Tracking lecture 2

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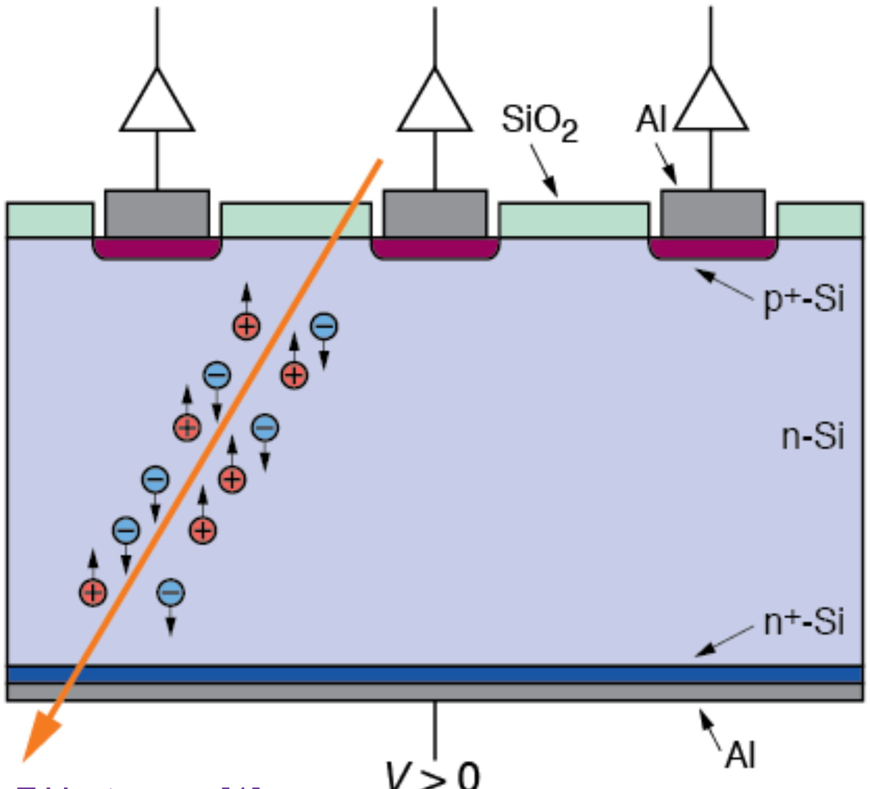
Silicon track detectors

Silicon track detectors

- Working principle



F.Hartmann [1]

- Silicon wafer patterned with strip or pixel implants
  - Readout electronics connected to implants
- Each p-n junction is reverse-polarized
  - Space charge region is depleted from mobile charge carriers and acts as an ionization chamber
- Ionizing particle produces electron-hole pairs
- Electrons and holes drift and induce signals in readout electronics

Silicon track detectors

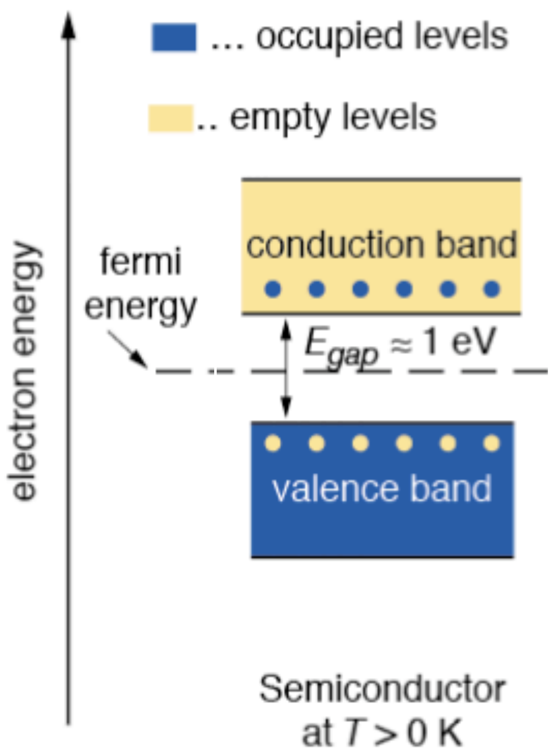
- Attractive features
  - About 3.10^4 electron-hole pairs created by Minimum-Ionizing Particles (MIP) in 300µm thick wafer; detectable with low-noise electronics
  - Fast signal (<10ns) thanks to high e- and hole mobility
  - Implant pattern sizes allow excellent hit position resolution (5~10µm)
  - Many different implant geometries are possible
  - Front-end electronics can, in principle, be implemented in the same wafer as the sensor
  - Can be made radiation-resistant

Silicon track detectors

- Less nice features…
  - Sensors, mechanical structures, readout cables, cooling tubes inside tracking volume -> high x/X_0 “material budget”
  - Cost per channel is high… but the driving cost is often not the sensors, it’s the number of channels
    - ***it’s the price to pay for high granularity***

Silicon track detectors

- Ionization yield



F.Hartmann [1]

- Signal in silicon benefits from the small energy difference between the valence and conduction bands, also called the band gap, E_{gap}
- For diamond/silicon/germanium

  E_{gap} = 5.5 eV/1.12 eV/0.66 eV
- The average energy loss required from a charged particle to produce an electron-hole pair is measured to be: diamond/silicon/germanium:

  13 eV/3.6 eV/2.9 eV

  ~10 times smaller energy to release an electron than in a gas (~30eV)

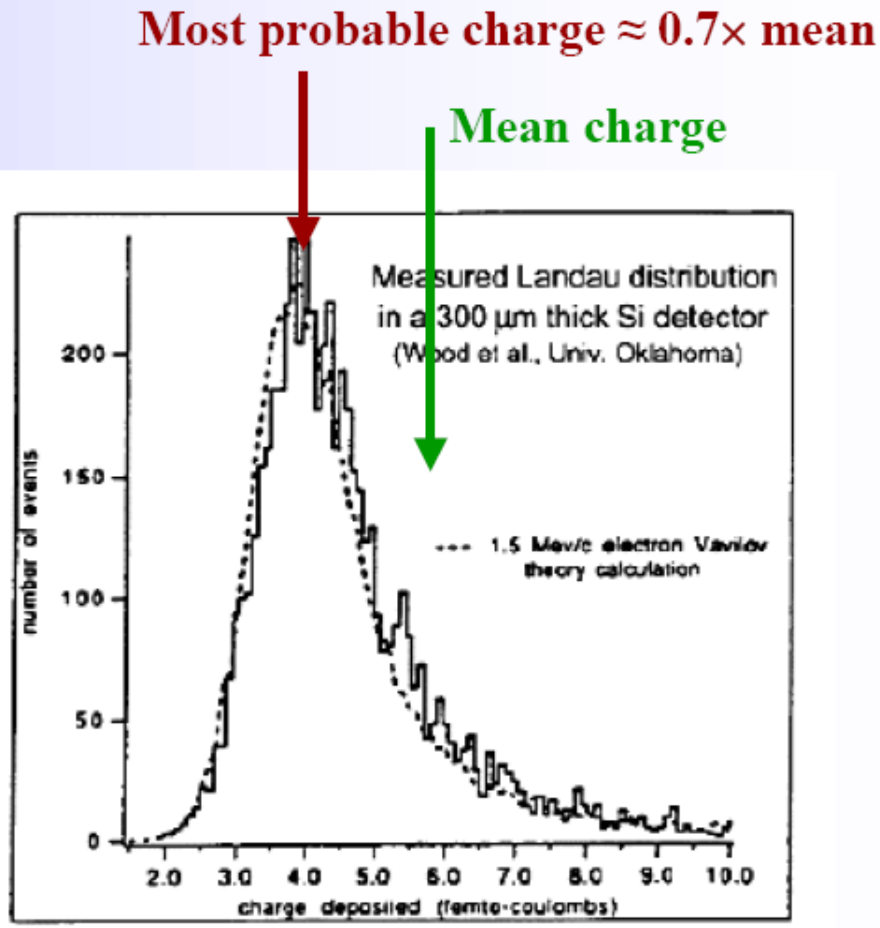
- ~10^3 times denser material: $\left.\frac{dE}{dx}\right|_{Si} = 3.87 MeV/cm$

→ ~10^4 more e-hole pairs created per cm (Si) than in gas

Energy loss distribution for MIPs

- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness
- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV
- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / μm (mean)
  ⇒ 108 e-h / μm (most probable)
- **Most probable charge** (300 μm)

  ≈ 22500 e ≈ 3.6 fC

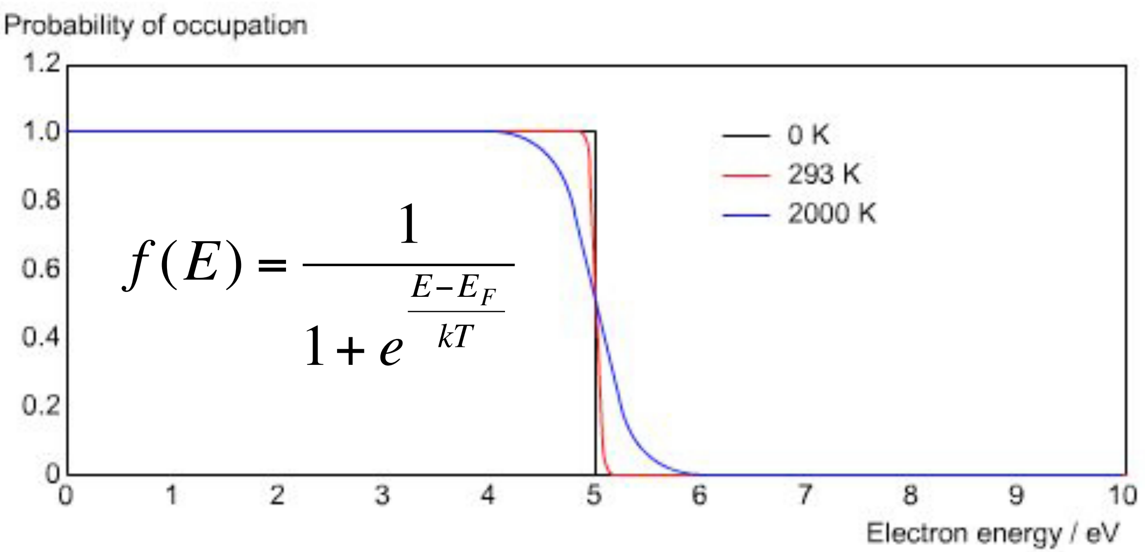


CERN Academic Training Programme 2004/2005

M.Moll [2]

Intrinsic (pure) Silicon

- The Fermi energy level E_F



$$f(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}}$$

- E_F corresponds to energy level with 50% probability of occupation
- It's in the middle of the band gap in pure Silicon
- At room temperature:
  - $kT = 0.025$ eV << E_{gap}

So ~1 out of 10^{12} electron is in conduction band

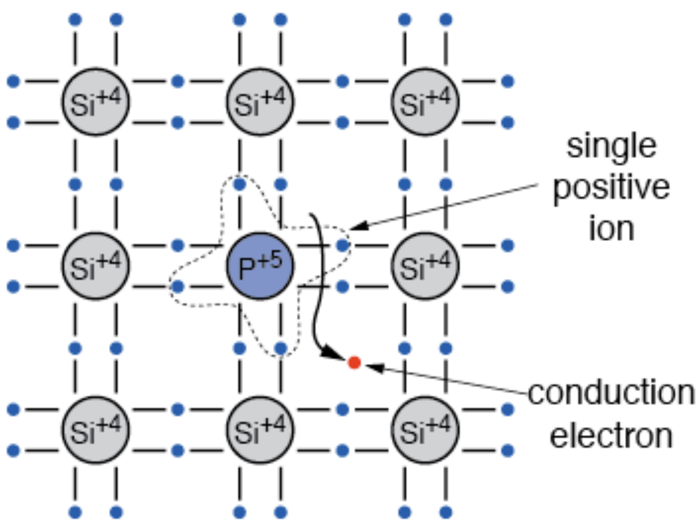
Concentration of electrons (and holes): $n_i \sim 1.45\ 10^{10}\ cm^{-3}$ at T = 300 K

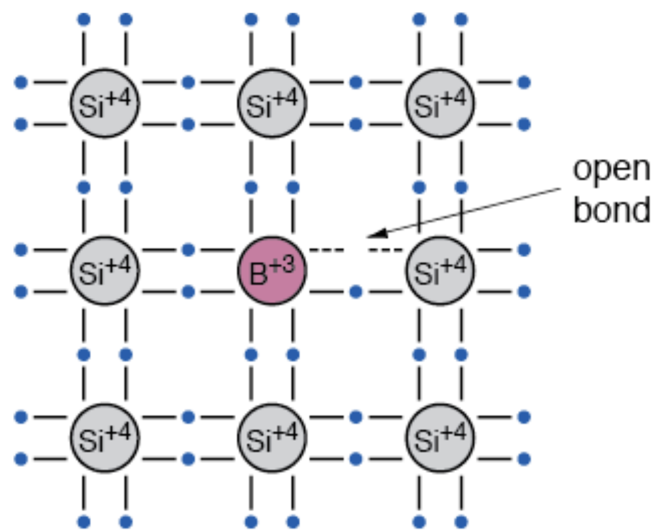
In a detection cell of 300µm thickness x 10cm strip length x 100µm strip pitch:
~$4.5\ 10^7$ free charge carriers >< ~$3.3\ 10^4$ e-hole pairs from a MIP

To avoid recombination of the signal with the free carriers, **reverse-polarized (depleted) *p-n* junctions are used**

Doping

- A semi-conductor is called extrinsic when the equilibrium between negative and positive free charges is broken. There are thus majority charge carriers and minority charge carriers. This is realized by doping, i.e. introducing a well-chosen impurity in the crystal in small parts (doping fraction $10^{-8} - 10^{-11}$). For Silicon:





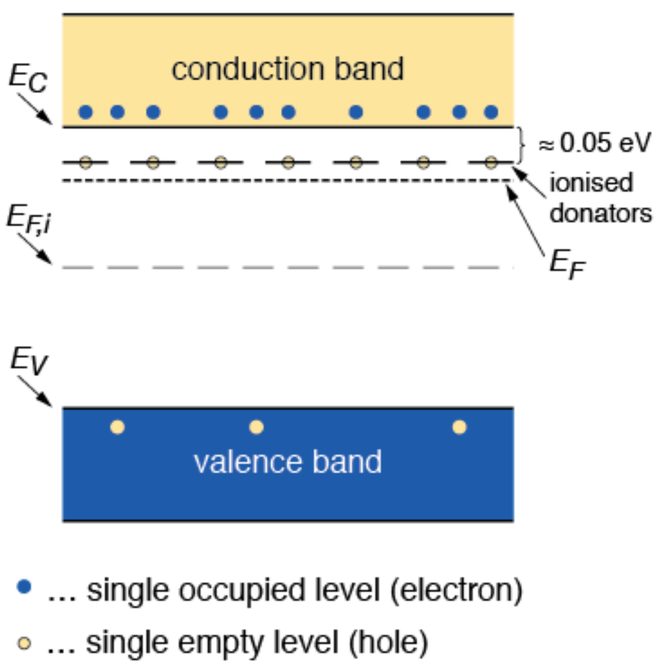
Dopant of the Vth group (e- donor)
5th electron weakly bound, easily freed
majority carriers: electrons
n-type

Dopant of the IIIrd group (e- acceptor)
Si electron easily captured
majority carriers: holes
p-type

Energy levels after doping

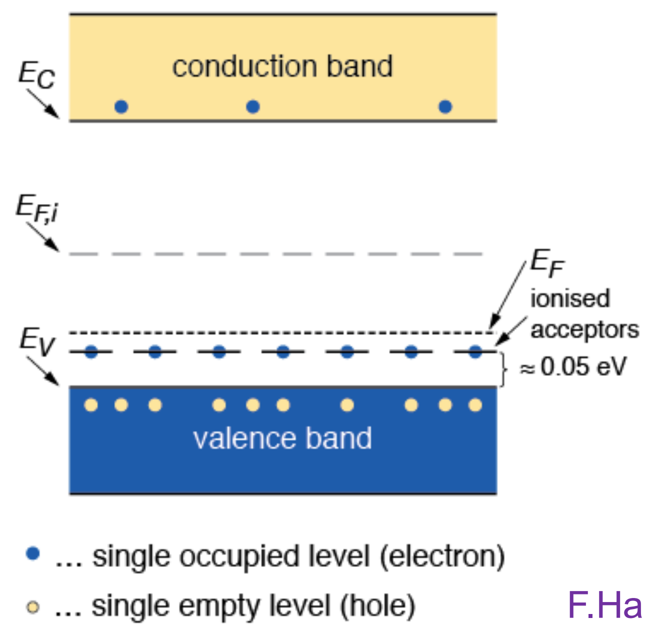
n-type

- The energy level of the donor is just below the edge of the conduction band
- At room temperature most donors are ionized, putting electrons in the conduction band
- The Fermi level E_F moves up



p-type

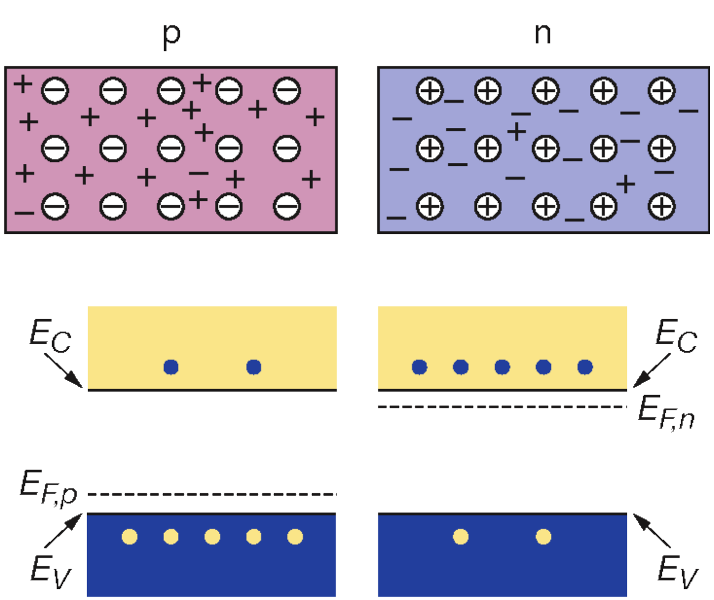
- The energy level of the acceptor is just above the edge of the valence band
- At room temperature most levels are occupied by electrons leaving holes in the valence band
- The Fermi level E_F moves down

