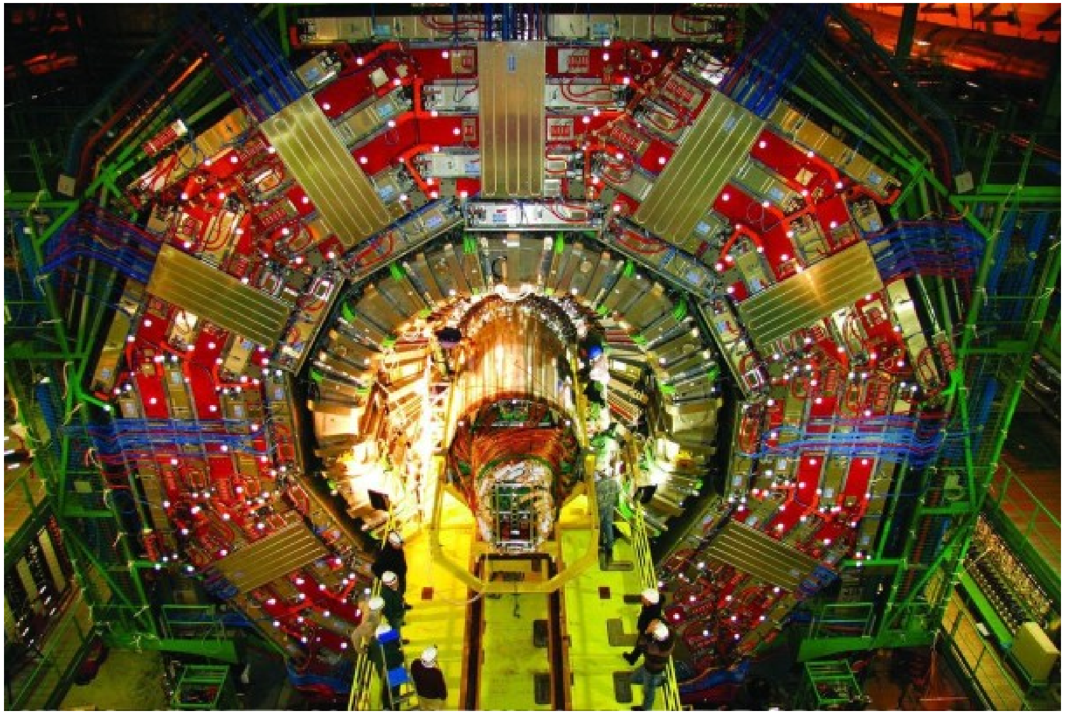
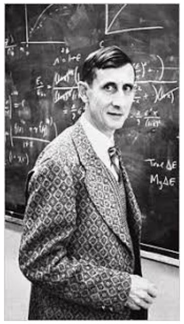


Instrumentation for Elementary Particle Physics

G71 Física de Partículas Elementales

Elementary Particle Physics

- Probes and explains new unexplored territories:
  Analysis of phenomena + Theory
- Develop new tools (technologies/methods) able to open new paths to the unknown : **Enabling instrumentation**



"New directions in science are launched by new tools much more often than by new concepts. The effect of a **concept-driven** revolution is to explain old things in new ways. The effect of a **tool-driven** revolution is to discover new things that have to be explained"

Freeman Dyson

"No one does it better than physicists when it come to innovation for instrumentation, and thus the future of all scientific fields rests on our hands"

Michael S. Turner

Elementary Particle Physics

and **Semi-conductors Detectors**: Enabling technology case

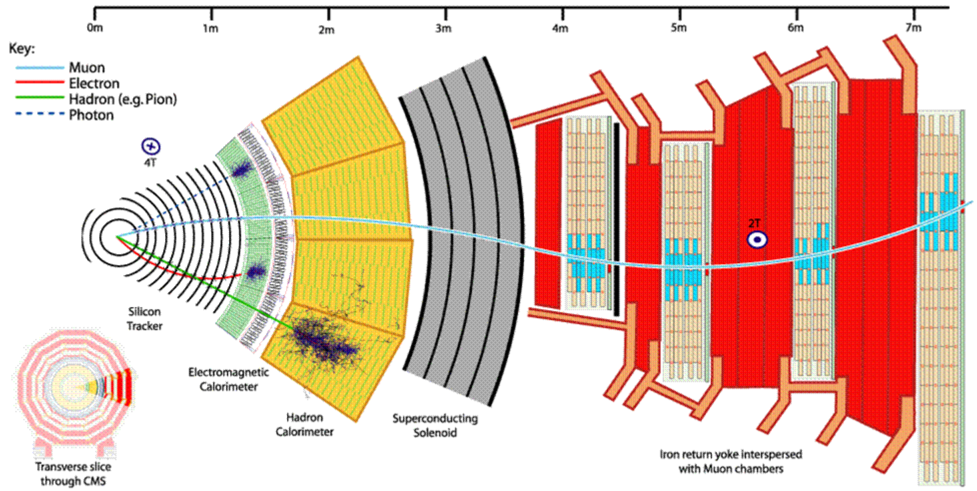
- 1951: First detectors with Germanium pn-Diodes (McKay)
- 1960: working samples of p-i-n-Detectors for α- und β-spectroscopy (E.M. Pell)
- 1964: use of semiconductor detectors in experimental nuclear physics (G.T. Ewan, A.J. Tavendale)
- 1960ies: Semiconductor detectors made of germanium and silicon become more and more important for energy spectroscopy
- **1980: Fixed target experiment with a planar diode (J. Kemmer)**
- 1980-1986: **NA11** and NA32 experiment at CERN to measure charm meson lifetimes with planar silicon detectors
- 1990ies (Europe): LEP Detectors (e.g. **DELPHI**)
- 1990ies and later (US): **CDF** and D0 at Tevatron
- Now: LHC Detectors with up to 200m^2 active detector area (CMS)

Goal of this hand-on training

- Understanding of the underlying principles concerning the detection of ionizing particles using Silicon as active (sensitive) media
    - 90% of the future EPP detectors.

- The pn semiconductor junction as the basic sensing element of the state-of-the-art detector systems in EPP
    - operational parameters and signal generation.

What do we measure?

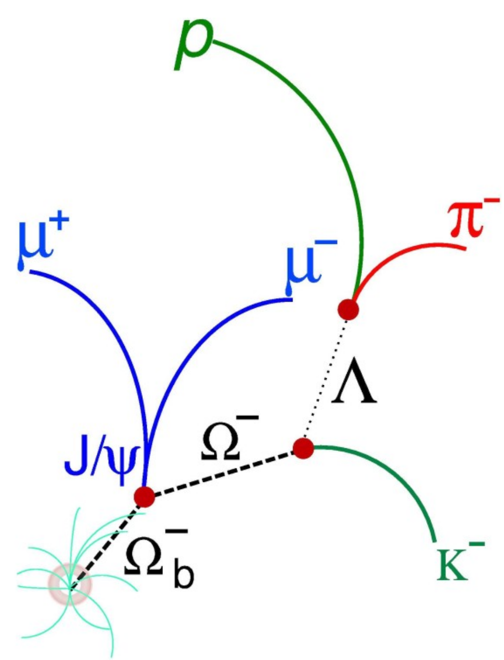


- Energy: calorimetry
- Momentum: magnetic deflection, tracking
- Charge: magnetic deflection, tracking
- Speed: time, Cherenkov, dE/dx,…
- Spin: topology, tracking
- Lifetime: secondary decay vertices, tracking

… of what?

$\gamma, W^{\pm}, Z^0, g, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \pi^{\pm}, \pi^0, \eta, f_0(600), \rho(770),$
$\omega(782), \eta'(958), f_0(980), a_0(980), \phi(1020), h_1(1170), b_1(1235),$
$a_1(1260), f_2(1270), f_1(1285), \eta(1295), \pi(1300), a_2(1320),$
$f_0(1370), f_1(1420), \omega(1420), \eta(1440), a_0(1450), \rho(1450),$
$f_0(1500), f_2'(1525), \omega(1650), \omega_3(1670), \pi_2(1670), \phi(1680),$
$\rho_3(1690), \rho(1700), f_0(1710), \pi(1800), \phi_3(1850), f_2(2010),$
$a_4(2040), f_4(2050), f_2(2300), f_2(2340), K^{\pm}, K^0, K^0_S, K^0_L, K^*(892),$
$K_1(1270), K_1(1400), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680),$
$K_2(1770), K_3^*(1780), K_2(1820), K_4^*(2045), D^{\pm}, D^0, D^*(2007)^0,$
$D^*(2010)^{\pm}, D_1(2420)^0, D_2^*(2460)^0, D_2^*(2460)^{\pm}, D_s^{\pm}, D_s^{*\pm},$
$D_{s1}(2536)^{\pm}, D_{sJ}(2573)^{\pm}, B^{\pm}, B^0, B^*, B_s^0, B_c^{\pm}, \eta_c(1S), J/\psi(1S),$
$\chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S), \psi(3770), \psi(4040), \psi(4160),$
$\psi(4415), \Upsilon(1S), \chi_{b0}(1P), \chi_{b1}(1P), \chi_{b2}(1P), \Upsilon(2S), \chi_{b0}(2P),$
$\chi_{b2}(2P), \Upsilon(3S), \Upsilon(4S), \Upsilon(10860), \Upsilon(11020), p, n, N(1440),$
$N(1520), N(1535), N(1650), N(1675), N(1680), N(1700), N(1710),$
$N(1720), N(2190), N(2220), N(2250), N(2600), \Delta(1232), \Delta(1600),$
$\Delta(1620), \Delta(1700), \Delta(1905), \Delta(1910), \Delta(1920), \Delta(1930), \Delta(1950),$
$\Delta(2420), \Lambda, \Lambda(1405), \Lambda(1520), \Lambda(1600), \Lambda(1670), \Lambda(1690),$
$\Lambda(1800), \Lambda(1810), \Lambda(1820), \Lambda(1830), \Lambda(1890), \Lambda(2100),$
$\Lambda(2110), \Lambda(2350), \Sigma^+, \Sigma^0, \Sigma^-, \Sigma(1385), \Sigma(1660), \Sigma(1670),$
$\Sigma(1750), \Sigma(1775), \Sigma(1915), \Sigma(1940), \Sigma(2030), \Sigma(2250), \Xi^0, \Xi^-,$
$\Xi(1530), \Xi(1690), \Xi(1820), \Xi(1950), \Xi(2030), \Omega^-, \Omega(2250)^-,$
$\Lambda_c^+, \Lambda_c^+, \Sigma_c(2455), \Sigma_c(2520), \Xi_c^+, \Xi_c^0, \Xi_c'^+, \Xi_c'^0, \Xi(2645)$
$\Xi_c(2780), \Xi_c(2815), \Omega_c^0, \Lambda_b^0, \Xi_b^0, \Xi_b^-, t\bar{t}$

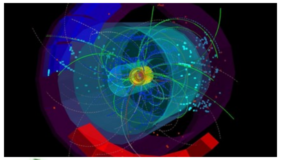
$e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, K^0, p^{\pm}, n$

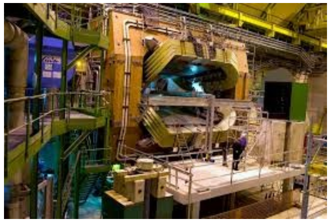


The instruments for EPP

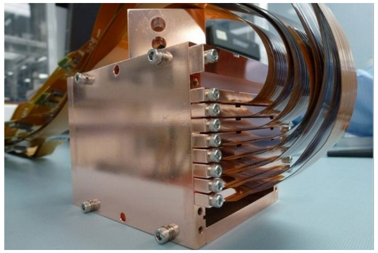
- Flagship EPP experiments
  - Colliders: accelerates and collides HEP particles
  - Detector: recording the collision debris

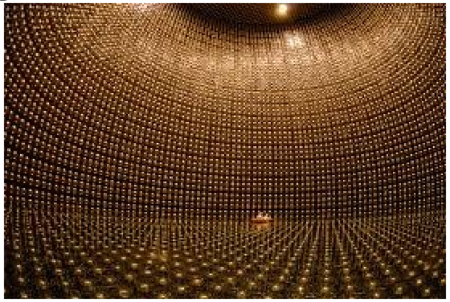




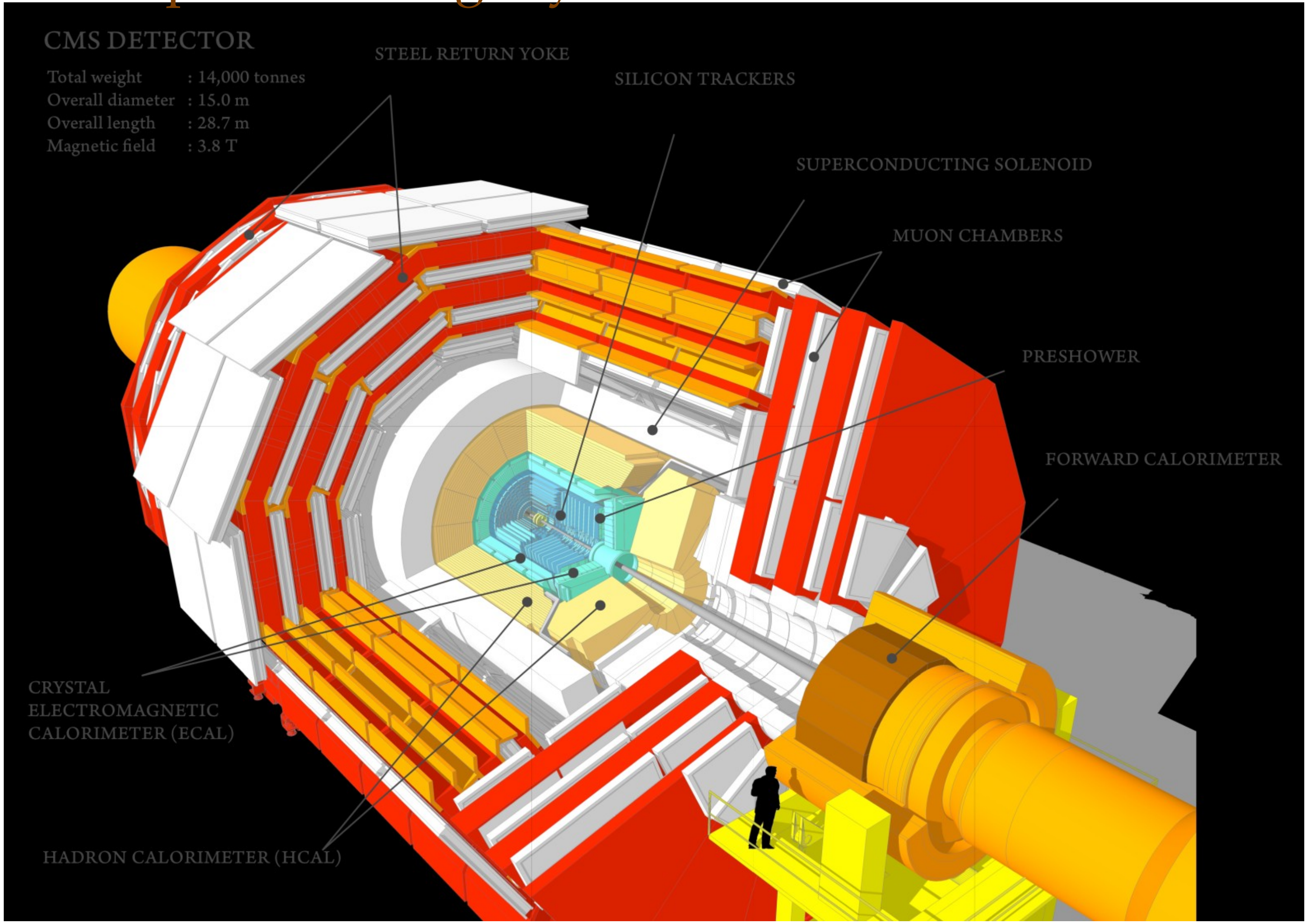

- Other non-collider experiments (astroparticles, neutrino physics, direct DM searches, etc):
  - high energy particle sources: cosmic or nuclear reactor
  - Large volumen detectors, Large Scale Telescopes





