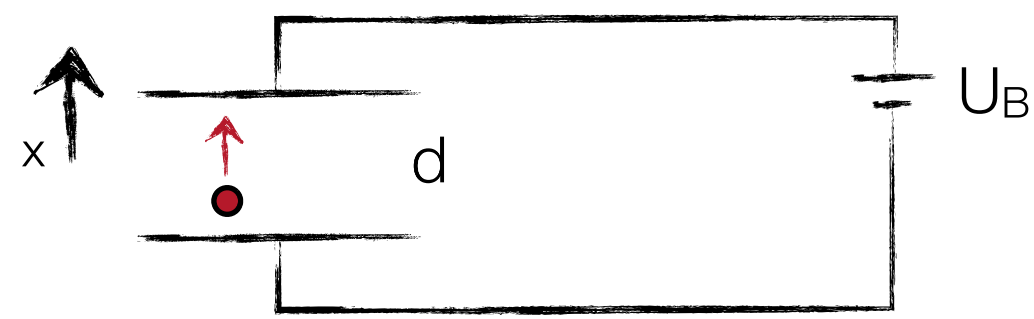
drift velocity

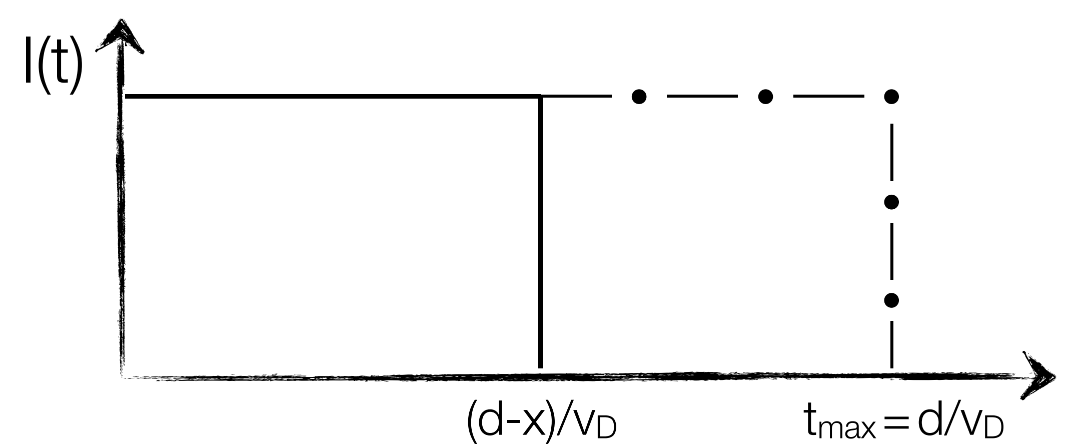
$$I = \frac{dQ}{dt} = \frac{dQ}{dx}\frac{dx}{dt} = \frac{e\,v_D}{d}$$

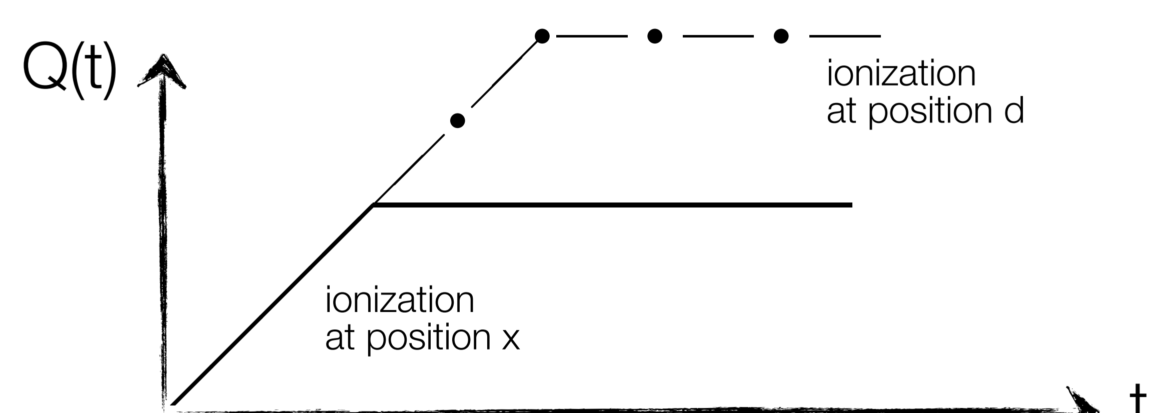
$$Q = e\frac{v_D}{d}\cdot t = e\frac{v_D}{d}\cdot\frac{d-x}{v_D}$$

$$= e\frac{d-x}{d}$$

Induced charge depends on
location of electron-hole production ...







Signal Pulse Shape

Pulse form for line source:
[simple estimate]

Current:

'location' of first pair; x(t) ...

$$I(t) = e\,\frac{v_D}{d}\cdot N_0\,\frac{d-x}{d}\;\Theta\left(\frac{d-x}{d}\right)$$

$$= e\,\frac{v_D}{d}\cdot N_0\,\frac{d-v_D t}{d}\;\Theta\left(\frac{d-v_D t}{d}\right)$$

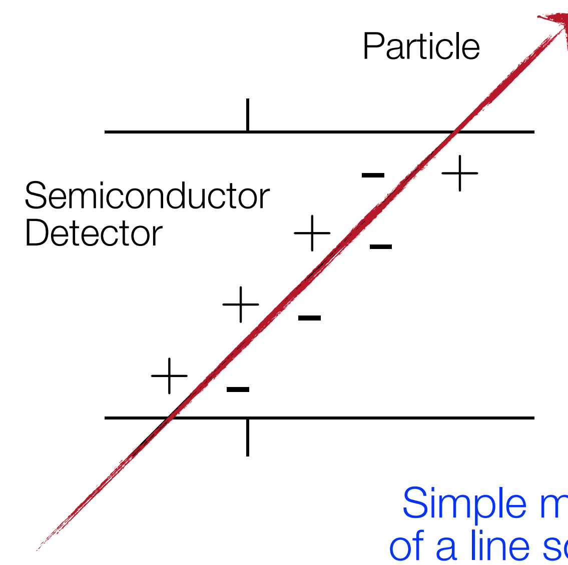
Charge:

$$Q(t) = N_0\, e\,\frac{v_D}{d}\int_0^t \left(1-\frac{t v_D}{d}\right)\Theta\left(1-\frac{t v_D}{d}\right)$$

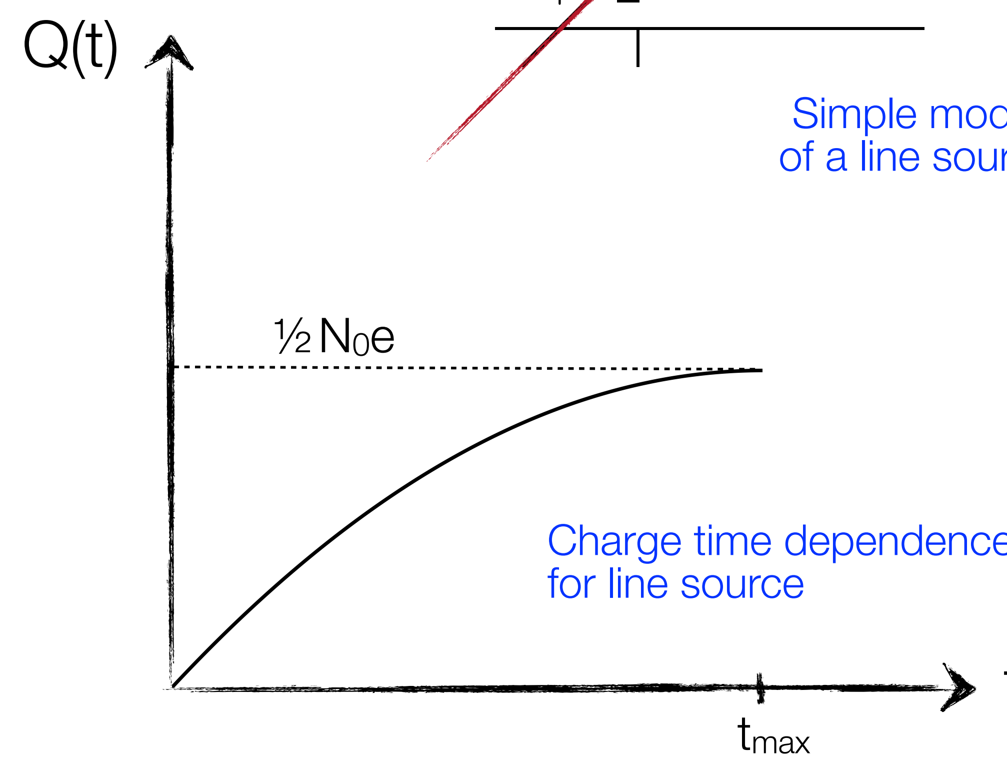
$$= N_0\, e\,\frac{v_D}{d}\left(t-\frac{t^2 v_D}{2d}\right)\Theta\left(1-\frac{t v_D}{d}\right)$$

Total charge after $t_{max} = d/v_D$:

$$Q(t_{\max}) = N_0\, e\,\frac{v_D}{d}\left(\frac{d}{v_D}-\frac{d^2}{v_D^2}\frac{v_D}{2d}\right) = \frac{N_0 e}{2}$$



Simple model of a line source



Charge time dependence for line source

Remark: such a signal is e.g. seen in LAr ionization chambers.

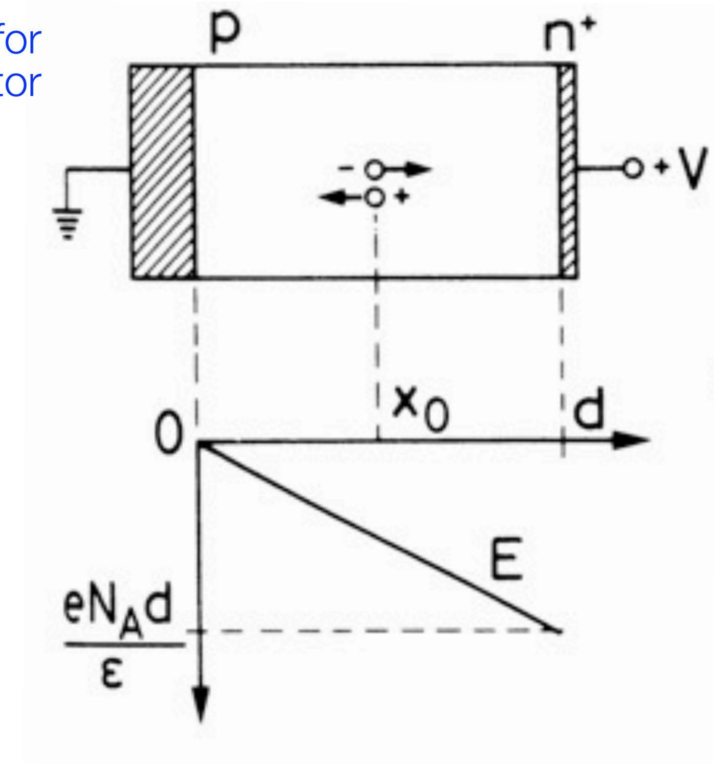
Electrons : Q_{max} = ½ $N_0 e$
Holes : Q_{max} = ½ $N_0 e$

$Q_{tot} = N_0 \cdot e$

Signal Pulse Shape

More realistic treatment:
Electric field is x-dependent ...

Use our example for typical Si-Detector



Electric field:

$$E = -\frac{eN_A}{\epsilon} \cdot x$$

assuming simple model for charge distribution over depletion zone ... [see above]

Conductivity:

$$\sigma = e(n\mu_e + p\mu_h) \approx eN_A\mu_h$$

[as here: $p \approx N_A$, $n \approx 0$]

Thus:

$$E = \frac{x}{\mu_h \tau} \quad \text{with } \tau = \epsilon/\sigma$$

[typical: τ = O(few ns)]

For an electron at location x within the depletion zone:

$$v = \frac{dx}{dt} = -\mu_e E = \frac{\mu_e}{\mu_h}\frac{x}{\tau}$$

i.e. drift velocity not constant!

Assuming μ_e, μ_h to be independent of E and thus of location x ...

$$x = x_0 \exp\frac{\mu_e t}{\mu_h \tau} \qquad \left[\text{and } t = \tau\frac{\mu_h}{\mu_e}\cdot\ln\frac{x}{x_0}\right]$$

$$Q_e(t) = -\frac{e}{d}\int_0^t \frac{dx}{dt}\,dt = \frac{e}{d}x_0\left(1 - \exp\frac{\mu_e t}{\mu_h \tau}\right)$$

Charge induced by electron as a function of time ...

Signal Pulse Shape

Induced charge
from electrons:

$$Q_e(t) = \frac{e}{d}x_0 \left(1 - \exp\frac{\mu_e t}{\mu_h \tau}\right)$$

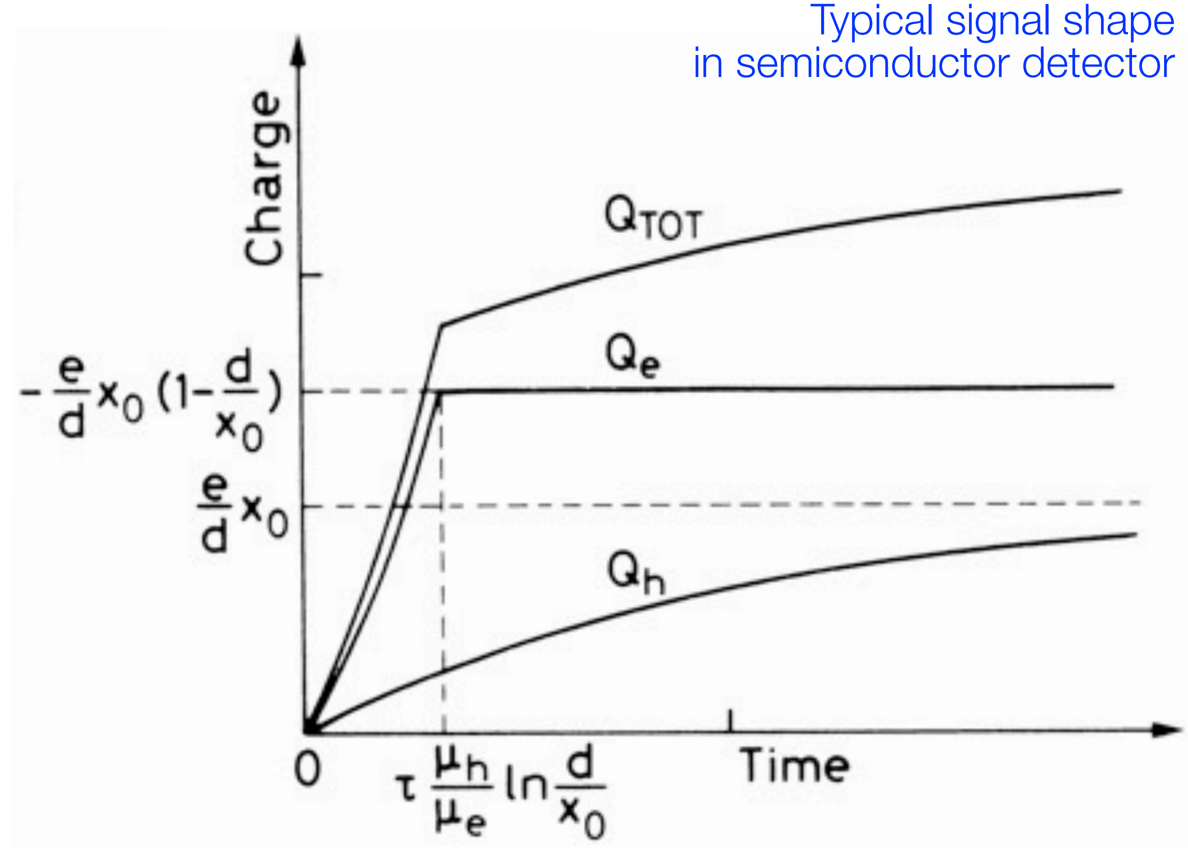
Similar for holes:

$$v = \frac{dx}{dt} = \mu_h\, E = -\frac{\mu_h}{\mu_h}\frac{x}{\tau} = -\frac{x}{\tau}$$
$$x = x_0 \exp\left(-\frac{t}{\tau}\right)$$

and thus:

$$Q_h(t) = -\frac{e}{d}x_0 \left(1 - \exp\left(-\frac{t}{\tau}\right)\right)$$

Typical signal shape
in semiconductor detector



Using:
$$t = \tau\,\frac{\mu_h}{\mu_e}\cdot \ln\frac{x}{x_0} \quad \text{and} \quad d = x$$

Summation yields:

$$Q_{\rm tot}(t) \;=\; Q_e(t) \;+\; Q_h(t)$$
$$Q_{\rm tot} \;=\; Q_e(t_d) \;+\; Q_h(t \to +\infty) = \frac{e}{d}x_0 \left(1 - \frac{d}{x_0}\right) - \frac{e}{d}x_0 = -e$$

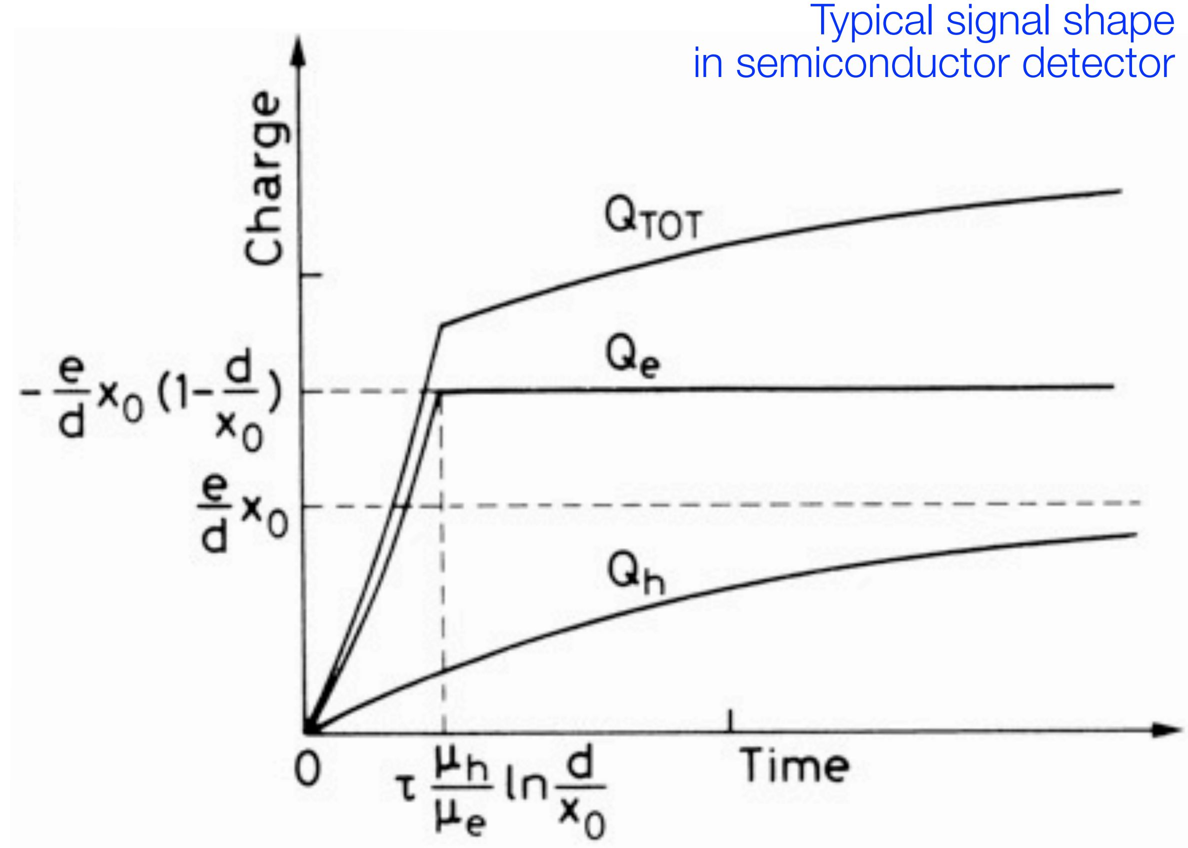
Signal Pulse Shape

Signal rise time
essentially determined by

$$\tau = \epsilon / \sigma$$

i.e. typically in the order of nanoseconds.
[Typical: $1/\sigma = \rho = 10000\ \Omega\text{cm}$; $\varepsilon \approx 10^{-12}\ \text{s}/\Omega\text{cm}$]

Typical signal shape
in semiconductor detector



[Using: $t = \tau\,\frac{\mu_h}{\mu_e}\cdot\ln\frac{x}{x_0}$ and $d = x$]

Further complications:

Consider particle trajectory
[here only for one electron-hole pair]

Tracks not exact line charge
[distributed over typically 50 - 100 μm width]

μ_e and μ_h not independent of E-field
[i.e. need to introduce μ(x) ...]

