JENNIFER2 SUMMER SCHOOL ON PARTICLE PHYSICS AND DETECTORS

20-27 ~~6-15~~ July 2020

KEK, ~~Tsukuba~~, Japan REMOTE

Particle Detectors 02

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Outline

01

- Introduction
- A tour of particle-matter interactions
  - Heavy charged particles
  - Electron and positrons
  - Hadrons
  - Neutrinos

02

- Detector technologies
  - Gas ionization detectors
  - Semiconductor detectors
  - Scintillators and photodetectors

03

- Modern detector systems
  - Tracking/vertexing
  - Particle identification
  - Calorimetry
- Conclusion

Particle detector technologies

The basis for detector systems

Detectable signals

- Ionization charge
- Scintillation light
- Cherenkov photons

- For neutral particles: first interaction produces charged particles and possibly a shower --> detection of charged particles with above signals

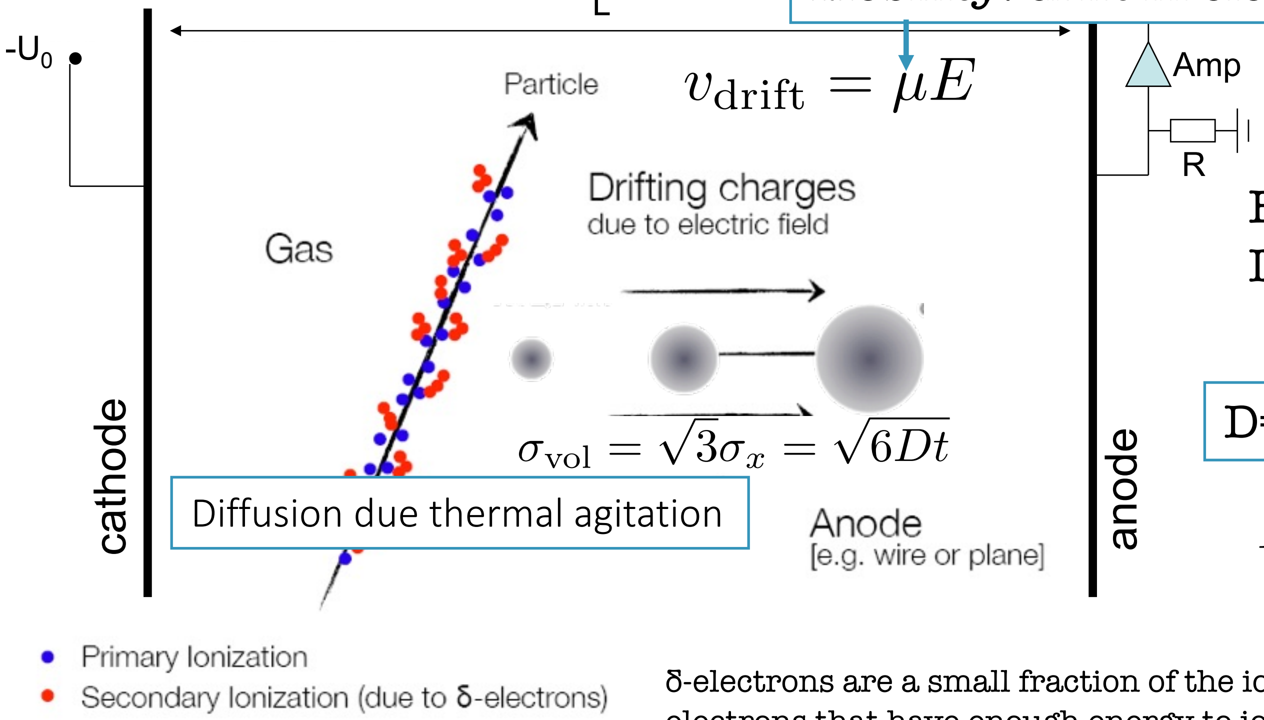
- To detect a signal:
  - Connect to electrodes collecting charge
  - Transform light in electrical signal
  - Connect to amplifier and readout system

Gas ionization detectors

Gas ionization detectors principle

Mobility: drift in electric field

$$v_{\mathrm{drift}} = \mu E$$



Electrons: $v_d \sim cm/\mu s$

Ions: $v_d \sim cm/ms$

$$\sigma_{\mathrm{vol}} = \sqrt{3}\sigma_x = \sqrt{6Dt}$$

Diffusion due thermal agitation

D=Diffusion coefficient

$$D = \mu \frac{kT}{e}$$

δ-electrons are a small fraction of the ionization electrons that have enough energy to ionize other atoms

Gas detectors parameters

- Ionization energy: E_i
- Energy per ion-e⁻ pair: W_i
  - Need more than the ionization energy to create a pair
- Number of primary ion-e pairs: n_P
- Number of total ion-e⁻ pairs: n_T
  - n_T is a factor 2-6 larger than n_P
- If L = layer thickness
- Typical values
  - W_i=30 eV
  - n_T=100 pairs / 3 keV energy loss

$$\langle n_T \rangle = \frac{L(-dE/dx)}{W_i}$$

Table of parameters for most common gases

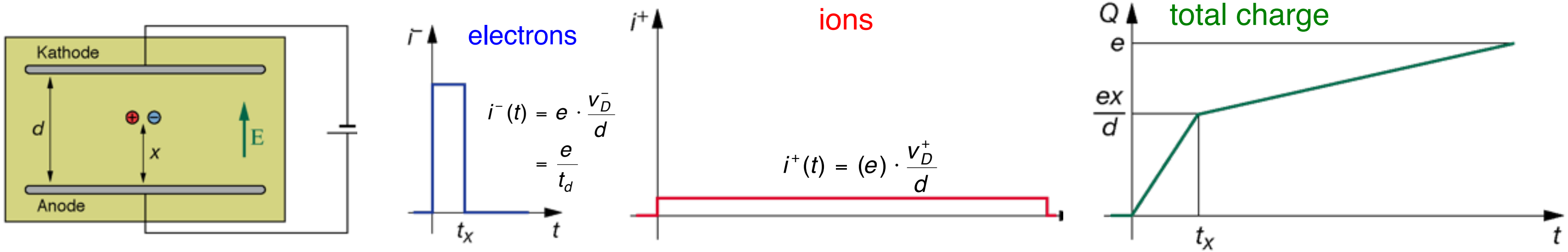
($E_i = I_o$)