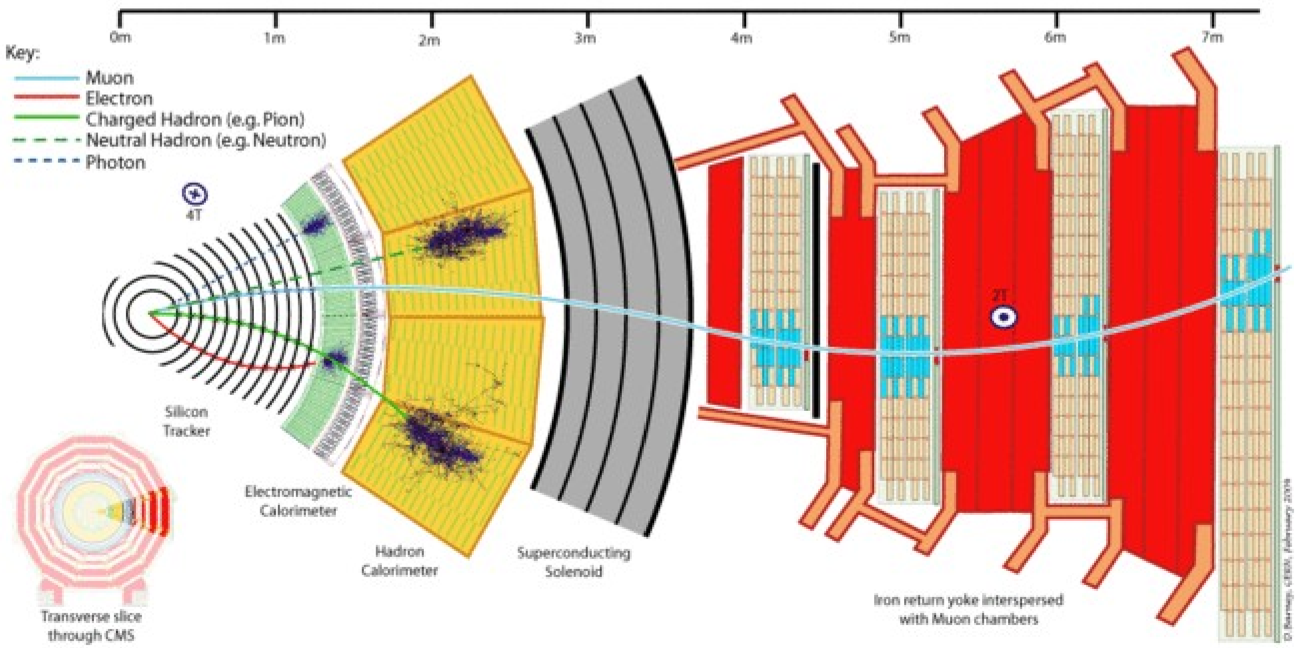
EPP Detectors

complex and huge systems



EPP Detector task

- Detect the "stable" particles out of the collision and measure their properties
  - Just 14 different particles e^{+-}, μ^{+-}, $\pi^{-1,0,-1}$,$K^{-1,0,-1}$,p^{+-}, n, γ



State of the Art @ LHC

Vertexing & Tracking

- Silicon Pixels & Strips
- Gaseous detectors (TPC)

Calorimetry

- Scintillator + Low Light Level photo detectors

Muon Detectors

- Gaseous Detectors (Drift Tubes, micropattern)

Particle ID

- Cherenkov
- ToF
- Transition Radiation

Detectors for the next decade

Vertexing & Tracking	Calorimetry	Muon Detectors	Particle ID
Silicon Pixels & Strips	Scintillator + Silicon PMT	Scintillator + Silicon PMT	Silicon PMT as photodet. or Silicon avalanche detector
	All Silicon	All Silicon	

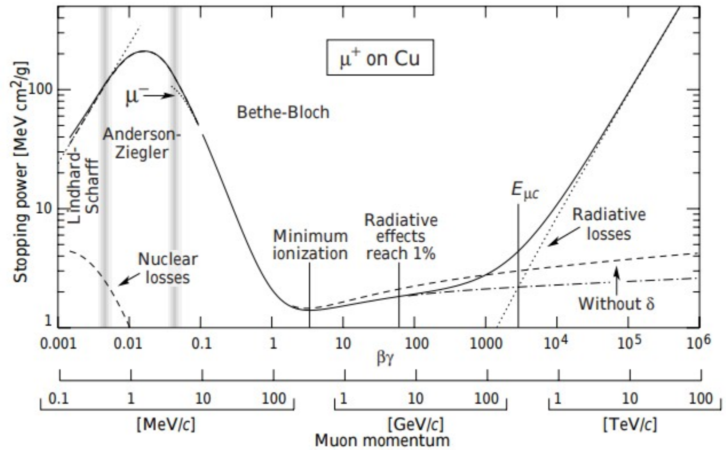
- **Silicon-based** sensors everywhere
- A further step forward in the integration of the front-end electronics and the sensors.

Particle Detection

- Signal creation: Particles interacting with matter
  - **Detector**: medium to interact

Bethe-Bloch [1]

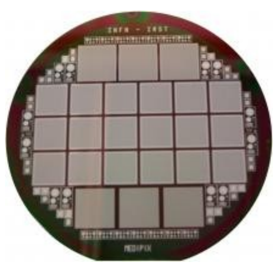
[1] http://pdg.lbl.gov/2000/passagerpp.pdf

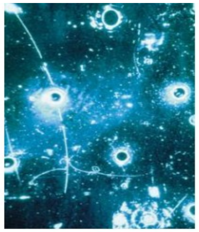


- Signal Measurement: produced charge carriers
  - collected on electrodes
  - induced signal on electrodes
  - created drops, bubbles, ...

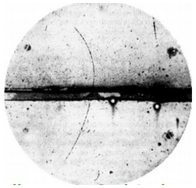
Needs an electric field to drift the carriers away

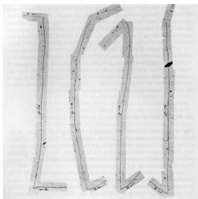
photographic emulsions, ...



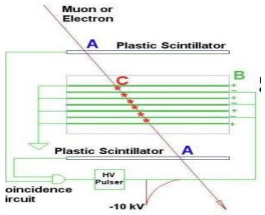


Neutral Currents 1973





C. Powell, Discovery of muon and pion, 1947

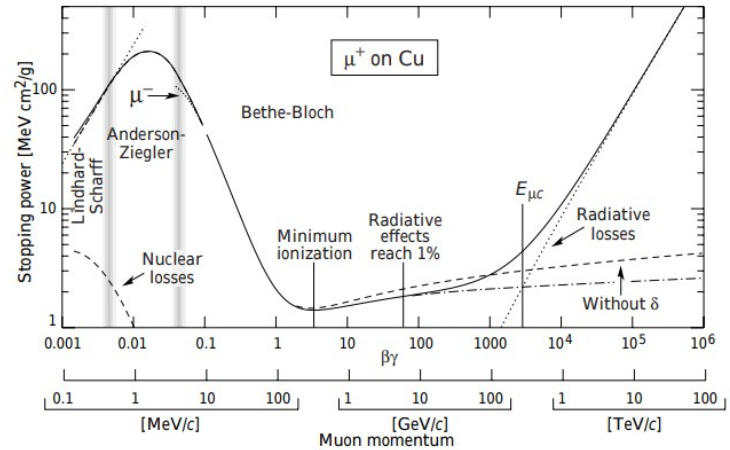


Modern Particle Detection

- **Signal creation**: Particles interacting with matter
  - *Detector*: medium to interact

Bethe-Bloch [1]

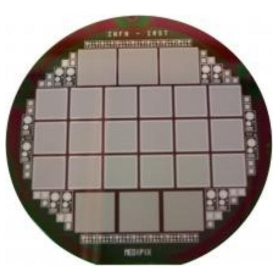
[1] http://pdg.lbl.gov/2000/passagerpp.pdf

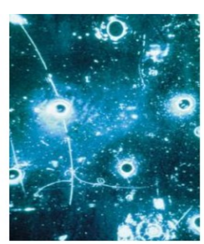


- **Signal Measurement**: produced charge carriers
  - collected on electrodes
  - induced signal on electrodes
  - created drops, bubbles, ...

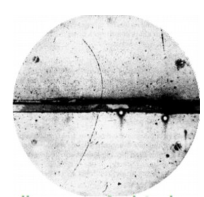
Needs an electric field to drift the carriers away

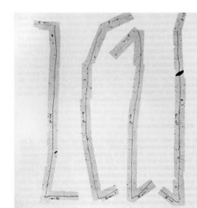
photographic emulsions, ...



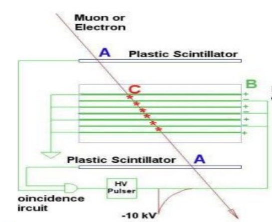


Neutral Currents 1973





C. Powell, Discovery of muon and pion, 1947



Modern particle detection (II)

Signal creation: Particles interacting with matter → Standard Model of Particle Physics

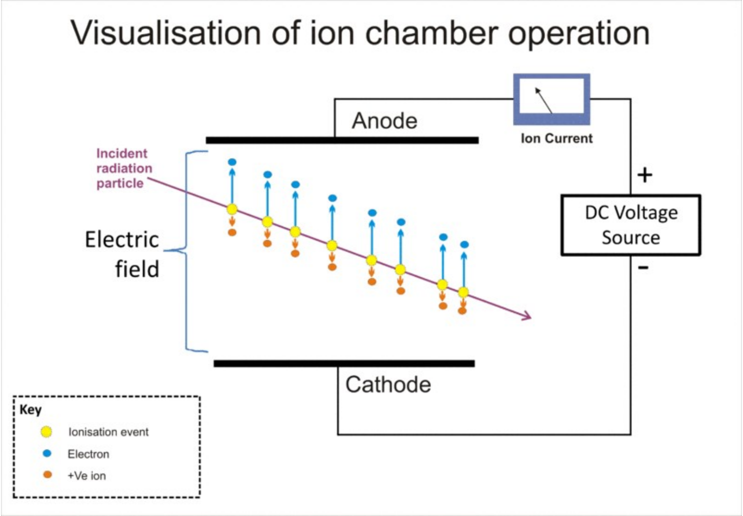
Signal measurement: Charges drifting in an electric field → Electrostatics

Modern particle detection (III)

- **Principle**: Movement of charges in electric fields → induces signal on readout electrodes
  → Ionization chambers, wire chambers, **solid state detectors**

IONIZATION CHAMBERS (as simplest example)

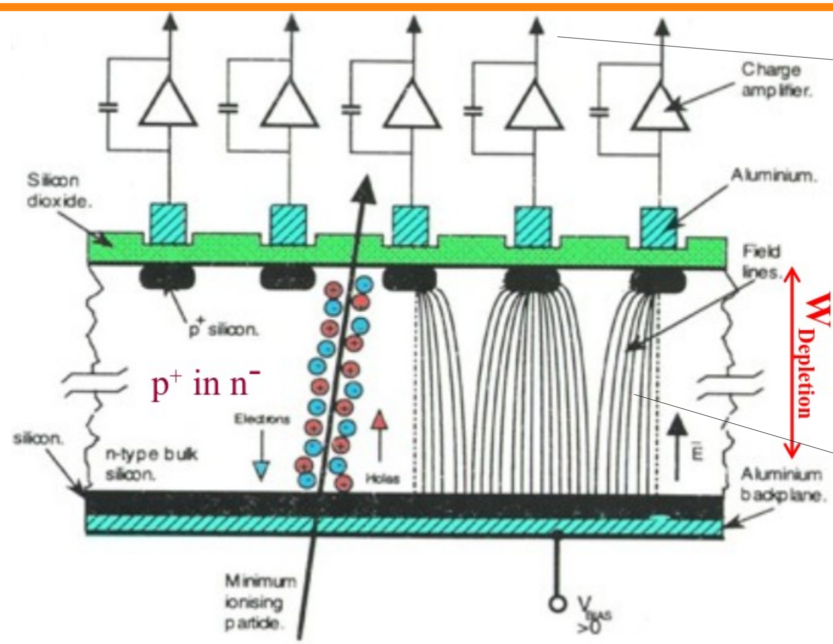
- **Charged Particles + photons** (in a very different way)
- <u>Ingredients</u>:
  - Medium to be ionized
  - Drift field
  - Collecting electrodes.