Potential losses due to traps
[loss or delayed charge induction]

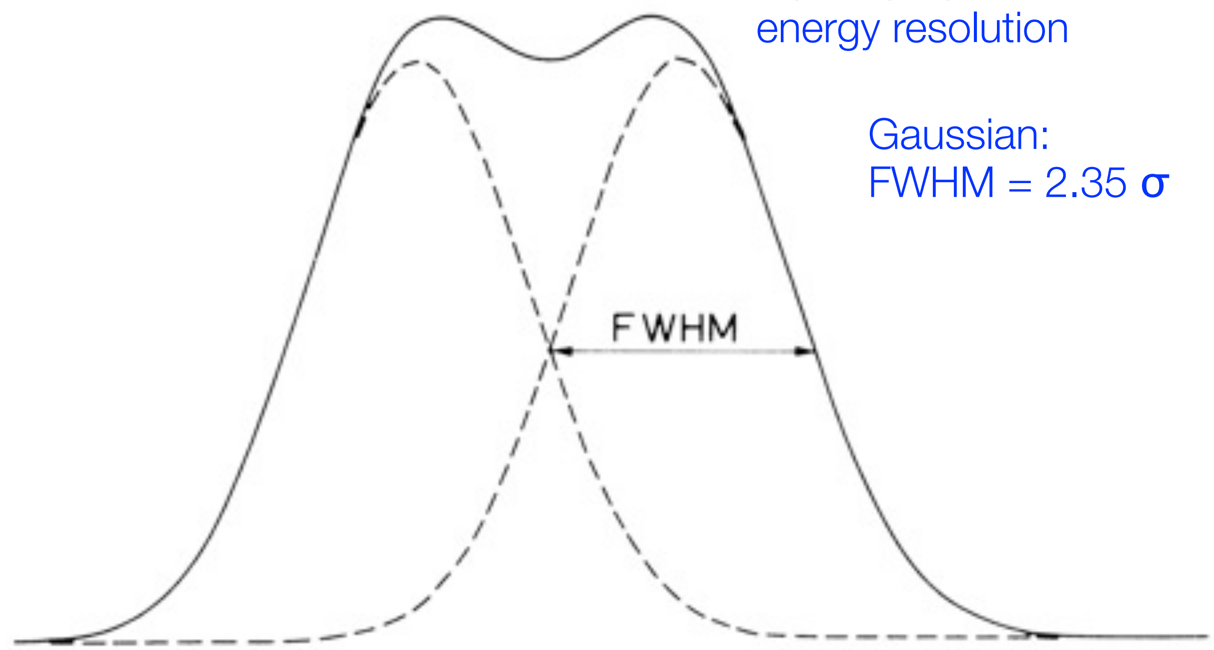
...

Ionization Yield and Fano Factor

Energy resolution:

$$\mathcal{R} = \frac{\Delta E}{E}$$

with ΔE defined
as full width half maximum ...



Definition of
energy resolution

Gaussian:
FWHM = 2.35 σ

Electron-hole pairs:
[or number of ionizations ...]

$$N_i = \frac{E}{\epsilon_0}$$

with ϵ_0 defined as average
energy per ionization ...

Resolution estimate:

$$E \sim N_i \,, \qquad \sigma^2 \sim N_i \,, \qquad \Delta E \sim 2.35\sigma \sim 2.35\sqrt{N_i}$$

$$\mathcal{R} = 2.35\,\frac{\sqrt{N_i}}{N_i} = 2.35\,\sqrt{\frac{\epsilon_0}{E}} \sim \frac{1}{\sqrt{E}}$$

If full energy is absorbed this estimate is incorrect, as E is fixed and thus cannot fluctuate, i.e. fluctuations are not all independent and ...

$$\sigma^2 = F N_i$$

[F: Fano Factor]

➛

$$\mathcal{R} = 2.35\,\frac{\sqrt{F N_i}}{N_i} = 2.35\,\sqrt{\frac{F\epsilon_0}{E}}$$

For many detectors F < 1;
yields better resolution ...
[e.g. semiconductors or gases]

Ionization Yield and Fano Factor

Energy loss:

Only ~1/3 of the energy loss produces electron-hole pairs;
About 2/3 is used for lattice excitations, i.e. phonons ...

Energy loss per process:

Phonon excitation : $E_x \sim 0.037$ eV
Ionization : $E_i = E_{gap} \sim 1$ eV [e.g. 1.1 eV for Si]

	ε_0 [@ 300 K]	ε_0 [@ 77 K]	E_{gap}
Si	3.6 eV	2.8 eV	1.1 eV
Ge	–	2.9 eV	0.7 eV

ε_0: mean energy per electron-hole pair

Energy conservation:

$$E_0 = E_i \cdot N_i + E_x \cdot N_x$$

$$E_x \cdot \Delta N_x + E_i \cdot \Delta N_i = 0$$

as fluctuations in N_i are compensated
by fluctuations in N_x to keep E_0 constant ...

with
E_0 : total energy deposited; fixed ...
N_x : number of excited phonons
N_i : number of ionization, i.e. electron-hole pairs
ΔN_x : fluctuations of N_x
ΔN_i : fluctuations of N_i

On average:

$$E_x \sigma_x = E_i \sigma_i$$

with $\sigma_i = \sqrt{N_i}$, $\sigma_x = \sqrt{N_x}$

➛ $$\sigma_i = \frac{E_x}{E_i}\sigma_x = \frac{E_x}{E_i}\sqrt{N_x}$$

Ionization Yield and Fano Factor

Variance of N_i:

using $N_i = E_0/\epsilon_0$

$E_0 = E_i \cdot N_i + E_x \cdot N_x$

➛ $N_x = (E_0 - E_i N_i)/E_x$

$$\sigma_i = \frac{E_x}{E_i}\sqrt{N_x} = \frac{E_x}{E_i}\sqrt{\frac{E_0}{E_x} - \frac{E_i}{E_x}N_i}$$

$$= \frac{E_x}{E_i}\sqrt{\frac{E_0}{E_x} - \frac{E_i}{E_x}\frac{E_0}{\epsilon_0}} = \sqrt{\frac{E_0}{\epsilon_0}}\underbrace{\sqrt{\frac{E_x}{E_i}\left(\frac{\epsilon_0}{E_i} - 1\right)}}_{\text{Fano Factor } F} = \sqrt{N_i\, F}$$

Yields resolution better than expected ...

Numbers:

Si : ε_0 = 3.6 eV @ 300 K F ≈ 0.1

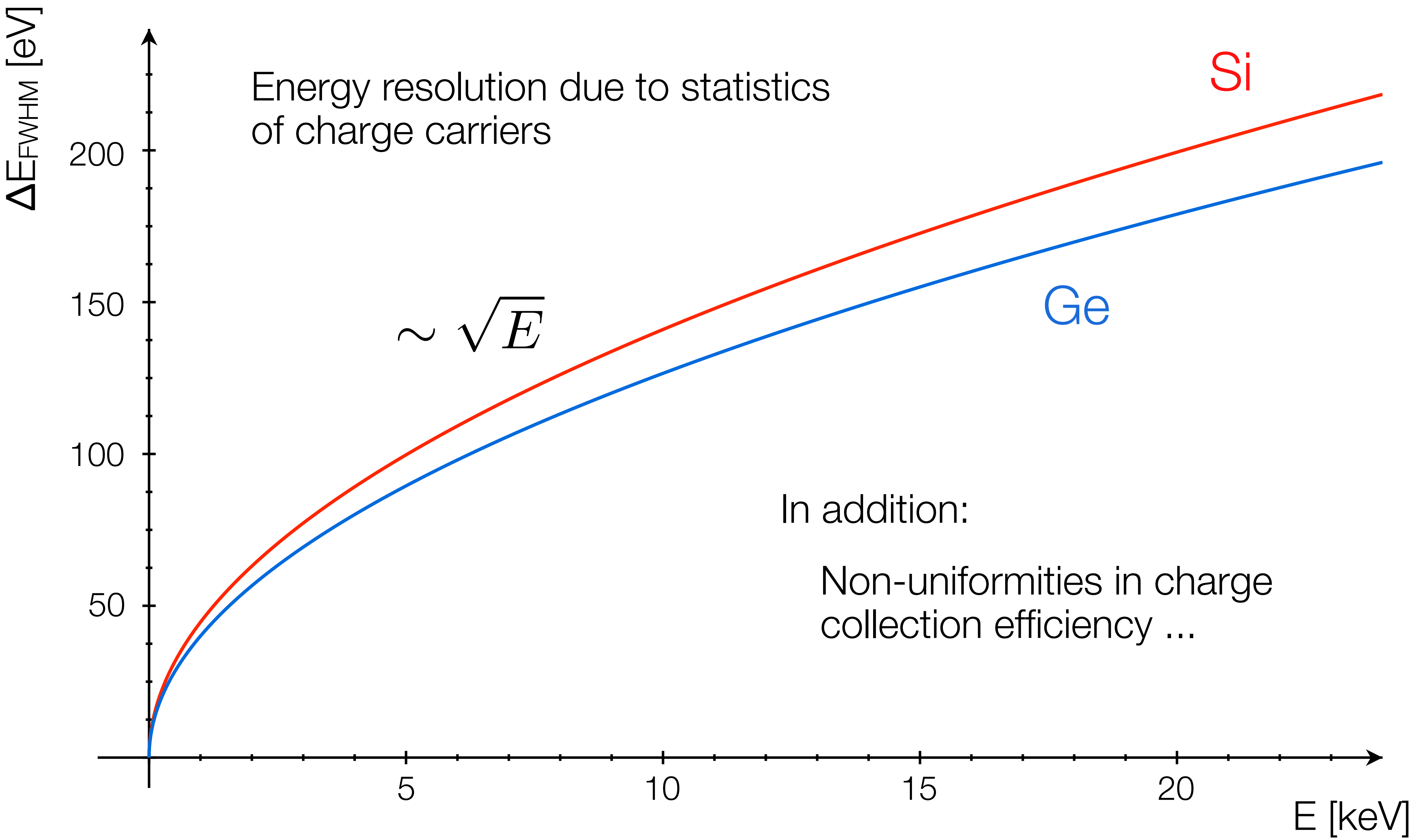
Ge : ε_0 = 2.9 eV @ 77 K F ≈ 0.1

Resolution:

$$\Delta E_{\mathrm{FWHM}} = 2.35 \cdot \epsilon_0 \sqrt{N_i\, F} = 2.35 \cdot \sqrt{\epsilon_0\, F\, E_0}$$

Example: Photon of 5 keV; $E_\gamma = E_0$ ➛ ΔE = 100 eV, ΔE/E = 2% [instead of 6%]

Energy Resolution



Energy Resolution

Comparison
of energy resolutions ...

Scintillator [NaI(Tl)]: 1 MeV photon; $\sigma/E \approx 2\%$; $\Delta E/E \approx 5\%$
[N_i = 40000 photons/MeV x η x Q.E.; η =0.2, Q.E. = 0.25; $\sigma/E = 1/\sqrt{N_i}$]

Semiconductor [Si]: 1 MeV photon; $\sigma/E \approx 0.06\%$; $\Delta E/E \approx 0.15\%$
[N_i = 300000 e/h-pairs/MeV; $\eta \approx 1$, Q.E. $\approx$ 1; F = 0.1 $\sigma/E = \sqrt{F}/\sqrt{N_i}$]

Energy resolution of a semiconductor detector
can be better by a factor 25 to 30.

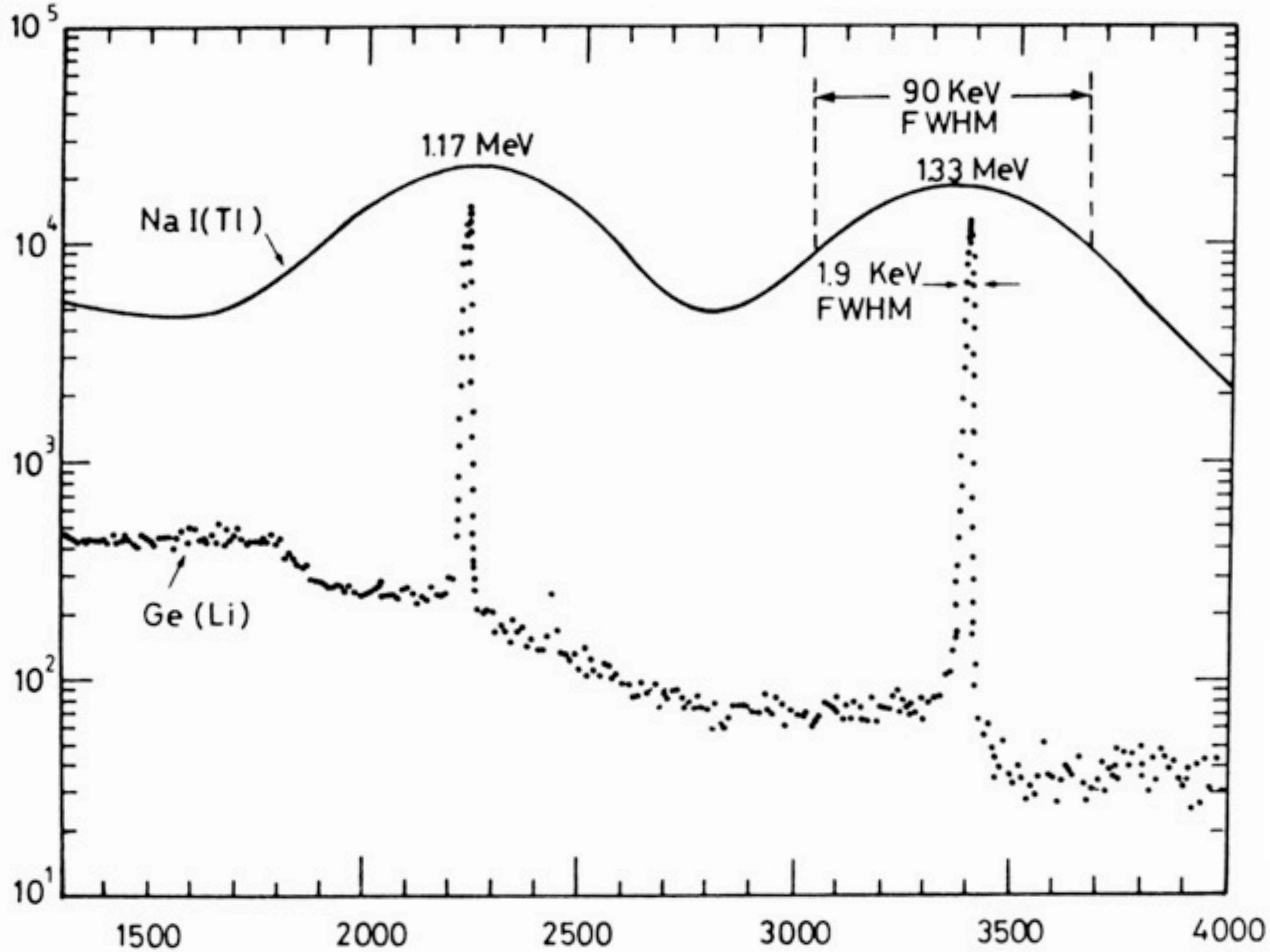
This is indeed observed:
[for E_γ = 1.33 MeV]

Ge(Li) Counter: Resolution of 0.15% possible (at ~ 1 MeV)

NaI(Tl) Detector: Resolution of about 6% (at ~ 1 MeV)

Energy Resolution

Events per Channel



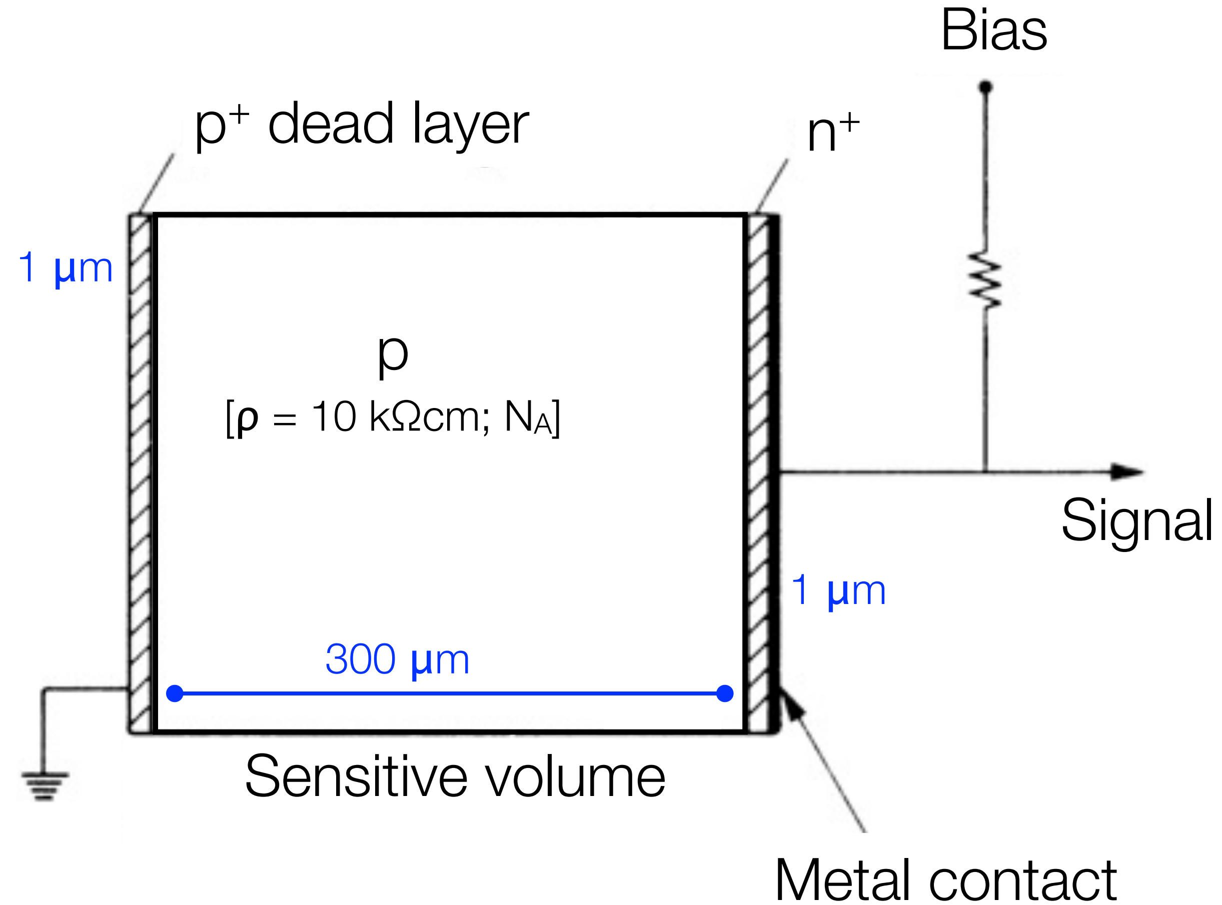
Channel Number

Comparison
of two ^{60}Co γ-spectra
one measured with NaI(Tl)
and With Ge(Li) Detector

Energy Measurement – Realization

Diffused Barrier Detectors
[or Diffused Junction Diodes]

[see above]



Material: p-type semiconductor
with n^+ and p^+ surface contacts ...