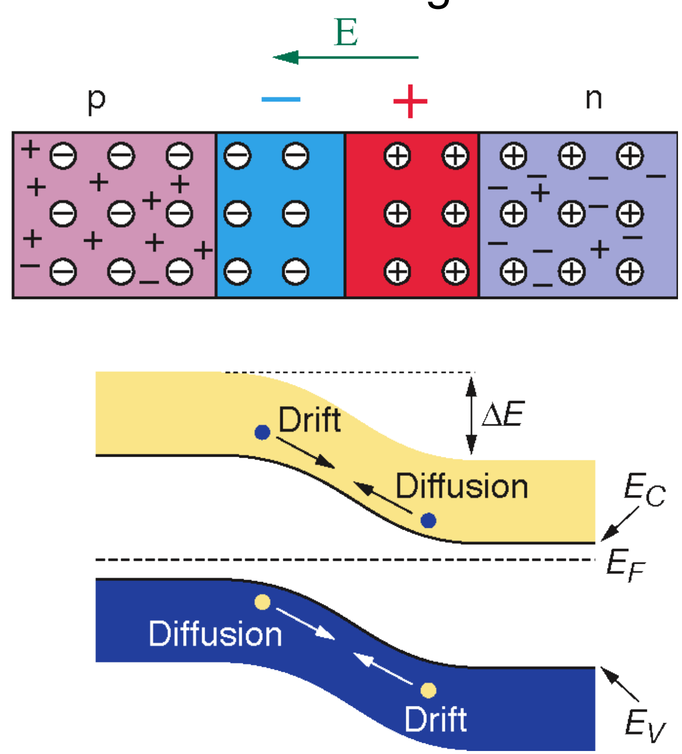


F.Hartmann [1]

The p-n junction

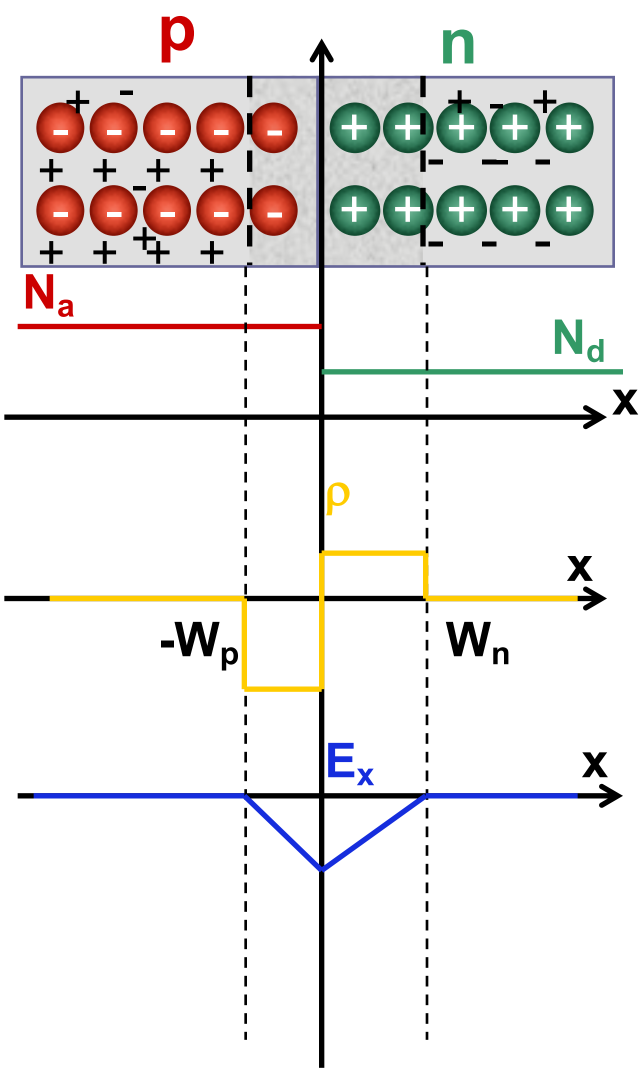
- At the interface between an n-type and a p-type semiconductor, the difference in carrier concentrations cause diffusion of majority carries to the other material until thermal equilibrium is reached. At this point the Fermi levels are equal.
- The remaining fixed ions create a space charge and an electric field stopping further diffusion.
- The stable space charge region is emptied from mobile charge carries and is called the depletion zone.





F.Hartmann [1]

The abrupt junction model



N_a, N_d concentrations of acceptors and donors in the p- et n-type silicon parts

In the depleted zone, the charge density writes:

$\rho(x) = -eN_a$, for $x<0$; $\rho(x) = eN_d$, for $x>0$

It is essentially zero elsewhere (electric neutrality)

By charge conservation:
$N_aW_p = N_dW_n$, with $\mathbf{W_p}$ and $\mathbf{W_n}$ the depleted depths in each silicon type

Integrating Gauss's law

$$\nabla.\vec{E} = \frac{\rho}{\varepsilon}$$

Leads to the expression of the electric field:

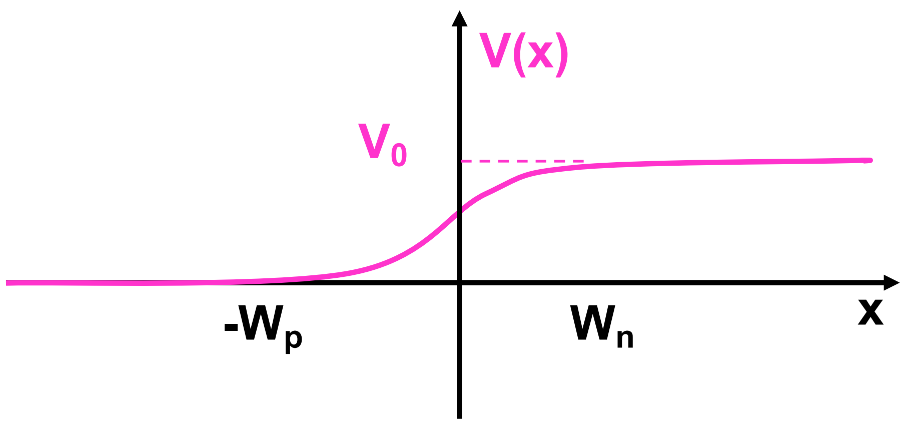
$$\mathbf{E_x = -\frac{dV(x)}{dx} = e\frac{N_d}{\varepsilon}(x - W_n),}\ \mathit{for}\ \mathbf{0 < x < W_n}$$

$$\mathbf{-e\frac{N_a}{\varepsilon}(x + W_p),}\ \mathit{for}\ \mathbf{-W_p < x < 0}$$

The abrupt junction model

Integrating the expression of $E_x(x)$ leads to a parabolic expression for the potential V(x); the integration constants are fixed by imposing continuity at x=0, and considering:

- electric neutrality: $N_a W_p = N_d W_n$
- The diode potential barrier $V_0 \approx E_{gap}/e$



Unbiased junction:
diode potential barrier $V_0 \approx 0.6$V
Width of depletion region ≈ a few tens of micrometers for N_a, N_d ~$10^{12}/cm^3$

Reverse-biased junction:
Positive voltage V_0 >> 0.6V on n-side increases potential barrier
Small current due to minority carriers thermally generated in depletion region

- so-called leakage current

Reverse-biasing the junction

Imposing an external potential V_0 >> 0.6 V one finds: $\mathbf{V_0 = \frac{e}{2\varepsilon}(N_d W_n^2 + N_a W_p^2)}$

And using $N_a W_p = N_d W_n$ one gets: $V_0 = \frac{e}{2\varepsilon} W_n^2 N_d \left(1 + \frac{N_d}{N_a}\right)$

In practice, a p-n junction is produced from a homogeneous substrate (the bulk), for instance n-type. The p-type region is added by diffusing the appropriate dopant (the implant) in the n-type substrate. The depth of the diffusion is small compared to the thickness of the bulk. If one wishes a thick depleted region, it should extend in the bulk, implying in this example $N_a >> N_d$

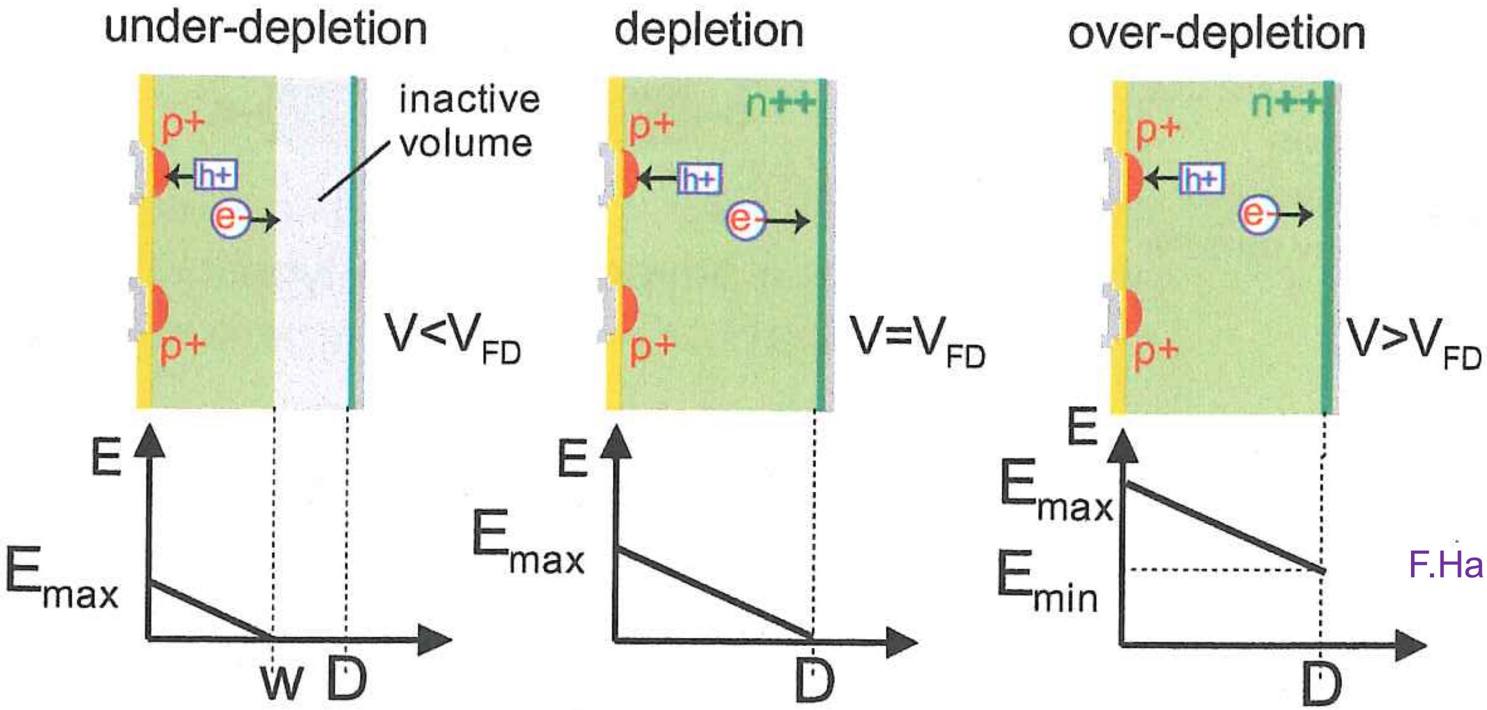
- typical values: $N_a \sim 10^{15}/\text{cm}^3$, $N_d \sim 10^{12}/\text{cm}^3$

In this case: $\mathbf{W \sim W_n = \sqrt{\frac{2\varepsilon V_0}{e N_d}}}$

At 300µm, the voltage for full depletion $V_{FD} \approx 150V$ for an n-type bulk of ~2 kΩ.cm resistivity, i.e. with a doping concentration of 2.2 $10^{12}/\text{cm}^3$
(exercice: check it)

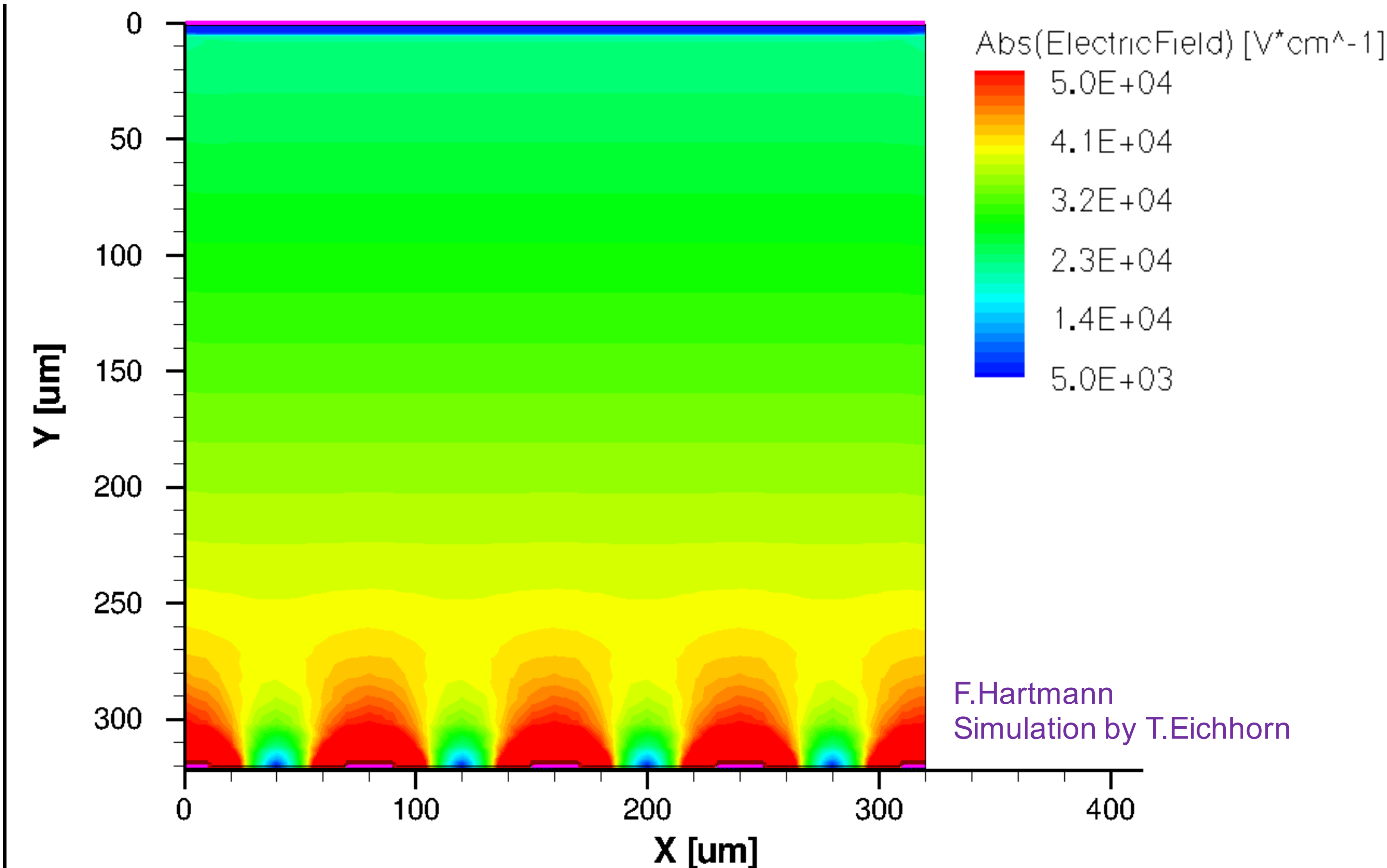
Field configurations

- There is a linearly-increasing **E** field across the sensor bulk
- The maximum is on the implants side
    - The maximum grows with bias voltage
- At $V<V_{FD}$ there is an undepleted zone on the backside
- To collect e- and holes from the entire thickness, the E field has to be non-zero across the whole bulk -> apply $V>V_{FD}$ (over-depletion)



F.Hartmann [1]

Field configurations



Measuring the depletion voltage

- **By measuring the leakage current (not reliable):**

  Ideally, the leakage current due to e-hole pairs thermally created in the depletion region is proportional to the depleted volume:

  $$I_{leak} \sim W \sim \sqrt{V_0}$$

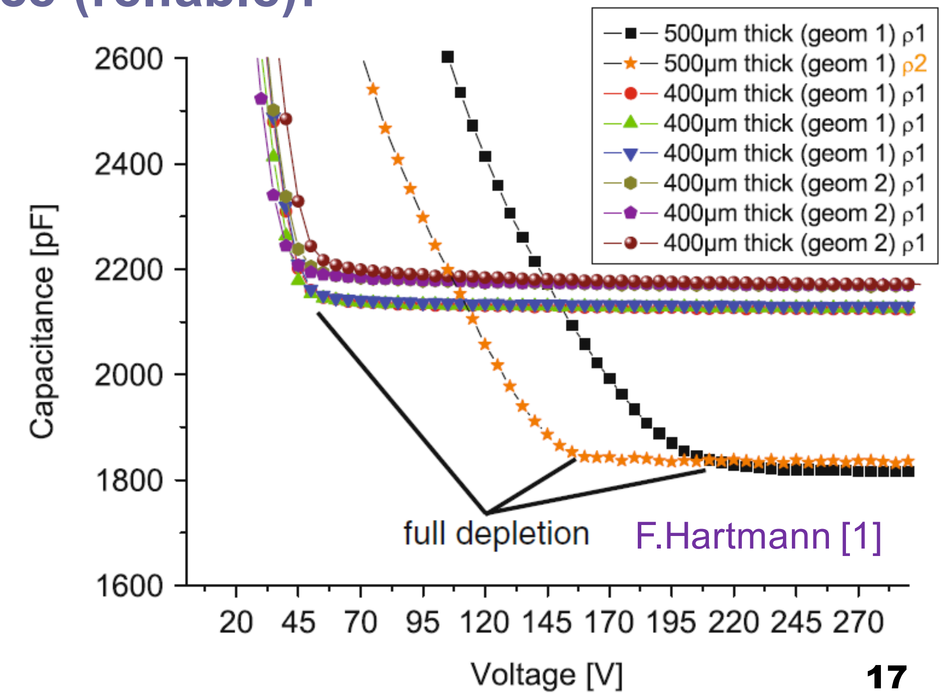
  In practice, trapping of charge carriers at low voltage, and charge amplification at high voltage, make this method unreliable

- **By measuring the capacitance (reliable):**

The depleted sensor acts as a //-plate capacitor of variable thickness W:

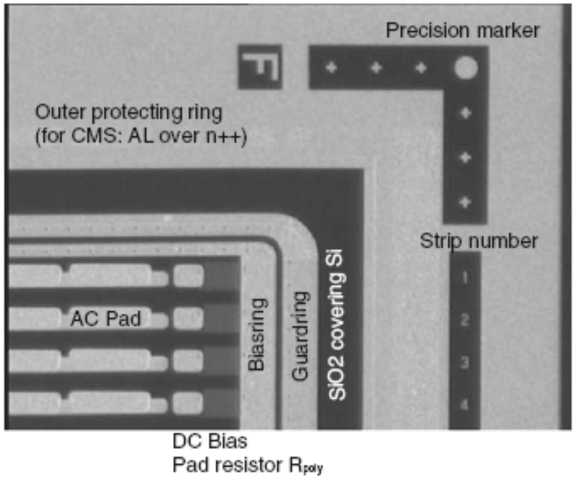
$$\boxed{C = A.\sqrt{\frac{\varepsilon_0 \varepsilon_r}{2\mu\rho|V_0|}}} \qquad \rho = \frac{1}{e\,\mu N_{eff}}$$

V … External voltage
ρ … specific resistivity
μ … mobility of majority charge carriers
N_{eff} … effective doping concentration
A … detector surface