Gas	ρ (g/cm^3) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg^{-1}cm^2)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195

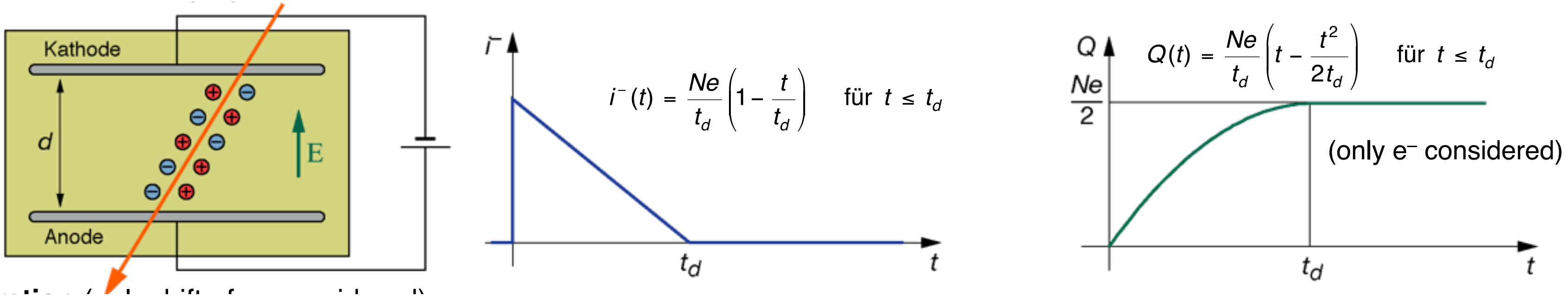
Quelle: K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992

Signal formation

- One electron-ion pair. Signal induced by drift of charge in the electric field. Shape depends on release point. Electrons much faster than ions.



- Continuous charge generation when many charges released



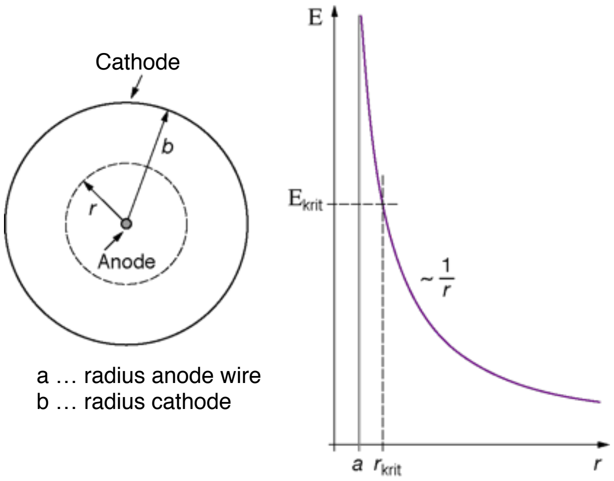
Transport effects

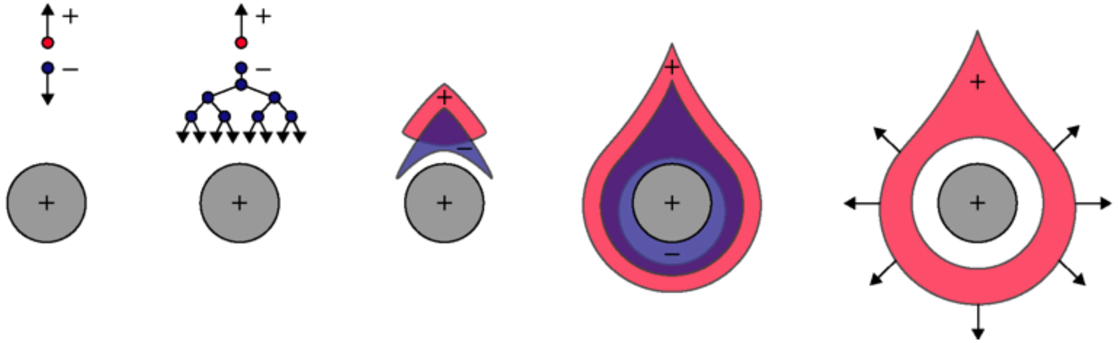
Many complex effects affect charge transport

- Recombination and electron attachment
  - Electronegative gases (O2, F, Cl) influences detection efficiency
- Diffusion
  - Influences special resolution
- Mobility
  - Influences the timing behavior
- Avalanche process via impact ionization
  - Primary electrons can produce secondary electrons and it is possible to create an avalanche
  - Multiplicate the collected charge → gas gain

Charge multiplication

- If a thin wire is used as anode in a cylindrical counter, the field goes like 1/r
- Below a certain radius electrons gain enough energy between collisions to ionize other atoms.