Impurities [e.g. phosphorus for n^+]
are diffused into one end of homogeneous p-type semiconductor at high T ~ 1000 °C

Typical dimensions:

Surface layers (n^+/p^+) : 0.1 to 2 µm
Depletion layer (p-type) : 300 µm

Disadvantages:

Highly doped n^+ surface leaves relatively thick dead layer for particles entering the detector ...
i.e. soft or short range particles (e.g. α's) not measured as they don't reach depletion layer ...
or part of the deposited energy is not measured ➛ degraded energy resolution

Alternative: Ion-implanted Diodes
[Advantage: Thinner entrance windows of ~50 nm; lower T ~ 500 °C yielding higher lifetime]

Energy Measurement – Realization

Surface Barrier Detectors

Very thin metal contact layers (~ 20 nm)

[n-type Si with gold or p-type Si with Aluminum]

Fabrication process: etching silicon surface
and depositing thin Au layer by evaporation ...

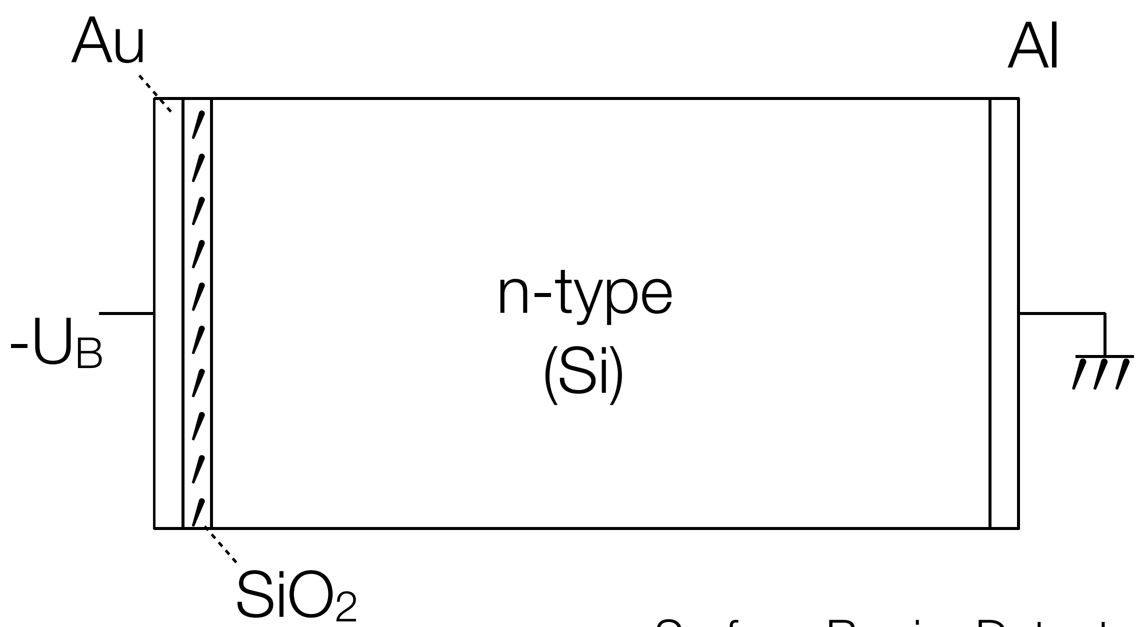
Processing temperature: 20 °C
Si-Surface must be oxidized before Au deposition ...

Electrons diffuse into metal ...

Different Fermi levels lead to contact electromotive force (emf); potential arises via equilibration process ...

Yields depletion depths of up to 5 mm [$\sim \sqrt{U_B}$]

Depletion zone extends through entire thickness of the silicon layer
[high depletion possible due to high resistance]



Surface Barrier Detectors
with thin gold layer
[Schottky Diode]

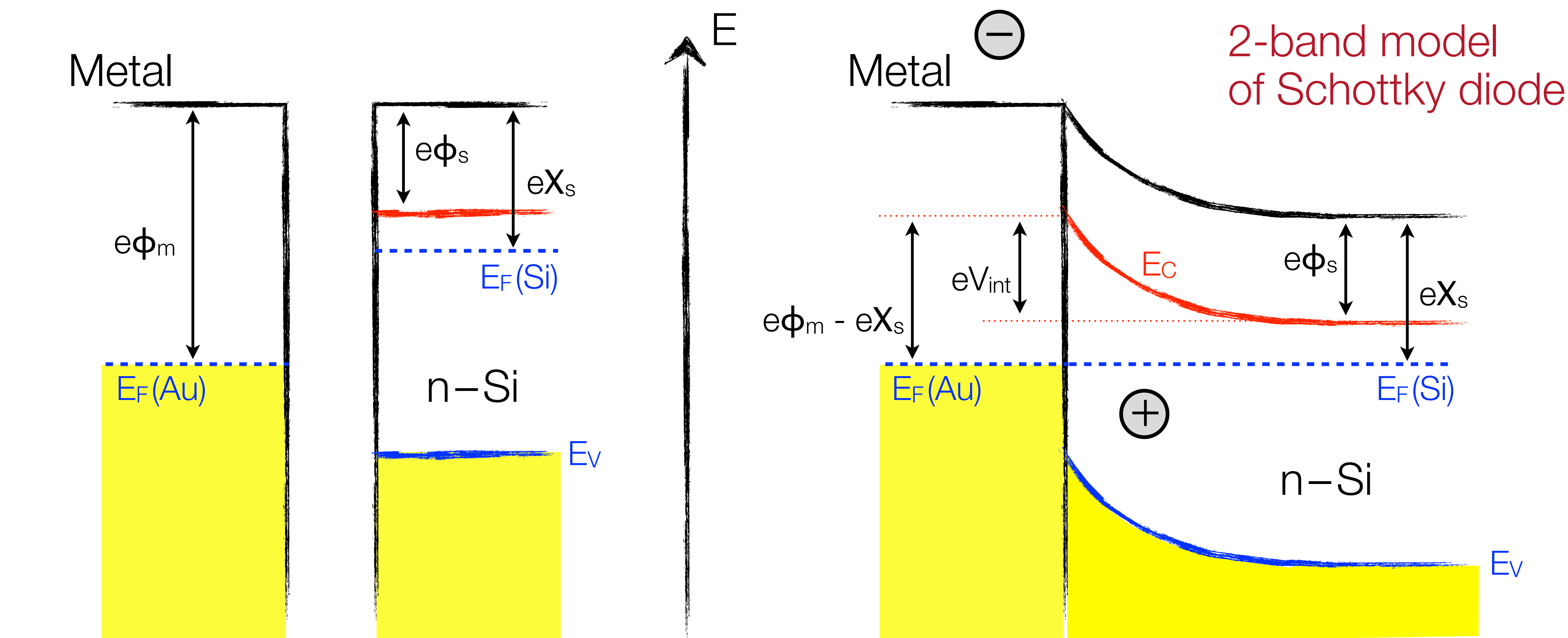
Advantages:

Thin entrance window ...
Full depletion allows dE/dx measurement
Applying $-U_B$ at metal: high potential barrier; no dark currents
Increasing bias voltage beyond full depletion ➛ faster signal rise

Disadvantage:

Sensitivity to visible light ...
requires light enclosure

Energy Measurement – Realization



Metal - Si
separate

Metal - Si
in contact

$e\phi_m$: work function of metal
$e\phi_s$: work function of semiconductor
eX_s : work affinity of semiconductor (material constant)

$e\phi_\Delta = e\phi_m - eX_s$ (potential well)
$eV_{int} \approx e\phi_m - e\phi_s$ (potential difference seen by carriers)

Results in strong E field at surface ...

Development of
Depletion zone:

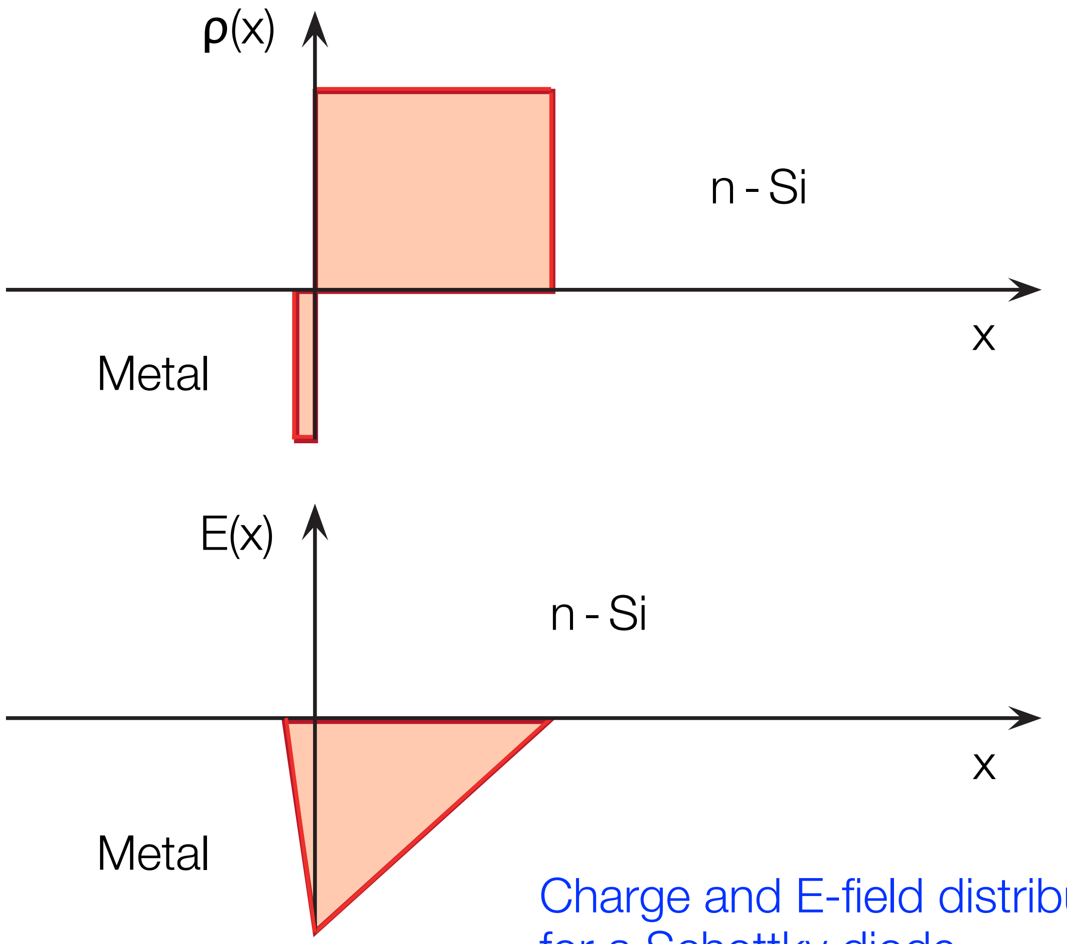
Occurrence of electromotive force ...

Electrons diffuse into metal until
Fermi levels become equal ...

Energy Measurement – Realization

Surface Barrier Detectors
can be operated as a diode.

[Schottky Diode]



Charge and E-field distribution for a Schottky diode

Metal-Si contact:

Electrons diffuse from metal to Si until

$E_F(\text{metal}) = E_F(\text{Si})$;

Strong electric field at boundary prevents further electron diffusion into metal

With bias voltage:

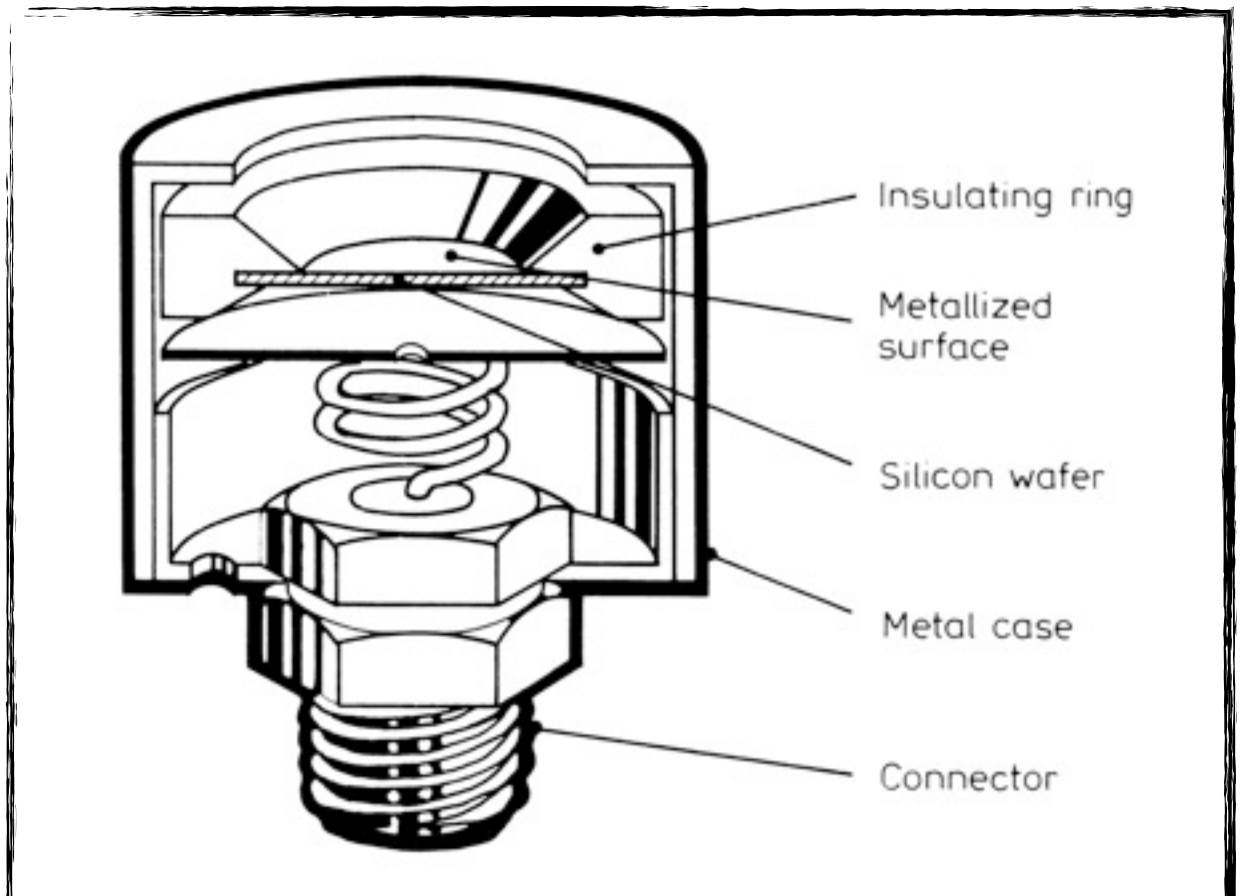
Reverse bias: positive potential of n - Si w.r.t metal; increased potential well, electron carriers cannot tunnel from Si to metal.

Forward bias: negative potential of n - Si w.r.t metal; decreased potential barrier, current can flow.