Modern particle detection (IV)

- Understanding the detection system

Signal measurement: Charges drifting in an electric field → Electrostatics

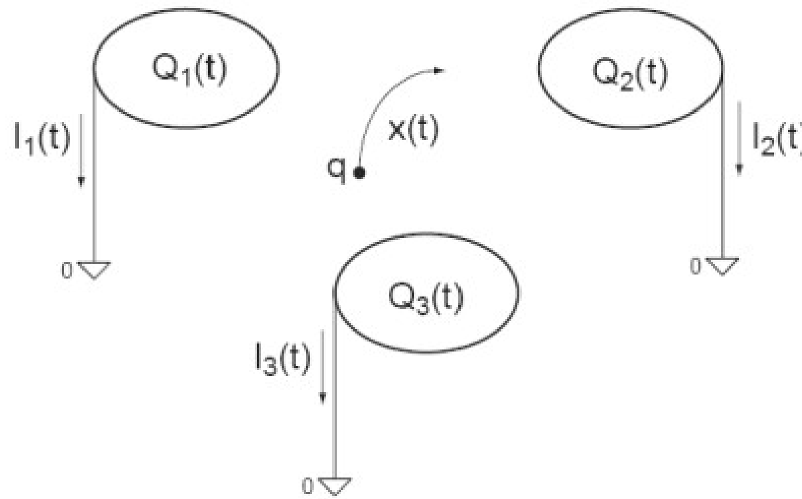


Induced charged in electrodes: Shockley-Ramo theorem

Solving Poisson equation for PN-junctions

The Shockley-Ramo theorem

- **What are the charges induced by a moving charge on electrodes that are connected with arbitrary linear impedance elements ?**



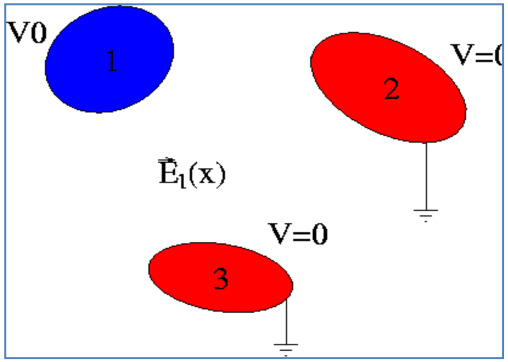
$$I_i(t) = qvE_w(\vec{x}(t)\,)$$

- The induced current on an electrodes system can be calculated considering the drift velocity of the charge carriers **weighted** by a magnitude (the weighting field) that depends on the position of the carrier

The S-R Theorem (II)

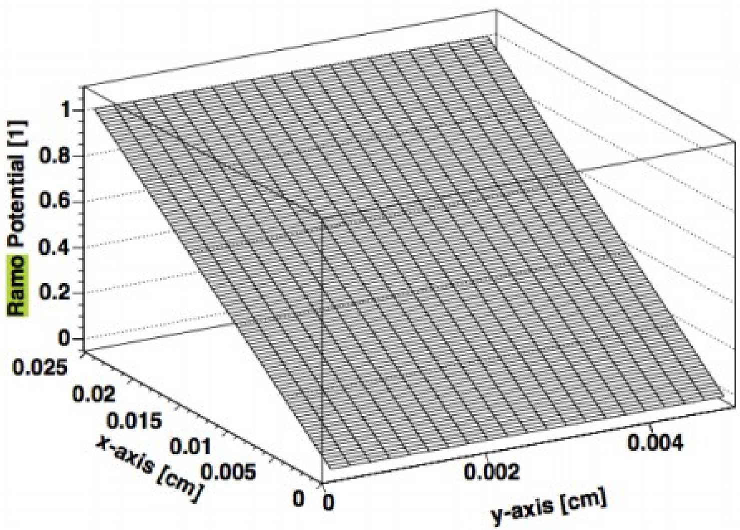
Ramo Theorem The current induced on a grounded electrode by a charge q moving along a trajectory x(t) is calculated the following way:

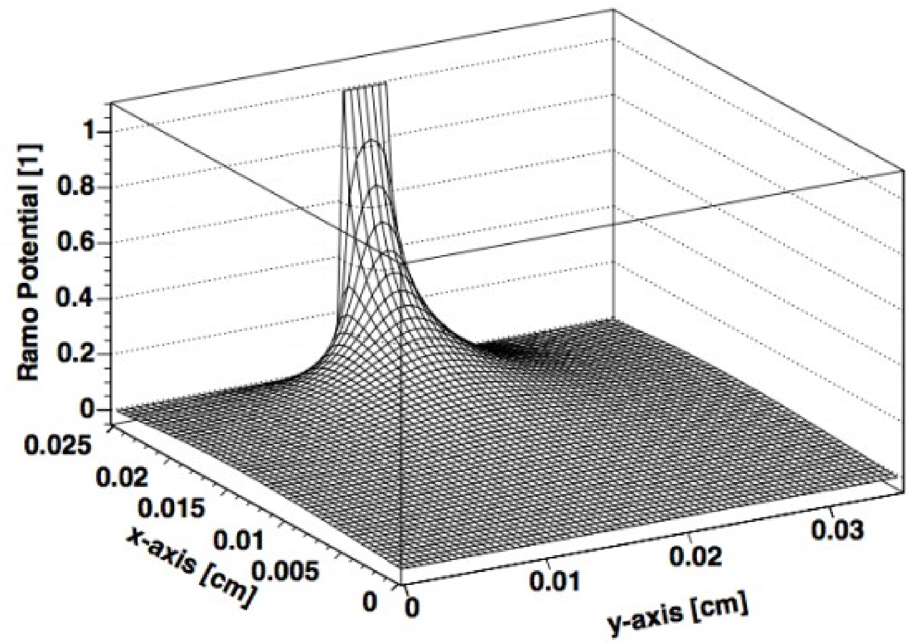
1. Remove the charge q from the setup,
2. put the electrode n to voltage V_0 while keeping all other electrodes grounded.
3. This results in an electric field $E_n(x)$, the **Weighting Field**, in the volume between the electrodes, from which the current is calculated by

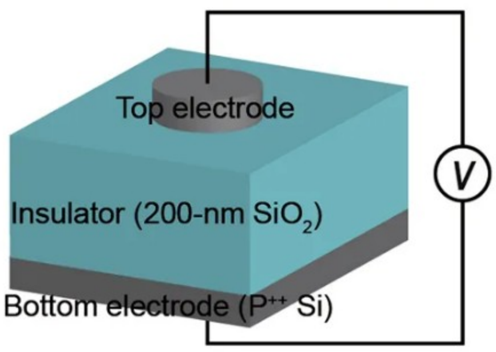


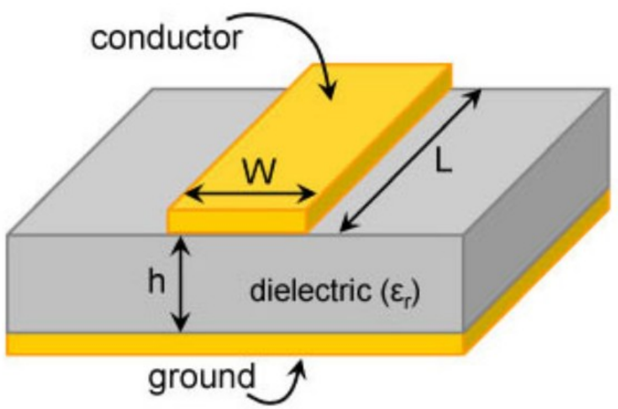
$$I_n(t) = -\frac{q}{V_0}\vec{E}_n[\vec{x}(t)]\frac{d\vec{x}(t)}{dt} = -\frac{q}{V_0}\vec{E}_n[\vec{x}(t)]\vec{v}(t)$$

The S-R Theorem (III)





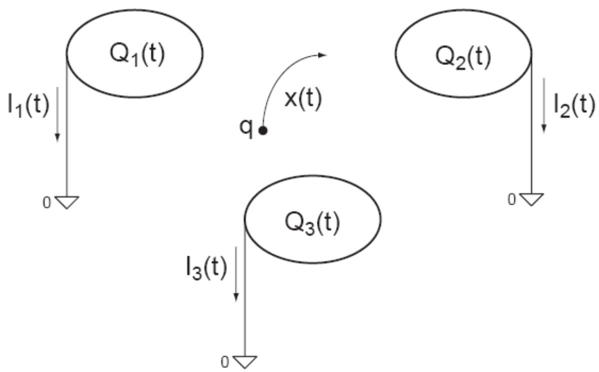




The S-R Theorem (IV)

The following relations hold for the induced currents:

1. The **charge induced** on an electrode in case a charge in between the electrode has moved from a point x_0 to a point x_1 is



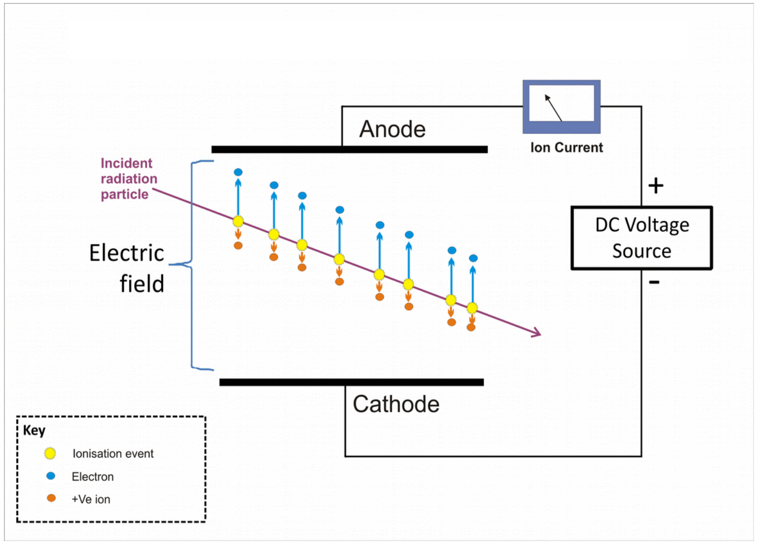
$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind}(t)dt = -\frac{q}{V_w}\int_{t_0}^{t_1} \boldsymbol{E}_n[\boldsymbol{x}(t)]\,\dot{\boldsymbol{x}}(t)dt = \frac{q}{V_w}[\psi_n(\boldsymbol{x}_1) - \psi_n(\boldsymbol{x}_0)]$$

and is independent on the actual path.

2. Once **ALL** charges have arrived at the electrodes, the total induced charge in the electrodes is equal to the charge that has **ARRIVED** at this electrode.

Ramo Theorem's consequences

- Signal is induced **since** charge creation
- The **total induced charge** in the collector electrode is equal to the **inductive charge**
- Total induced charged in the non-collector electrodes is zero (bipolar signal)



The PN junction & solid state detectors

Solid State detectors

Gas as ionized medium is being replaced by Silicon: WHY?

For Ionization chambers, in principle any material could be used that allows for charge collection at a pair of electrodes.

	Gas	liquid	solid
Density	low	moderate	high
Z	low	moderate	moderate
Ionization energy ε_i	moderate	moderate	small
Signal velocity	moderate	moderate	fast

Ideal properties:

Low ionization energy → Larger charge yield dq/dE

→ better energy resolution

$\Delta E/E \sim N^{-1/2} \sim (E/\varepsilon_i)^{-1/2} \sim \varepsilon_i^{1/2}$

High electric field in detection volume → fast response

better charge collection efficiency

Solid State detectors (II)

Property		Si	Ge	GaAs	Diamant
Z		14	32	31/33	6
A		28.1	72.6	144.6	12.0
Band gap	[eV]	1.12	0.66	1.42	5.5
radiation length X_0	[cm]	9.4	2.3	2.3	18.8
mean energy to generate eh pair	[eV]	3.6	2.9	4.1	~ 13
mean E-loss dE/dx	[MeV/cm]	3.9	7.5	7.7	3.8
mean signal produced	[$e^-/\mu m$]	110	260	173	~ 50
intrinsic charge carrier concentration n_i	[cm^{-3}]	$1.5 \cdot 10^{10}$	$2.4 \cdot 10^{13}$	$1.8 \cdot 10^{6}$	$< 10^{3}$
electron mobility	[cm^2/Vs]	1500	3900	8500	1800
hole mobility	[cm^2/Vs]	450	1900	400	1200

Si

• currently best compromise for strip detectors

Ge

• small band gap→high amount of charge produced →good for energy measurements

• high intrinsic charge carrier concentration →has to be cooled (liquid N_2)

GaAs

• good ratio generated charge/ noise

• but: charge collection efficiency strongly dependent on purity and composition

• radiation hard

Diamond

• radiation hard, but still quite expensive

• charge collection length ~ 80µm

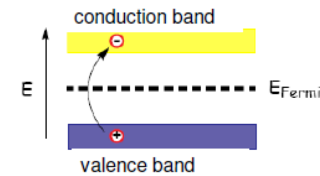
Solid State detectors (III)

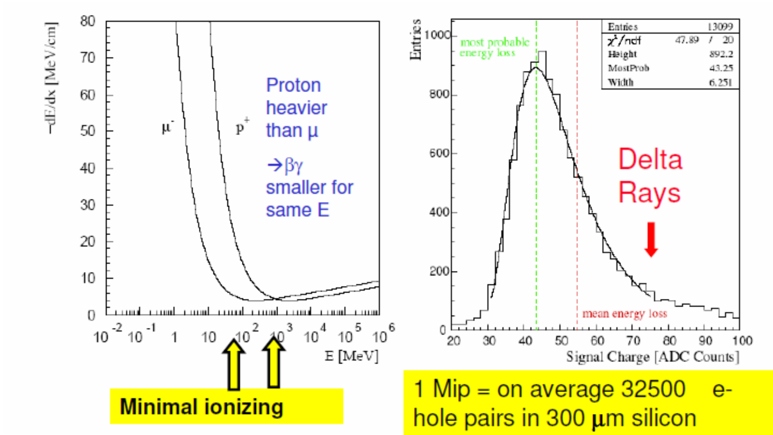
- At room temp., semiconductors has free electrons & holes moving
- To detect the signal created from a particle passing through the Si, first **get rid** of the free carriers

- Conduction band really empty only at T=0
- Distribution according Fermi-Dirac Statistics
- Number of electrons in conduction band at room temp.:

$$n_i = \sqrt{n_V n_C} \cdot \exp\left(-\frac{E_{Gap}}{2kT}\right) = 1.5\times10^{10}\ \mathrm{cm}^{-3}$$

→Ratio of electrons in conduction band 10^{-12} (Silicon ~5×10^{22} Atoms/cm^3)





Bethe-Bloch Formula

Landau distribution

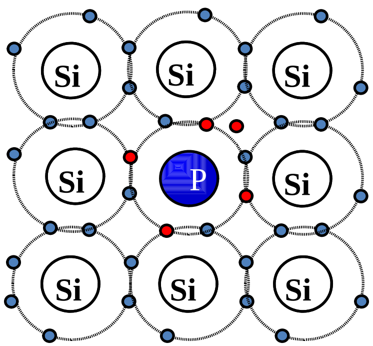
→ The most creative trick is to deplete the detector of free electrons and holes is to use doped Si and a power supply

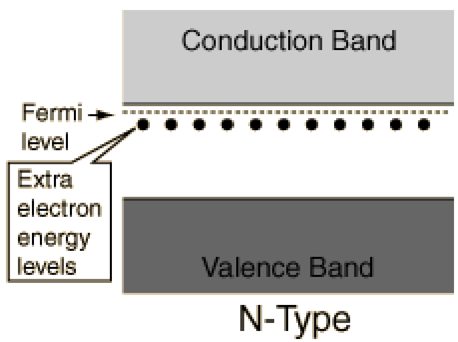
Doping and resistivity

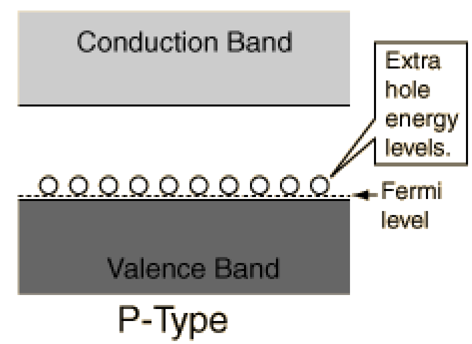
- **Doping:** **n-type Silicon**
  - add elements from Vth group
  donors (P, As,..)
  - electrons are majority carriers