Photon emission possible in multiplication → secondary ionization.
Some form of quenching is necessary to prevent secondary avalanches

Signal in cylindrical wire chamber

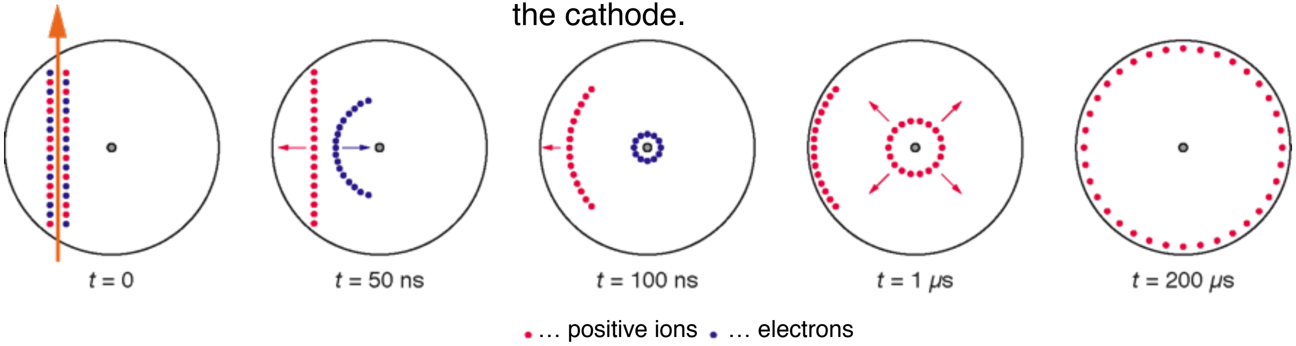
Charged particle produces primary ionization along the track.

Primary e^- drift quickly to the anode wire. Ions drift much slower to the cathode cylinder.

The primary e^- reach the region of high field and produce secondary ionization ➜ charge carrier avalanche around the wire. The primary ions continue to drift to the cathode.

The ions produced in the secondary ionization drift also to the cathode. The secondary e^- are generated close to the anode.

Finally also the secondary ions reach the cathode.

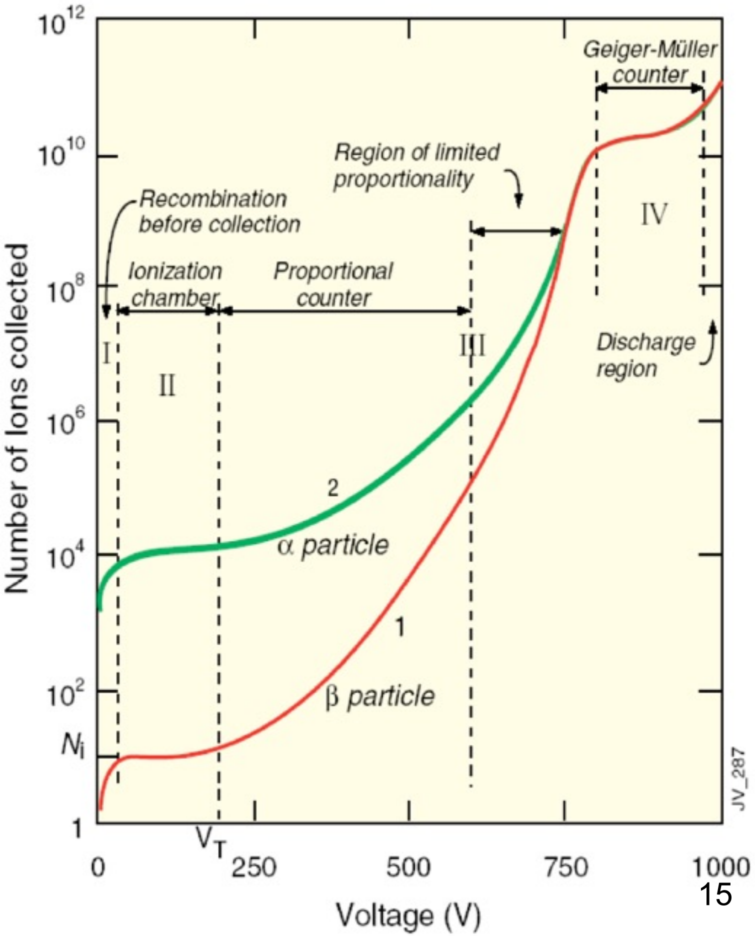


The induced signal is by far dominated by the movement of the ions!