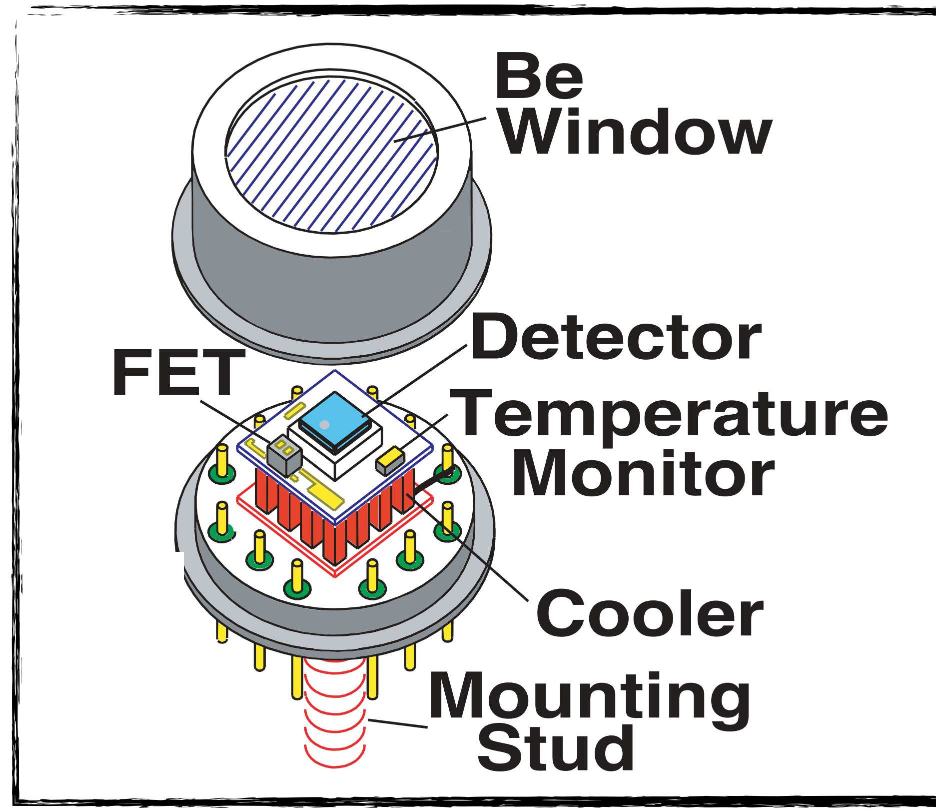
Energy Measurement – Realization

Examples of
Surface Barrier Detectors
[SSB]

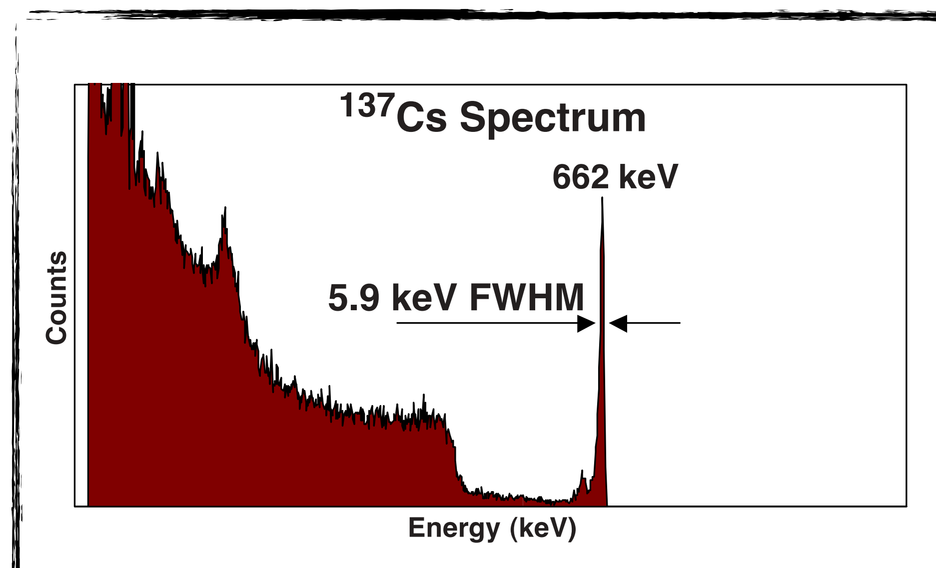
[Cross section of typical SSB]



[CdTe x-ray and γ-ray detector]



AmpTek



AmpTek

Energy Measurement – Realization

p-i-n Detectors:
[Lithium drift diodes]

Obtain thicknesses
greater than few millimeter ...

[needs very high resistivity; intrinsic semiconductor]

Idea:
Create thick depletion layer by
compensation of donors or acceptors ...

[i.e. produce intrinsic layer]

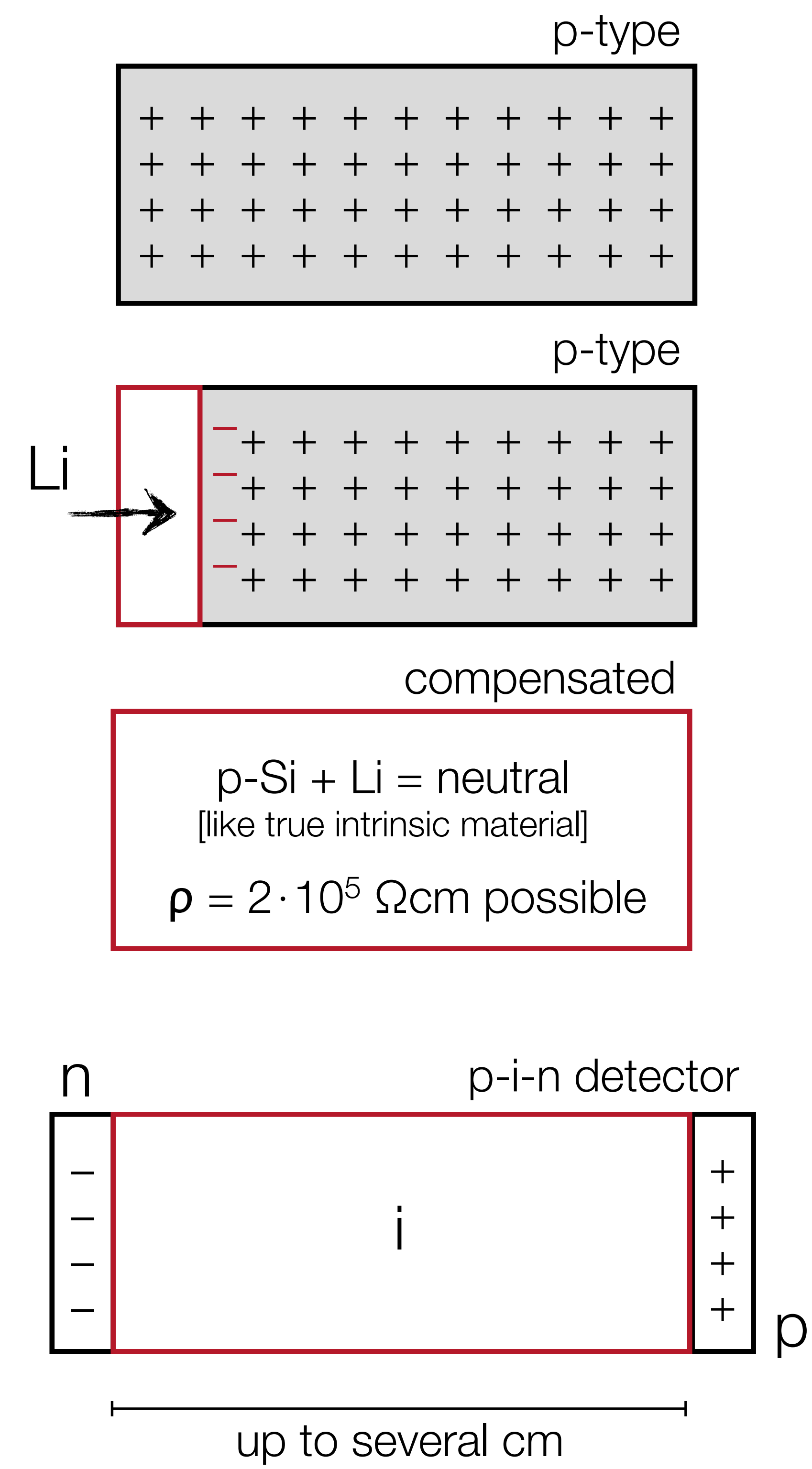
Compensation process:

i. Start with high purity p-type Ge or Si
[acceptor typically B (boron)]

ii. Bring semiconductor in contact
with Li bath @ 350-400 °C;
[Li diffuses into p-layer]

iii. Apply external field; Li drifts far into
crystal and compensates B locally
[equilibration process]

Ge(Li) detectors need
permanent cooling



Energy Measurement – Realization

Intrinsic Ge Detectors:
[High Purity Ge Detectors]

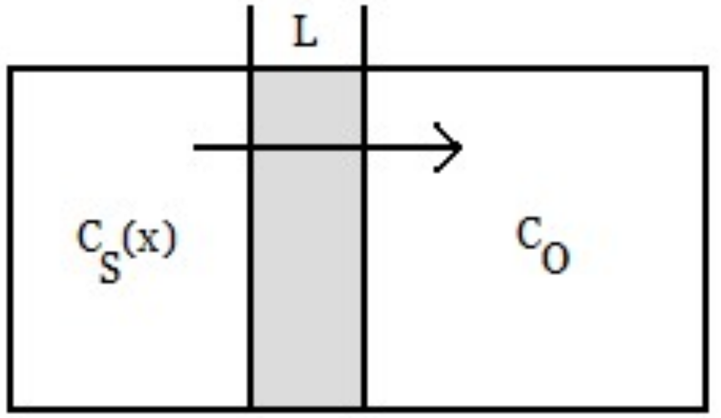
Since 1980ies: possibility to produce very pure Germanium,
i.e. produce intrinsic semiconductor without need for compensation ...

Advantage: no cooling needed
[except for noise reduction]

Purification process: zone melting

Successively melting narrow regions of a crystal moves impurities to end of ingot ...
Repeating process yields very high purities [< 10^9 impurity atoms per cm^3]

Zone melting



Applications:
[depends on detector size and energy range]

- γ-spectroscopy
- low energy electron detection
- detection of strongly ionizing particles
- dE/dx for particle ID
- ...

Position Sensitive Detectors

Motivation:

b-Quark tagging & life time measurements
via secondary vertex finding ...

e.g.: $p\bar{p} \rightarrow t\bar{t} + X$ [Tevatron]

$\hookrightarrow b\bar{b}W^+W^-$

$pp \rightarrow H + X$ [LHC]

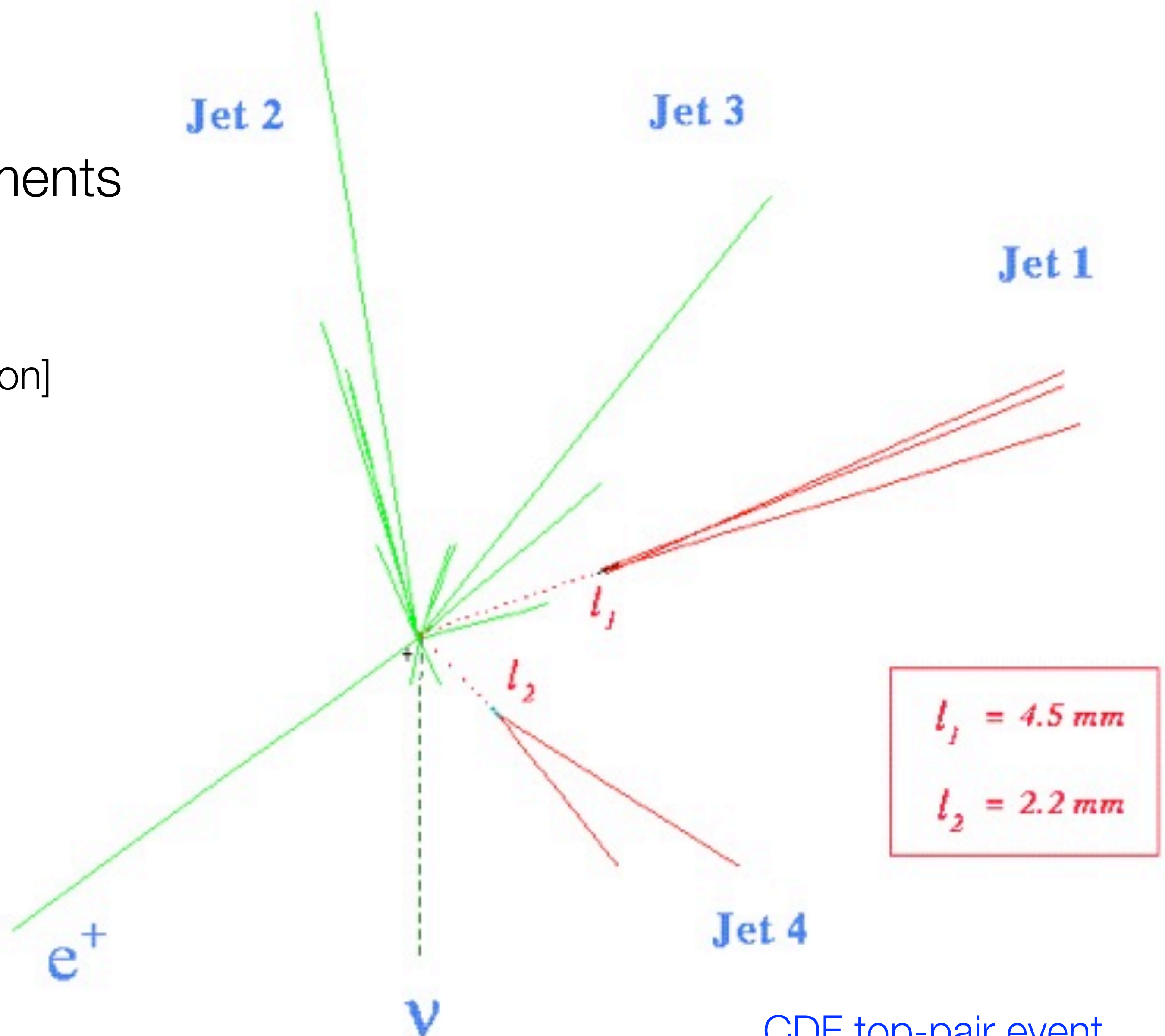
$\hookrightarrow b\bar{b}$

Typical lifetime: $\tau = 10^{-12} \ldots\ldots 10^{-13}$ s

$\gamma c\tau = \gamma \cdot 3 \cdot 10^{10}$ cm/s $\cdot\, 10^{-13}$ s
$= \gamma \cdot 30$ µm

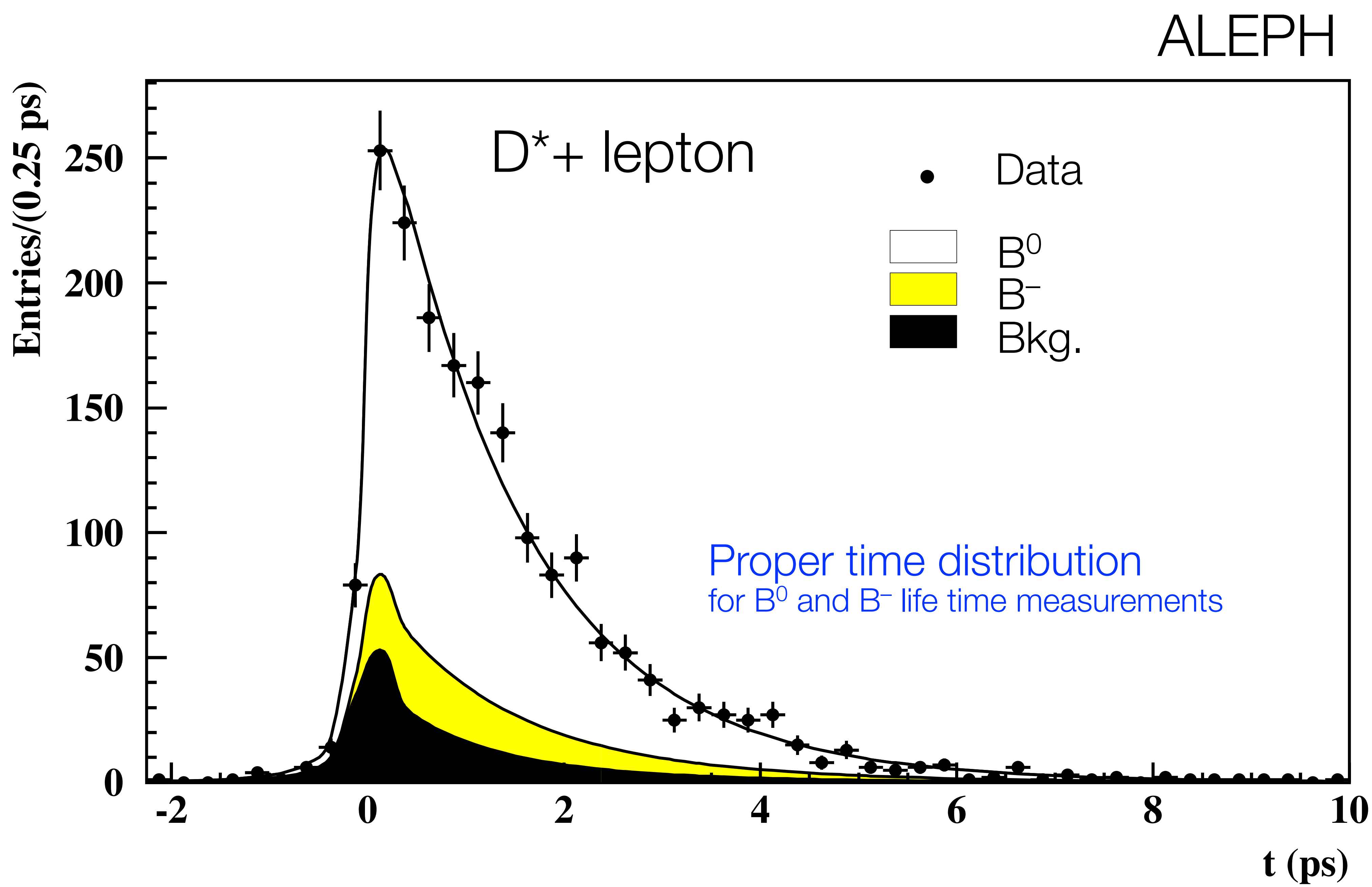
Thus:

To measure lifetime in picosecond regime
one needs spacial resolution of the order of 5 - 30 µm ...



CDF top-pair event
[M_{top} = 170 ± 10 GeV]

Position Sensitive Detectors



Position Sensitive Detectors

Principle:

Segmentation
into strips, pads, pixels ...