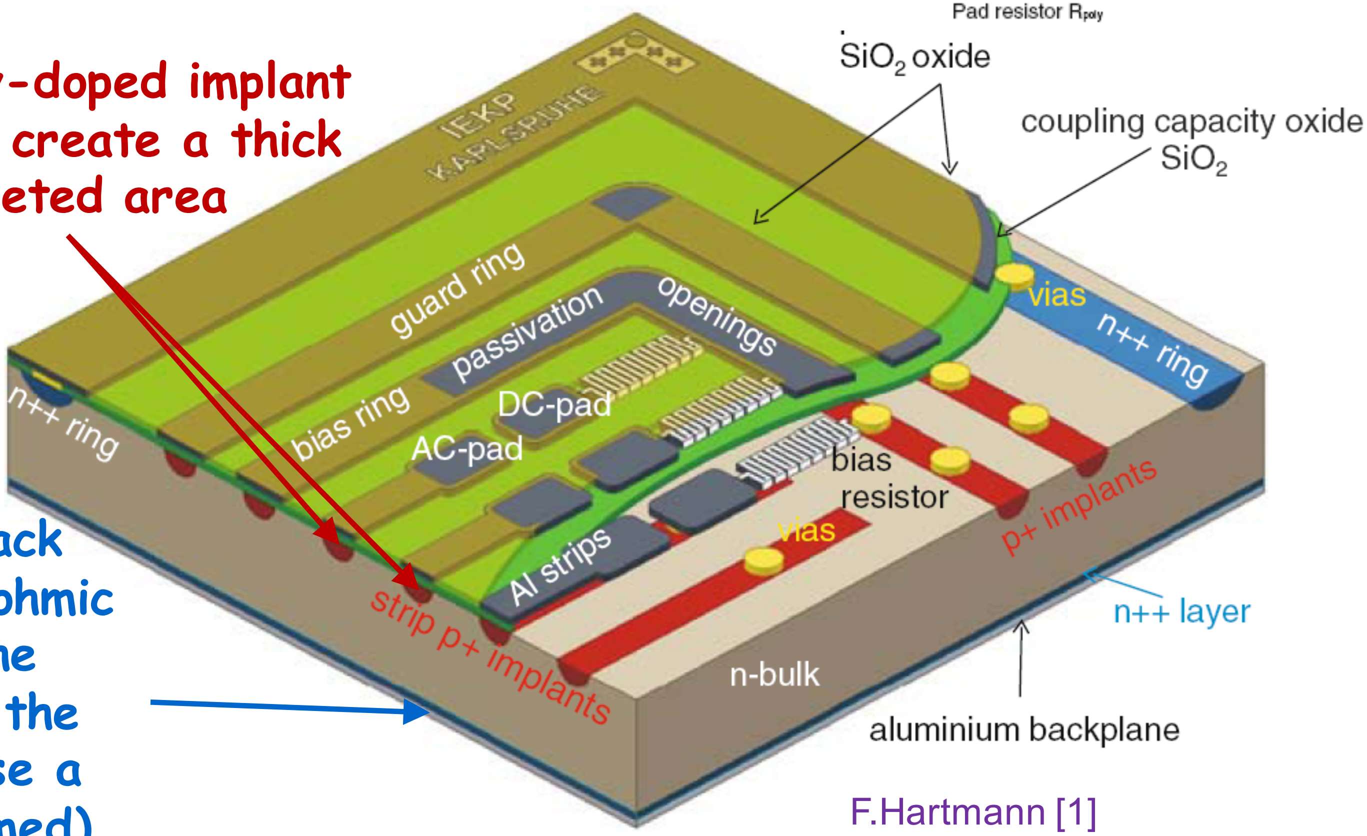


A track detector

- To reach the desired position resolution, the implant is shaped in closely-spaced strips, each of them connected to a readout channel.



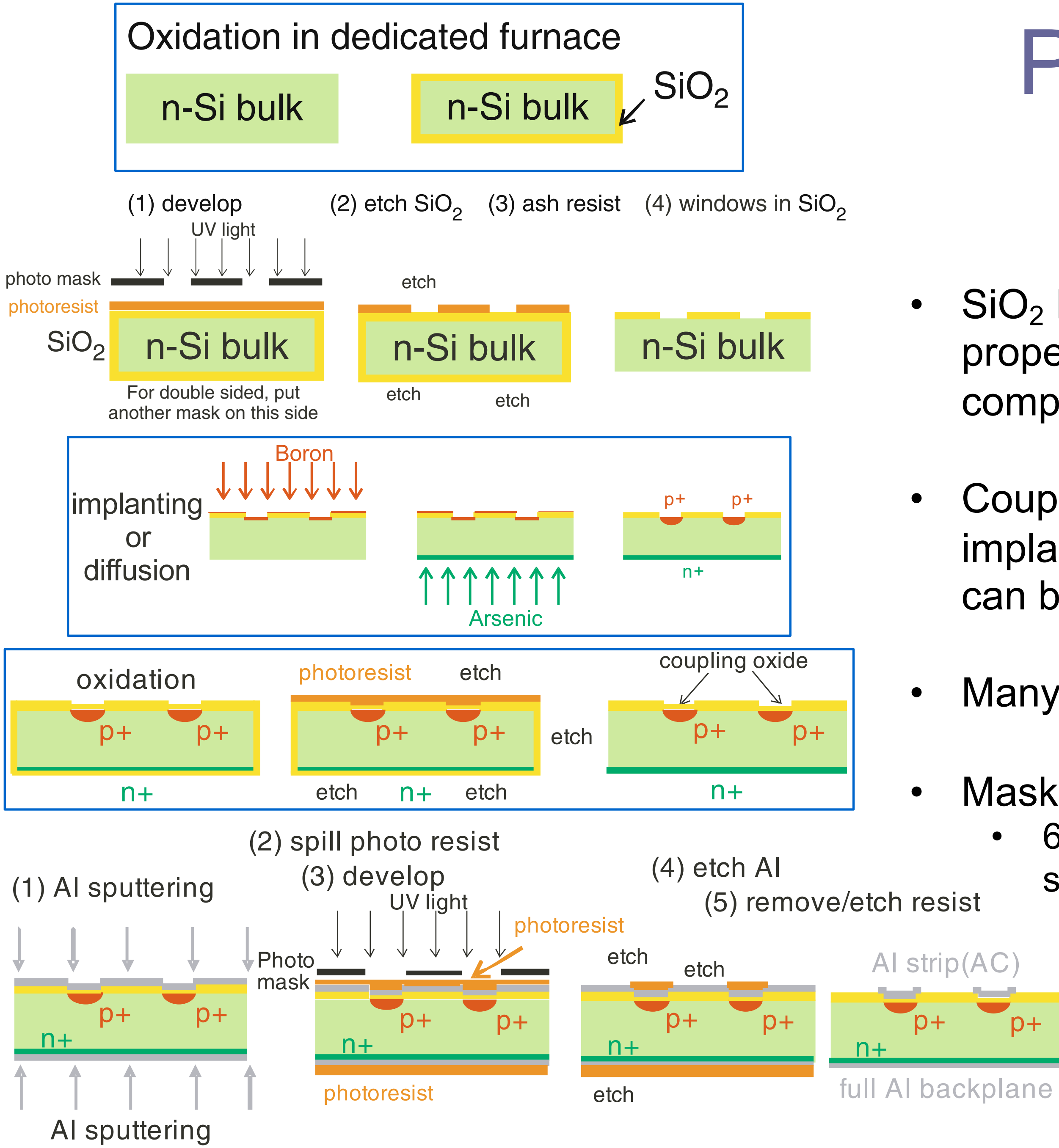
p^+: highly-doped implant strips to create a thick depleted area



F.Hartmann [1]

n^{++}: highly-doped back layer to allow a good ohmic contact between the backplane metal and the Silicon bulk (otherwise a Shottky diode is formed)

Production process

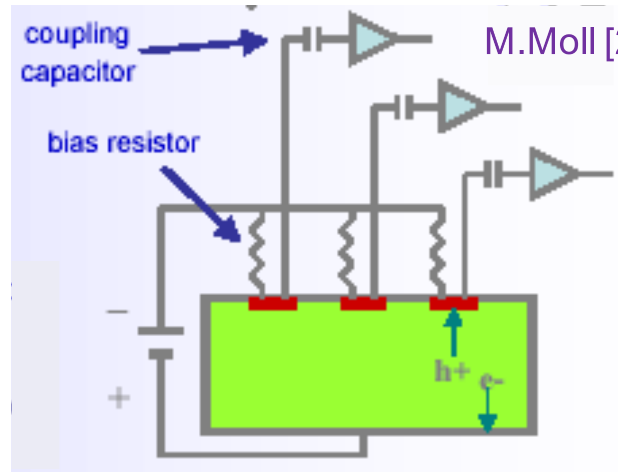


- SiO_2 has excellent insulating properties and high lattice compatibility with Si
- Coupling capacitors between implants and readout amplifiers can be embedded in the process
- Many processing steps
- Masks are very expensive
  - 6 or 8 inch-size with features as small as few µm

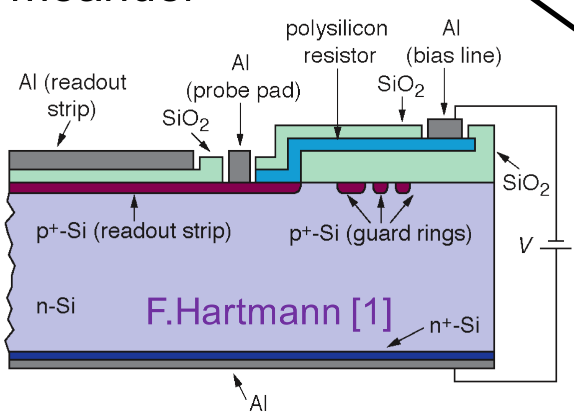
F.Hartmann [1]

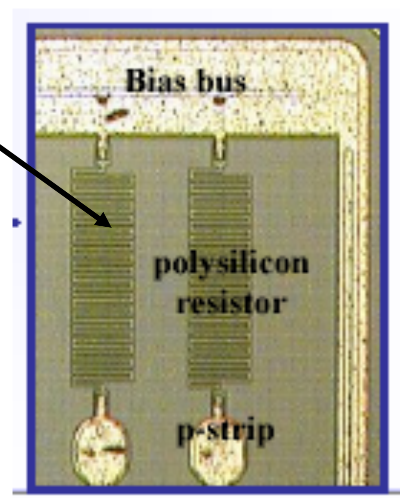
Coupling of the readout amplifiers

- To read the charge induced on each strip, the strips must be insulated from each other by a large resistance (10 MΩ), and the amplifier is coupled through a capacitor that filters the leakage current
- These elements are integrated to the substrate.

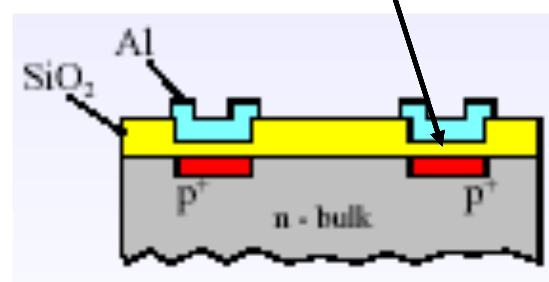


The resistor is made of a polycrystalline silicon meander

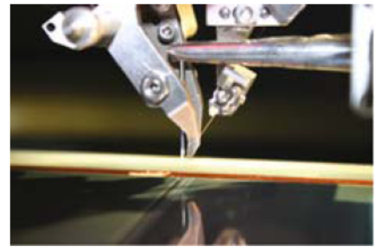


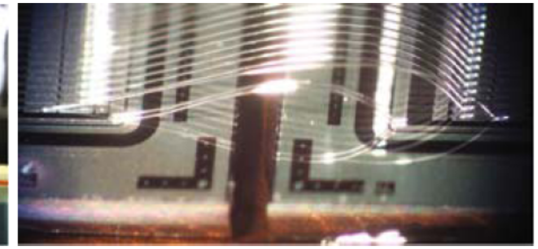


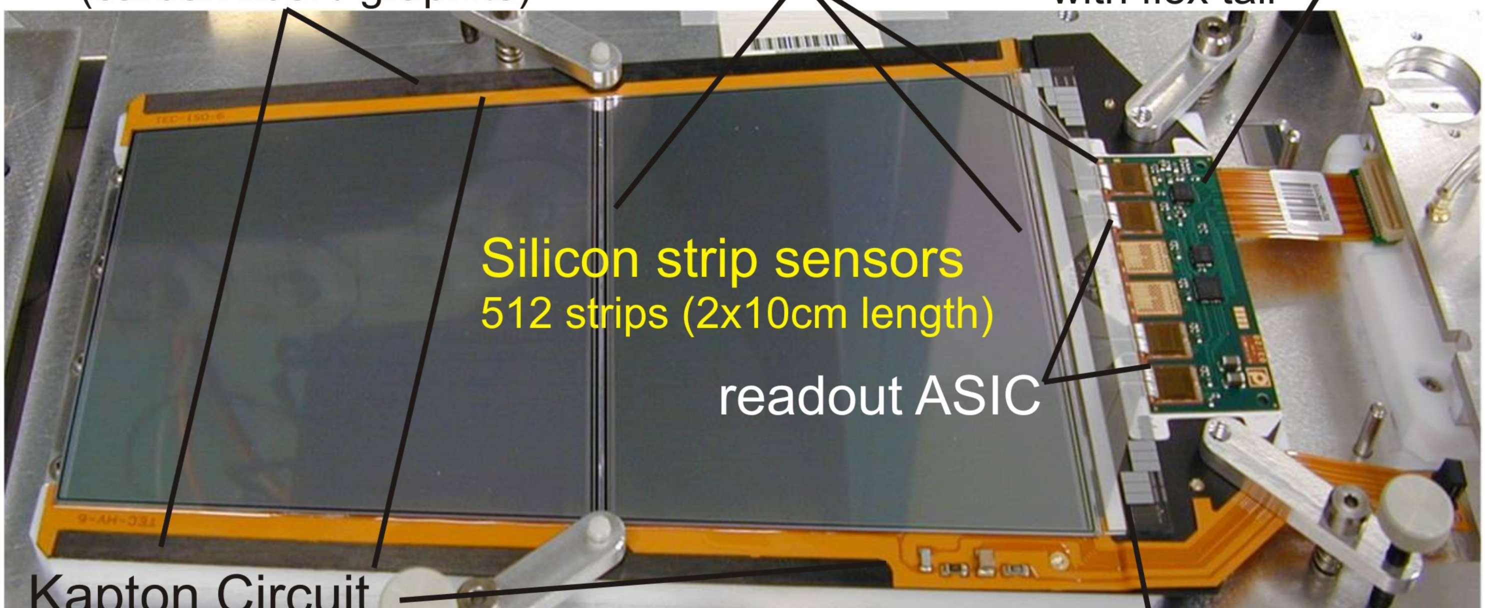
The capacitor is made by a SiO_2 dielectric layer between the p^+ strip and the readout contact



From sensor to module



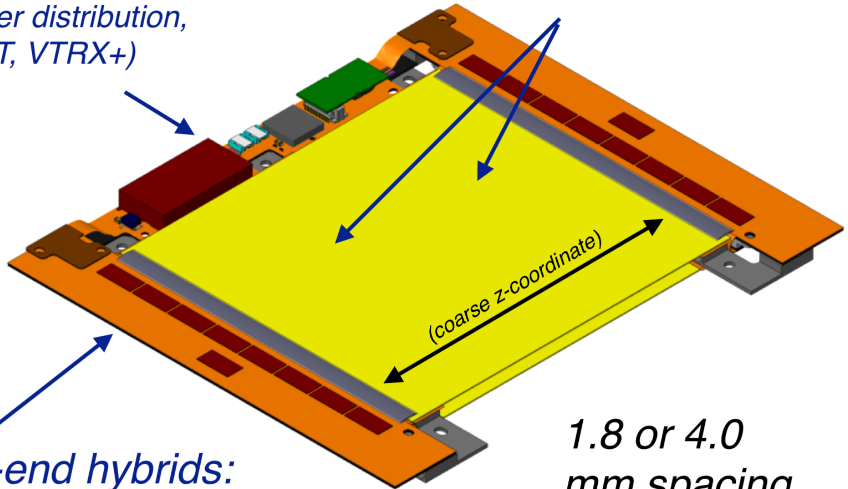




CMS upgrade trigger-enabled tracking module

service hybrid
(Power distribution, lpGBT, VTRX+)

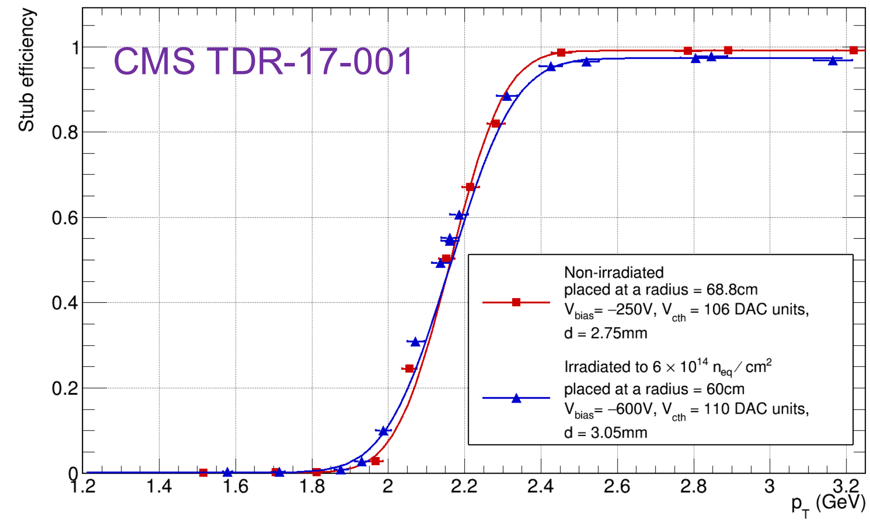
90 cm² active area
2 × 1016 strips 5cm × 90 µm



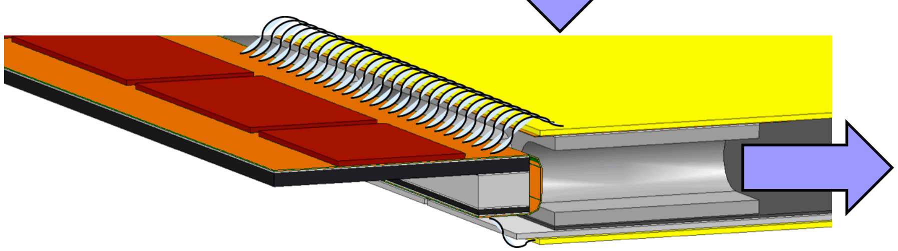
front-end hybrids:
8 CBC readout ASICs
1 Concentrator (CIC) ASIC