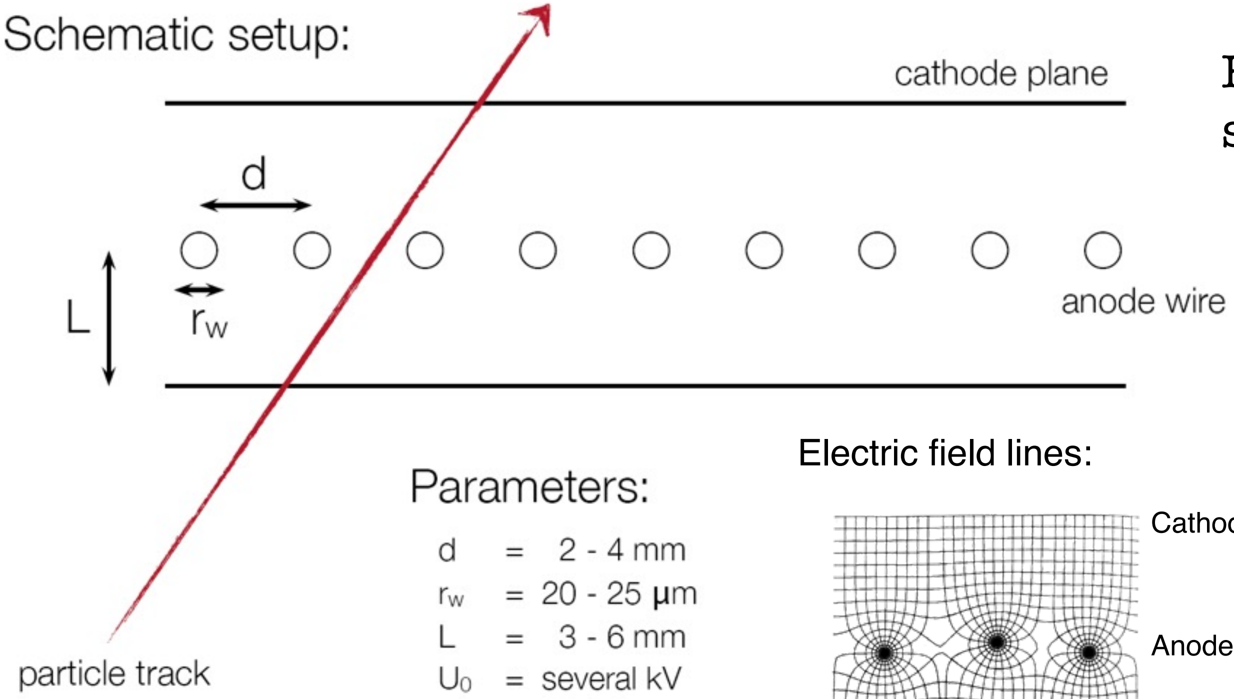
M.Krammer

Gas amplification

- Ionization mode
  - Full charge collection
  - No multiplication, gain ≈ 1
- Proportional mode
  - Signal proportional to primary ionization
  - Secondary avalanches need quenches
  - gain ≈ 10^4 - 10^5
- Limited proportional mode (streamer)
  - Strong photoemission
  - Requires strong quenching or pulsed HV
  - gain ≈ 10^{10}
- Geiger mode
  - Massive photoemission
  - Full length of anode ire affected
  - Discharge stopped by HV cut



Multi-wire proportional chamber (MWPC)



Parameters:

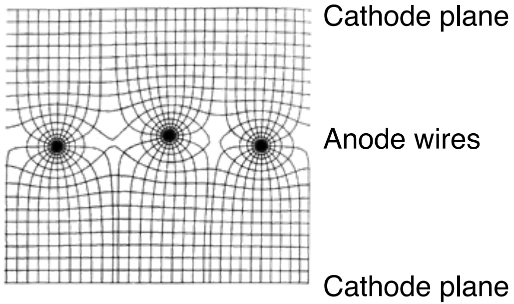
d	=	2 - 4 mm
r_w	=	20 - 25 μm
L	=	3 - 6 mm
U_0	=	several kV

Total area: $O(m^2)$

Resolution looking at single wire

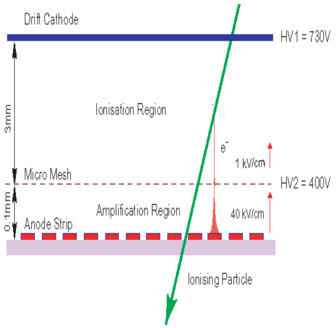
$$\sigma_x = \frac{d}{\sqrt{12}} = 0.6 - 1.2\, mm$$

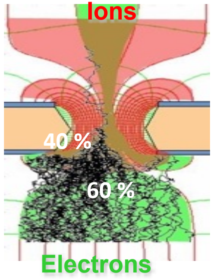
Electric field lines:

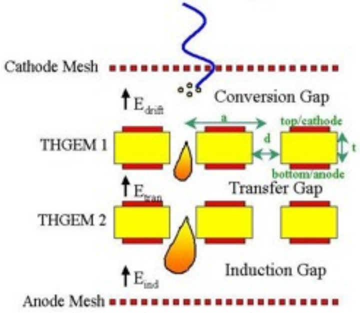


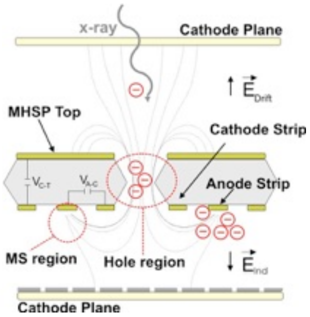
Micro pattern gas detectors

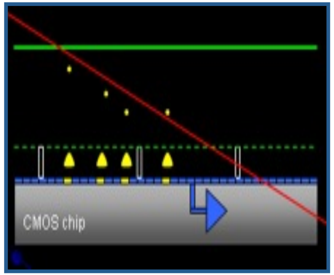
- The concept of gas multiplication can be implemented in many different ways using high precision photolithographic techniques, without using wires.