Typical parameters:

Thickness: 150 - 500 μm
Strip separation (pitch): 20 - 150 μm
Resolution: 5 - 40 μm (pitch/$\sqrt{12}$)

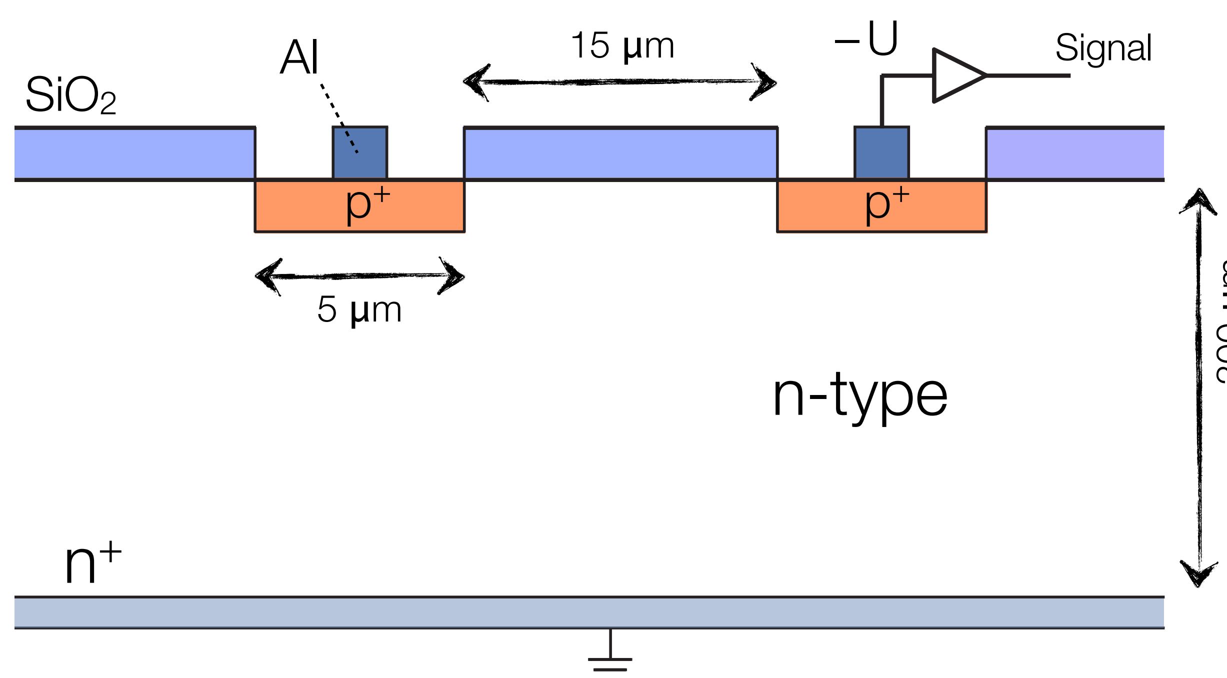
Charge collection: 20 ns
Charge integration: 120 ns

Operation voltage: 160 V

Output signal:

Total charge: Q_{out} ~ 4 fC

Average energy loss of MIP: 300 eV/μm; Si: 3.6 eV/pair.
Thus 80 electron-hole pairs per μm;
300 μm thickness ➛ 25000 pairs/MIP



Schematics of
Silicon Strip Detector

[from 1983]

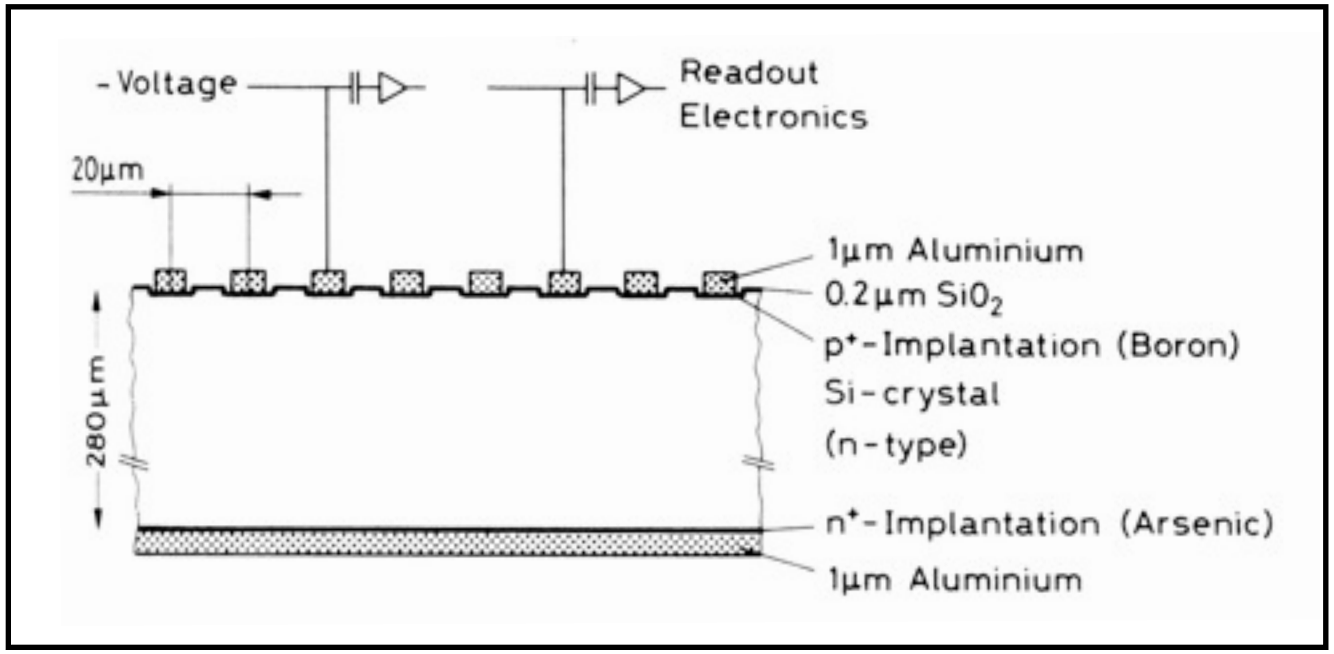
High resistive n-type silicon
onto which p+ diode strips with
aluminum contacts are implanted

Position Sensitive Detectors

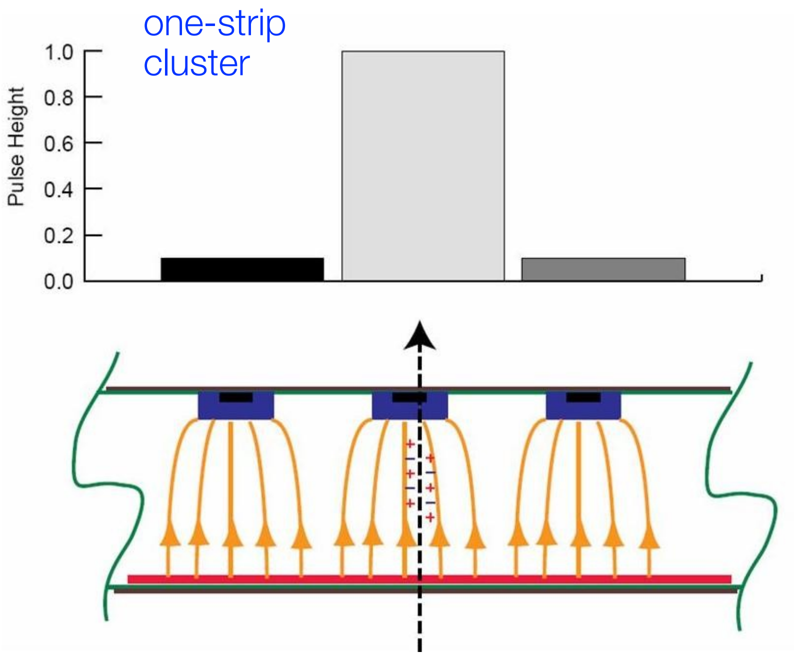
Readout:

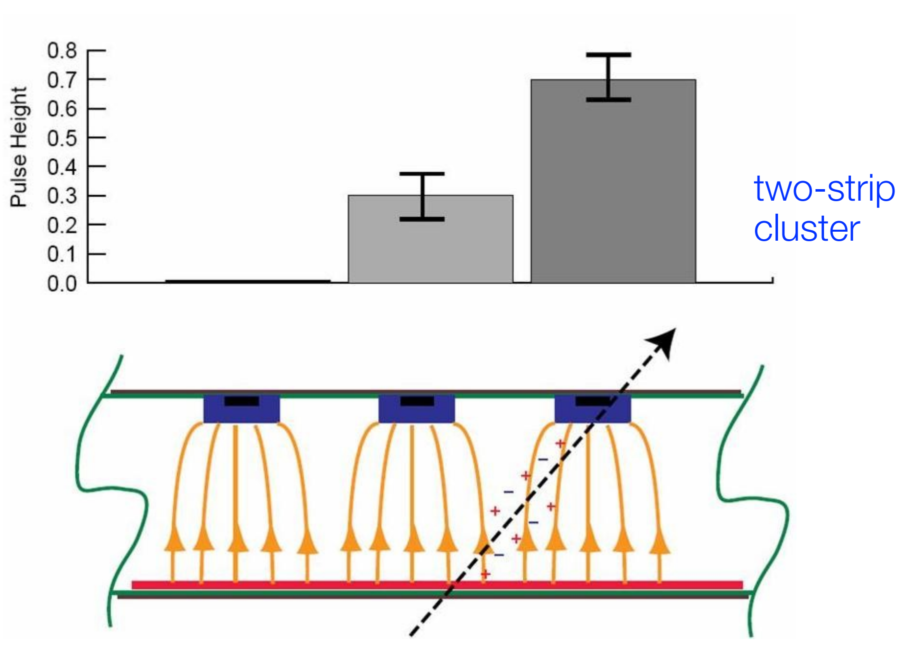
Reduction of electronic channels using charge devision method ...

Calculate center of gravity of collected charges ...



Original schematics of first micro-strip detector [Hyams et al., 1983]

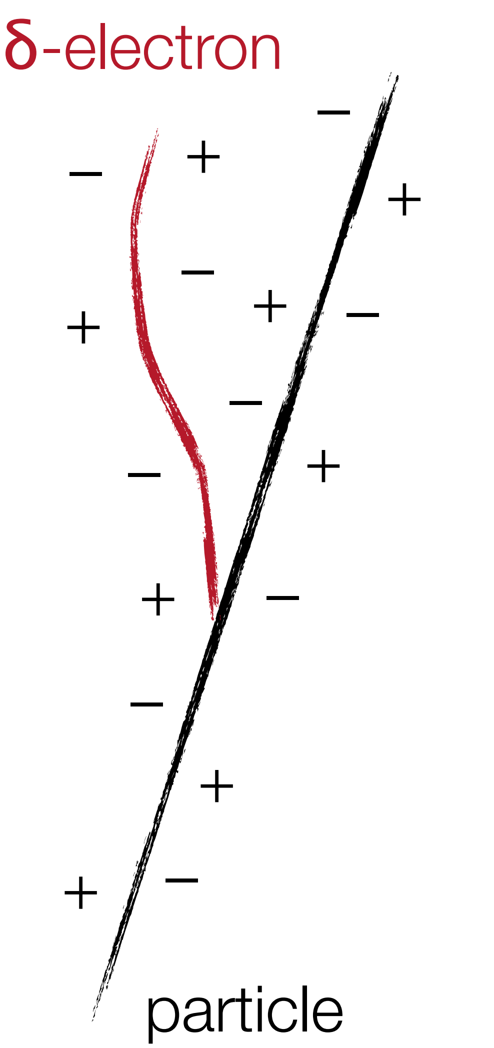




Position Sensitive Detectors

Limitations:

High energy δ-electrons limit spatial resolution as they shift center of gravity of the signal ...



Rough estimate:

[Perpendicular scattering; δ ⊥ track]

r_δ : average range of δ-electron
N_δ : number of electron-hole pairs from δ-electron
N_p : number of electron-hole pairs from primary track

Then:

$$\Delta x = \frac{N_\delta \cdot \frac{r_\delta}{2}}{N_\delta + N_p}$$

Example:

100 μm thick Si-counter

Pion [5 GeV] : 240 eV/μm ➛ 6700 electron-hole pairs
δ-electron : with 10% probability T > 20 keV; r_δ = 5 μm
complete absorption ➛ 5500 electron-hole pairs

➛ $$\Delta x = \frac{5500 \cdot 2.5\mu\text{m}}{6700 + 5500} = 1.1\mu\text{m}$$

resolution limitation;
increases with thickness

Position Sensitive Detectors

Limitations:

Landau fluctuations: production of δ-electrons can disturb charge devision ...

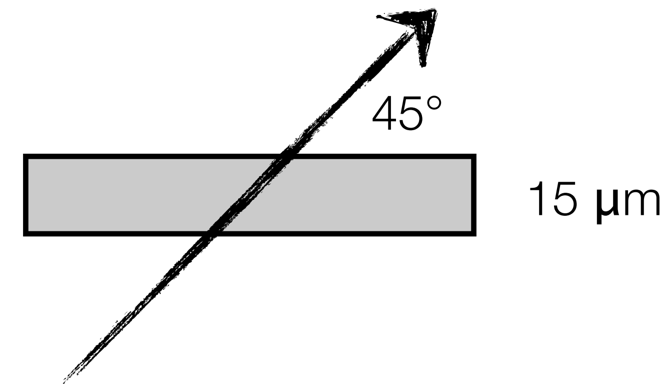
[worse for thick counters; see figure]

Noise: position measurement requires S » N; center of gravity influenced by S/N.

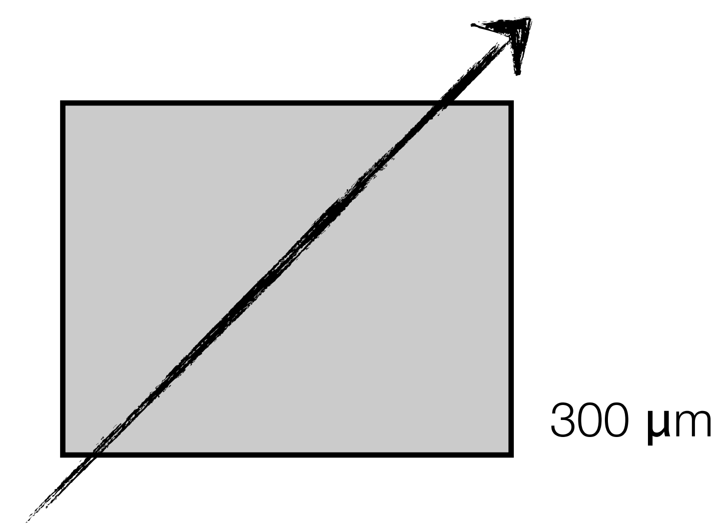
Diffusion: smearing of charge cloud deteriorates double hit resolution

Magnetic field: Lorentz force has impact on drifting electrons and holes.

[track signal displaced if E not parallel to B-field]

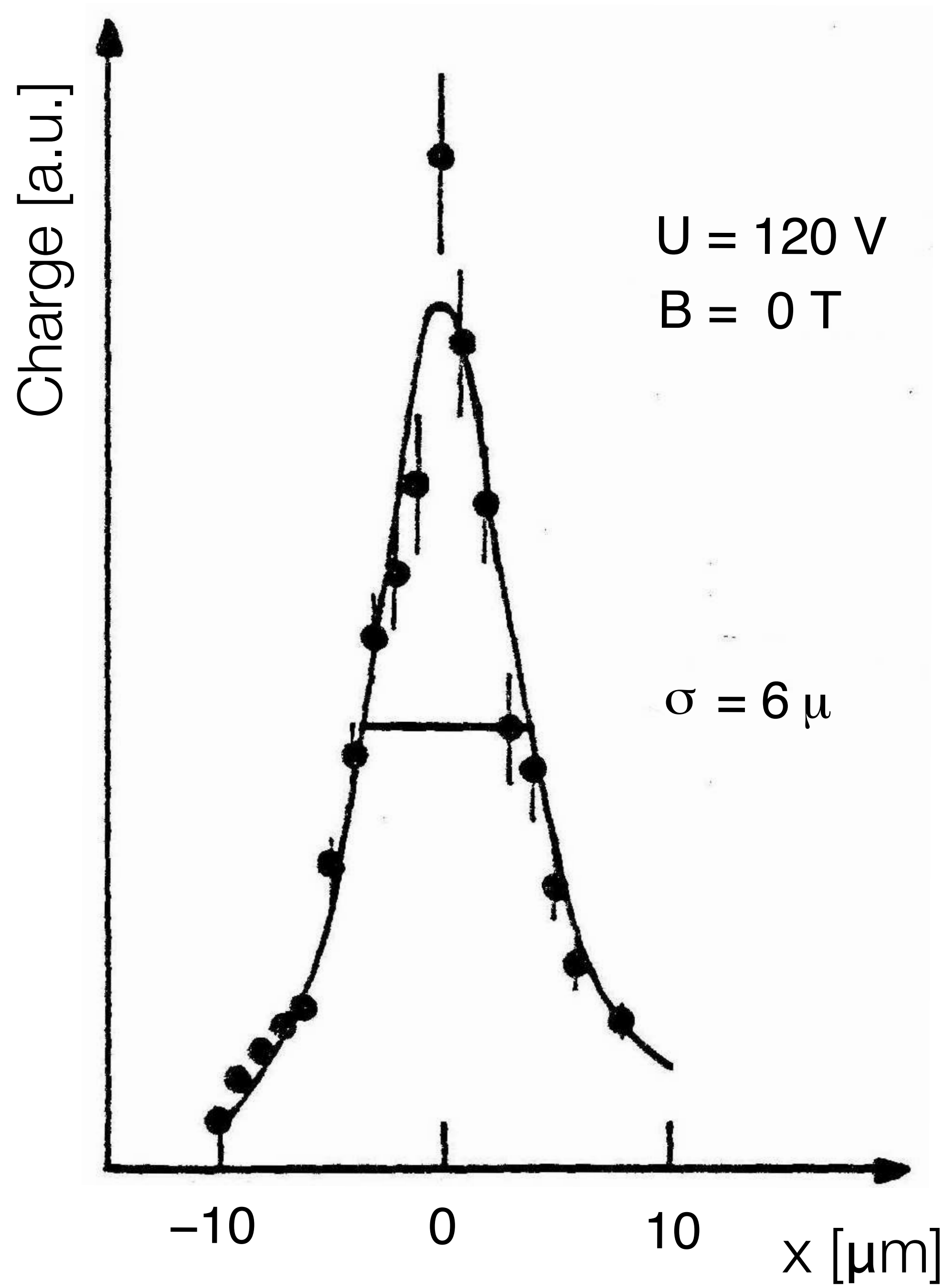


Energy loss ≈ 5 keV
10% probability to produce 5 keV δ
Resolution limited to 15 µm/$\sqrt{12}$ ≈ 4 µm

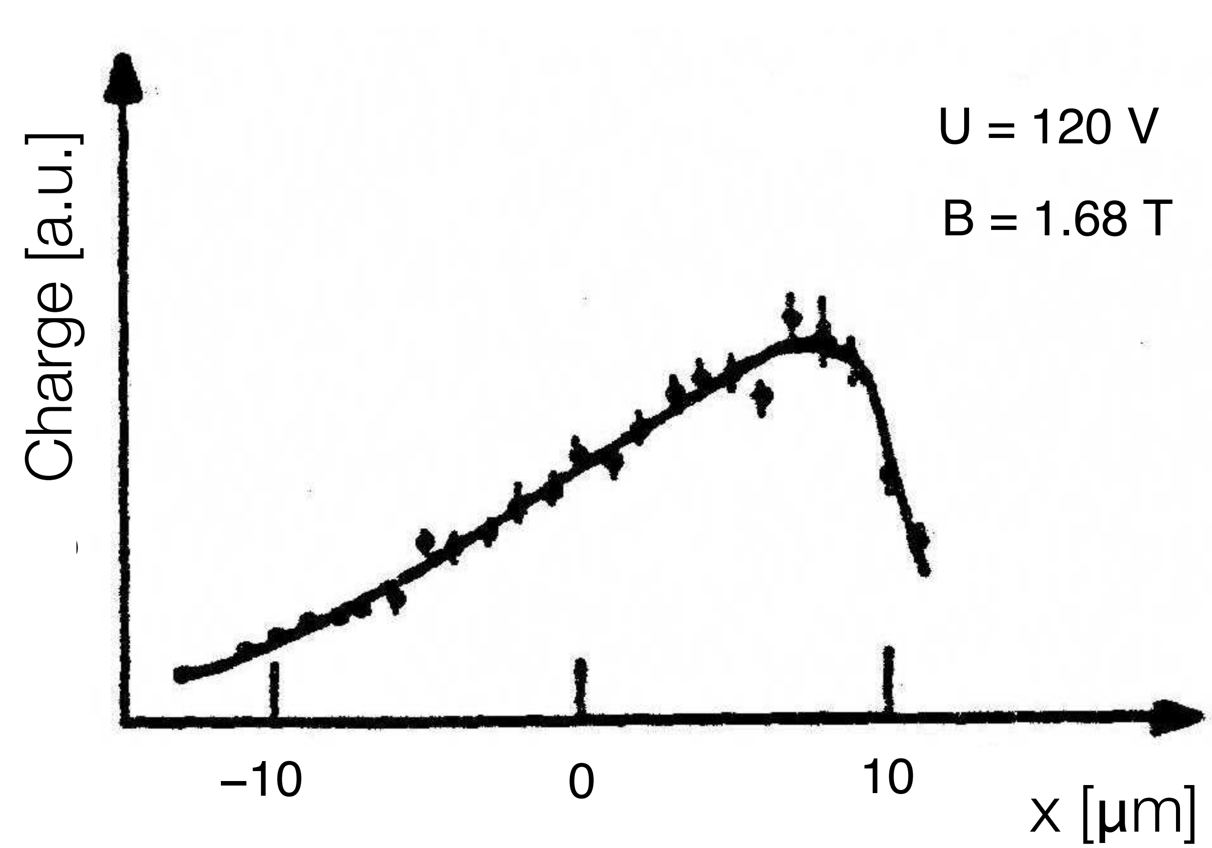


Energy loss ≈ 100 keV
10% probability to produce 100 keV δ
Resolution limited to 300 µm/$\sqrt{12}$ ≈ 90 µm

Position Sensitive Detectors

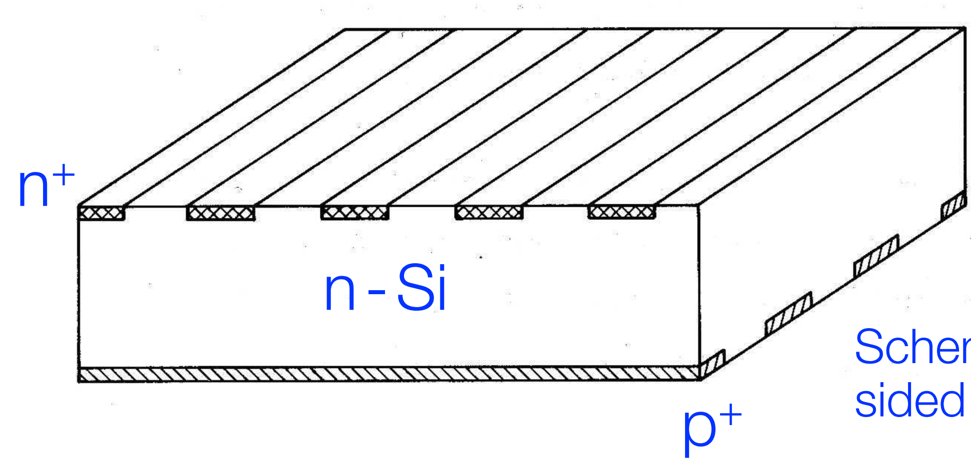


Spatial distribution of collected charge
in presence of magnetic field



Position Sensitive Detectors

Next step:
Double sided
micro-strip detectors ...