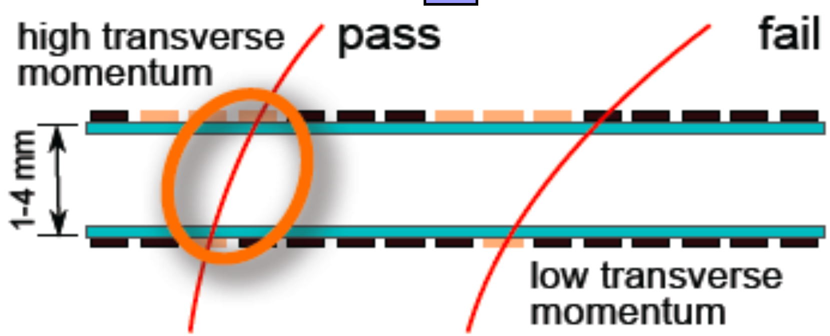
1.8 or 4.0 mm spacing

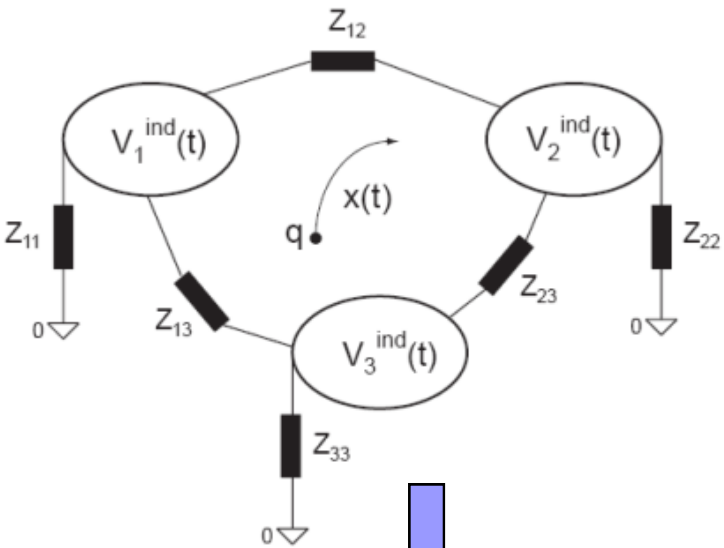
Track finding efficiency vs "p_T"



Same chip reads both sensors





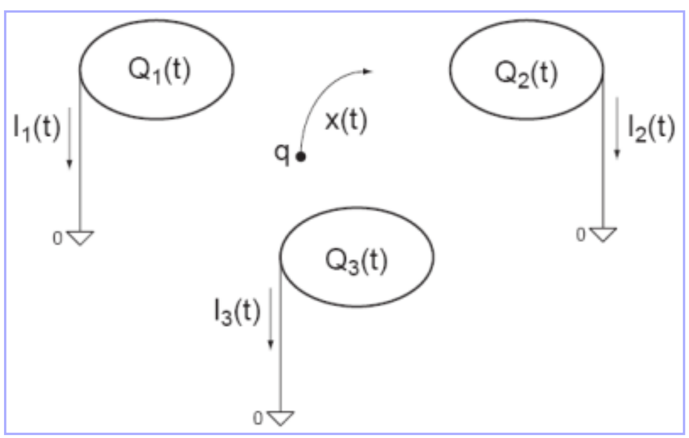


Signal induction

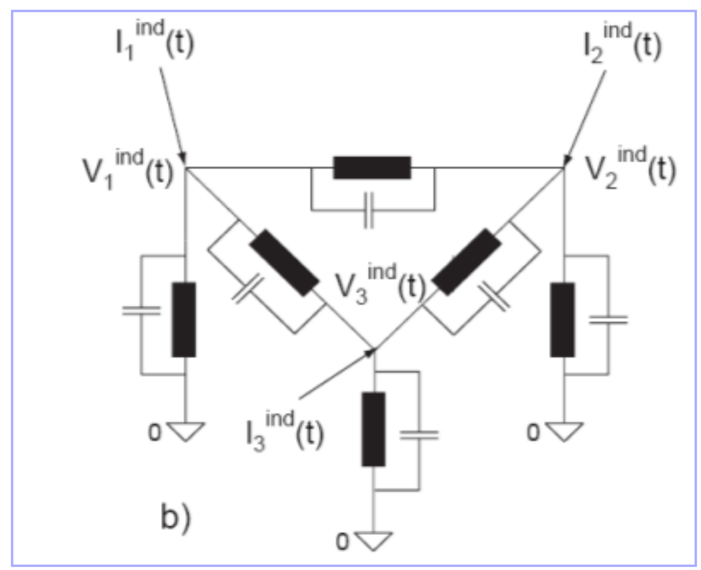
(from slides by W.Riegler [3])

What are the currents induced by the drift of e- and holes on a network of electrodes (ovals) connected to each other by interstrip and backplane capacitances and resistances (Z_{ij}) and front-end electronics (triangles) ?

Drift of e- and holes (q with position x(t)) induce currents $I_i(t)$ on the electrodes

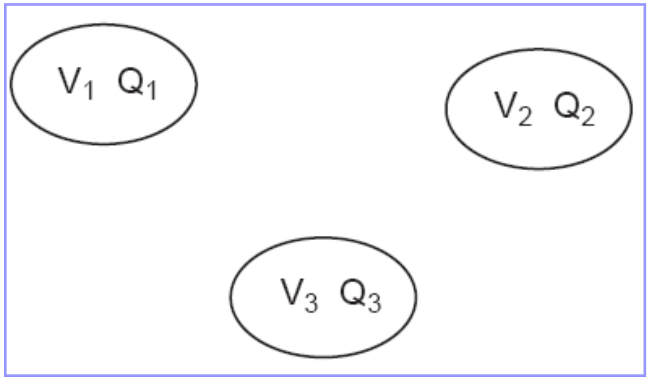


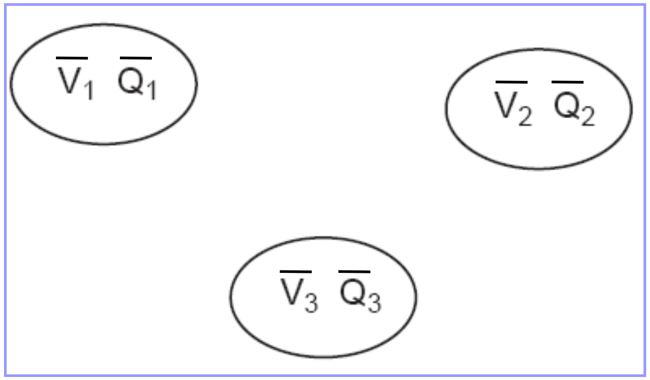
These act as current sources into the impedance network



Signal induction

Placing charges on metal electrodes results in certain potentials of these electrodes. A different set of charges results in a different set of potentials.





The reciprocity theorem states that:

$$\sum_{n=1}^{N} Q_n \overline{V}_n = \sum_{n=1}^{N} \overline{Q}_n V_n$$

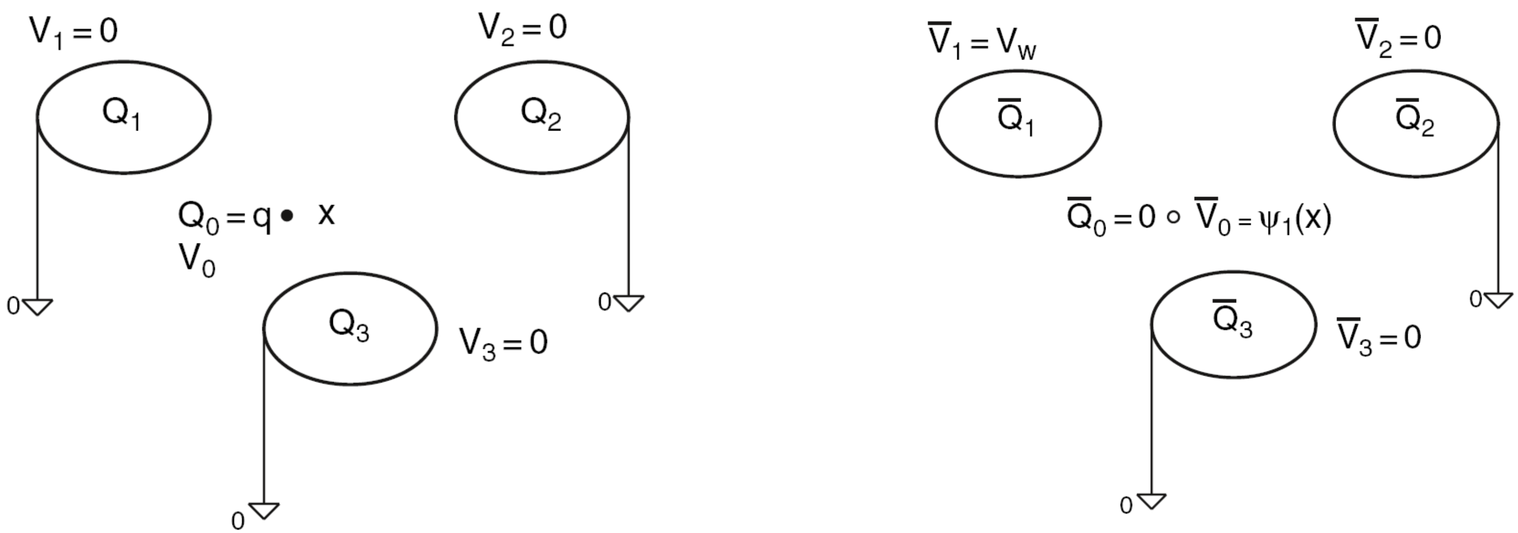
This can be shown using one of Green's identities (see backup).

By choosing $\overline{V}_n$ and $\overline{Q}_n$ wisely, we can get the charge Q_i on the electrode of interest

Signal induction

We assume three grounded electrodes and a point charge in between. We want to know the charges induced on the grounded electrodes. We assume the point charge to be an very small metal electrode with charge q, so we have a system of 4 electrodes with V_1=0, V_2=0, V_3=0, Q_0=q.

We can now assume another set of voltages and charges where we remove the charge from electrode zero, we put electrode 1 to voltage V_w and keep electrodes 2 and 3 grounded.



Using the reciprocity theorem $\displaystyle\sum_{n=1}^{N} Q_n \overline{V}_n = \sum_{n=1}^{N} \overline{Q}_n V_n$ **we get**

$$q\overline{V}_0 + Q_1 V_w = 0 \qquad \rightarrow \qquad Q_1 = -q\frac{\overline{V}_0}{V_w}\,.$$

Signal induction

The voltage $\overline{V_0}$ is the voltage at the place x of the moving point charge q, in the second electrostatic state, where the only electrode with non-zero voltage is the electrode of interest (electrode 1).

Let's call the potential field in this configuration $\psi(x)$, the weighting potential of electrode 1. We have:

$$Q = -\frac{q}{V_w}\,\psi(\vec{x})$$

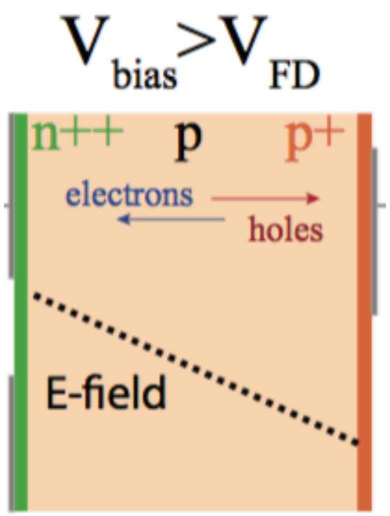
Since the charge is moving, $\vec{x}$ depends on time t: $Q(t) = -\frac{q}{V_w}\,\psi\left(\vec{x}(t)\right)$

Inducent current, $I(t)$ taken positive when exiting the electrode:

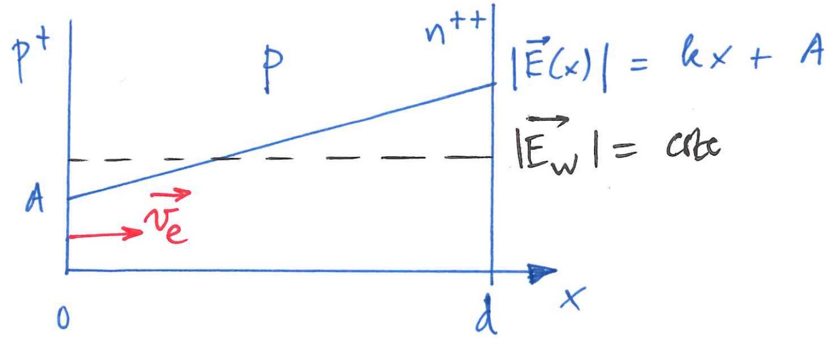
$$I(t) = -\frac{dQ}{dt} = \frac{q}{V_W}\vec{\nabla}\psi\left(\vec{x}(t)\right)\frac{d\vec{x}(t)}{dt} = -\frac{q}{V_W}.\overrightarrow{E_W}\left(\vec{x}(t)\right).\vec{v}(t)$$

where $\vec{v}(t) = \frac{d\vec{x}(t)}{dt}$ is the speed of the moving charge, and $\overrightarrow{E_W}\left(\vec{x}(t)\right)$ is the weighting field of electrode 1. This expression of $I(t)$ is called Ramo's theorem.

Exercise



- Let's compute the collection time of electrons and the expression of the current induced by their motion, in the following situation:
  - an overdepleted detector of p-type bulk
  - d = 300μm active depth
  - Electrons are injected at a single point at the p^+-backside
  - The readout electrode is on the n^{++}-side
  - $E_{min} = A = 2.10^4\ V.cm^{-1}$
  - $E_{max} = 5.10^4\ V.cm^{-1}$
  - Electrons mobility: $\mu_e = \frac{v_e}{E} = 1400 cm^2 s^{-1} V^{-1}$



$$|\vec{v}_e| = v_e(x) = \mu_e E(x) = \mu(kx+A)$$

$$x(t) = \int_0^t v_e(x)\,dt = \int_0^t \mu(kx(t)+A)$$

$$\frac{dx(t)}{dt} = \mu k x(t) + \mu A$$

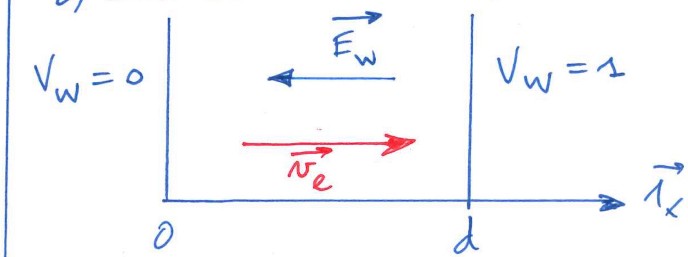
Solution: $x(t) = \frac{A}{k}\left[e^{\mu k t} - 1\right]$; $x(0) = 0$ cm

1) collection time: $t = \frac{1}{\mu.k}\ln\left(\frac{kd}{A}+1\right)$

$$k = \frac{5.10^4 - 2.10^4\ [V.cm^{-1}]}{300.10^{-4}\ [cm]} = 10^6\ V.cm^{-2}$$

$$t = \frac{1\ [s]}{1400.10^6}\ln\left(\frac{10^6.3.10^{-2}}{2.10^4}+1\right) = 6,5.10^{-10}\ s$$

2) Induced current :



$$\left(\frac{\vec{E}_w}{V_w}\right) = \left(\frac{1}{d}\right)(-\vec{1}_x)$$

$$\vec{v}_e = \frac{dx}{dt}\vec{1}_x = \frac{A}{\cancel{k}}\mu\cancel{k}\,e^{\mu k t}\,\vec{1}_x$$

$$I(t) = (-)q_e\left(\frac{-1}{d}\vec{1}_x\right).A\mu e^{\mu k t}\,\vec{1}_x$$

$$= \frac{q_e}{d}A\mu\, e^{\mu k t}$$

Units: $[C.cm^{-1}].[V.cm^{-1}].[cm^2 s^{-1} V^{-1}]$
$= [C.s^{-1}]$:)

⇒ exponential rise of current; negative current flowing out of electrode (V) (electron moving towards it).

$I(t=0) = \frac{q_e}{d}A\mu = -1,5.10^{-10}$ A/él.

time constant: $\frac{1}{\mu k} = 7,1.10^{-10}$ s

Also: check that $\int_{t=0}^{t_{arrival}} I(t)\,dt = q_e$!-)

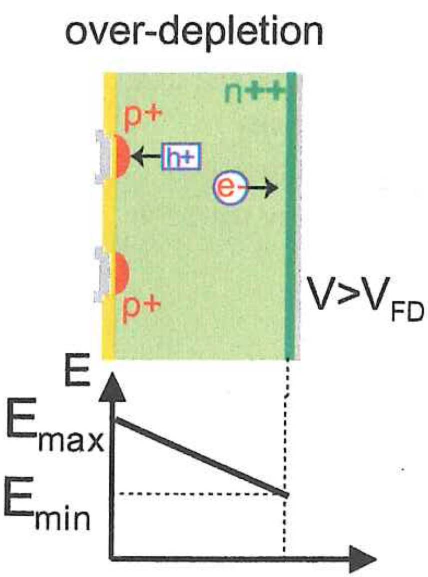
Pulse shapes

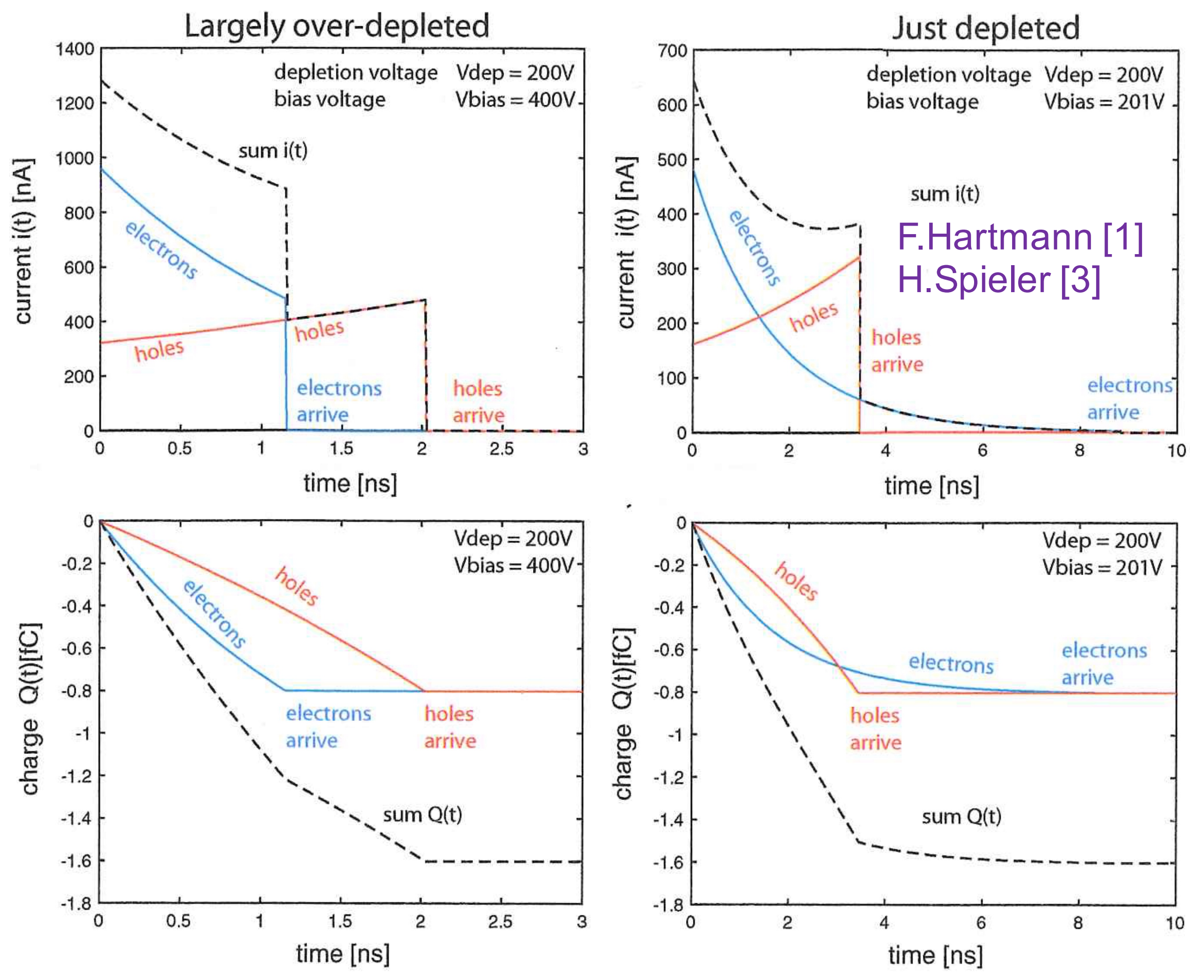
$$I(t) = -\frac{q}{V_W}.\overrightarrow{E_W}(\vec{x}(t)).\vec{v}(t)$$

The current induced is large:

1. **when the speed of the e- or holes is large, i.e. when the drift field is large**
2. **when the weighting field is large**

Simulation:
300 µm diode; n-type bulk
10000 e-h pairs injected at
150 µm depth
Signal on p-implant





F.Hartmann [1]
H.Spieler [3]

Position resolution

The interstrip distance or “**pitch**”, p, is typically in the range 20-200 µm.