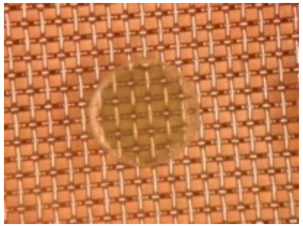




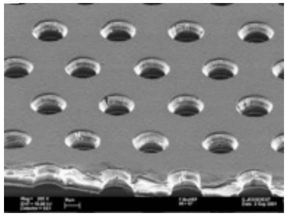




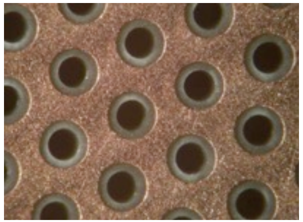




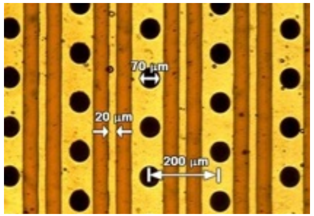
Micromegas



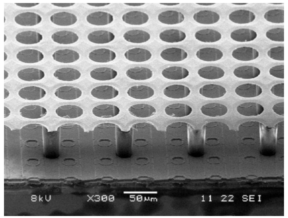
GEM



THGEM



MHSP



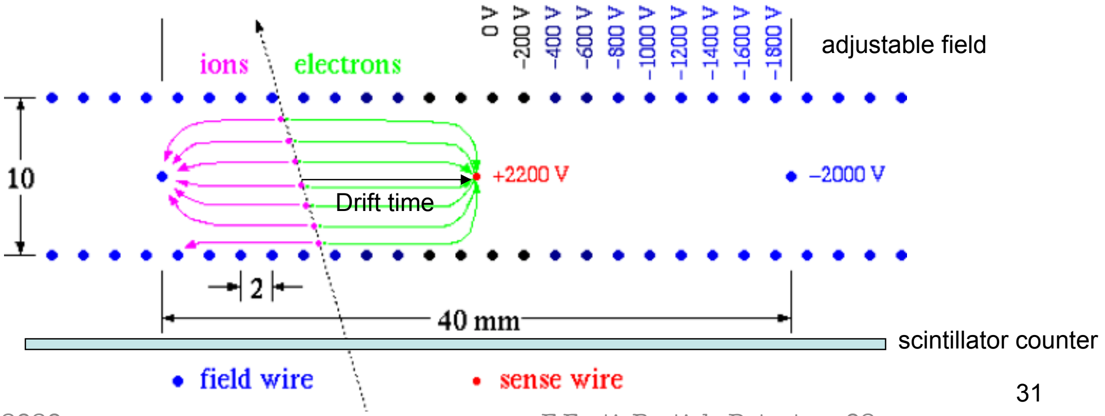
Ingrid

2

L. Ropelewski

Drift chamber

- An alternative way to obtain spatial information: measure the electron drift time.
  - Time measurement started by an external fast detector (eg scintillator)
  - Electrons drift to the anode (sense wire) in the field created by the cathodes (must be as uniform as possible)
  - The electron arrival stops the time measurement



$$x = \int_0^{t_D} v_D dt$$

Drift Chamber – spatial resolution

Resolution determined by
accuracy of drift time measurement ...

Influenced by:

Diffusion [$\sigma_{Diff.} \sim \sqrt{x}$]

see above: $\sigma^2 \sim 2Dt = 2Dx/v_D \sim x$ ...

δ-electrons [σ_δ = const.]

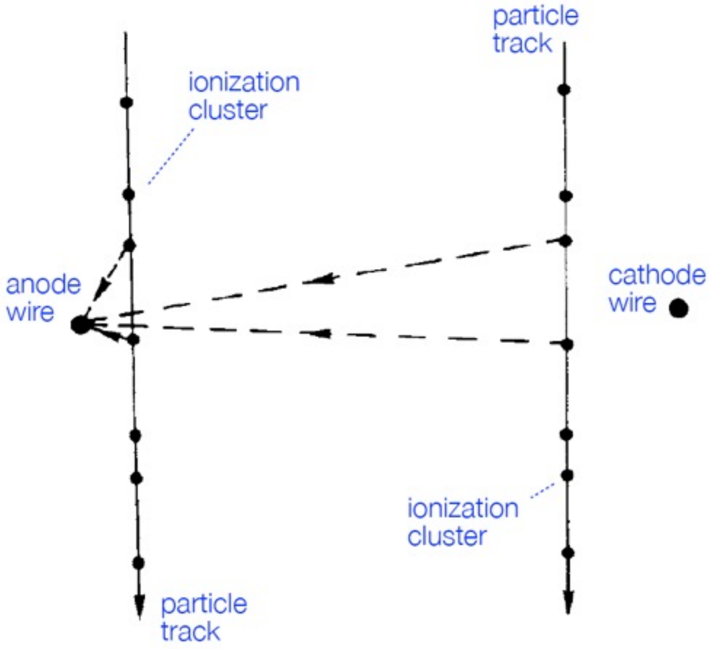
independent of drift length; yields constant term in spatial resolution ...

Electronics [$\sigma_{electronics}$ = const.]

contribution also independent of drift length ...

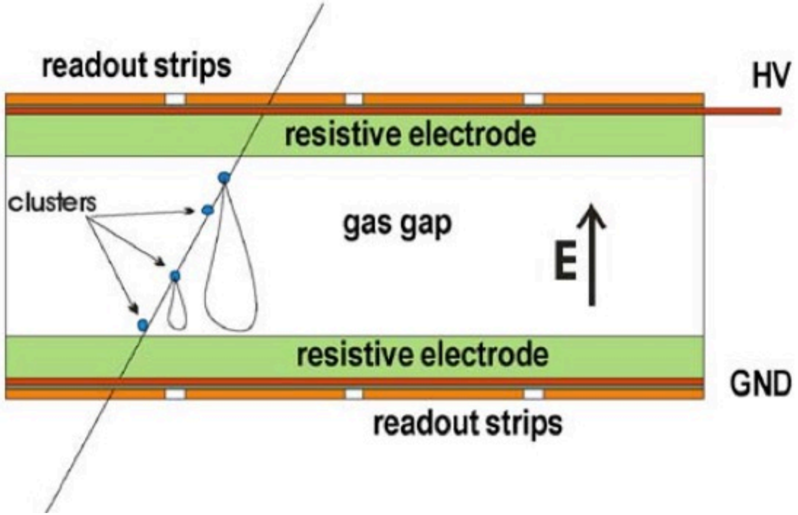
Primary ionization statistics [$\sigma_{prim} = 1/x$]

Spatial fluctuations of charge-carrier production result in large drift-path differences for particle trajectories close to the anode ...
[minor influence for tracks far away from anode]



Resistive plate chambers (RPC)

- Ionization chamber operated in avalanche or streamer mode
- Gas gap typically 2mm
- Resistive electrodes made of phenolic-melaminic (bakelite) or glass.
- Signal induced on readout electrode