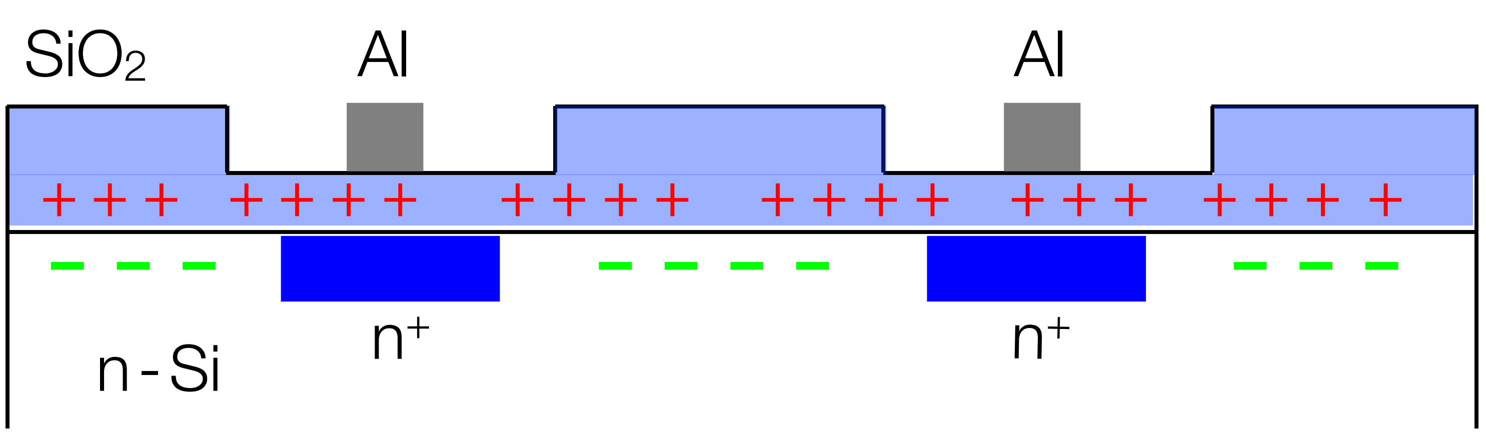
Schematics of a double
sided micro-strip detector

n^+ strips on one side
p^+ strips on other side

Yields high spatial resolution
in both x and y direction ...

But:

Strips need insulation to avoid that positive space charge attracts electrons from n-layer



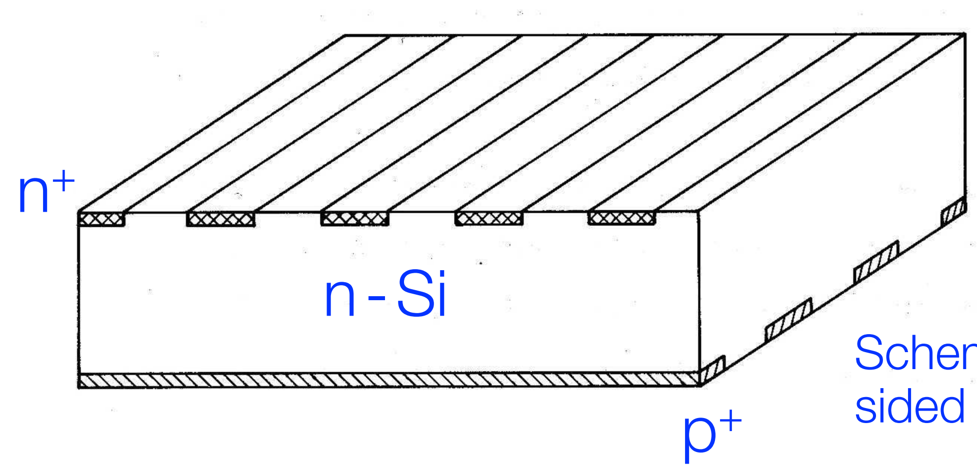
Need blocking electrodes
to separate n^+ strips ...

Closeup of of n^+ side of
double sided micro-strip detector

Position Sensitive Detectors

Next step:

Double sided micro-strip detectors ...



Schematics of a double sided micro-strip detector

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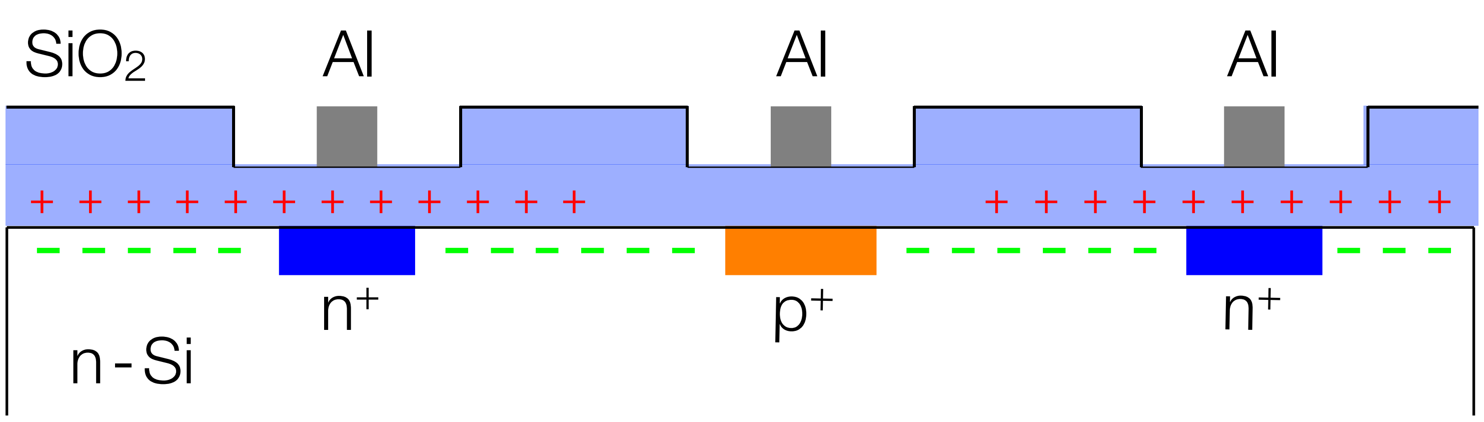


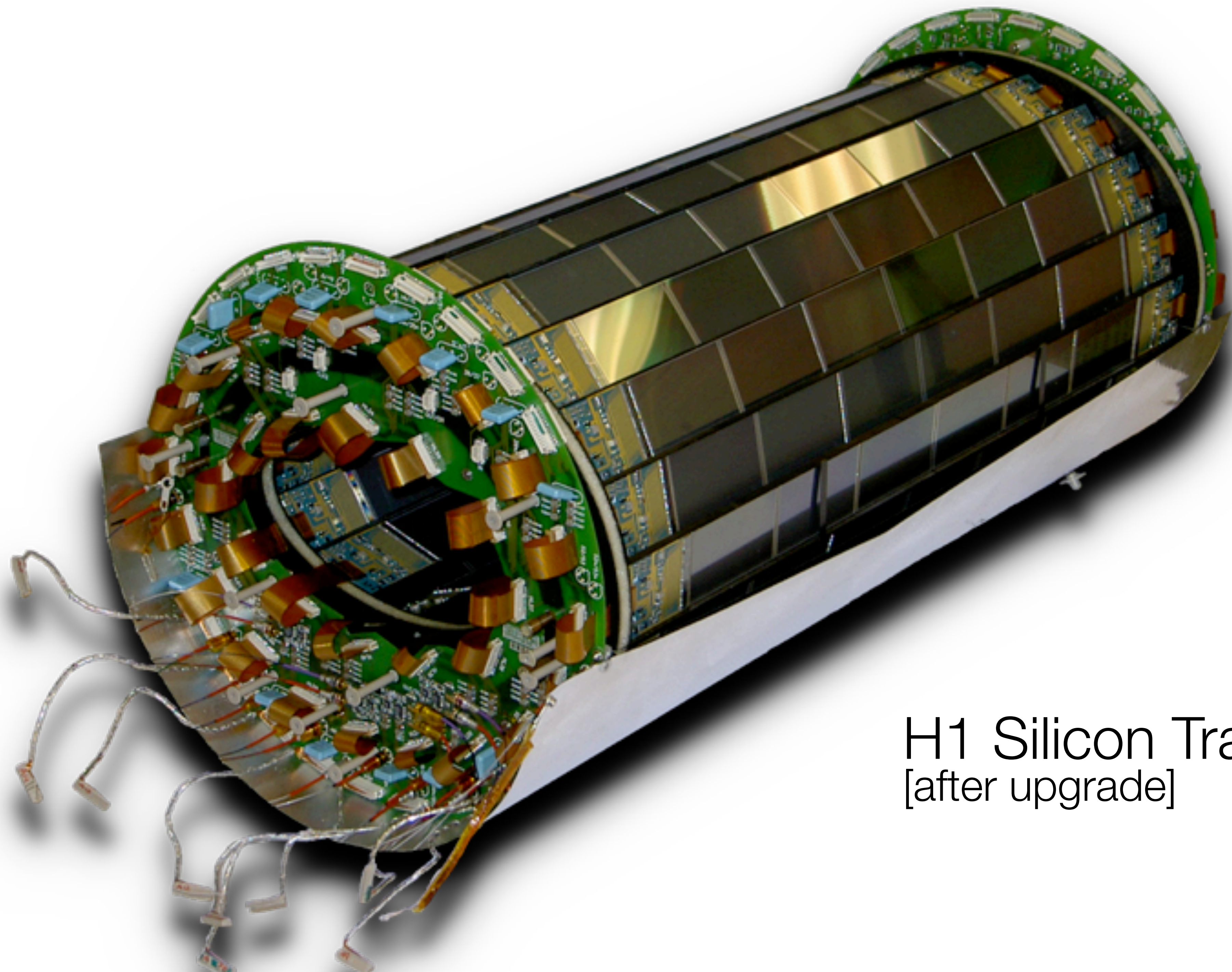
Closeup of of n^+ side of double sided micro-strip detector

Need blocking electrodes to separate n^+ strips ...

Add p^+ electrodes ...

Alternative: add Al contact with negative bias voltage ...

Position Sensitive Detectors



H1 Silicon Tracker
[after upgrade]

Position Sensitive Detectors

Position Sensitive Detectors

Pixel detectors:

Like micro-strips, but 2-dim. segmentation ...

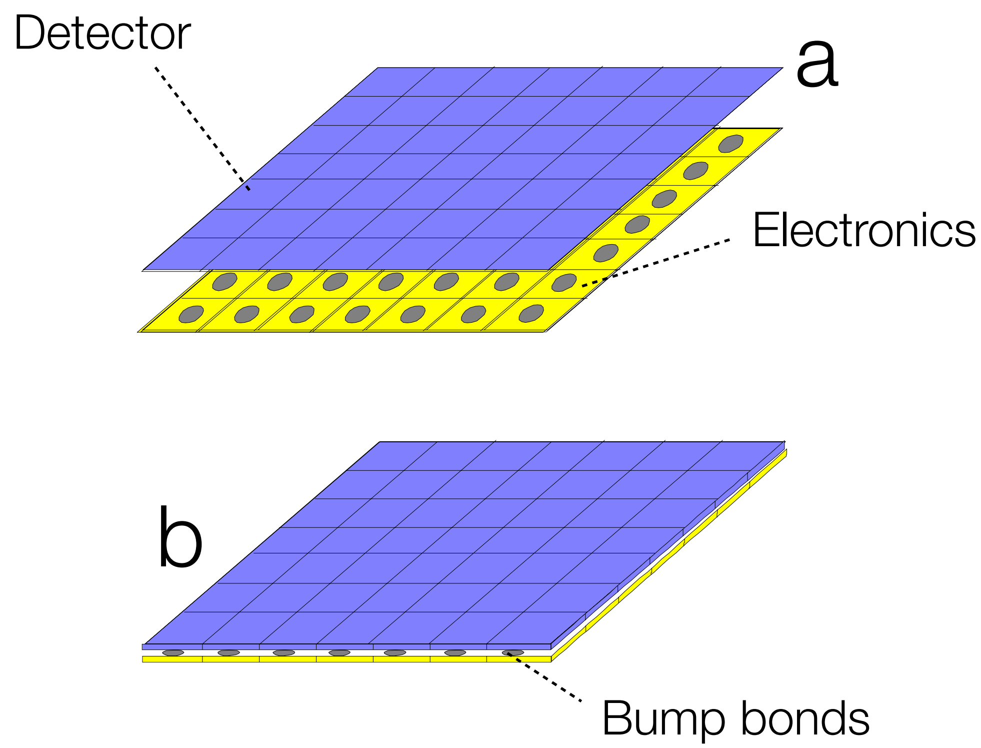
Advantage:

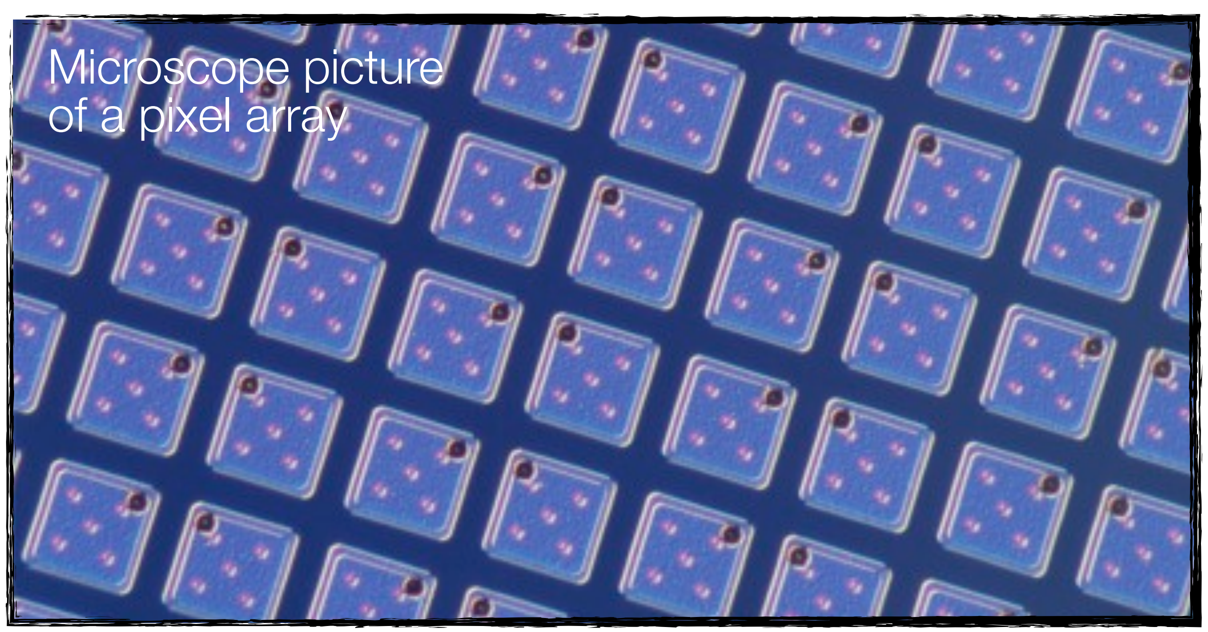
As for micro-strips 2-dim. information,
but higher occupancy allowed;

Lower noise due to lower capacitance ...

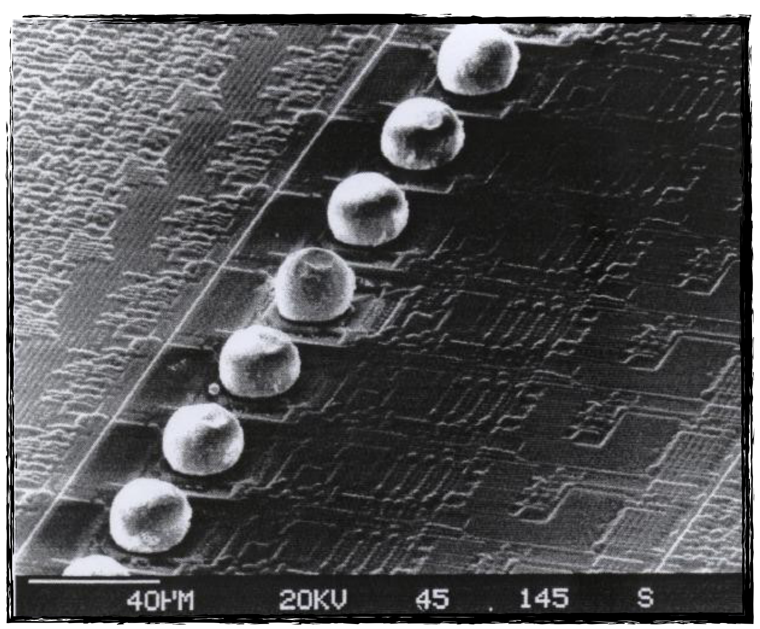
Disadvantage:

Huge number of readout channels;
Complicated technology ("bump bonding")
Requires sophisticated readout architecture ...