- **Doping:** **p-type Silicon**
  - add elements from IIIrd group
  acceptors (B,..)
  - holes are the majority carriers

e.g. Phosphorus







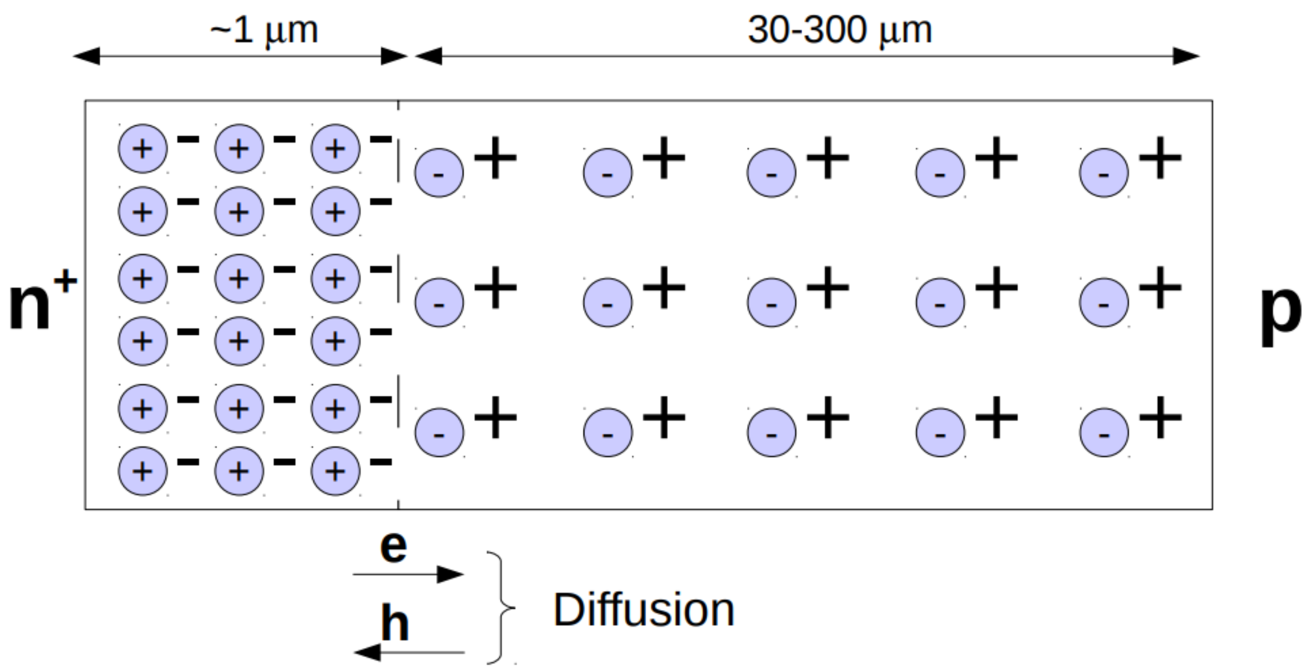
- **Resistivity**
  - carrier concentrations n, p
  - carrier mobility μ_n, μ_p

$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

	detector grade	electronics grade
doping	≈ 10^{12} cm^{-3}	≈ 10^{17} cm^{-3}
resistivity ρ	≈ 5 kΩ·cm	≈1 Ω·cm

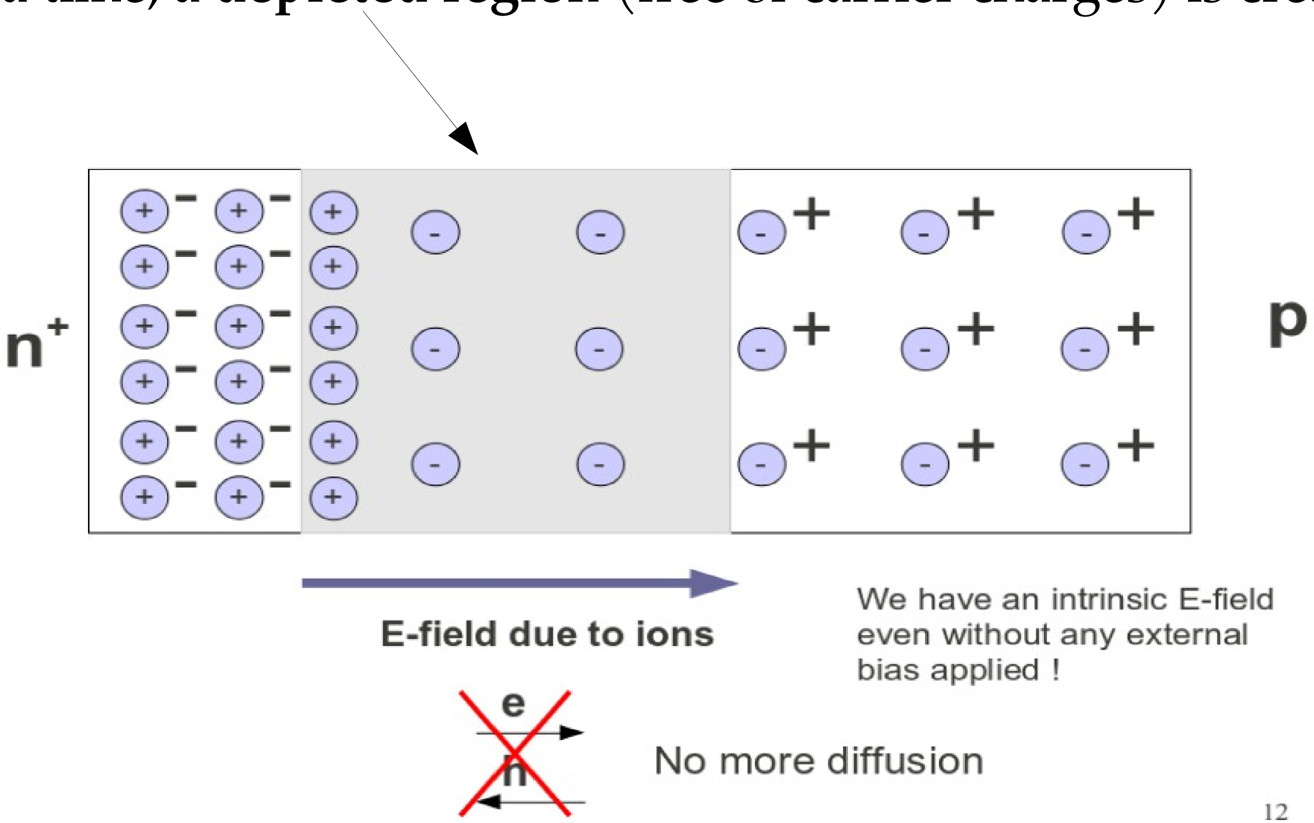
The PN junction

- Put in contact a heavily doped (n) thin slice with a lightly doped (p) thick bulk of Silicon



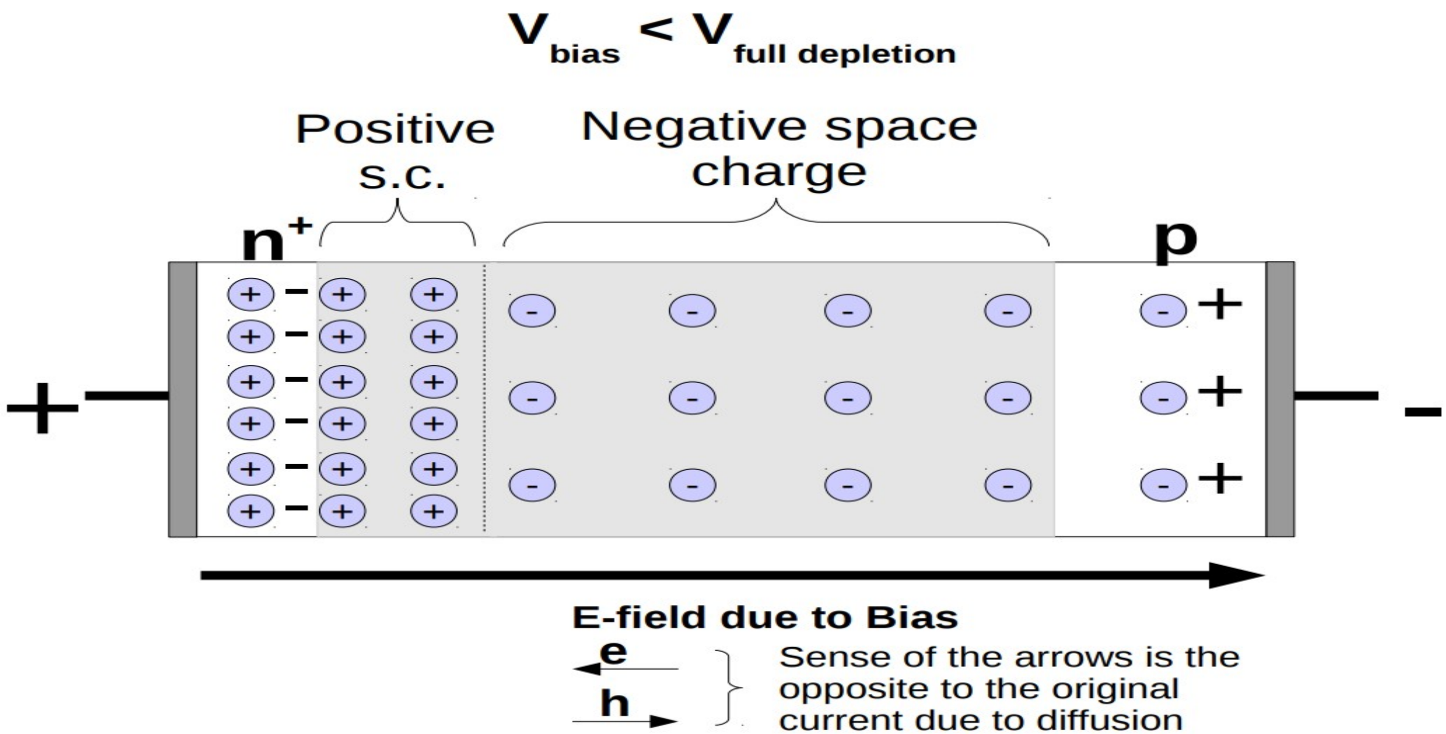
The PN junction (II)

- After a time, a **depleted region** (free of carrier charges) is created



The PN junction (II)

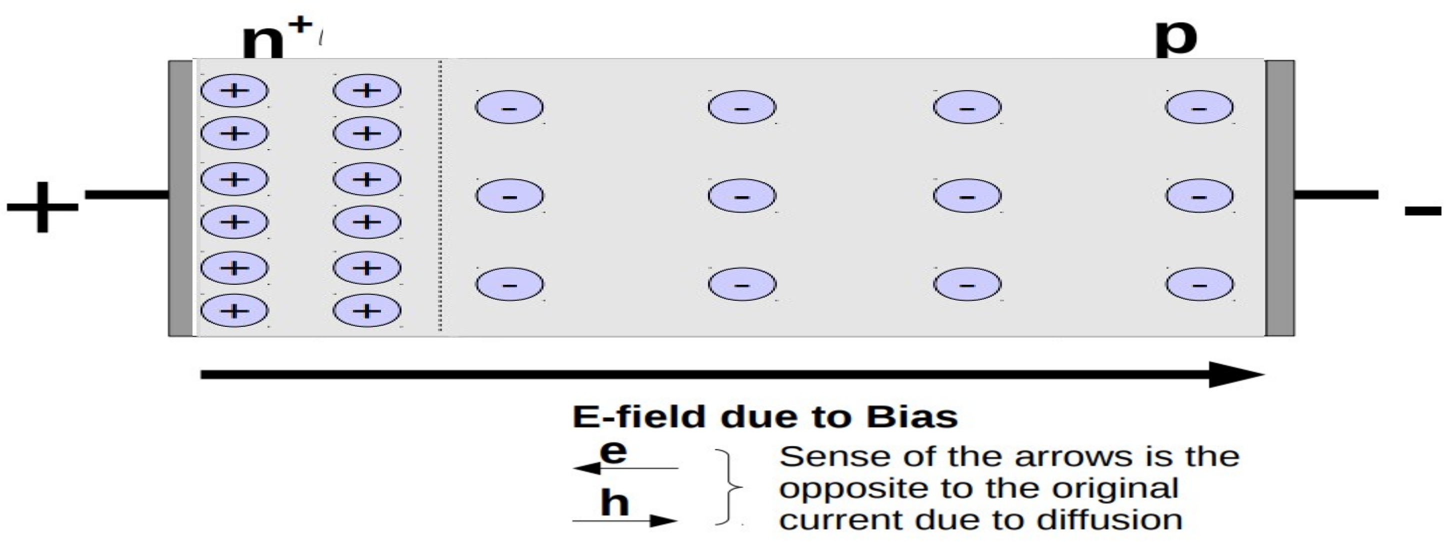
- Enlarge the depletion region, by applying a reverse bias voltage



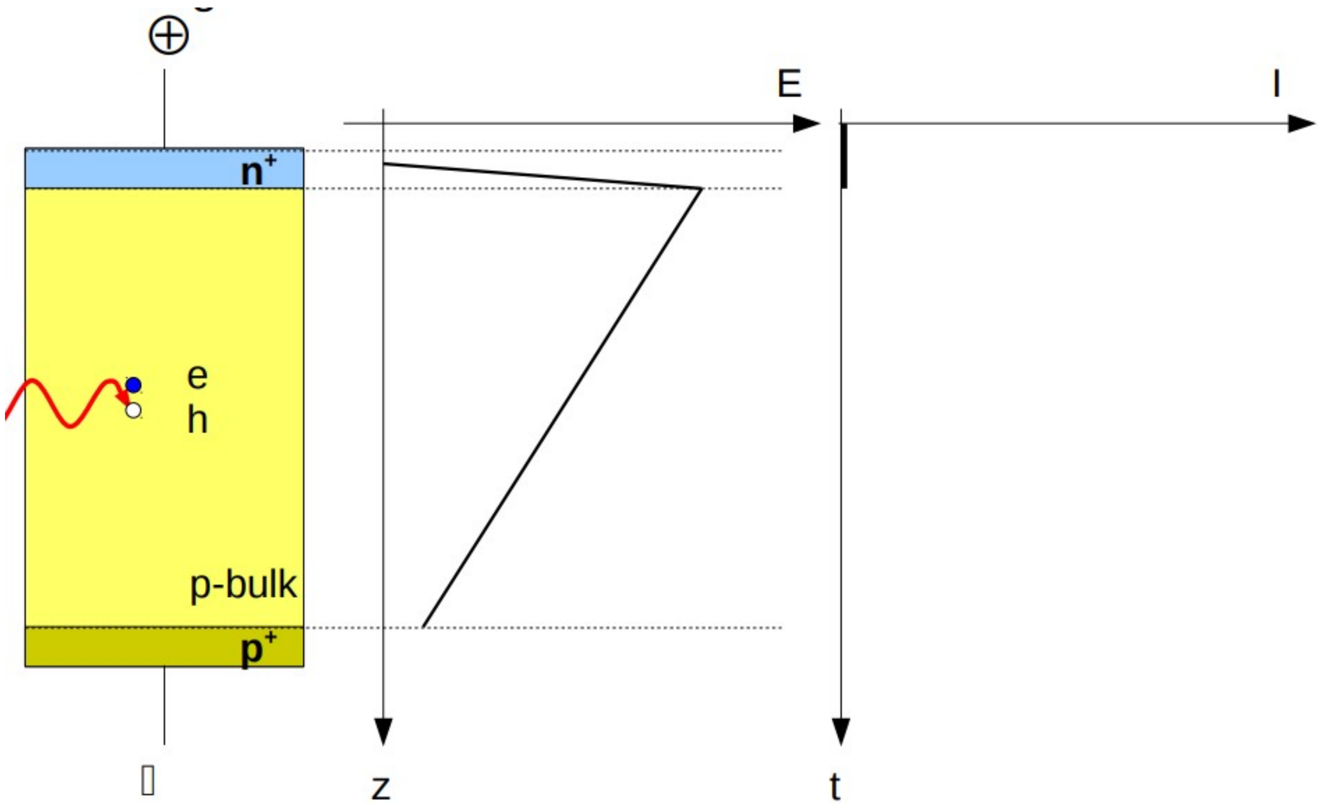
The PN junction (III)