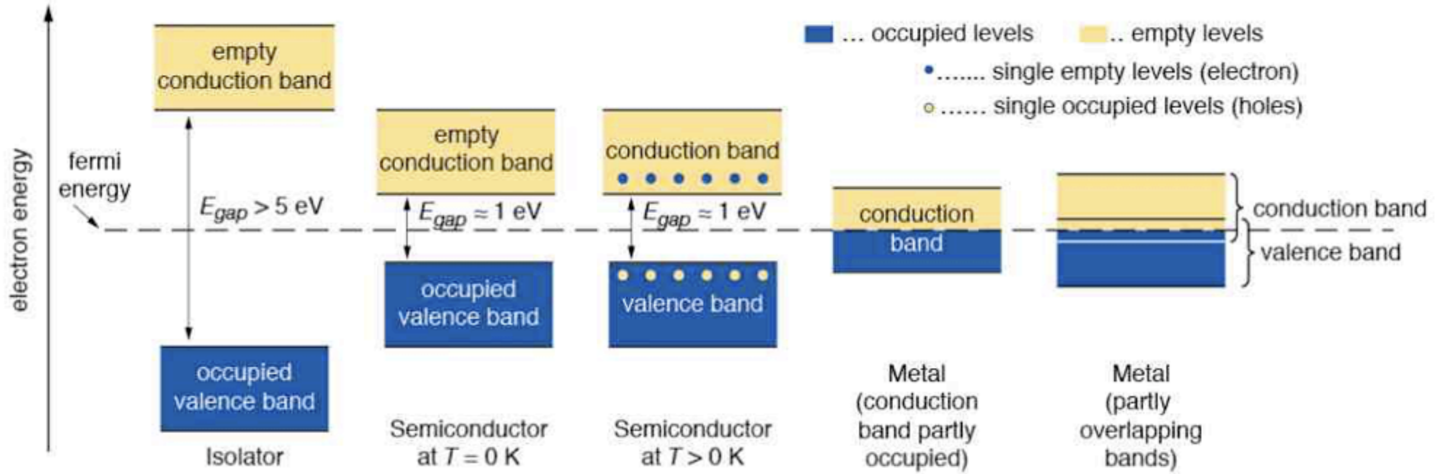


Space resolution ~mm
Fast timing (~1ns)
Designed to cover large area

Semiconductor detectors

Semiconductor ionization detectors

- Basic principle is the same as the ionization chamber
- But in semiconductors at non-zero temperature charge carriers are present, competing with ionization charge.



Intrinsic carrier concentration

- Because of the small band gap in semiconductors, at room temperature electrons can be excited to the conduction band, leaving holes in the valence band. And then recombine with holes.
- At thermal equilibrium a balance between excitation-recombination is reached leading to the "intrinsic carrier concentration" $n_e = n_h = n_i = 1.45 \cdot 10^{10} cm^{-3}$

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

N_C, N_V =density of states at the edge of the conduction and valence band

- Because of this intrinsic carrier if we polarize an intrinsic semiconductor a large current flows → cannot work as the ionization chamber

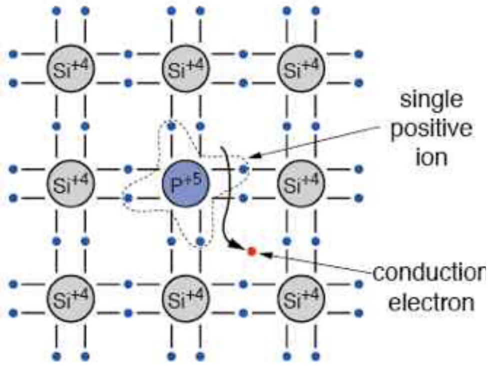
Properties of intrinsic semiconductors

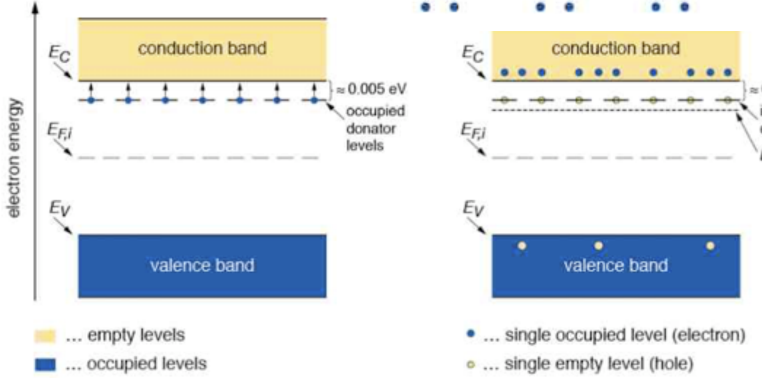
	Si	Ge	GaAs [III-V Semiconductor]
E_{gap} [eV]	1.11	0.67	1.43
n_i @ 150 K [m^{-3}]	$4.1 \cdot 10^{6}$	—	$1.8 \cdot 10^{0}$
n_i @ 300 K [m^{-3}]	$1.5 \cdot 10^{16}$	$2.4 \cdot 10^{19}$	$5.0 \cdot 10^{13}$
m_e^*/m_e	0.43	0.60	0.065
m_h^*/m_e	0.54	0.28	0.50
Energy/e-hole-pair [eV]	$3.7^{\dagger}$	$3.0^{\dagger}$	—