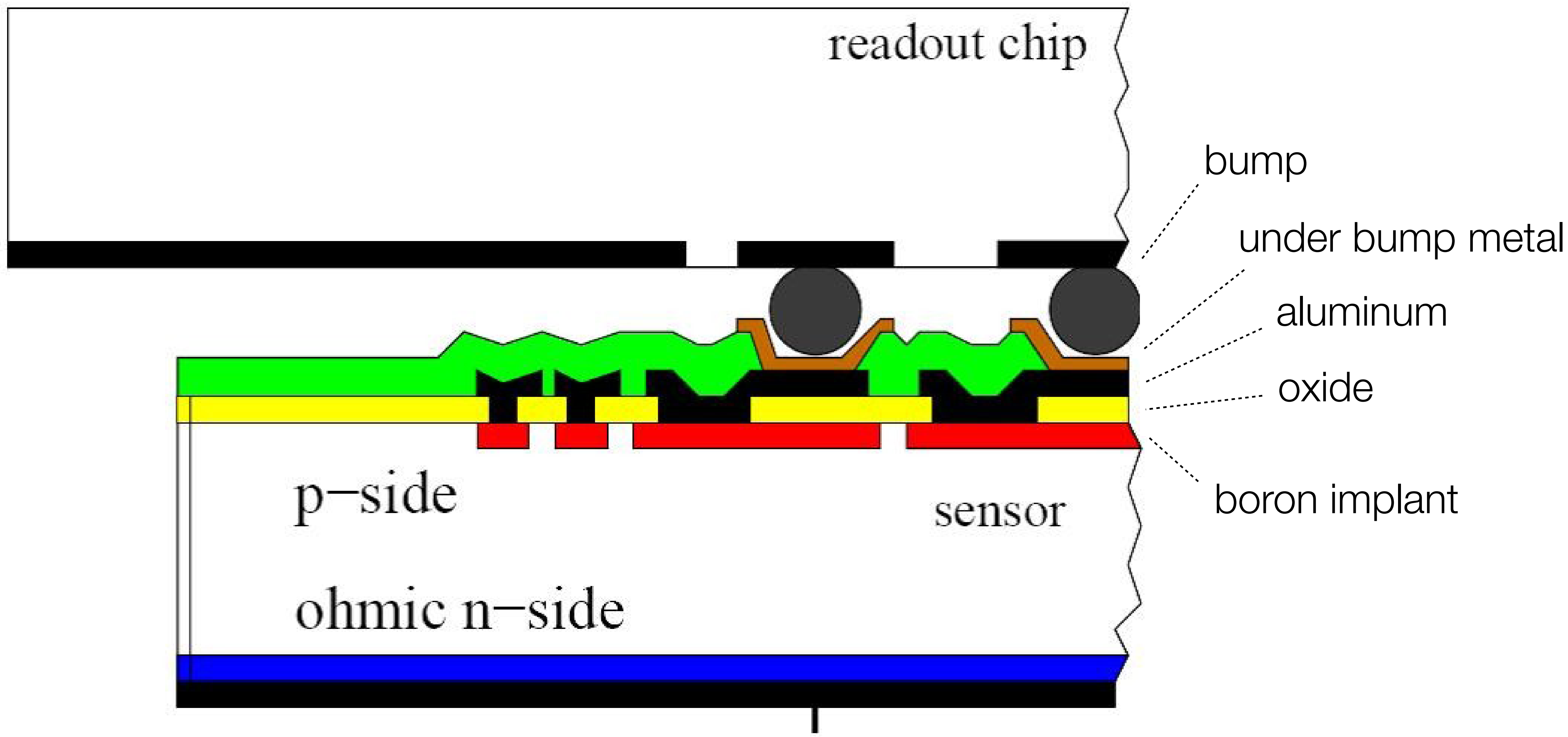


Microscope picture of a pixel array

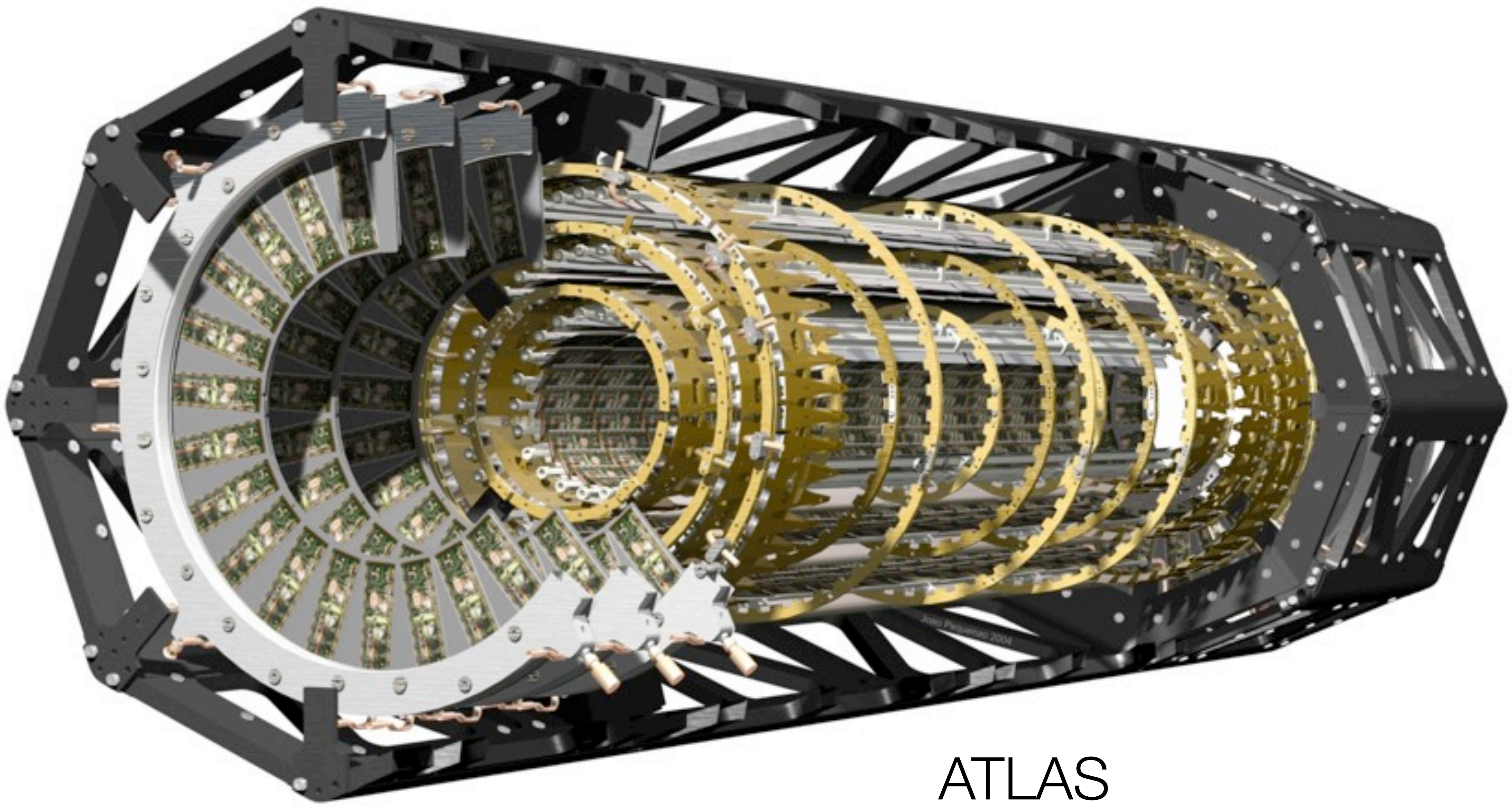


SEM Photograph of solder bumps

Position Sensitive Detectors

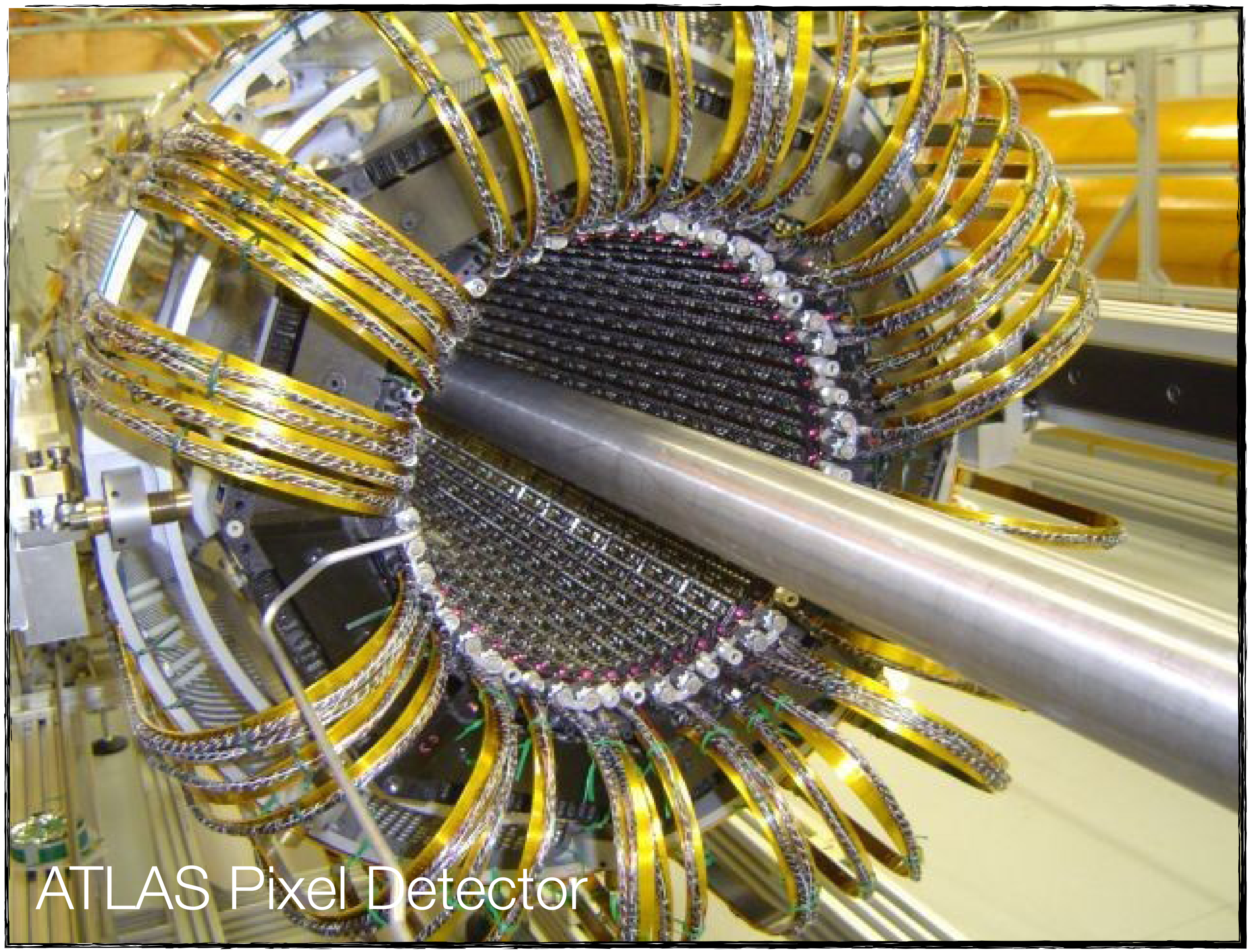


Position Sensitive Detectors



ATLAS
Pixel Detector
[nominal resolution: Rϕ ~ 12 μm]

Position Sensitive Detectors



CCD – Charge Coupled Devices

The Nobel Prize in Physics 2009

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

"for the invention of an imaging semiconductor circuit – the CCD sensor"

Photo: U. Montan

Charles K. Kao

1/2 of the prize

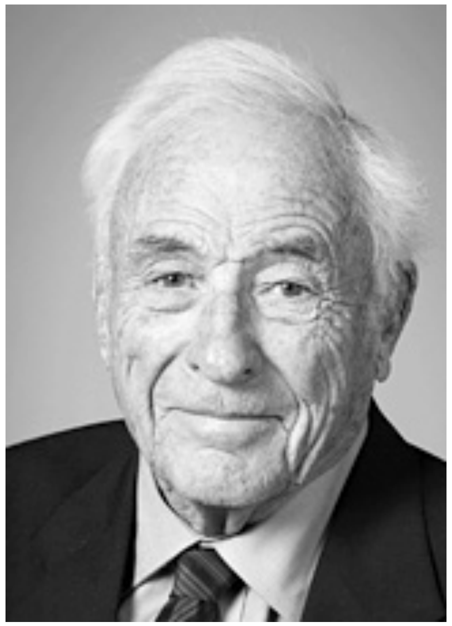


Photo: U. Montan

Willard S. Boyle

1/4 of the prize

Photo: U. Montan

George E. Smith

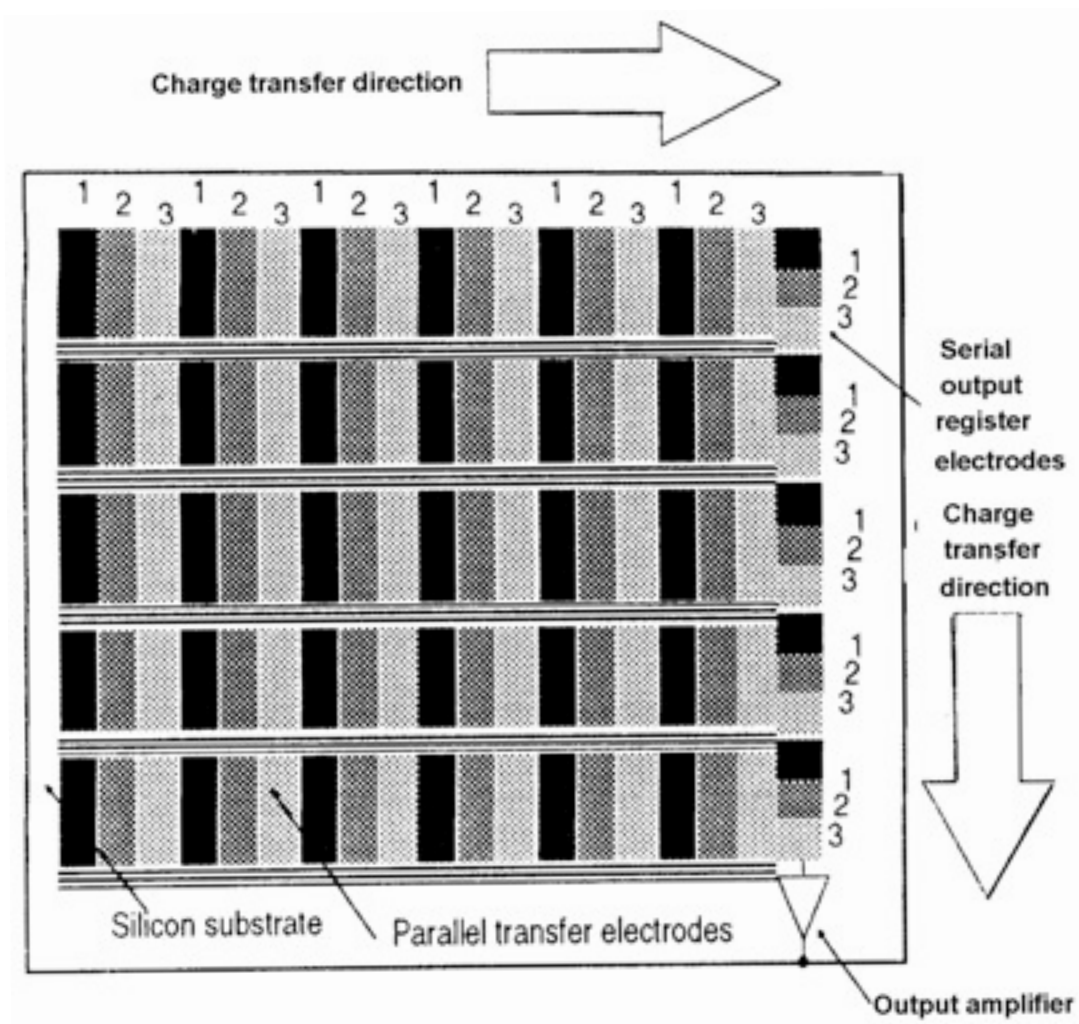
1/4 of the prize

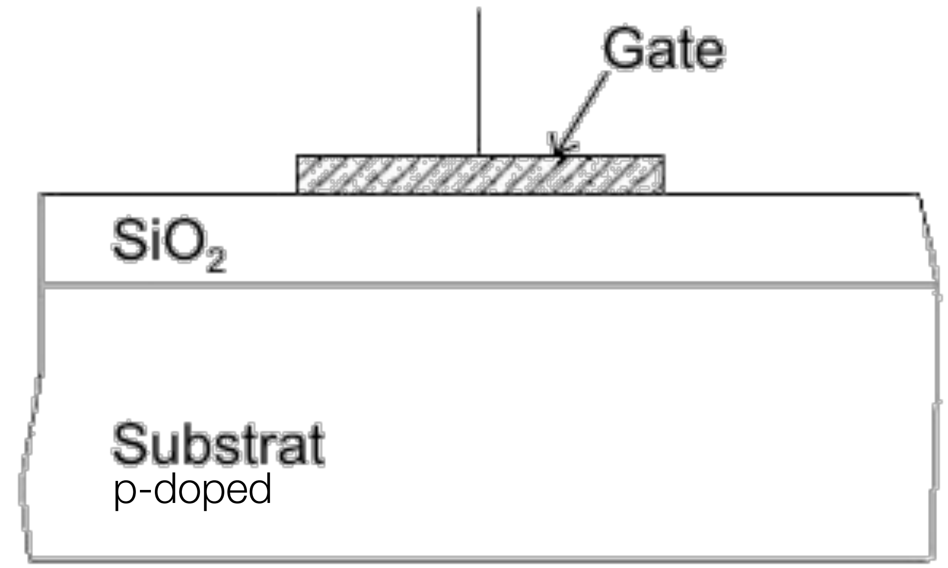
CCD – Charge Coupled Devices

MOS Structure
[Metal-Oxide-Silicon]

CCD: Many independent and separately switchable gates ...