- Enlarge the depletion region, by applying a reverse bias voltage

$$V_{bias} \geq V_{full\ depletion}$$

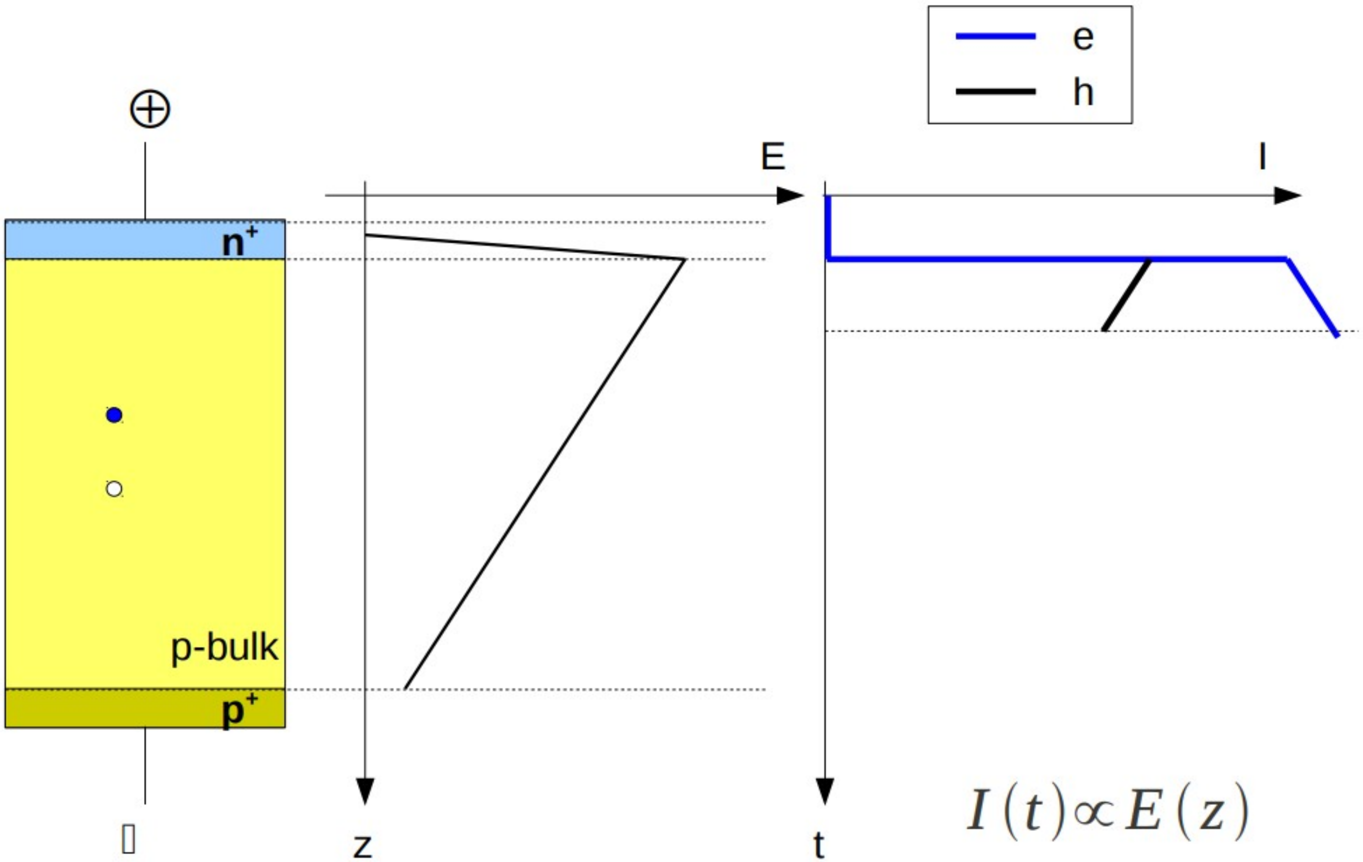


The PN junction as Detector



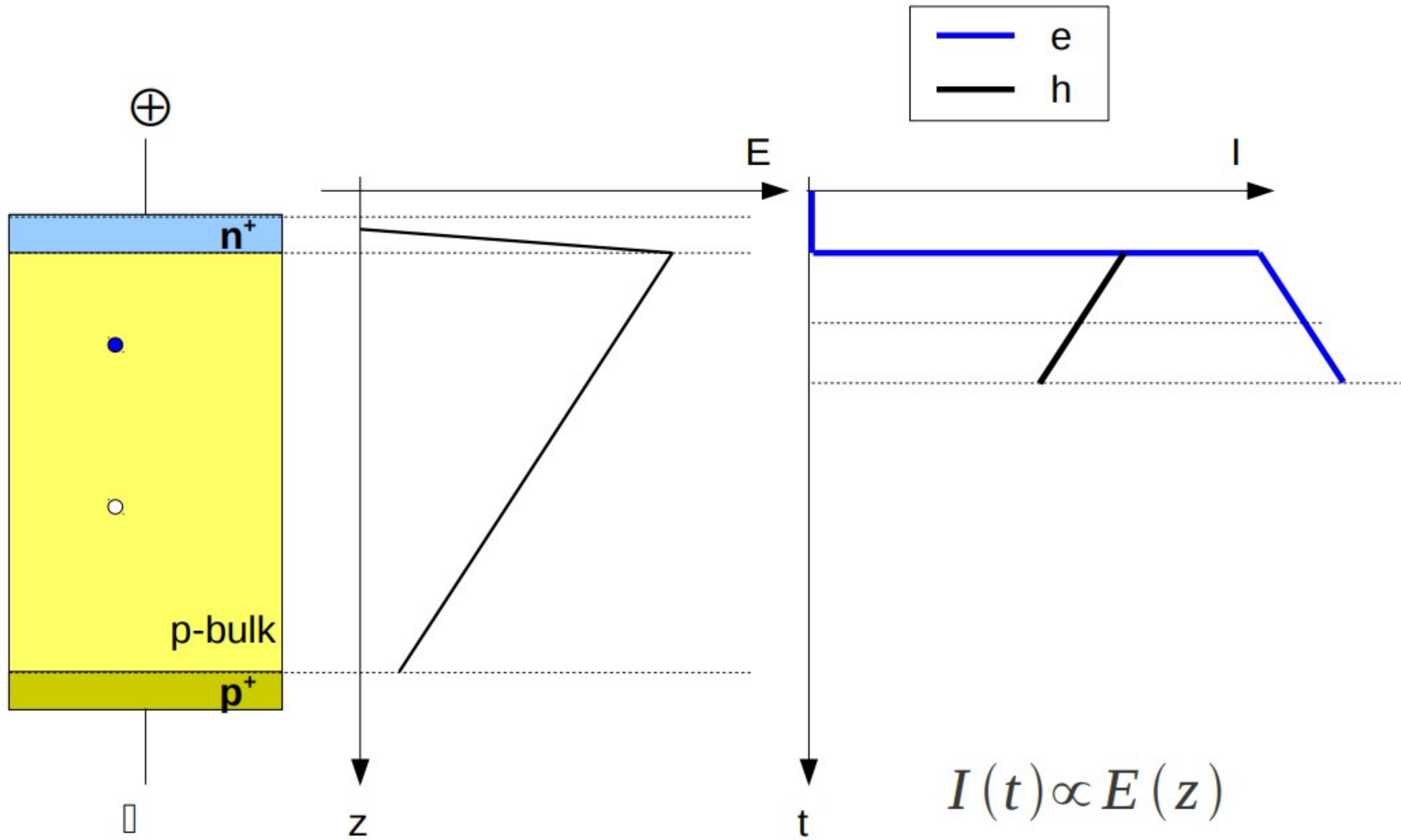
$$I(t) = q_e v_{drift} E_W \propto v_{drift} = \mu(E)E \Rightarrow I(t) \propto E(z)$$