† at 77 K

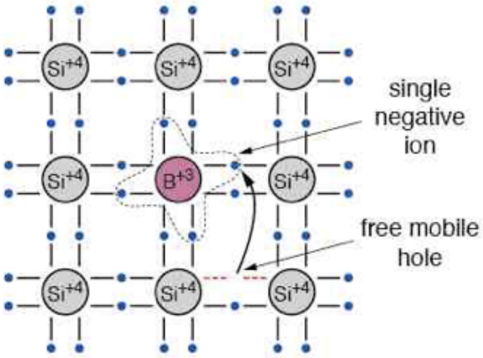
Doping: control density of carriers

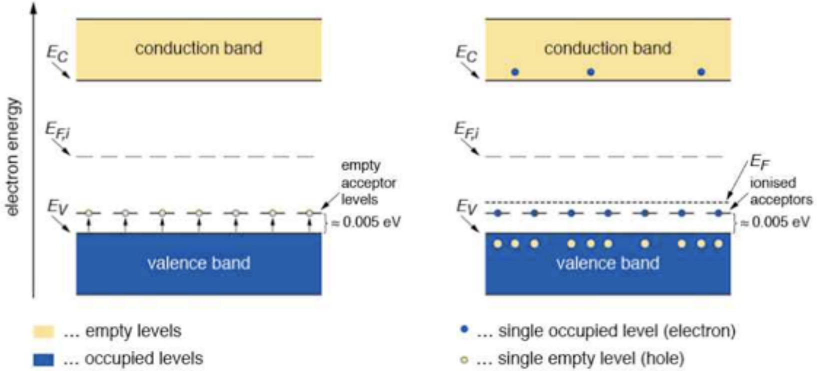
N-type doping
P, As, Sb (5 e)





P-type doping
Al, B, Ga (3 e)

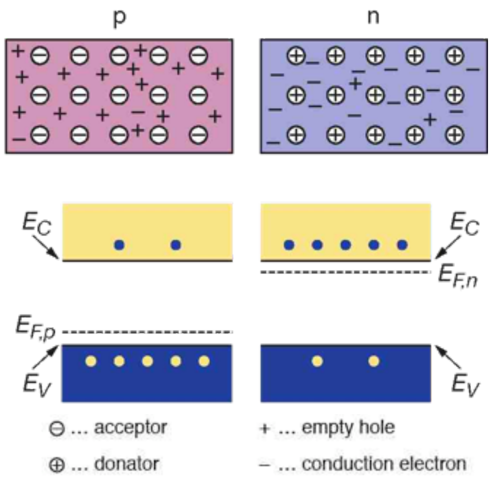


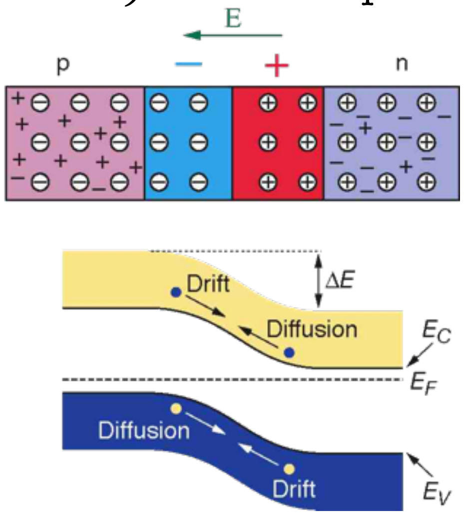


At equilibrium $n_e \cdot n_h = n_i^2$

Junction

- At the interface on n-type and p-type semiconductor the different electron/hole density causes diffusion.
  - Electrons from the n-type recombine with holes from the p-type
- An electric field is created by the fixed ions that remain behind (space charge)
  - At equilibrium the drift current from the electric field balances the diffusion current in the opposite direction
- The zone without free carriers (and electric field) is called depletion zone

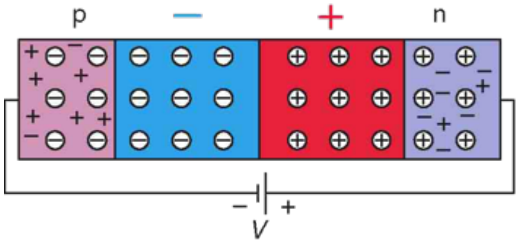


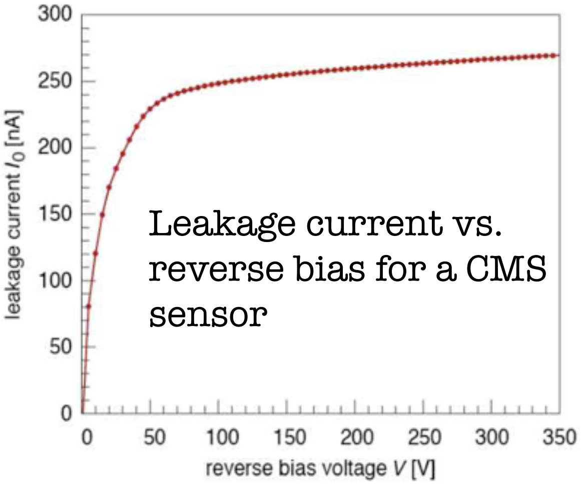


Depletion of sensor

- Applying an external reverse voltage one can extend the depletion zone
- The potential barrier between p and n is increased, and the current is very small (leakage current)

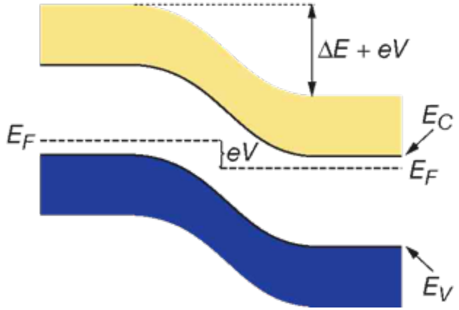
p-n junction with reverse bias





Leakage current vs. reverse bias for a CMS sensor

The depletion is zone is the sensitive volume of the detector since generated ionization charge can be collected using the electric field



Example of a typical p-n junction

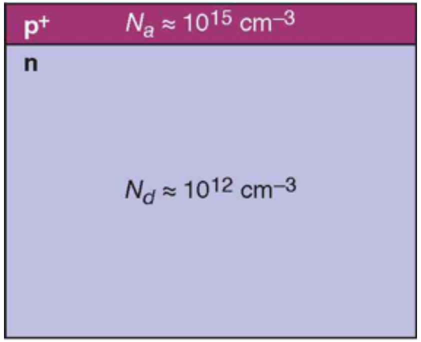
Effective doping concentration $N_a = 10^{15}$ cm^{-3} in p+ region and $N_d = 10^{12}$ cm^{-3} in n bulk.