Binary (digital) readout

- If the strips are read out in a binary way (signal above or below threshold) and if a single strip carries a signal, the hit position is the middle of that strip, and the position resolution is:

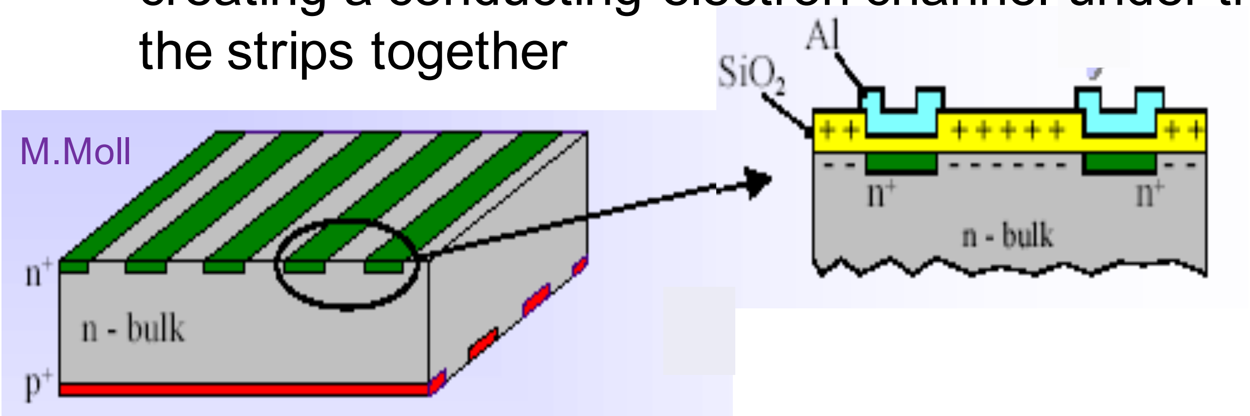
$$\sigma = \frac{\mathbf{p}}{\sqrt{\mathbf{12}}} \simeq 5 - 50\mu\text{m}$$ (R.M.S. of a uniform distribution of width p)

Analog readout

- The amplitudes of the signals in neighbouring strips can be used to compute the center-of-gravity of the deposited ionization charge
- For tracks impinging at normal incidence, this requires specific design, as the diffusion of charges in silicon is small
  - A few tens of µm for 300 µm of drift

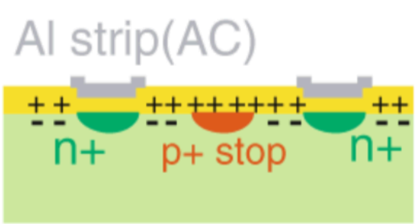
n-strips in a p-bulk

- Patterning the back side gives 2nd coordinate (in principle)
- n-in-p sensors are more radiation-hard
- Caveat:
  - typical good-quality oxide layer has fixed positive charges, creating a conducting electron channel under the oxide, shorting the strips together



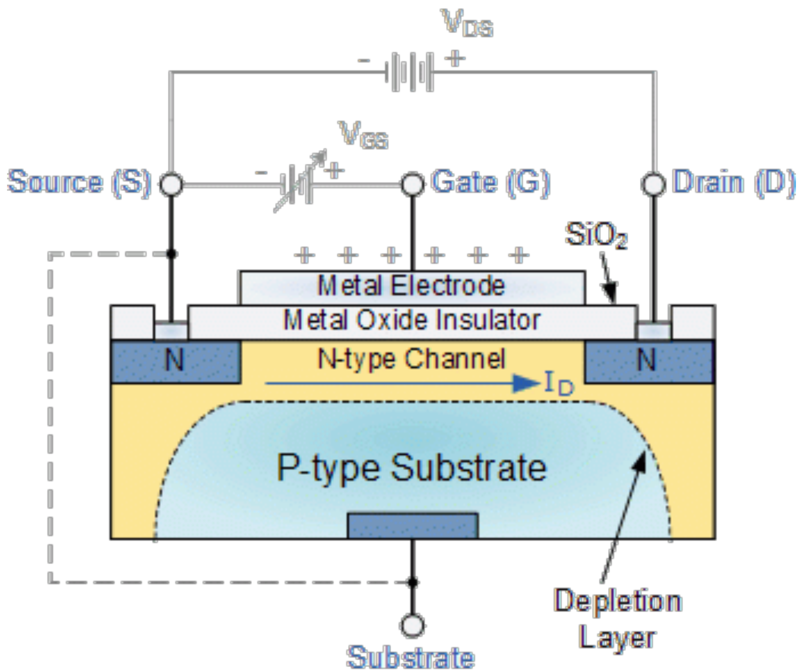
F.Hartmann [1]
M.Moll [2]
G.Lutz [4]

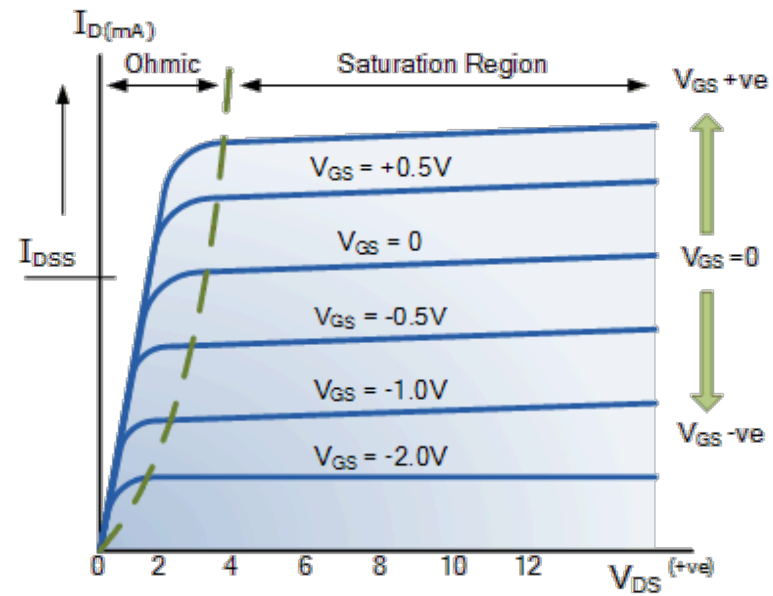
- Solution:
  - p+ implants (p-stops) create fixed negative charges repelling electrons, insulating the strips



n-strips in a p-bulk

- The structure is very similar to the widely-used **Metal-Oxide-Silicon Field-Effect Transistor** (MOSFET)
  - Without p-stops, our n-in-p sensor is similar to a depletion-mode (normally-ON) N-channel MOSFET ☺
  - MOSFETs also appear in integrated readout amplifiers, and in monolithic detectors combining sensor and amplifiers in same Silicon wafer (see later)

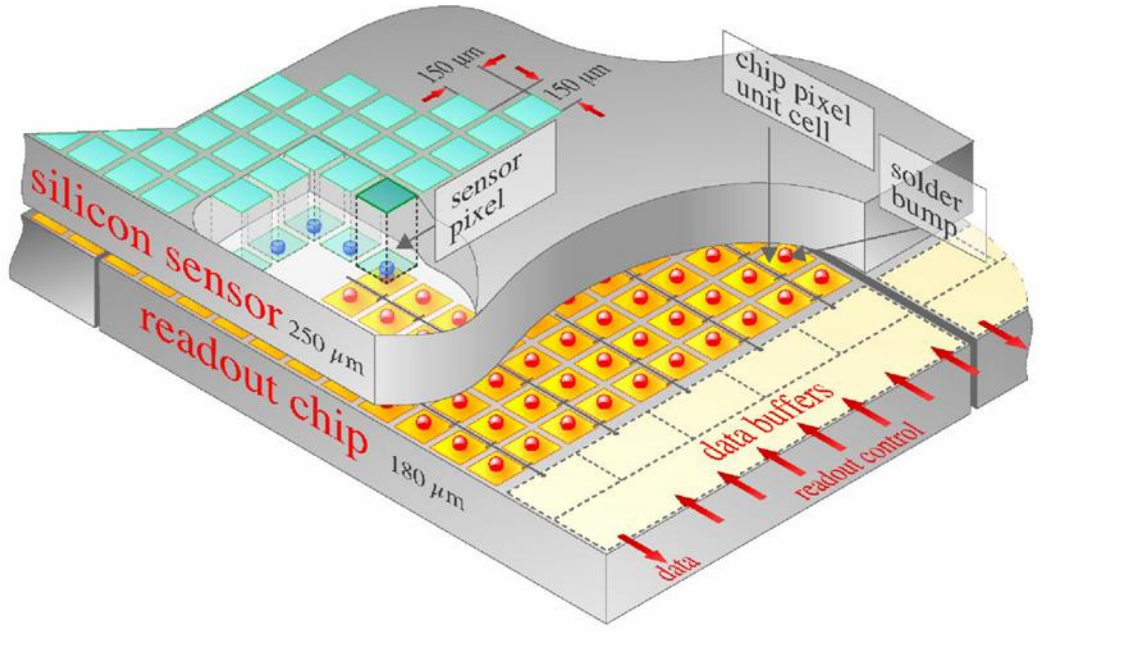




https://www.electronics-tutorials.ws

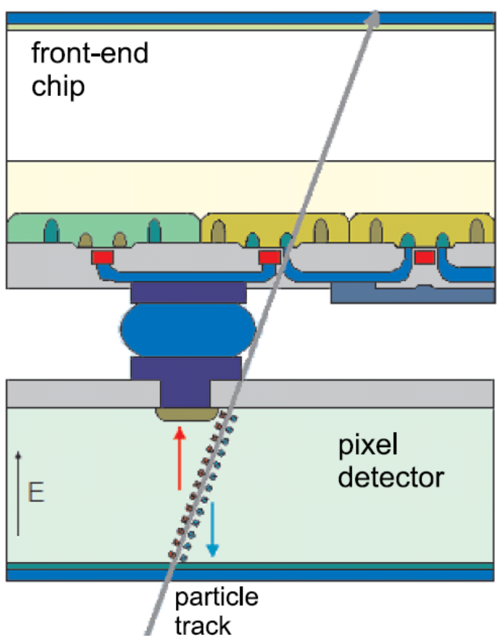
Silicon pixel detectors

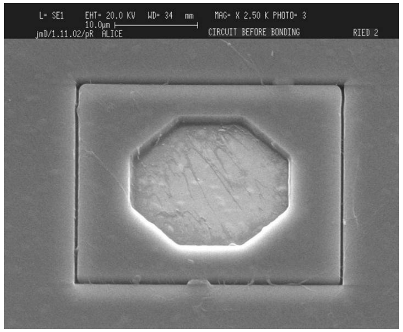
- Pixelated sensor and readout chip

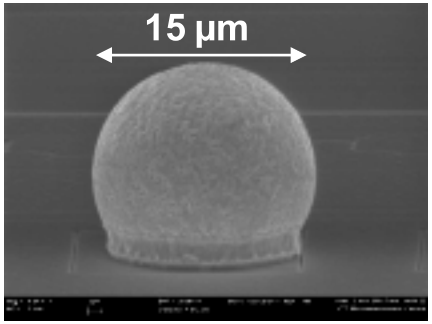


Difficulty: connect the electronics to each pixel

Solution: bump bonding



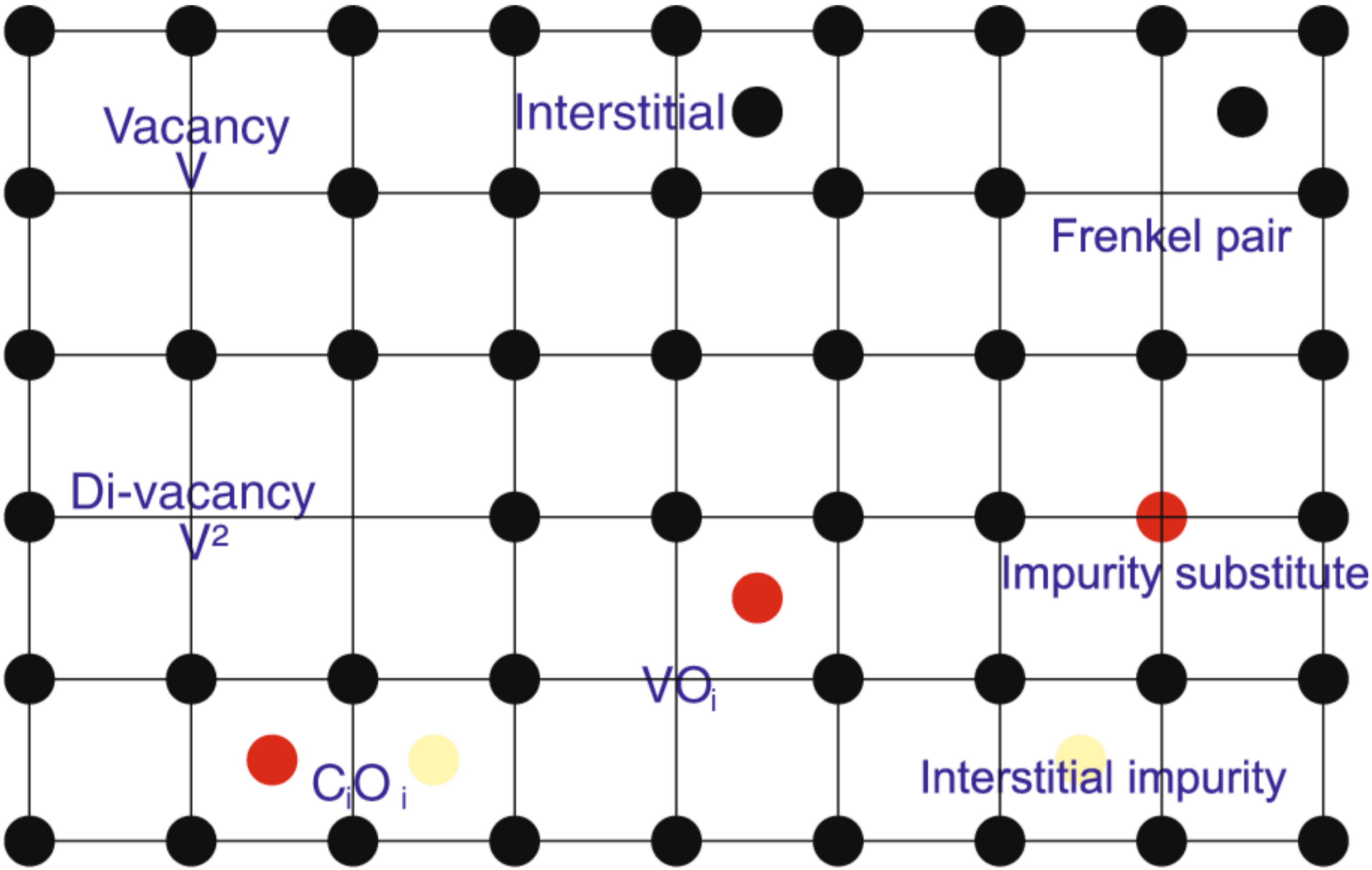




Radiation damage

Radiation damage

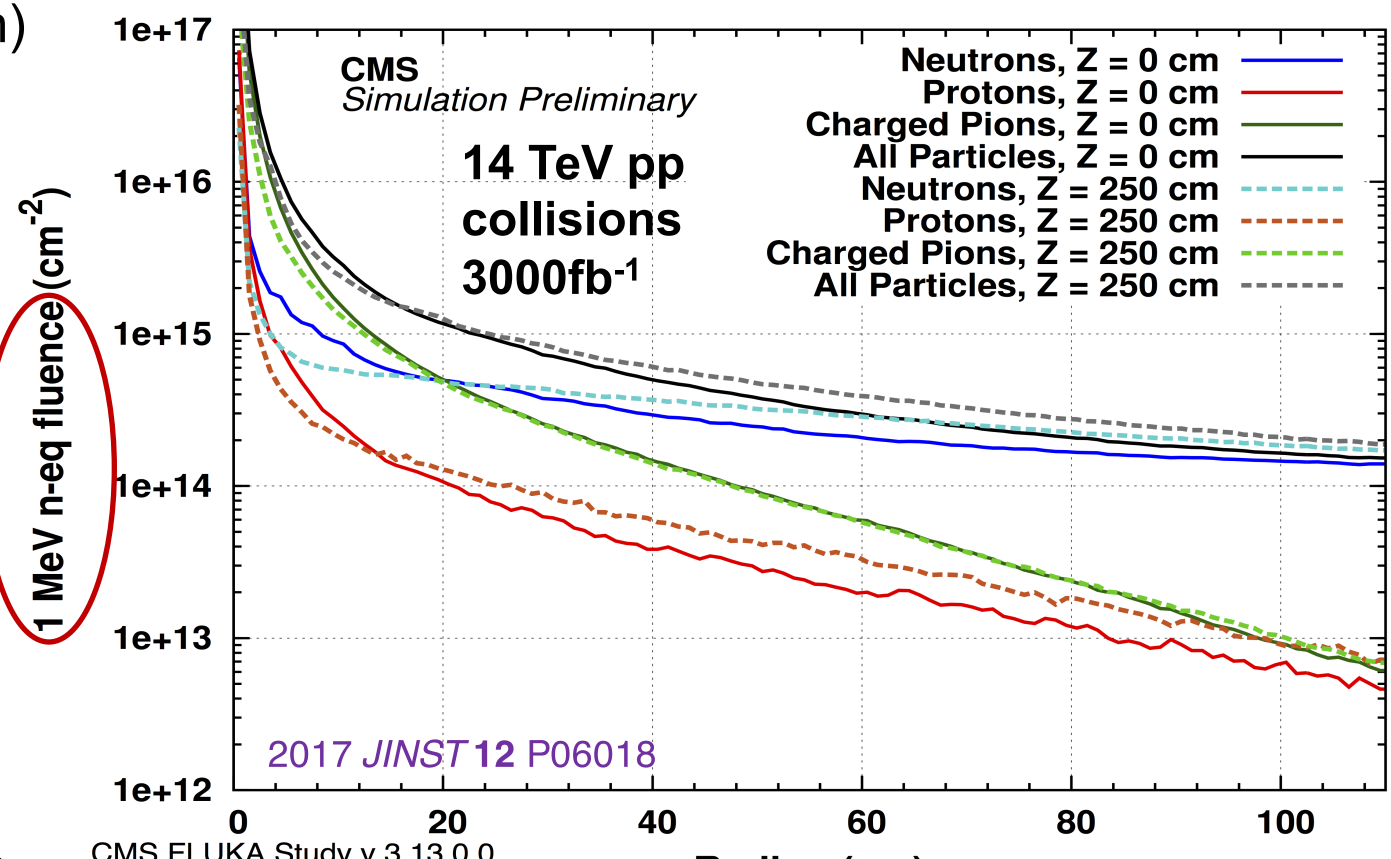
- Radiation produces defects in Silicon lattice