The PN junction as Detector

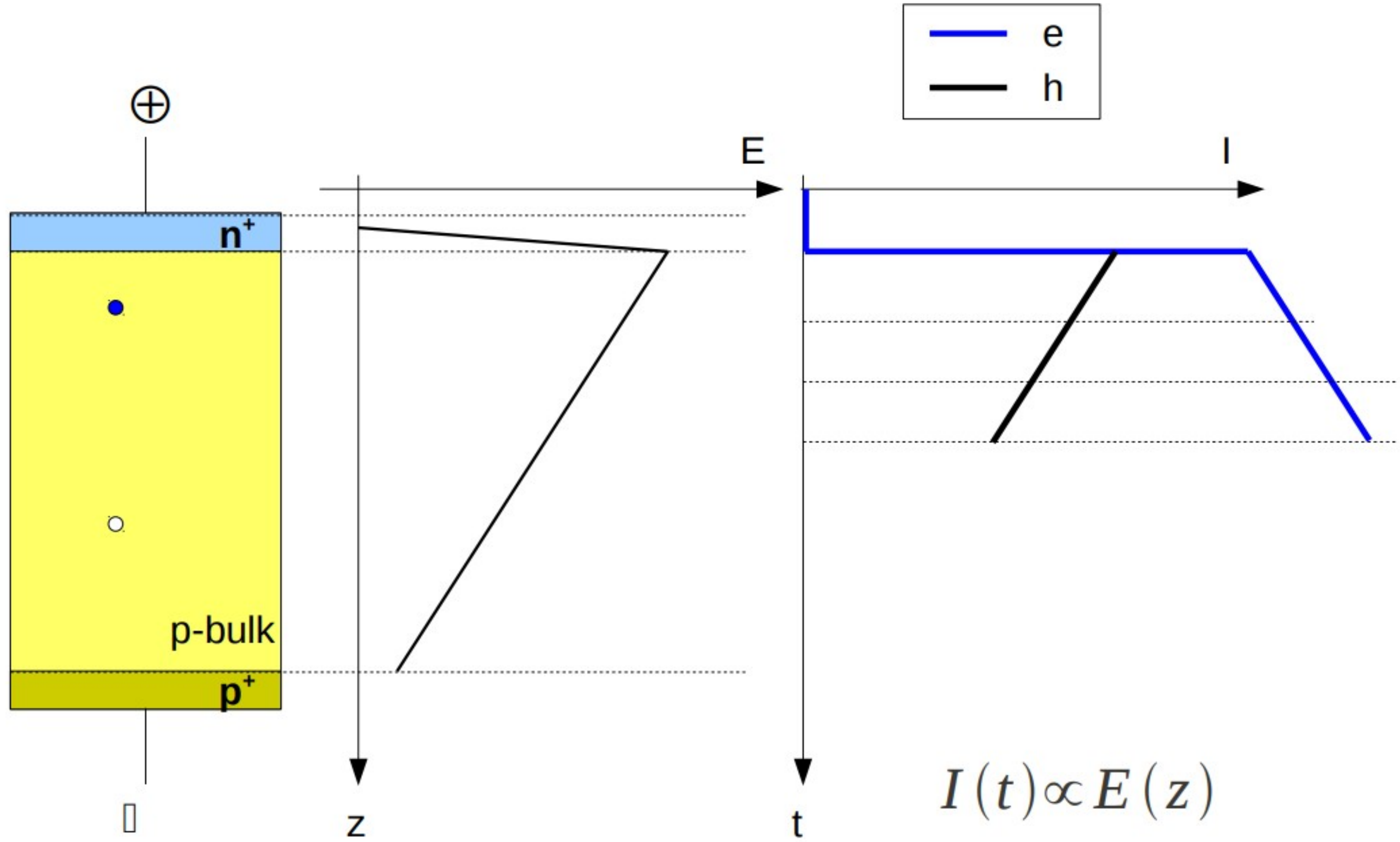


$$I(t) \propto E(z)$$

The PN junction as Detector

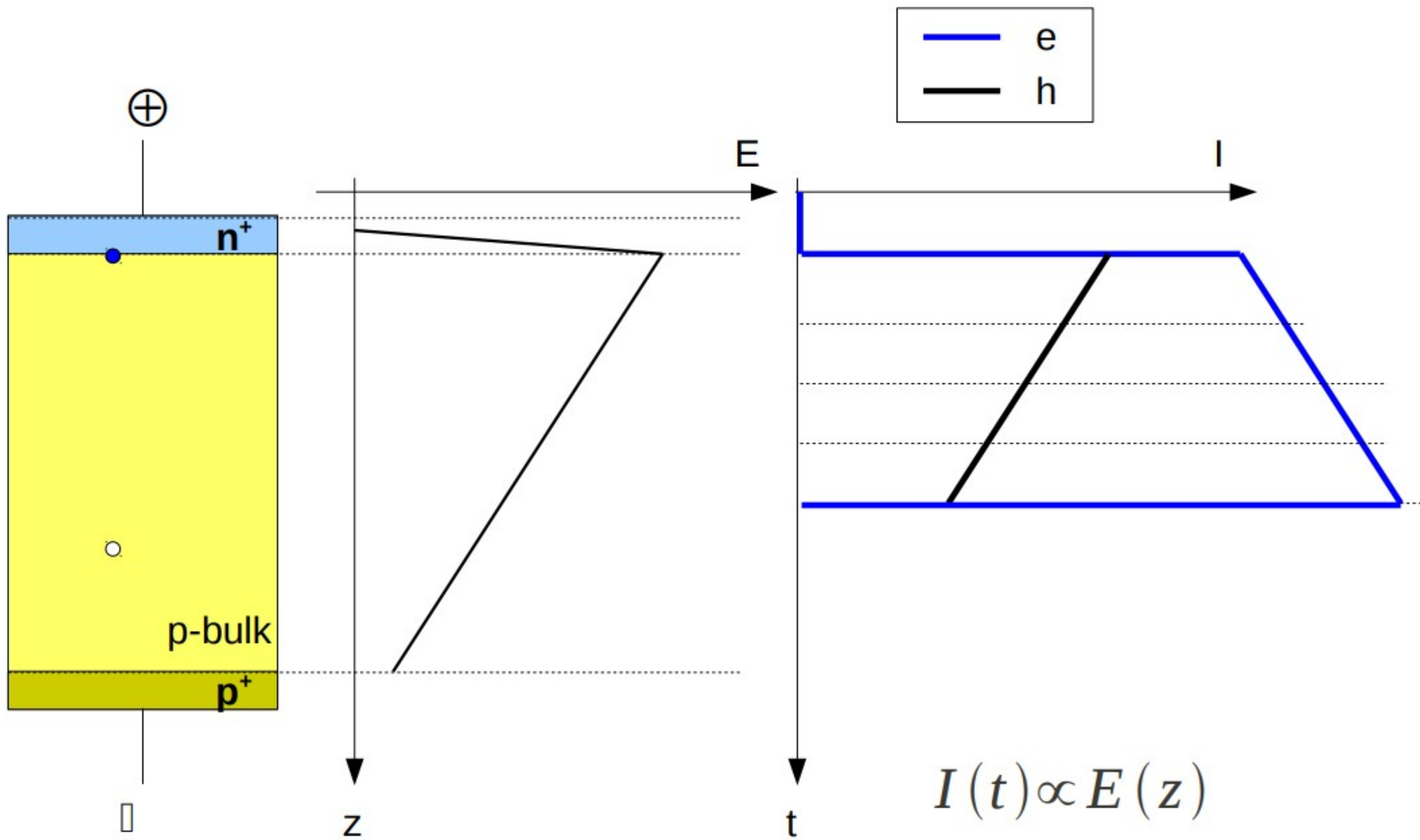


The PN junction as Detector



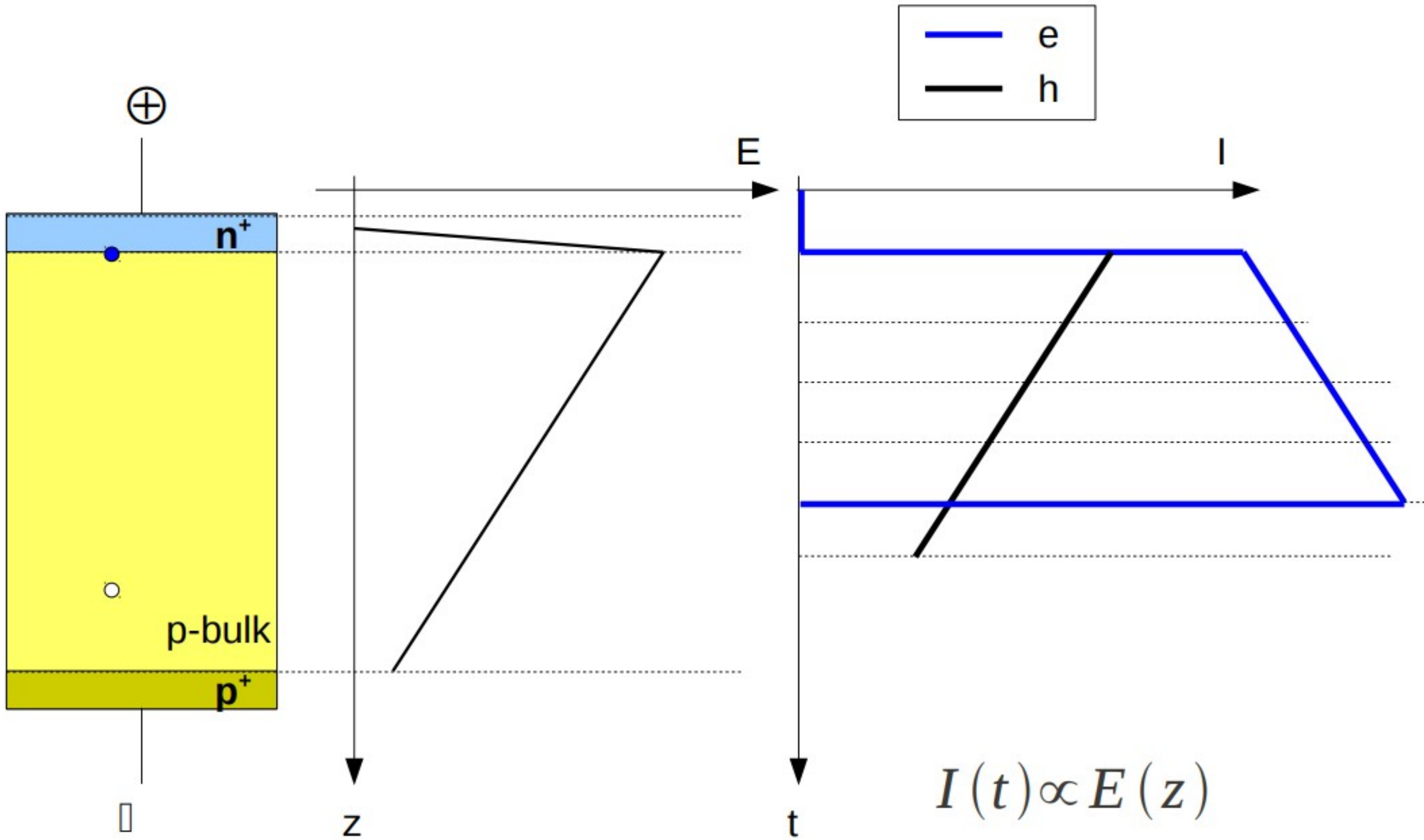
$$I(t) \propto E(z)$$

The PN junction as Detector



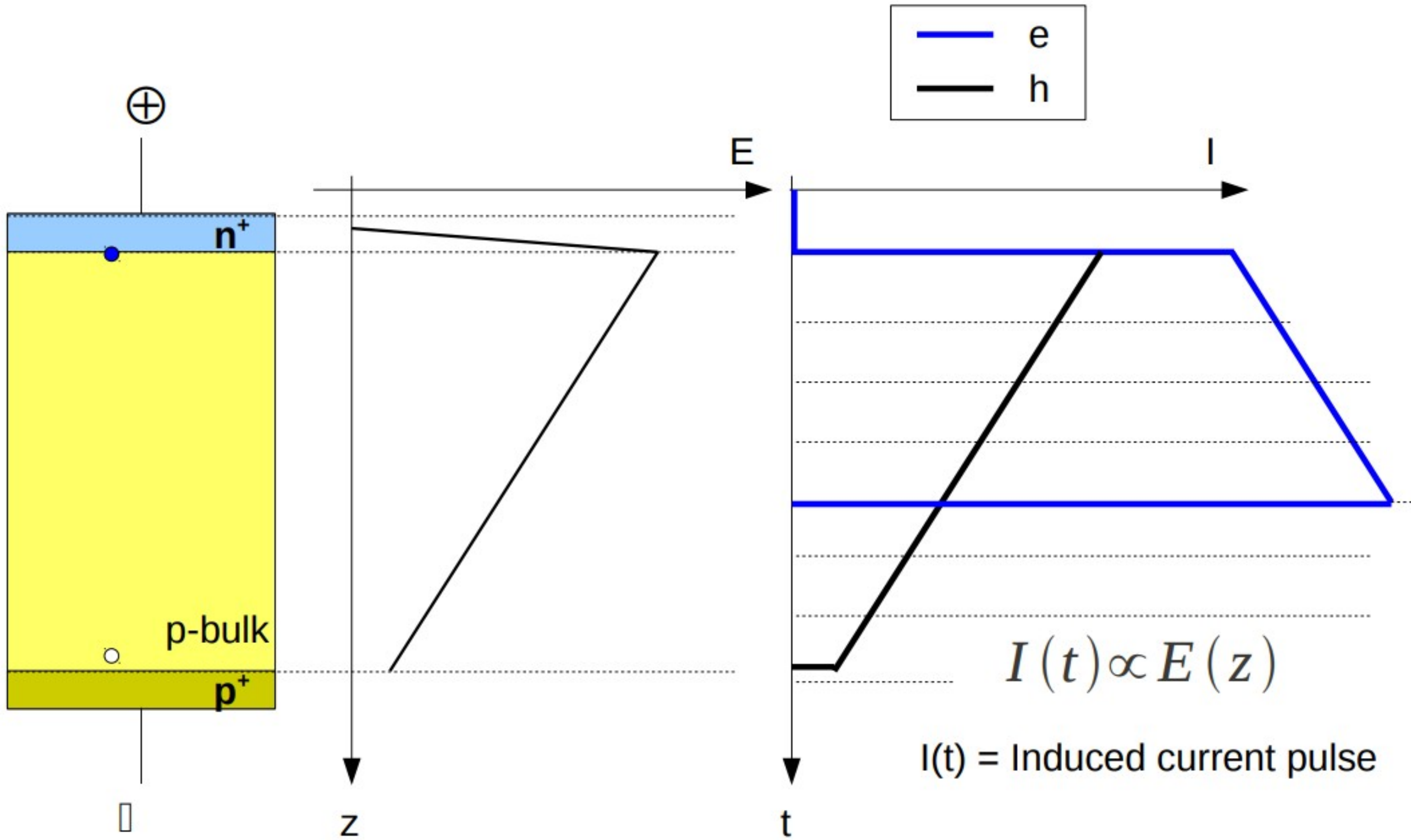
$$I(t) \propto E(z)$$

The PN junction as Detector



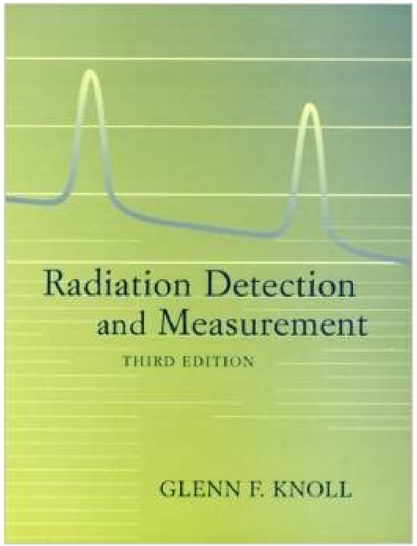
$$I(t) \propto E(z)$$

The PN junction as Detector

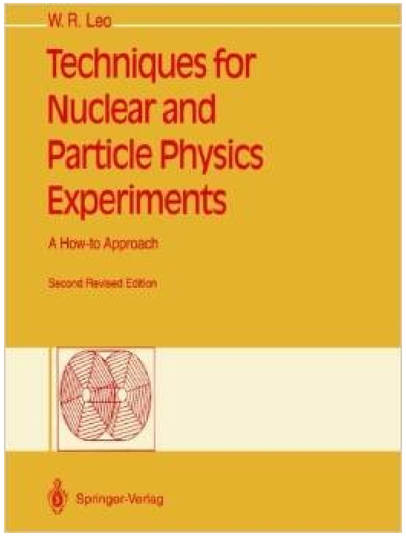


References

Radiation Detection and Measurement
(G. F. Knoll)

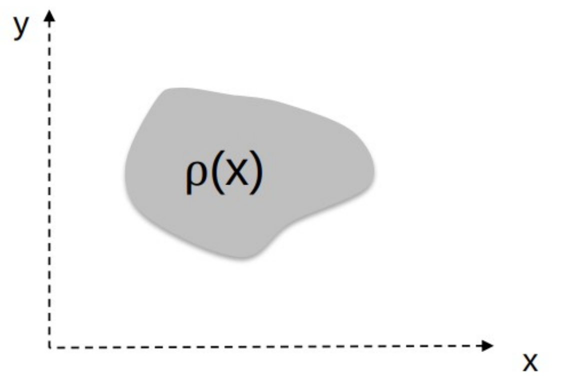


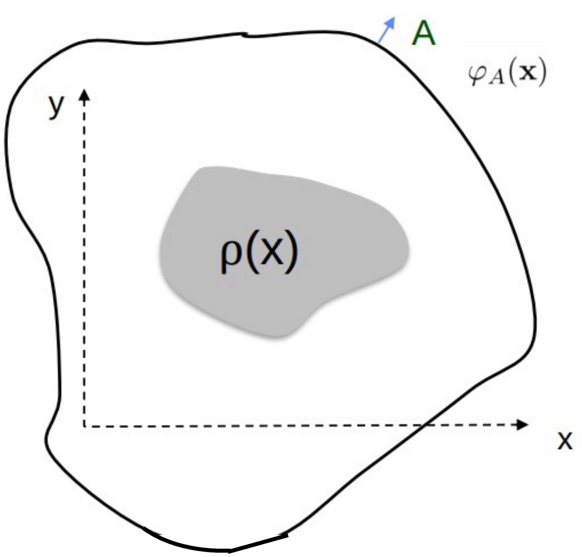
Techniques for Nuclear and Particle Physics Experiments (W.R. Leo)



BACKUP SLIDES

Electrostatics





Potential for a given charge distribution

$$\varphi(\mathbf{x}) = \frac{1}{4\pi\varepsilon_0}\int \frac{\rho(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}d^3x' \qquad \mathbf{E}(\mathbf{x}) = -\nabla\varphi(\mathbf{x})$$

Charge distribution with boundary condition, Poisson equation:

$$\Delta\varphi(\mathbf{x}) = -\frac{\rho(\mathbf{x})}{\varepsilon_0} \qquad \varphi(\mathbf{x})|_{\mathbf{x}=\mathbf{A}} = \varphi_A(\mathbf{x})$$

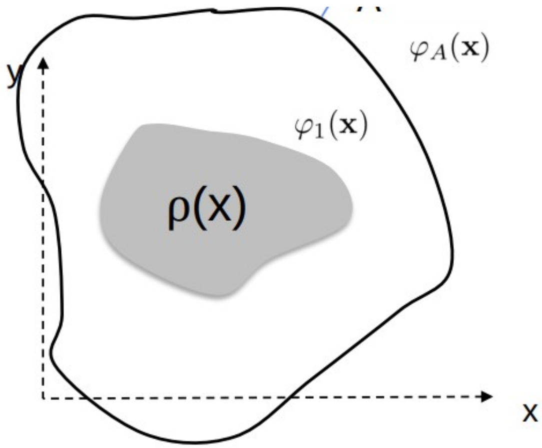
In regions of space without charge and given boundary, Laplace equation:

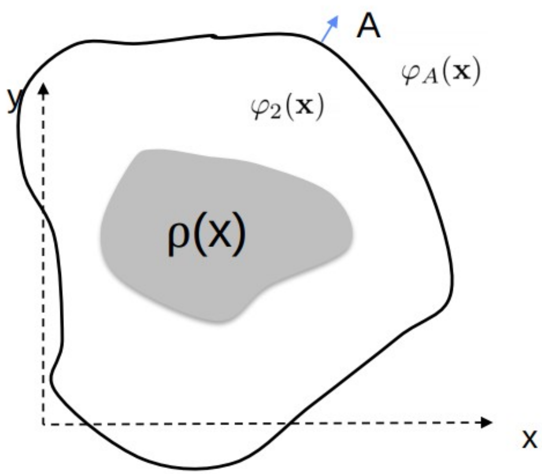
$$\Delta\varphi(\mathbf{x}) = 0 \qquad \varphi(\mathbf{x})|_{\mathbf{x}=\mathbf{A}} = \varphi_A(\mathbf{x})$$

Gauss Law:

$$\oint_A \mathbf{E}(\mathbf{x})d\mathbf{A} = \frac{1}{\varepsilon_0}\oint_V \rho(\mathbf{x})dV$$

Uniqueness





Let's assume we have two solutions of the same Poisson equation

$$\Delta\varphi_1(\mathbf{x}) = -\rho(\mathbf{x})/\varepsilon_0 \qquad \Delta\varphi_2(\mathbf{x}) = -\rho(\mathbf{x})/\varepsilon_0$$

$$\varphi_1(\mathbf{x})|_{\mathbf{x}=A} = \varphi_2(\mathbf{x})|_{\mathbf{x}=A} = \varphi_A(\mathbf{x})$$

The difference between these two solutions must satisfy the Laplace equation

$$\varphi(\mathbf{x}) = \varphi_1(\mathbf{x}) - \varphi_2(\mathbf{x}) \qquad \Delta\varphi(\mathbf{x}) = 0$$

In general it holds that

$$\nabla\left(\varphi(\mathbf{x})\nabla\varphi(\mathbf{x})\right) = (\nabla\varphi(\mathbf{x}))^2 + \varphi(\mathbf{x})\Delta\varphi(\mathbf{x})$$

Using the fact that $\Delta\varphi(\mathbf{x}) = 0$ and applying Gauss' theorem we have

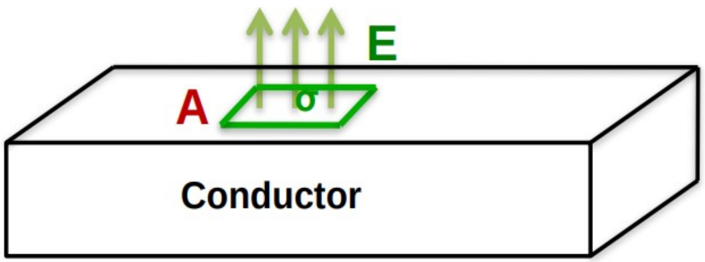
$$\oint_A \varphi(\mathbf{x})\nabla\varphi(\mathbf{x})d\mathbf{A} = \int_V (\nabla\varphi(\mathbf{x}))^2 d^3x$$

In case $\varphi_1 = \varphi_2$ on the surface we have $\varphi = 0$ on the surface and the left side vanishes. That means that the right hand side must also vanish and we have

$$\nabla\varphi(\mathbf{x}) = 0 \quad \rightarrow \quad \nabla\varphi_1(\mathbf{x}) = \nabla\varphi_2(\mathbf{x})$$

Defining the potential $\varphi_1(\mathbf{x})$ on the entire surface therefore uniquely defines the electric field in the volume. The same holds in case we define $\nabla\varphi_1 d\mathbf{A}$ on the entire surface. Evidently the uniqueness theorem also holds in case we define $\varphi_1(\mathbf{x})$ on a fraction of the surface and $\nabla\varphi_1 d\mathbf{A}$ on the rest of the surface.