[electronically shielded potential wells]



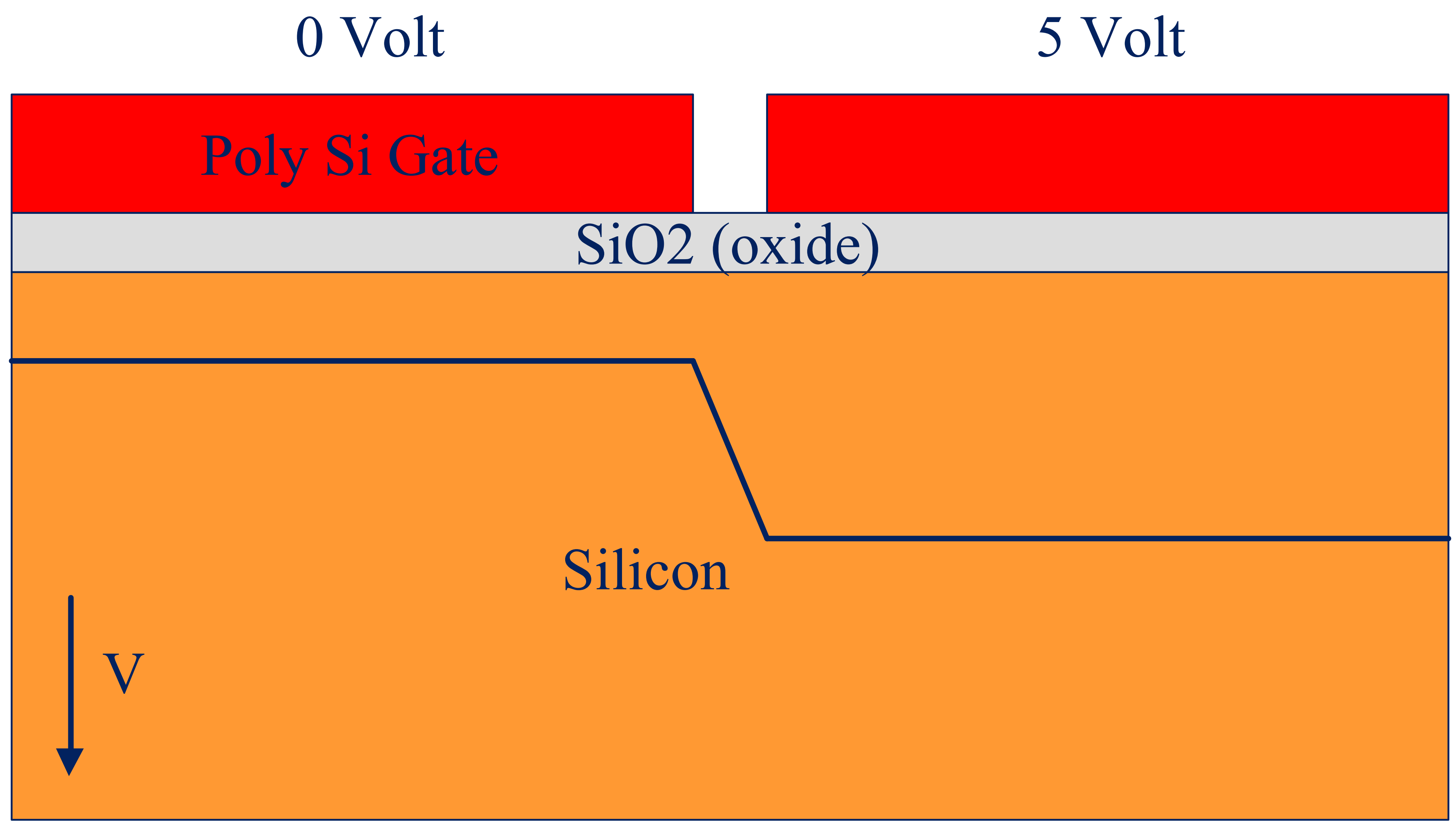


Gates/pixels store charges produced by ionizing tracks/light;

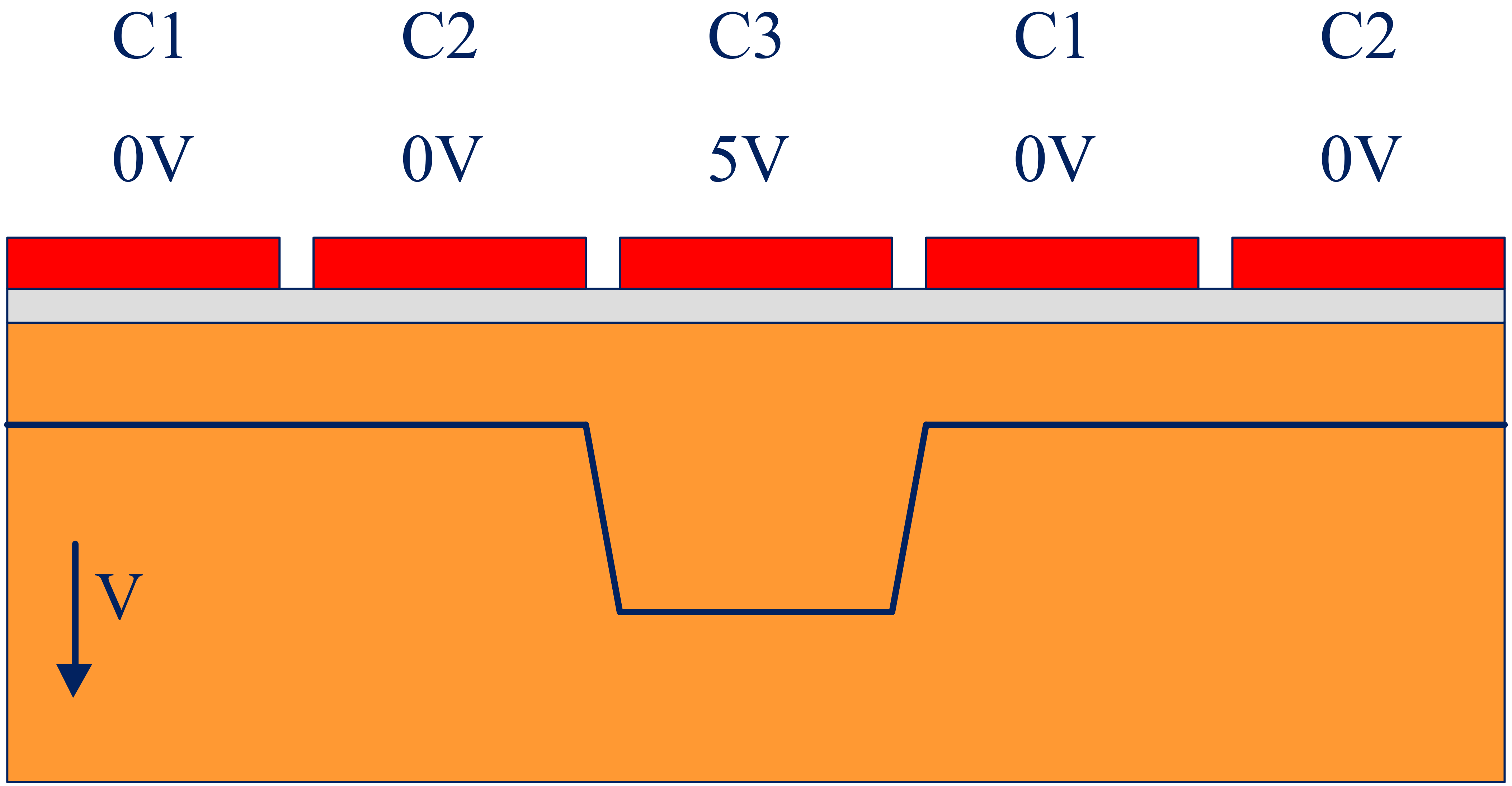
[pixel size: 50 x 50 μm^2; sometimes 20 x 20 μm^2]

Information is transferred sequentially to charge sensing pre-amplifier ...

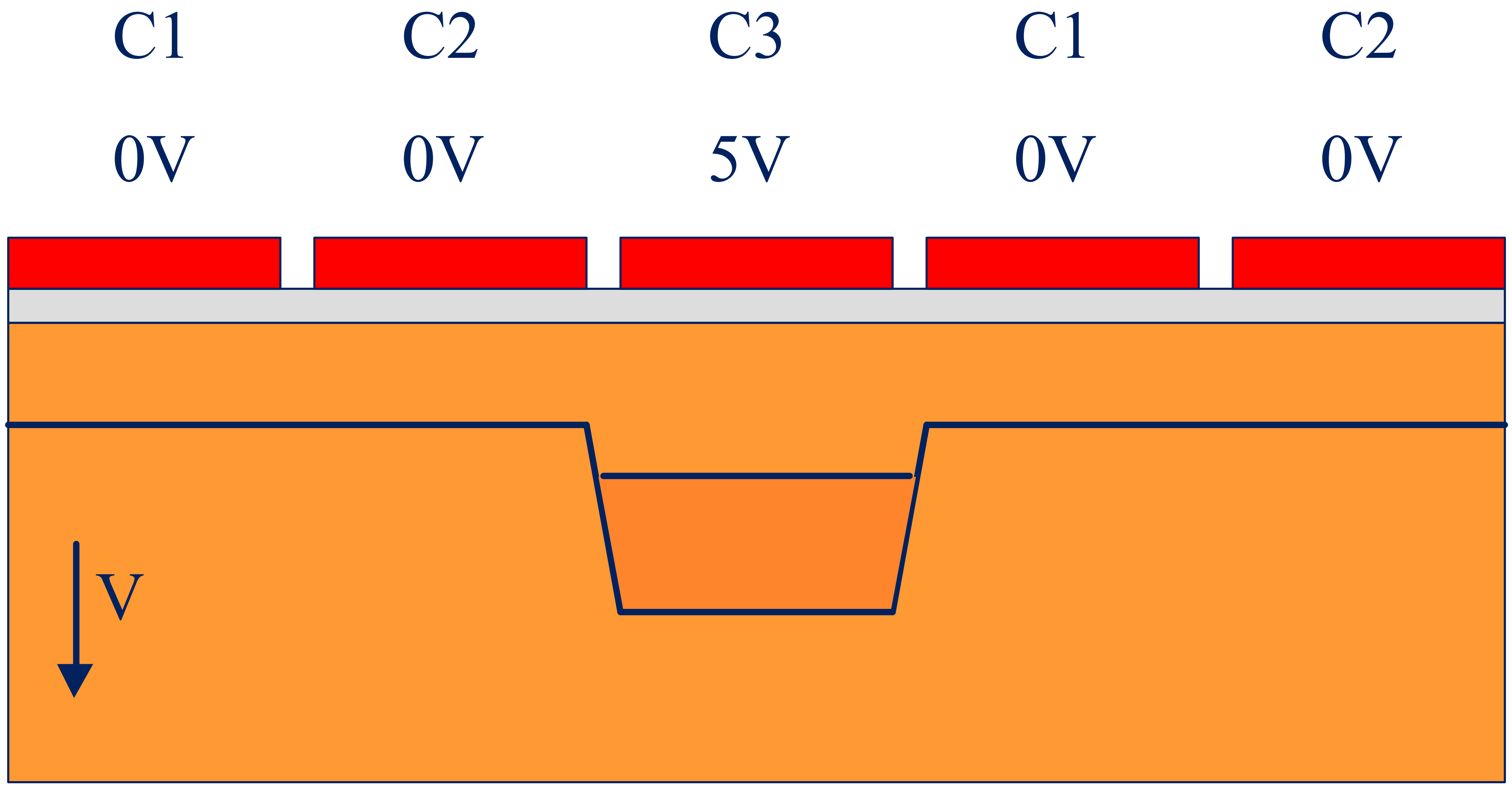
CCD – Charge Coupled Devices



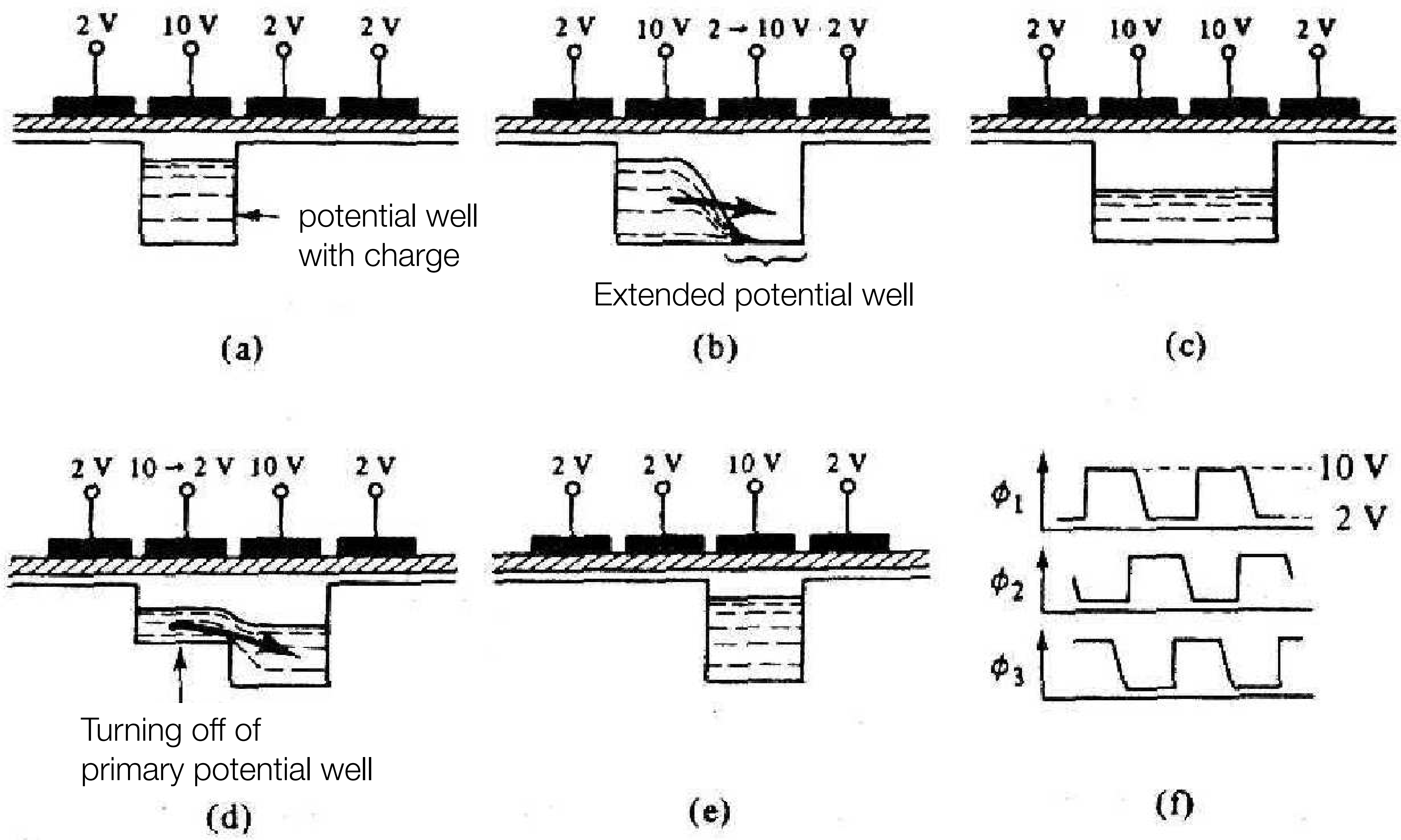
CCD – Charge Coupled Devices



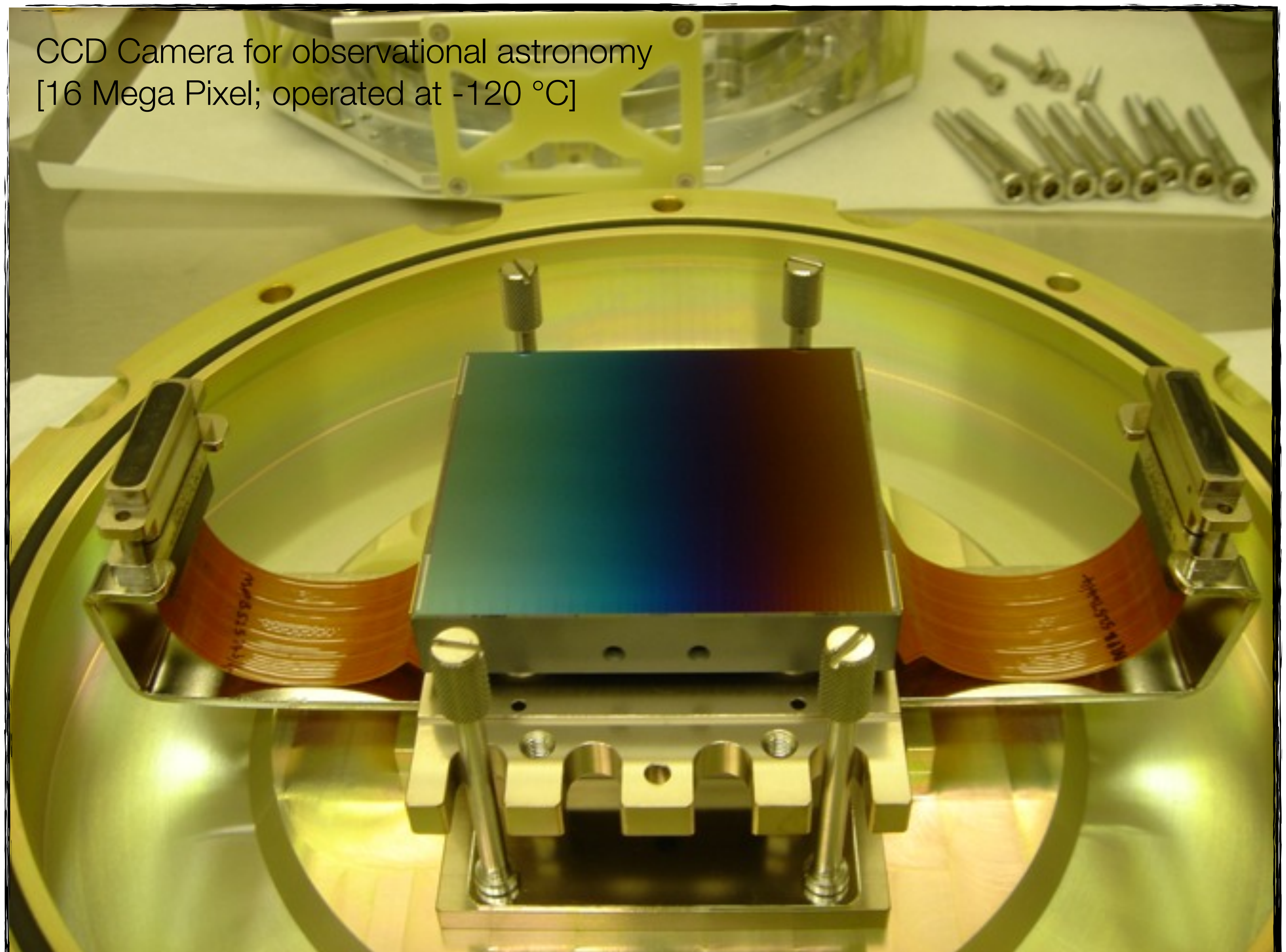
CCD – Charge Coupled Devices



CCD – Charge Coupled Devices



CCD – Charge Coupled Devices



CCD Camera for observational astronomy
[16 Mega Pixel; operated at -120 °C]