Radiation damage

- A concern at high-luminosity experiments, notably at HL-LHC
- Damage mostly due to neutrons, protons and charged pions, of very different energy spectra
- Particle fluxes are normalized to 1 MeV neutrons, characteristic of emission by detector activated by primary hadrons (e.g. calorimeter back-splash)

Damage-weighted flux, normalized to damage of 1 MeV neutrons



Non-Ionizing Energy Loss (NIEL) model

Lattice damage characterized by "displacement damage" functions:

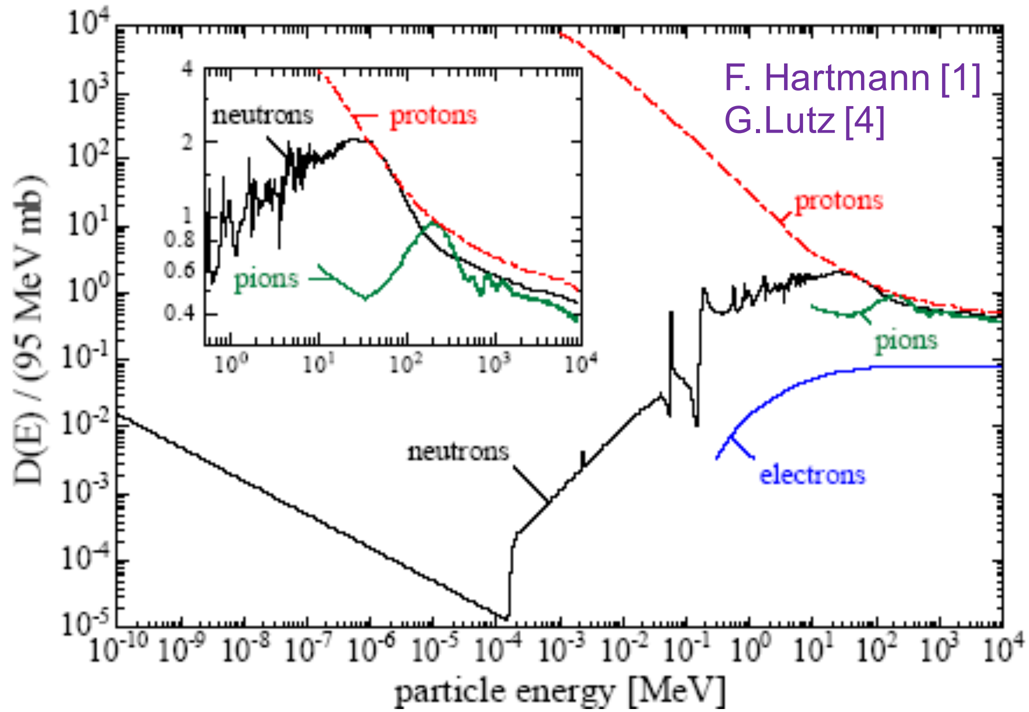
$$D(E)[MeV.mb] = \frac{dE}{dx}(E)[MeV.cm^2g^{-1}].\frac{A[g.mol^{-1}]}{N_A[mol^{-1}]}$$

$D(E)$ depends on particle type and energy through defect production cross sections

→ **Neutrons of 1MeV as reference particles „equivalent fluence Φ_{eq}"**

Irradiation "hardness" factor:

$$\kappa = \frac{\int D(E)\phi(E)dE}{95MeVmb \cdot \Phi} = \frac{\Phi_{eq}}{\Phi}$$



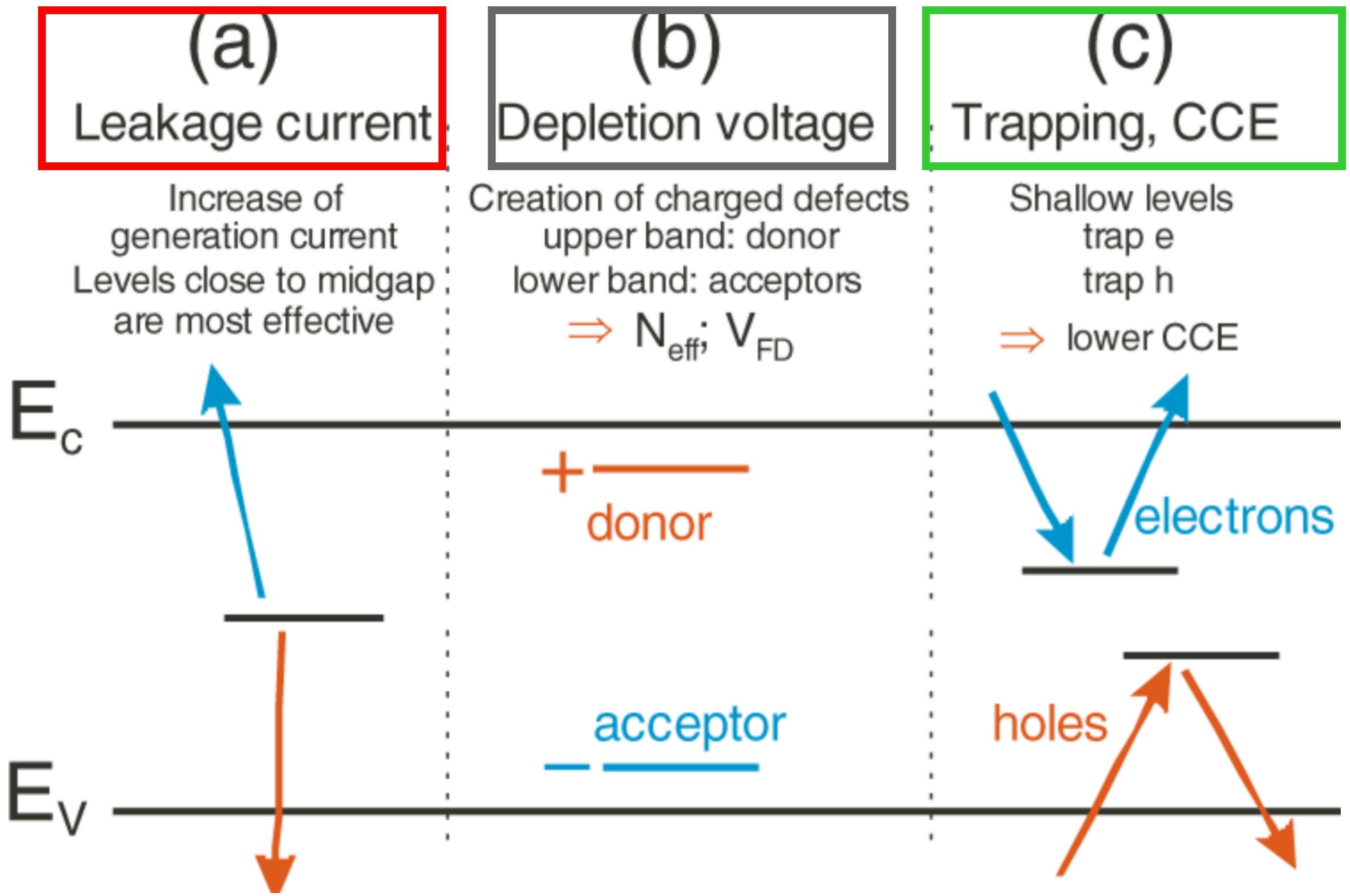
Note the huge difference: in Silicon:

- Ionization (MIP): $\frac{dE}{dx} = 3.87MeV/cm$
- NIEL (1 MeV neutron): $\frac{dE}{dx} = 5.0KeV/cm$

Radiation damage

- Defects introduce extra energy levels in band gap, with different consequences:

F. Hartmann [1]



Annealing

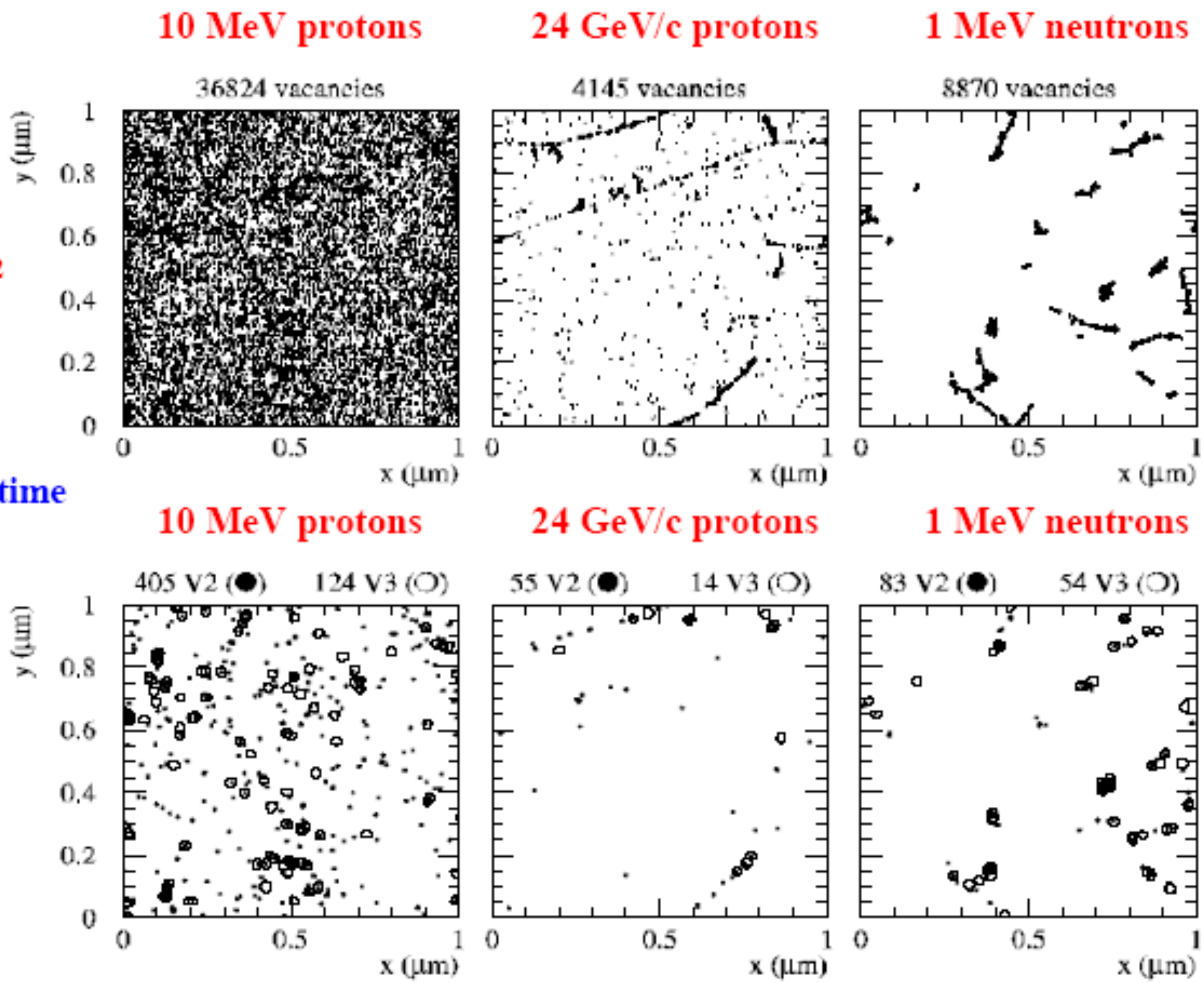
- Defects diffuse, migrate and combine: *annealing*
- Temperature and time-dependent !!

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

I,V random walk + recombination or defect formation

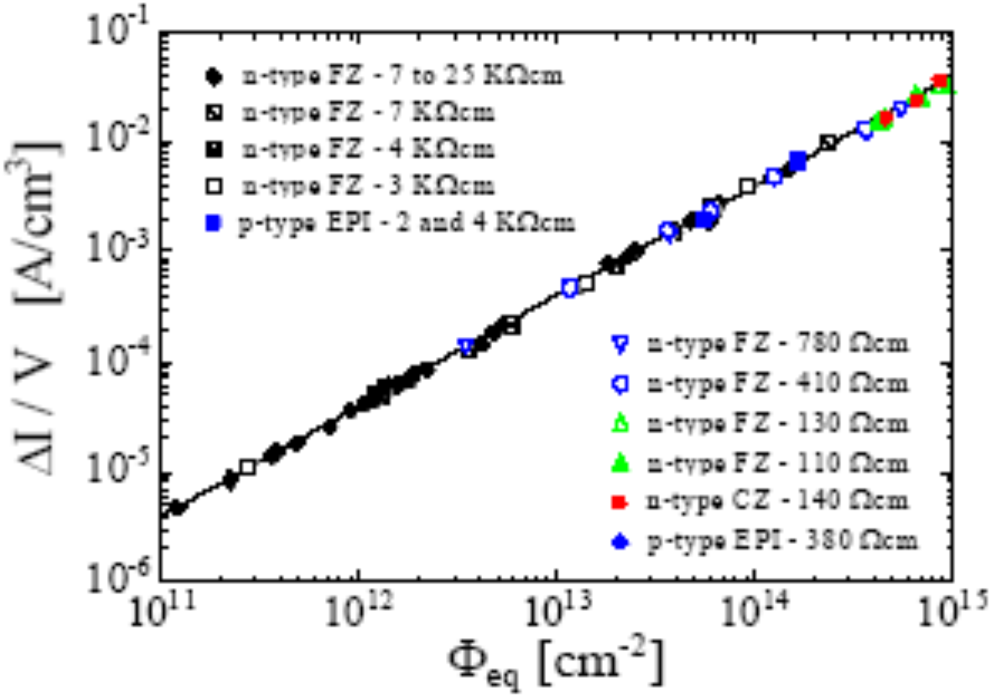
time

Final constellation of V_2 and V_3



[Mika Huhtinen ROSE TN/2001-02]

Leakage current



- Linear increase of current with ϕ_{eq} fluence during irradiation, for a wide range of Silicon resistivity, doping type and production process
  - In agreement with NIEL model

Current damage rate:

$$\alpha = \frac{\Delta I}{Vol.\phi_{eq}}$$

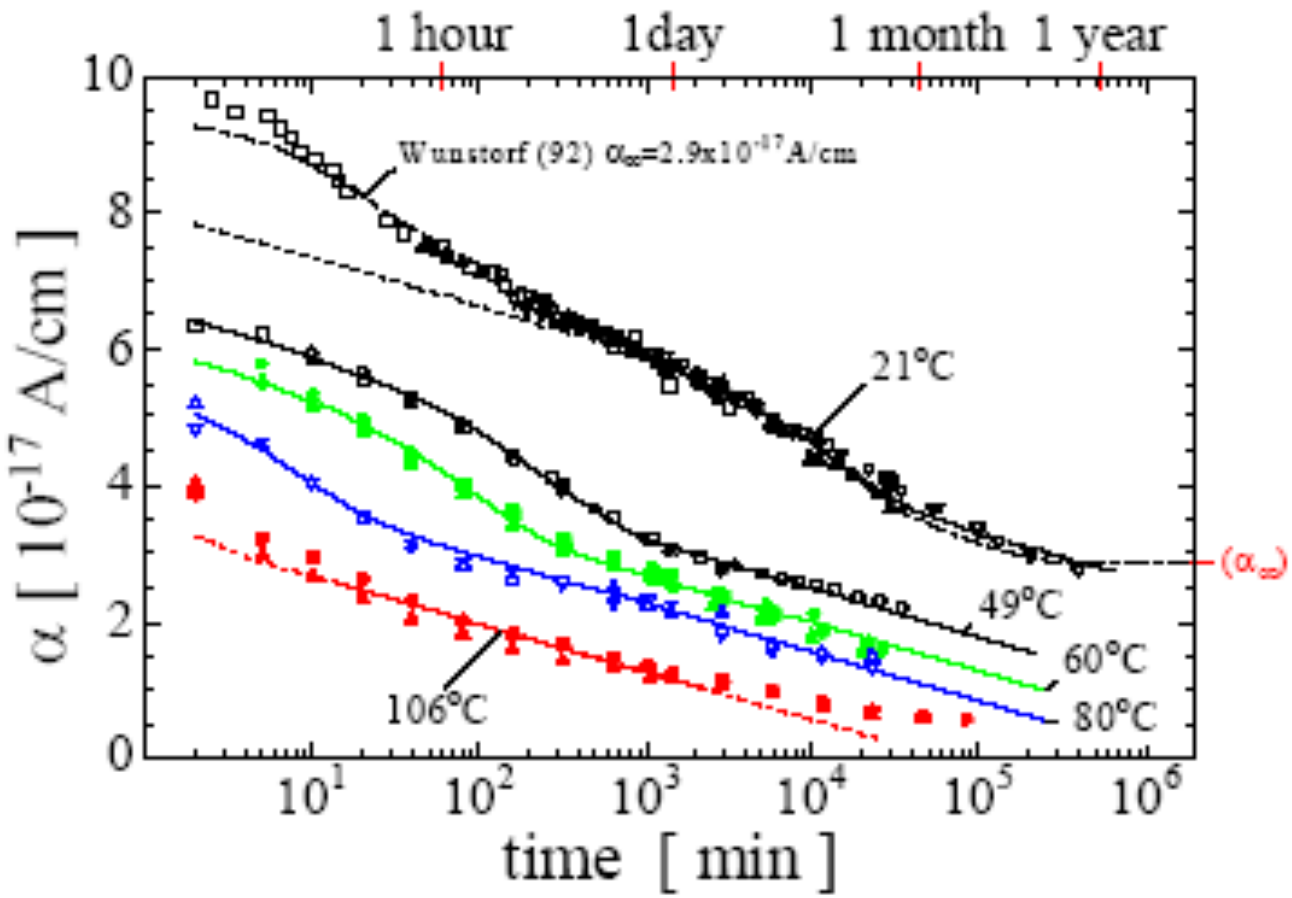
Strongly temperature dependent ➔ $\alpha(T)$ — 20° C: α = 4,00 ·10^{-17} A/cm