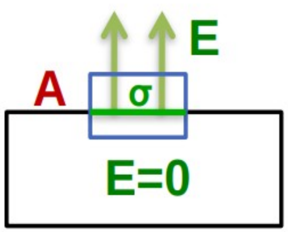
Conductors



In conducting materials, charge will move as long as there is an electric field present.

A static situation is only achieved once the electric field inside the conductor is zero and therefore also the charge density inside the conductor is zero. All the charge is sitting on the surface of the conductor.

The electric field on the surface of the conductor must be perpendicular to the conductor, since a component parallel to the conductor would again move the charge.



$$\oint_S \mathbf{E}(\mathbf{x})\, d\mathbf{A} = \frac{1}{\varepsilon_0} \oint_V \rho(\mathbf{x})\, d^3x$$

Moving a test charge across the surface of the conductor one crosses the field lines perpendicular and no work is performed. A conductor surface is therefore and equipotential surface.

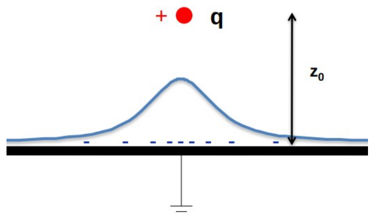
Since the electric field inside the conductor is zero and the field-lines are perpendicular to the surface, we can use Gauss law to relate the surface charge density to the field on the surface:

$$EA = \frac{1}{\varepsilon_0}\sigma A \qquad \rightarrow \qquad \sigma = \varepsilon_0 E$$

→ The charge density (C/m^2) at a given point on the conductor surface is equal to ε_0 times the electric field in this point.

Induced Charges

- A point charge q at a distance z_0 above a grounded metal plate 'induces' a surface charge → **What's the induced charge in the electrode?**



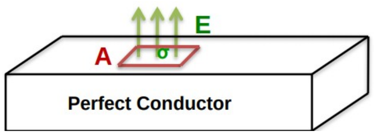
- **Electrostatic** problem:
  1. Solve Poisson equation with b.c. $\varphi = 0$ in the conductor surface

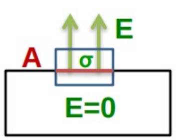
$$\Delta\varphi = -\frac{\rho}{\varepsilon_0} \quad \vec{E} = -\vec{\nabla}\varepsilon$$

  2. Calculate Electric field in the surface of the electrode

$$\oint \vec{E} d\vec{A} = \frac{1}{\varepsilon_0} \oint \rho dV \quad \text{(Gauss Law)}$$

  - **Metal surfaces**: electric field is perpendicular to the surface, charges are only in the surface. Surface charge density (σ) and electric field (E) on the surface are related by:





$$E\ A = \frac{1}{\varepsilon_0}\sigma A \rightarrow \sigma = \varepsilon_0 E \text{ (, i.e. } \sigma(x,y) = \varepsilon_0 E(x,y))$$

  3. Integrate over the electrode surface:

$$Q_{ind} = \int_S \sigma\, dS = \varepsilon_0 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} E(x,y) dx dy$$

Induced Charges (II)

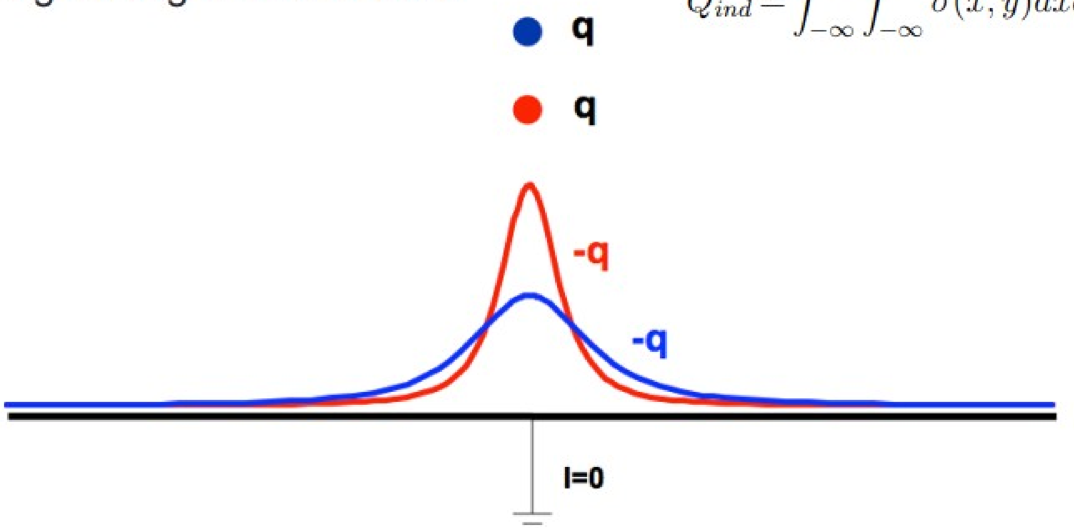
- A point **charge q at distance z_0** above a **grounded metal plate** induces a surface charge
- Different positions of q yield different charge distributions
- Here image charges can be used

$$E_z(x,y) = -\frac{q z_0}{2\pi\varepsilon_0 (x^2+y^2+z_0^2)^{3/2}}$$

$$E_x, E_y = 0$$

$$\sigma(x,y) = \varepsilon_0 E_z(x,y)$$

$$Q_{ind} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sigma(x,y)\,dx\,dy = -q$$



Quick remember image charge method:
https://en.wikipedia.org/wiki/Method_of_image_charges

Induced Charges (III)

If we segment the metal plate
and keep individual strips grounded:

- Surface charge does not change compared to continuous plate
- The charge on each segment is now depending on position of q
- The **movement** of charge q **induces a current**

Method for image charges created for irregular geometries is required

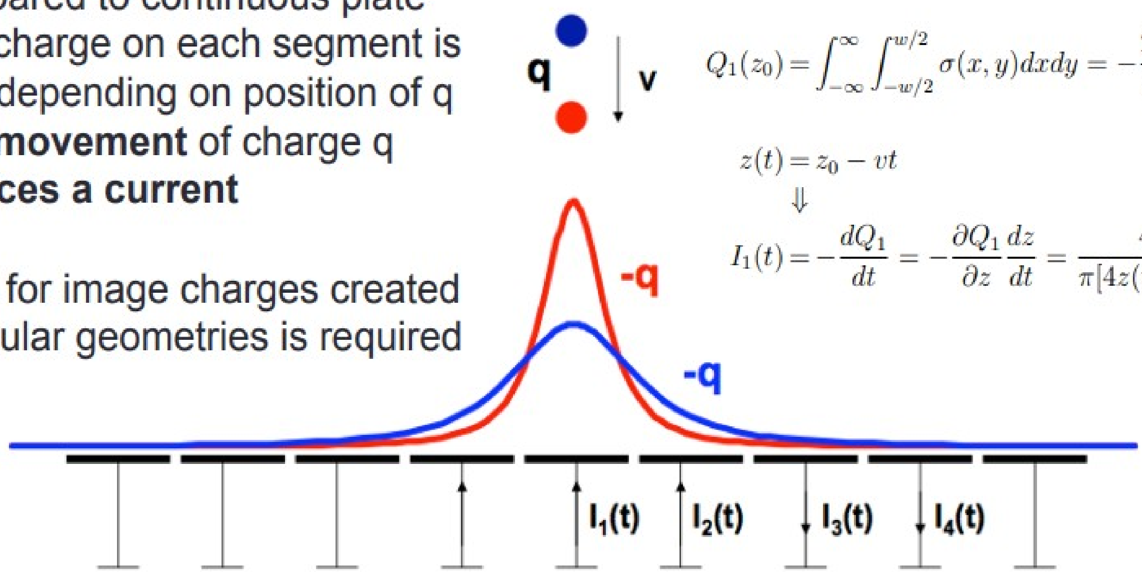
$$E_z(x,y) = -\frac{q z_0}{2\pi\varepsilon_0 (x^2+y^2+z_0^2)^{3/2}}$$

$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2} \sigma(x,y)\,dx\,dy = -\frac{2q}{\pi}\arctan\frac{w}{2z_0}$$

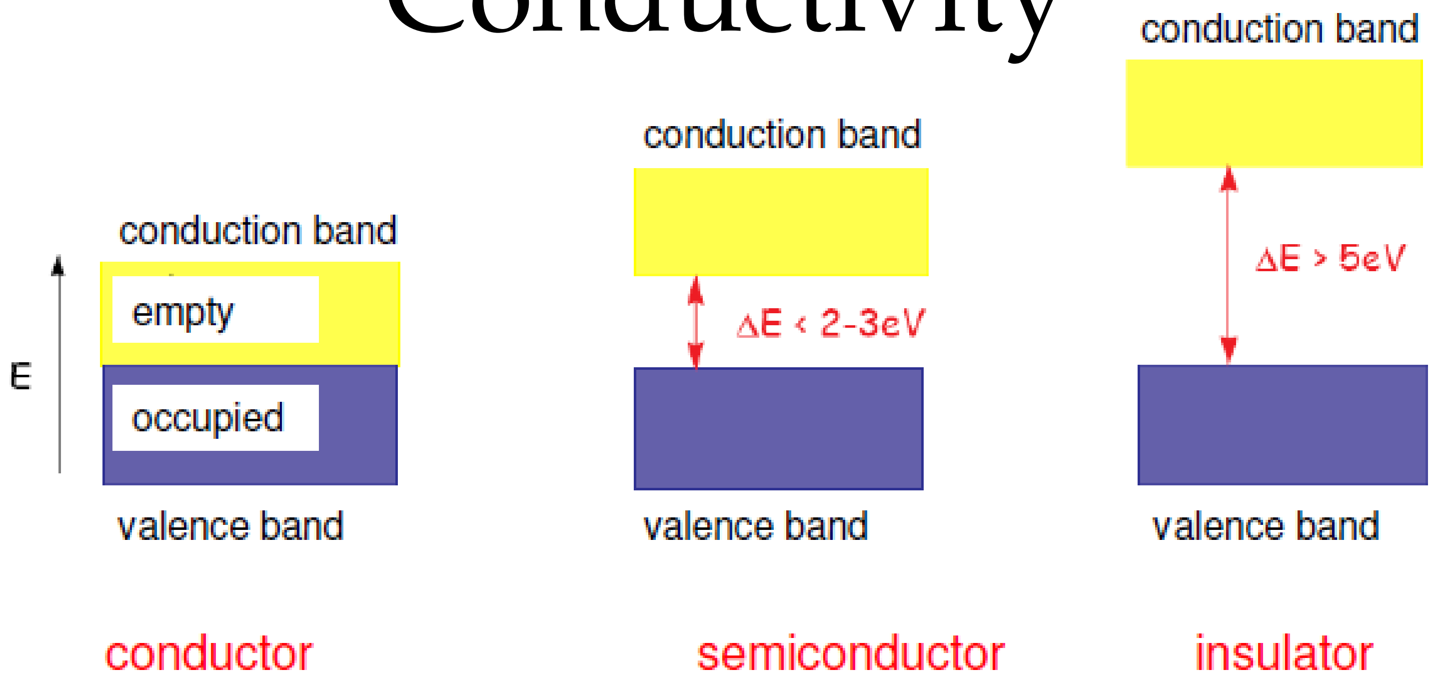
$$z(t) = z_0 - vt$$

$$\Downarrow$$

$$I_1(t) = -\frac{dQ_1}{dt} = -\frac{\partial Q_1}{\partial z}\frac{dz}{dt} = \frac{4qw}{\pi[4z(t)^2+w^2]}\cdot v$$



Conductivity

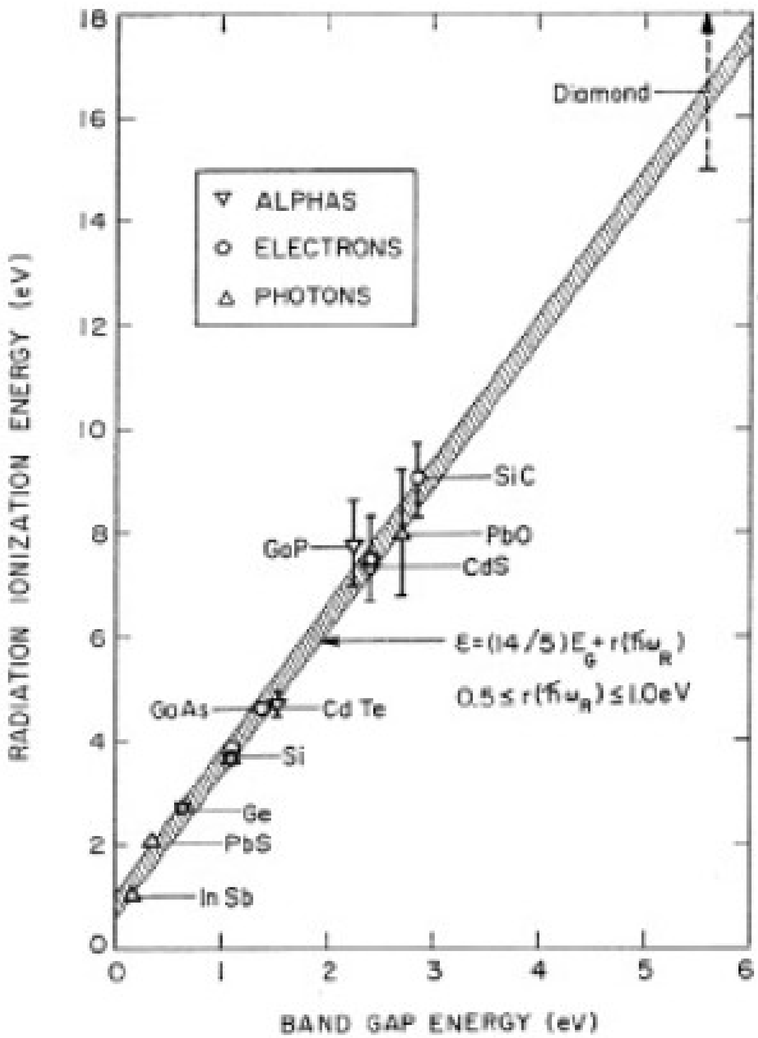


The probability that an electron occupies a certain energy level is given by the Fermi-Dirac-Distribution:

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$ and for holes $$f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_F-E)/kT} + 1}$$

For intrinsic semiconductors (e and h concentration equal): $E_F = E_{gap}/2$

Semiconductors

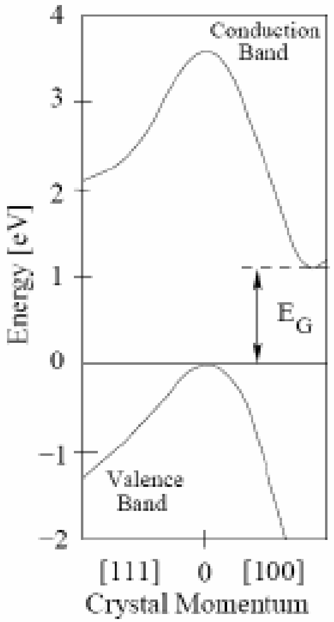


Ratio E_{ion}/E_{Gap} independent of

- material
- type of radiation

Reason: Fraction of energy going into phonons (momentum transfer) is approximately the same for all semiconductors.

Semiconductors: Silicon



•indirect band gap δ E = 1.12 eV
compare to kT = 0.026 eV at room temp. → dark current under control

(indirect: maximum of valence band and minimum of conduction band at different crystal momenta →E and p can only be conserved if additional phonons are excited)

• energy per electron-hole pair: 3.6 eV
(rest in phonons, compared to ~30eV for noble gases)

• high density compared to gases: ρ=2.33g/cm^3

• with $dE/dx|_{min}$=1.664 MeV/g cm^2:

N=1.664 MeV/g cm^{2}x2.33g/cm^3/3.6eV
→~32000 electron-hole pairs in 300µm (MIP)

• good mechanical stability → possible to produce mechanically stable layers of this thickness

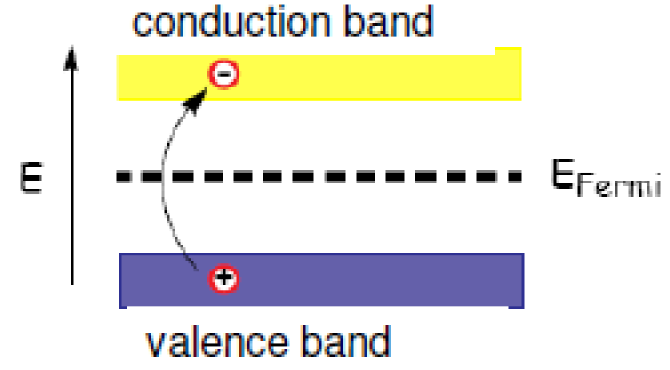
• large charge carrier mobility
→ fast charge collection δ t~10ns

Signal formation in Silicon

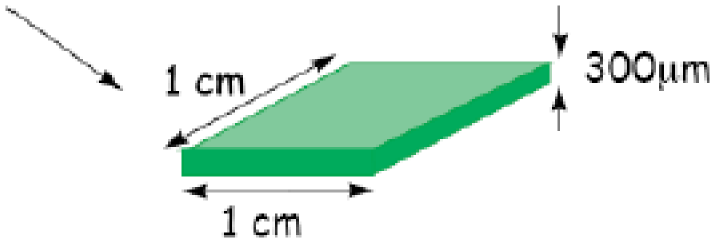
- Conduction band really empty only at T=0
- Distribution according Fermi-Dirac Statistics
- Number of electrons in conduction band at room temp.:

$$n_i = \sqrt{n_V n_C} \cdot \exp\left(-\frac{E_{Gap}}{2kT}\right) = 1.5\times10^{10}\ \mathrm{cm}^{-3}$$

→Ratio of electrons in conduction band 10^{-12}
(Silicon ~5×10^{22} Atoms/cm^3)



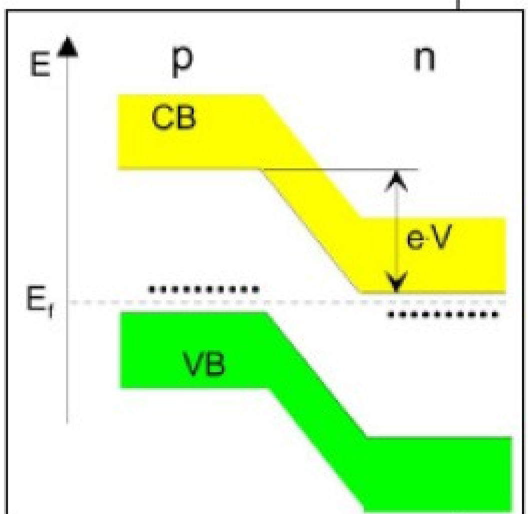
- A volume of intrinsic Si of 1cm x 1cm x 300µm contains ~4.5×10^8 free charge carriers at RT compared to only 2.3×10^4 electron-hole pairs for a MIP.

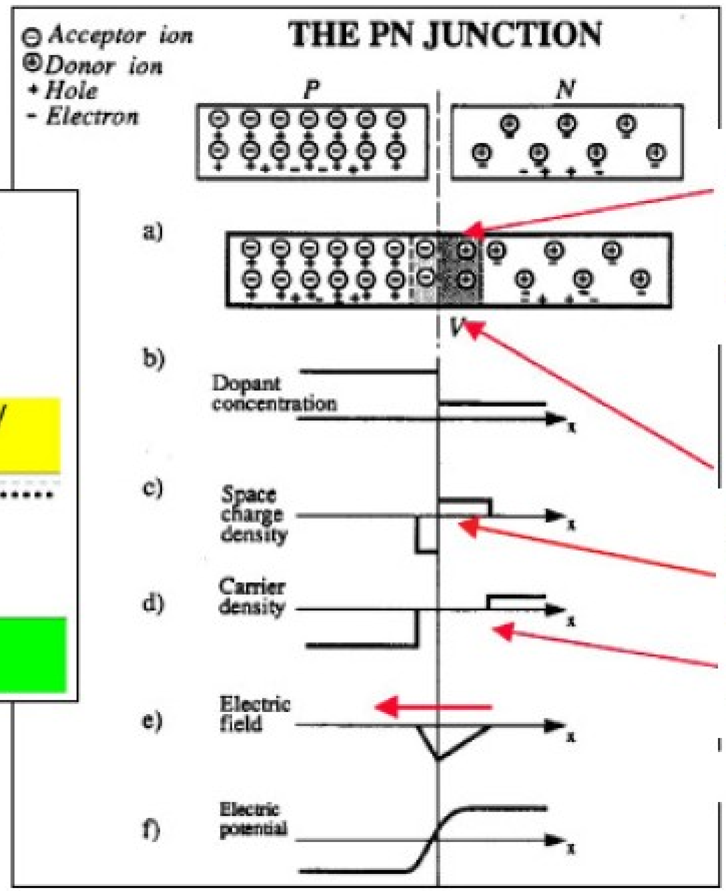


→To detect this signal, the number of free charge carriers has to be reduced drastically.
Possibilities are:

- cooling
- pn-junction in reverse bias

PN Juntion Overview





Diffusion of e in p zone

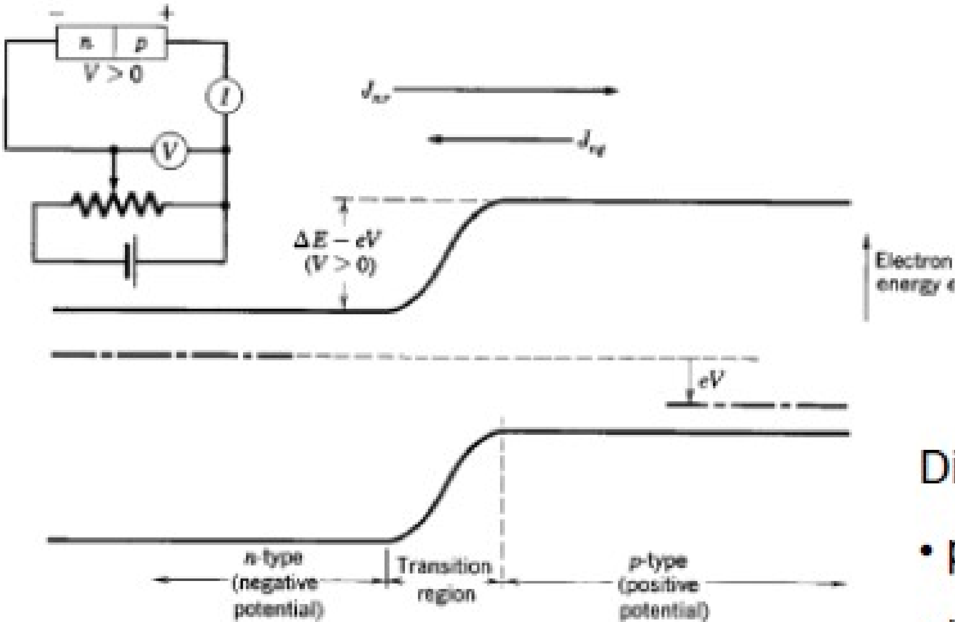
Diffusion of holes in n zone

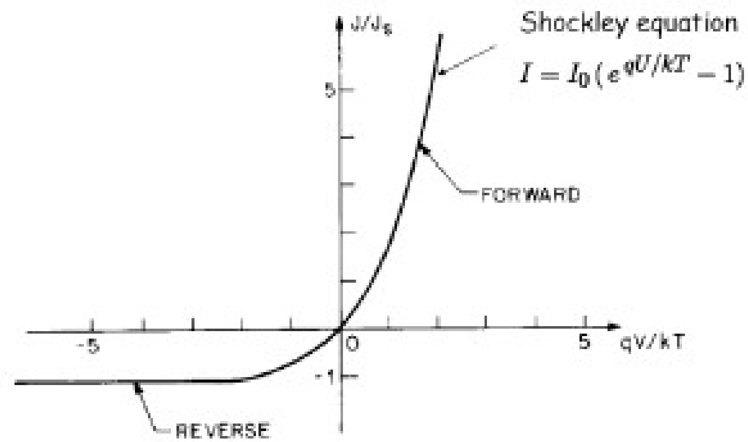
Depletion zone

Asymmetry due to different levels of doping

No free charge carriers

PN Junction in Forward Bias





from Sze, Physics of Semiconductor Devices

Diode in Forward Bias

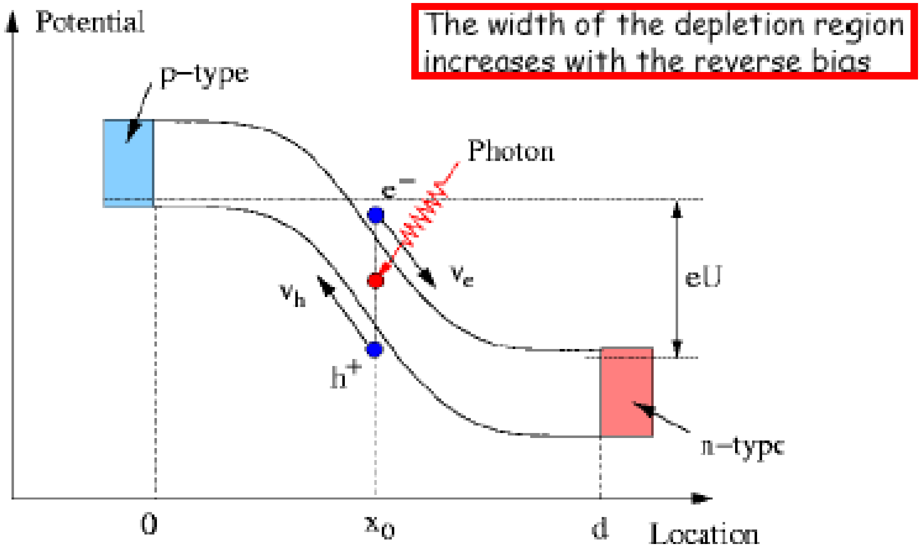
- positive potential at p-region
- negative potential an n-region
- The external voltage reduces the potential barrier.

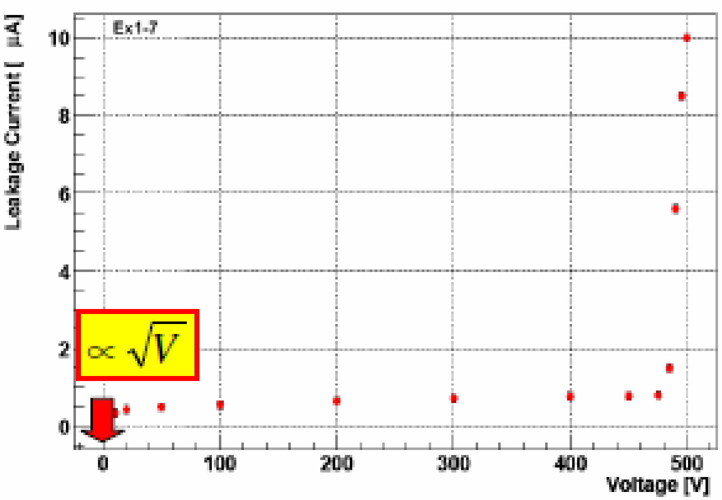
→electrons from the n-region can cross the barrier.

PN Junction in Reverse Bias

- The external voltage increases the potential barrier
- **The depletion zone can be used as detector, since it contains an electric field (and is depleted of free charges).**

Leakage current: Thermal generation of e h pairs → temperature dependant





Break through:

Detector behaves like a conductor (charge avalanche)

Depletion Voltage calculation (diode)

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

with $$\frac{d}{dx}\phi(x=w)=0$$

$$\phi(x=w)=0$$

w = depletion depth
d = detector thickness
U = voltage

N_{eff} = effective doping concentration

$$-\frac{d}{dx}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)$$

$$\phi(x) = \frac{1}{2}\cdot\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)^2$$

$$C = \frac{dQ}{dU} = \frac{dQ\cdot dw}{dw\cdot dU}$$

$$dQ = q_0\cdot\left|N_{eff}\right|\cdot A\cdot dw$$

$$w(V) = \sqrt{\frac{2\varepsilon\varepsilon_0}{q_0\left|N_{eff}\right|}\cdot V}$$

$$dw = \sqrt{\frac{\varepsilon\varepsilon_0}{q_0\left|N_{eff}\right|2U}}\cdot dU$$

depletion voltage

$$V_{dep} = \frac{q_0}{2\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2$$

effective space charge density

$$C(U) = A\cdot\sqrt{\frac{\varepsilon\varepsilon_0 q_0\left|N_{eff}\right|}{2U}}$$

$$C(w) = \frac{\varepsilon\varepsilon_0 A}{w}$$