Current: $I \propto \exp(-E_{eff}/2k_B T)$ — -10° C: α = 1.86 ·10^{-18} A/cm

- **Our concerns:**
  - Electronics noise due to current fluctuations at the input of the amplifiers
  - Joule effect in sensor: $P_J = \mathrm{V.I}$ increases exponentially with sensor temperature, while cooling capacity only proportional to $(T^o_{sensor} - T^o_{coolant})$

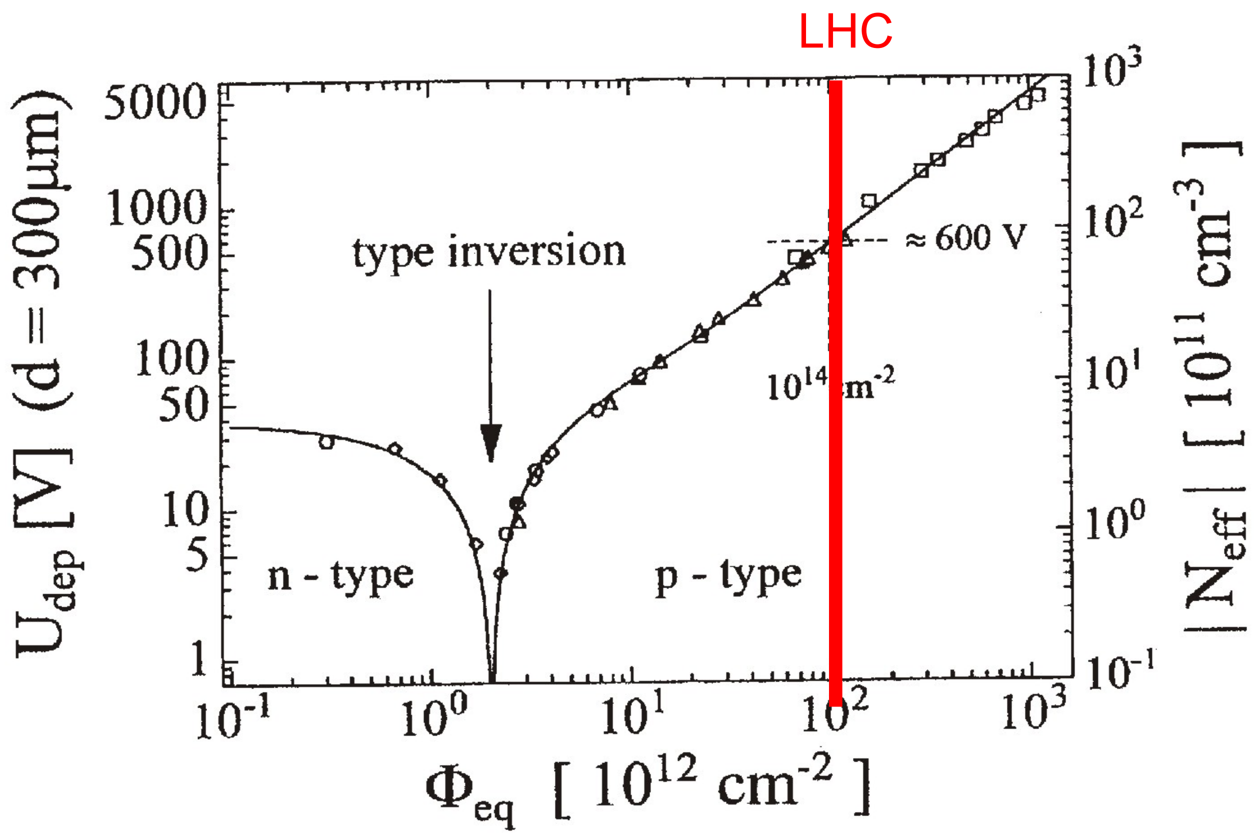
Annealing of the leakage current

- ❑ Leakage current decreases with time
- ❑ Decrease is faster at higher temperature
- ❑ Can be used to some extent to mitigate radiation damage



Depletion voltage

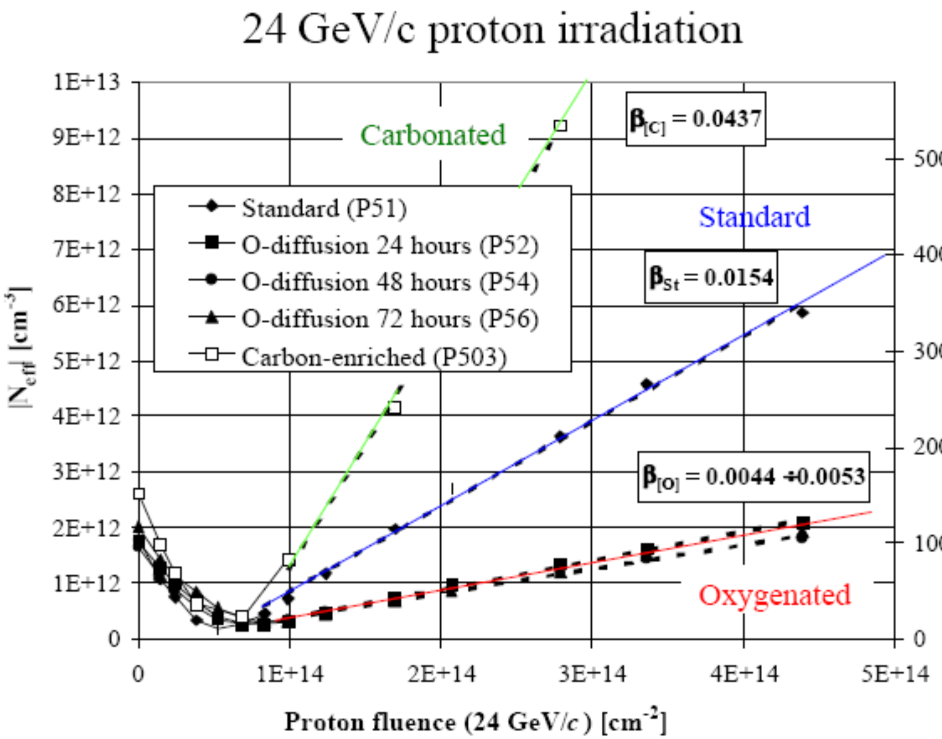
- Most irradiation damages in Silicon behave like acceptors
- Starting with **n**-type Si → **p**-type: **„type inversion“** also called **Space Charge Sign Inversion (SCSI)**



For LHC fluences ($2.4\cdot10^{14} n_{1MeV}/cm^2$) high full depletion voltages are expected !

Effective doping concentration N_{eff}

Influence of Carbon and Oxygen concentration



Compared to standard silicon:

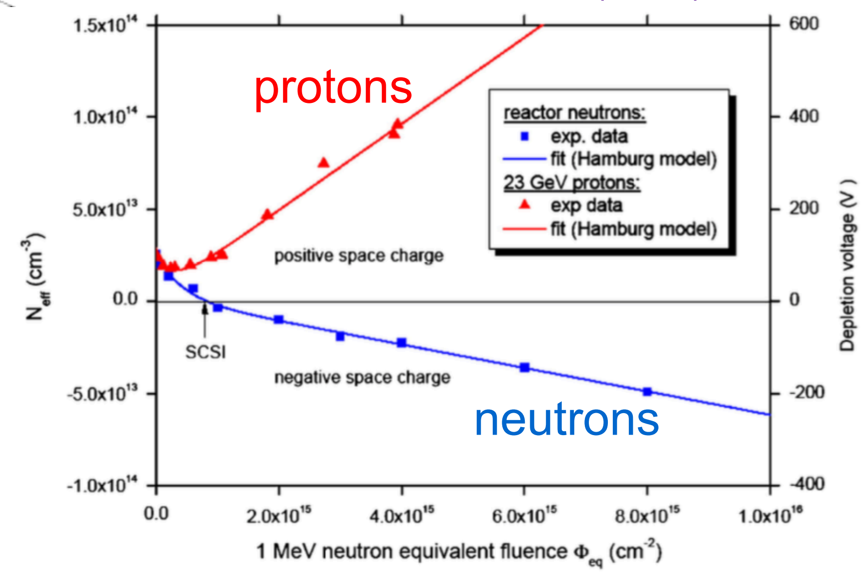
- **High Carbon ⇒ less radiation tolerant**
- **High Oxygen ⇒ more radiation tolerant**

Michael Moll - CERN EP-TA1-SD Seminar - 14.2.2001

Contrary to NIEL hypothesis, change in N_{eff} depends on material...

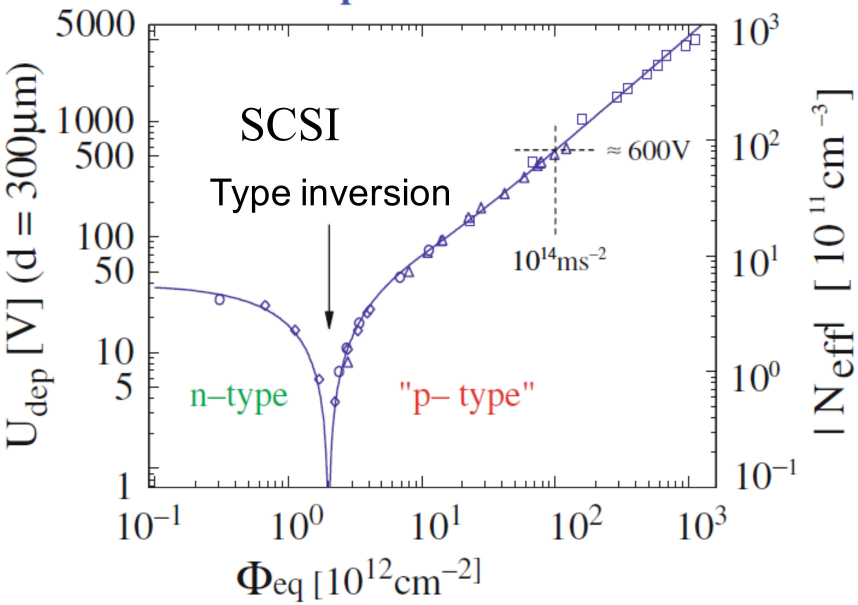
...and on particle type

I.Pintilie et al., NIMA 611 (2009)52-68

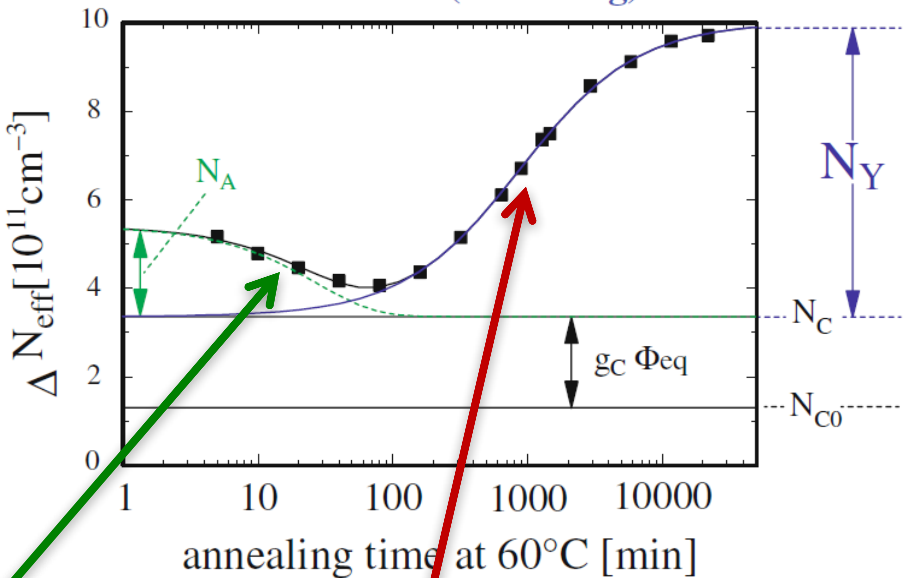


N_{eff} and annealing

…. with particle fluence :



…. with time (annealing) :



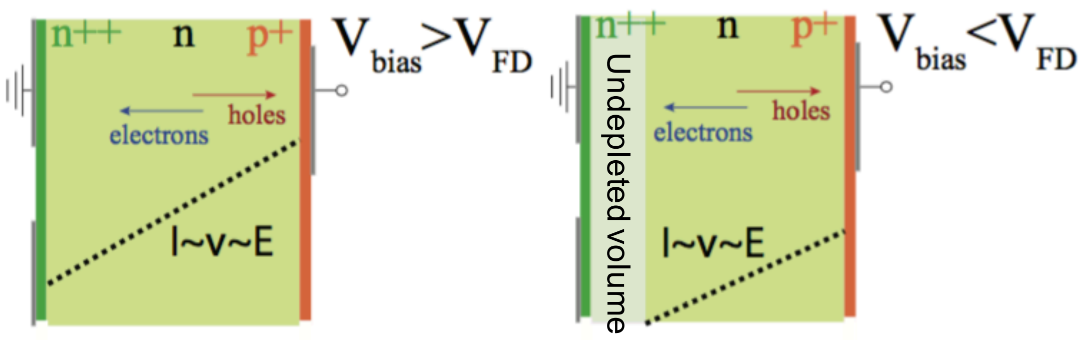
- Different defects evolve differently and with different time constants
  - Short-term beneficial annealing; long-term reverse annealing
- The evolution also depends on temperature
  - Annealing can be slowed down or even “frozen” at -10° C

Bottom line:

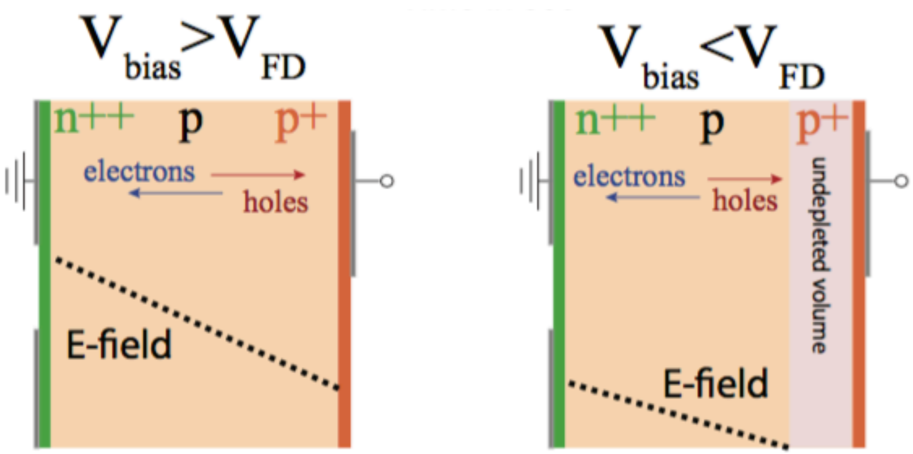
1) Make irradiation tests with both neutrons and protons
2) Characterize every new material (also wrt. annealing of N_{eff})
3) Beware of reverse annealing

Where is the depletion zone ??

Before type inversion: main junction **pn**



After type inversion: main junction **np**
(remember n-bulk → p-bulk)



F.Hartmann [1]

After type inversion:

- **n-p** is main pn-junction (not **p-n** anymore)
- Depletion zone grows from other side

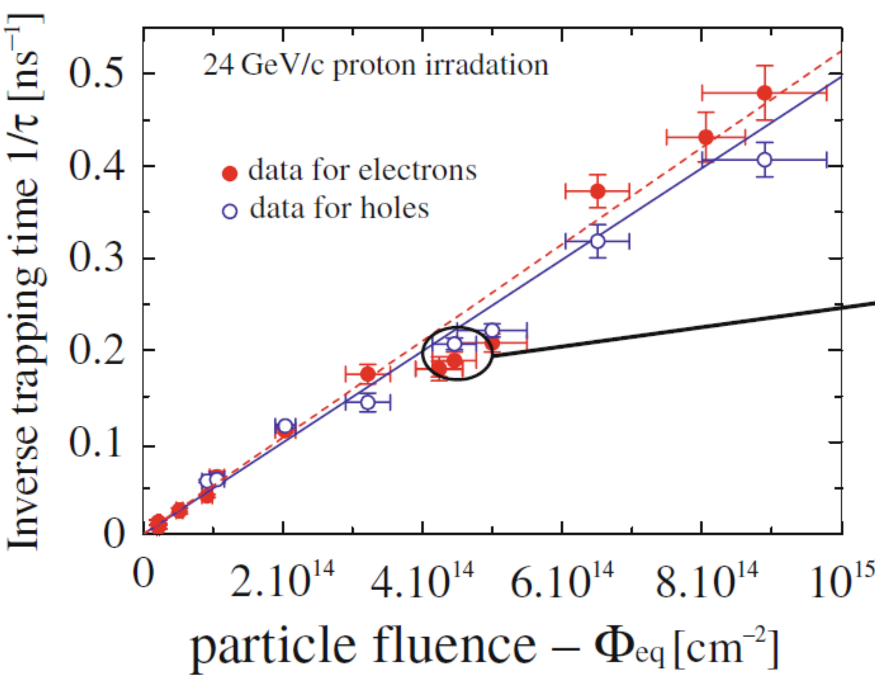
- **On p-side: low field; and if under-depleted, the electrodes are screened (no signal induced)**
  - **P strips -in-n bulk sensors cannot be run under-depleted after type inversion**
    - **Present CMS strip sensors**
- **n-in-p or n-in-n can run partially depleted !**
  - ***CMS pixel sensors (n-in-n)***
  - ***HL-LHC pixel and strip sensors (n-in-p)***

Trapping

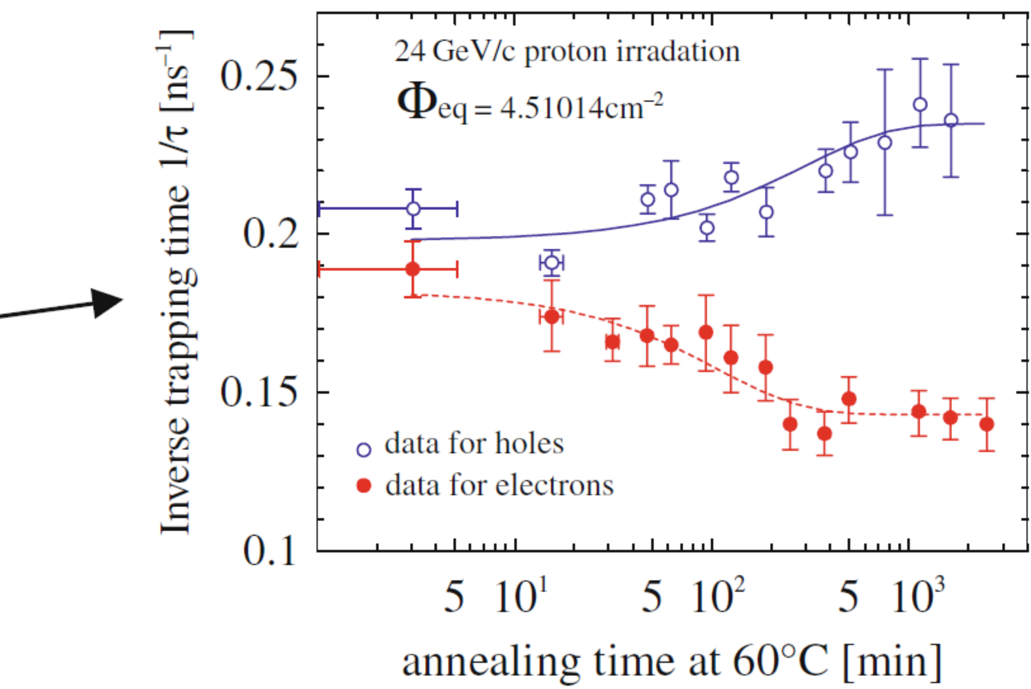
- Charge carriers can be trapped by some type of defects (long-lived energy levels)
- Trapping time τ_{eff} changes with Φ_{eq}; little annealing
- Different materials behave differently
- $\tau_{eff}\,(10^{15}\ n1\ MeV/cm2) = 2\ ns$: $\quad x = (10^{7}\ cm/s) \cdot 2 \cdot ns = 200\mu m$
- $\tau_{eff}\,(10^{16}\ n1\ MeV/cm2) = 0.2\ ns$: $\quad x = (10^{7}\ cm/s) \cdot 0.2 \cdot ns = \underline{\boldsymbol{20\mu m}}$

Bottom line: at large Φ_{eq}, charge collection becomes a competition between drift and trapping $\Longrightarrow$ *operate at high fields*! (and with n-in-p sensors)

Increase of inverse trapping time (1/τ) with fluence

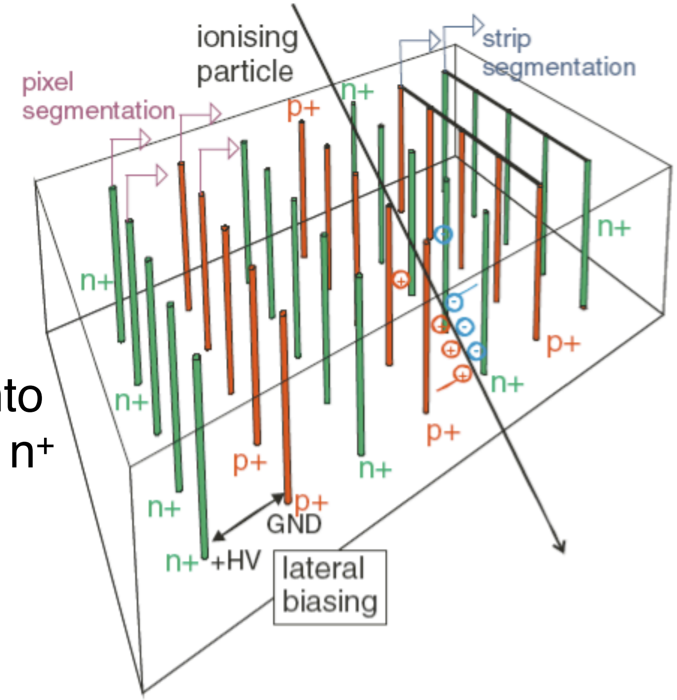


..... and change with time (annealing):



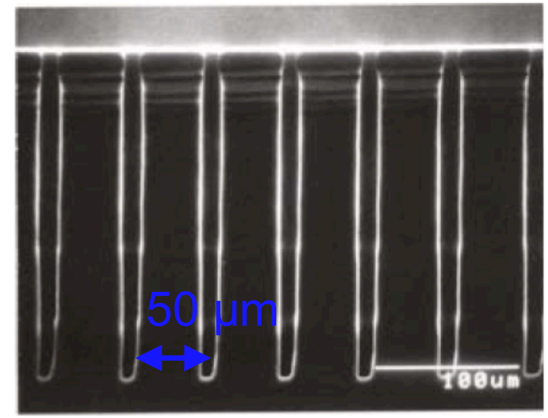
Sensor developments

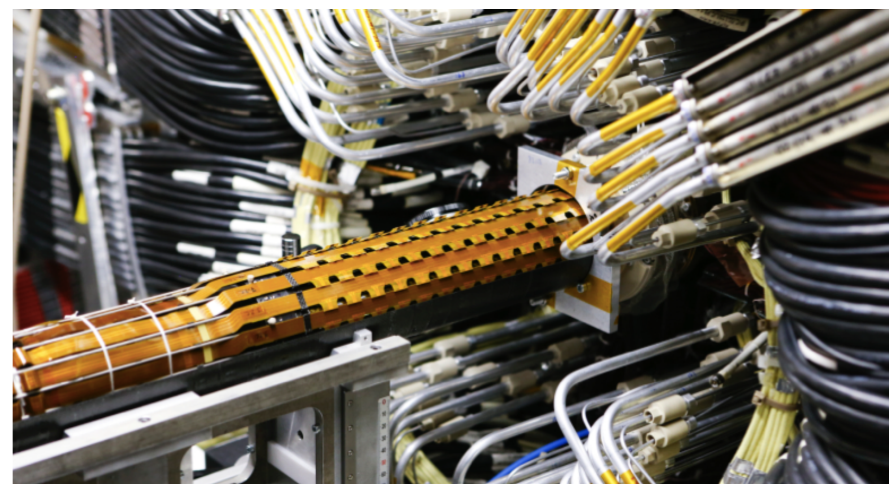
3D sensors



- Non-planar implant structure
- Deep holes are etched into the Silicon and filled with n^+ and p^+ material
- Depletion is sideways. Distances between electrodes are small ⇒ depletion voltage can be much smaller and charge carriers travel much shorter distances
- Hence less vulnerable to trapping

DRIE –
Deep Reactive Ion Etching

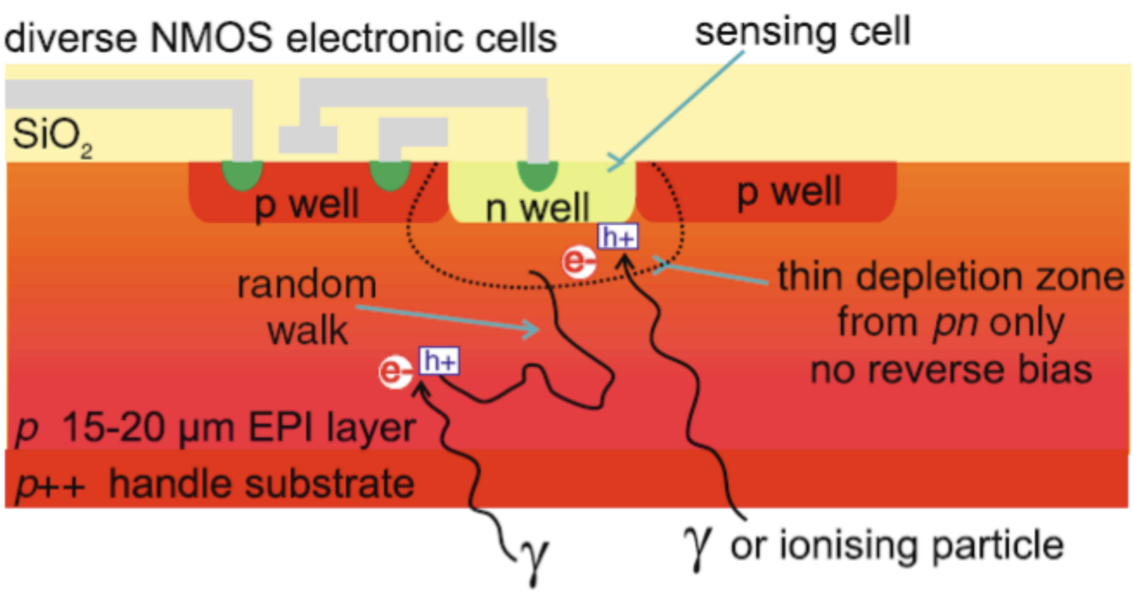




Very radiation tolerant detectors, first use in ATLAS Insertable B layer (IBL) 3.3 cm radius - improved impact parameter resolution

Monolithic Active Pixel Sensors

- Electronics and sensor are integrated into the same Silicon wafer



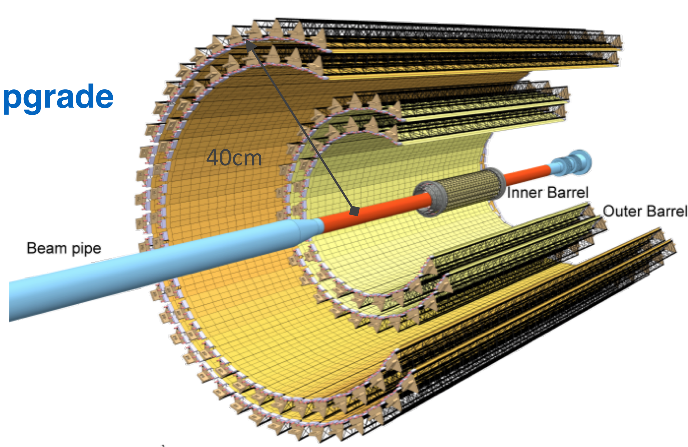
Pros:

- No depletion voltage
- Very thin
- Very low noise
- In cell signal processing
- Very high resolution

Cons:

- Small signal
- Slower
- Not radiation-hard

ITS upgrade

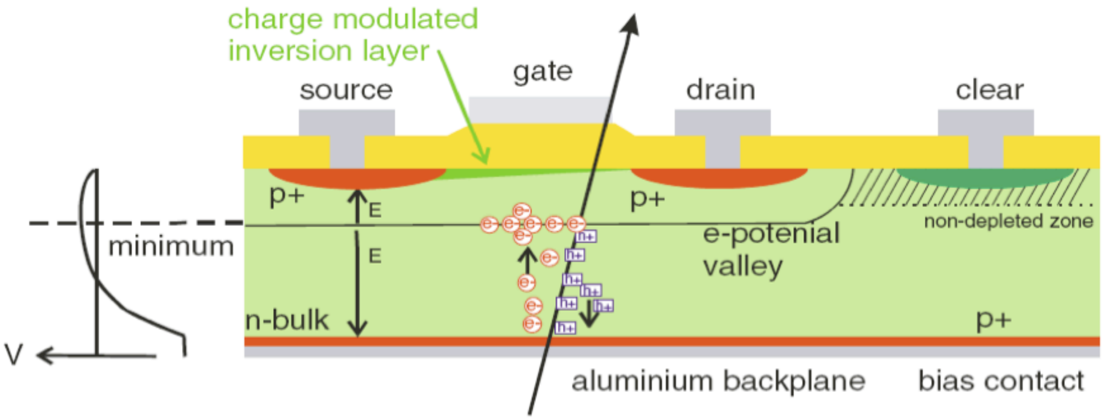


10m² in production for ALICE upgrade (LHC Run 3)
29μm x 27μm pixels
5μm x 5μm resolution

Y.Corrales Morales, EPS2019

DEPFET pixel detector

- Each pixel is a **p**-channel FET on top of an **n**-type bulk
- The bulk is fully depleted, with a potential minimum under the FET
- Electrons released by an ionizing particle accumulate in the potential minimum
  - “internal gate“ effect: these electrons modulate the FET current
- Periodic clear needed
-



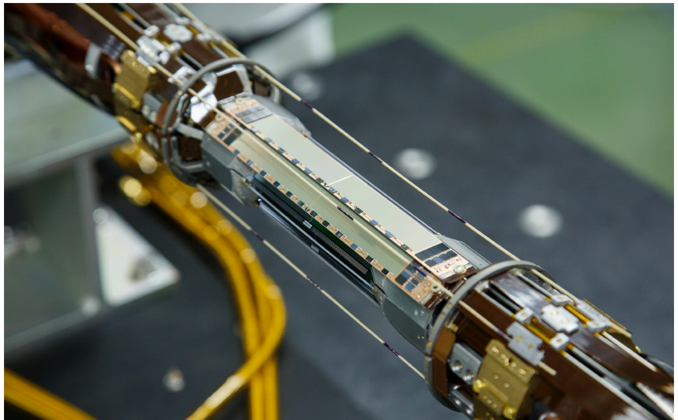
H.Ye, EPS2019

Pros:
- Large signal: Belle II:

$$g_q = \frac{\partial I}{\partial q} \approx 500 \, \frac{pA}{e^-}$$

- low power

Cons:
- Slower; not radiation-hard



Belle II pixel detector
- 2 layers of DEPFET sensors @ r = 14(22) mm
- Sensitive area per module: L1: 12.5mm x 44.8mm, L2: 12.5mm x 61.44mm
- Sensor thickness: 75 µm, 0.21% X_0 per layer

Summary

- Si detectors can provide fast (<10 ns) trackers of very high position resolution (down to a few µm) and of very high granularity (25µmx25µm or smaller)
- The main cost is often not the sensors
  - It's granularity (#electronics channels) that is expensive…
  - …although, sensors beyond industry standards can be very costly
- Main disadvantages are:
  - a large amount of scattering material
  - sensitivity to radiation
- Radiation hardness is being improved for HL-LHC applications

Silicon track detectors

- References:

[1] F.Hartmann, « Evolution of silicon sensor technology in particle physics », Springer, 2009.

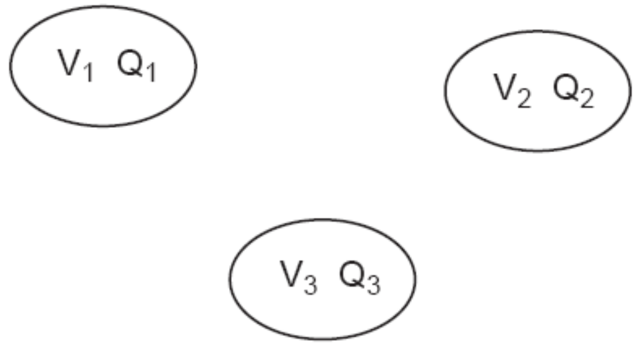
[2] W.Riegler, “Particle detectors – part 4: Tracking with Gas and Solid State Detectors”, 2008 CERN Summer student lectures, http://indico.cern.ch/event/34199/material/slides/

[3] H.Spieler, “Semiconductor Detector Systems”, Clarendon Press, Oxford, 2005.

[4] G.Lutz, “Semiconductor Radiation Detectors”, Springer, 1999.

BACKUP

Reciprocity theorem



Setting the three electrodes to potentials V_1, V_2, V_3 results in charges Q_1, Q_2, Q_3. In order to find them we have to solve the Laplace equation

$$\Delta\varphi = 0$$

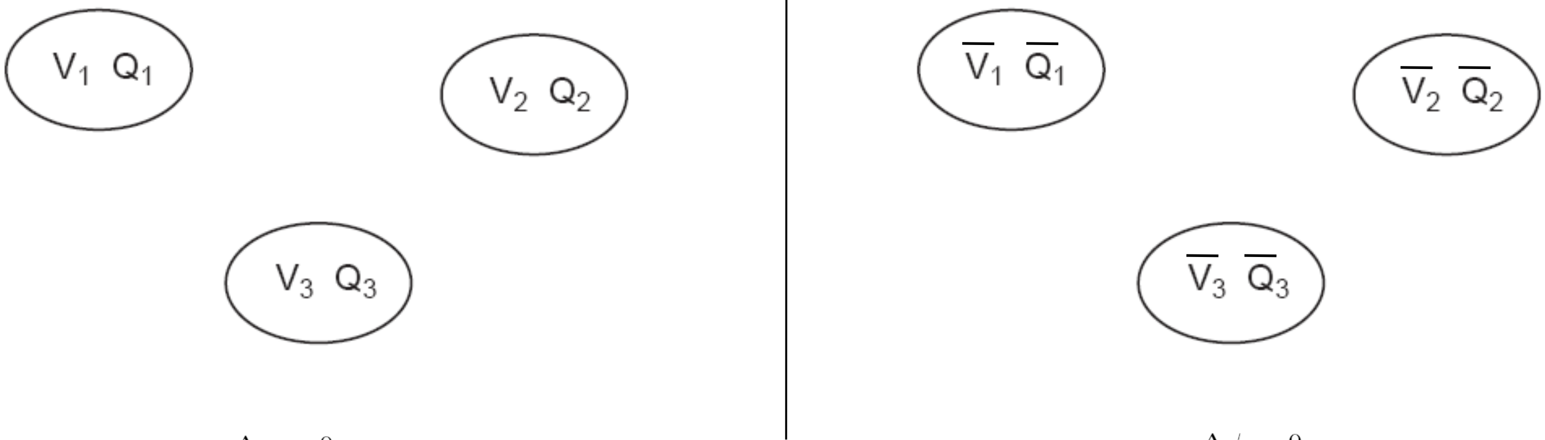
with boundary condition

$$\varphi|_{\vec{A}_1} = V_1 \qquad \varphi|_{\vec{A}_2} = V_2 \qquad \varphi|_{\vec{A}_3} = V_3$$

And the calculate

$$Q_1 = \oint_{\vec{A}_1} -\vec{\nabla}\varphi \, d\vec{A} \qquad Q_2 = \oint_{\vec{A}_2} -\vec{\nabla}\varphi \, d\vec{A} \qquad Q_3 = \oint_{\vec{A}_3} -\vec{\nabla}\varphi \, d\vec{A}$$

Reciprocity theorem



$$\Delta\varphi = 0 \qquad\qquad \Delta\psi = 0$$

$$\varphi|_{\vec{A}_1} = V_1 \quad \varphi|_{\vec{A}_2} = V_2 \quad \varphi|_{\vec{A}_3} = V_3 \qquad\qquad \psi|_{\vec{A}_1} = \overline{V}_1 \quad \psi|_{\vec{A}_2} = \overline{V}_2 \quad \psi|_{\vec{A}_3} = \overline{V}_3$$

$$Q_1 = \oint_{\vec{A}_1} -\vec{\nabla}\varphi\, d\vec{A} \quad Q_2 = \oint_{\vec{A}_2} -\vec{\nabla}\varphi\, d\vec{A} \quad Q_3 = \oint_{\vec{A}_3} -\vec{\nabla}\varphi\, d\vec{A} \qquad \overline{Q}_1 = \oint_{\vec{A}_1} -\vec{\nabla}\psi\, d\vec{A} \quad \overline{Q}_2 = \oint_{\vec{A}_2} -\vec{\nabla}\psi\, d\vec{A} \quad \overline{Q}_3 = \oint_{\vec{A}_3} -\vec{\nabla}\psi\, d\vec{A}$$

$$\oint_{\vec{A}} \left(\varphi\vec{\nabla}\psi - \psi\vec{\nabla}\varphi\right) d\vec{A} = \oint_V (\varphi\Delta\psi - \psi\Delta\varphi)\, dV$$

$$\longrightarrow \quad \sum_{n=1}^{N} Q_n \overline{V}_n = \sum_{n=1}^{N} \overline{Q}_n V_n$$

Reciprocity Theorem

It related two electrostatic states, i.e. two sets of voltages and charges