Without external voltage:

$$W_p = 0.02\ \mu\text{m}$$
$$W_n = 23\ \mu\text{m}$$

Applying a reverse bias voltage of 100 V:

$$W_p = 0.4\ \mu\text{m}$$
$$W_n = 363\ \mu\text{m}$$



p$^+$n junction

Width of depletion zone in n bulk:

$$\boxed{W \approx \sqrt{2\varepsilon_0\varepsilon_r \mu\rho|V|}}$$

with $\rho = \dfrac{1}{e\,\mu N_{eff}}$

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

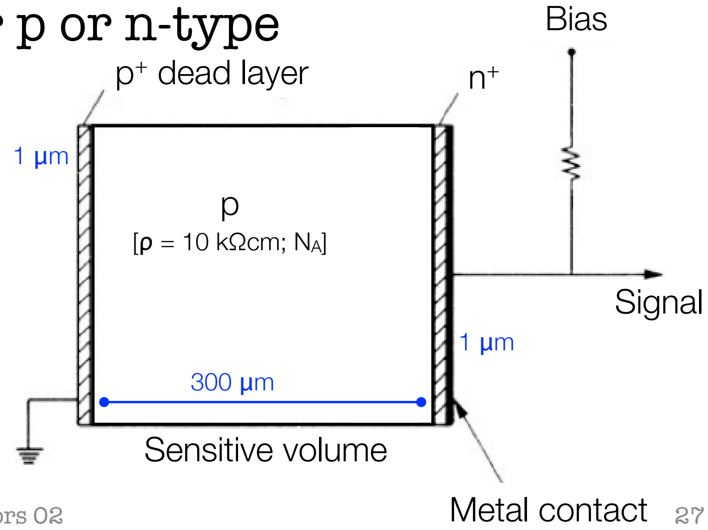
The depletion voltage is the voltage at which the depletion zone extends through the full thickness

Polarization

- To polarize the sensor one needs metallic contacts and a bias resistor.
- The signal can in general be extracted from both sides
- A MIP in 300µm of silicon releases 24000 e- ~ 4fC: very small charge.
- Note: the detector bulk can be either p or n-type
- Need to make sure electric field does not cause breakdown

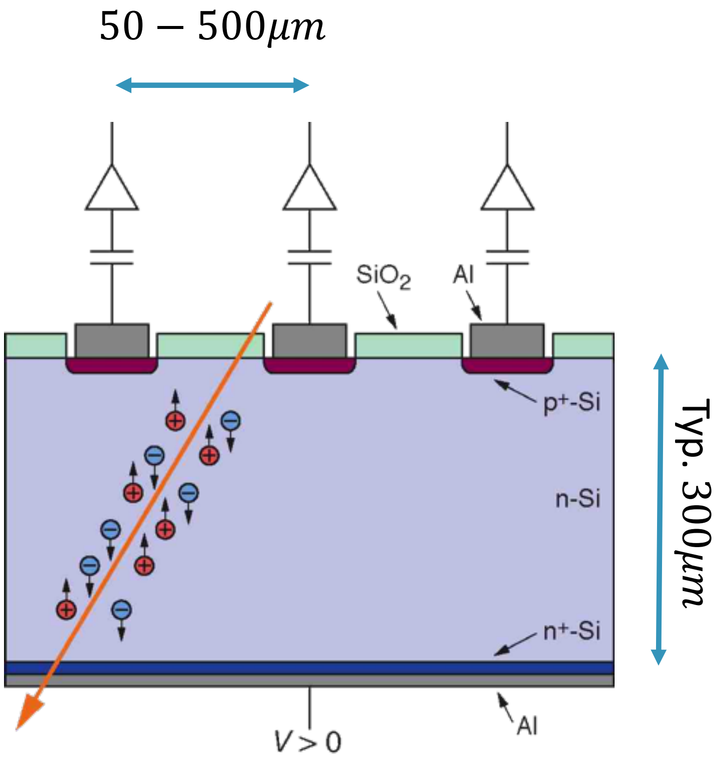
$$E = \frac{U}{d} = \frac{100\ \mathrm{V}}{300 \cdot 10^{-6}\ \mathrm{m}} \approx 3 \cdot 10^{5}\ \frac{\mathrm{V}}{\mathrm{m}}$$

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



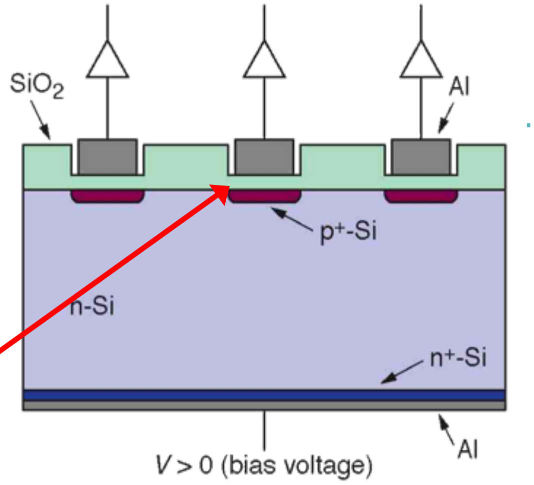
Strip detectors

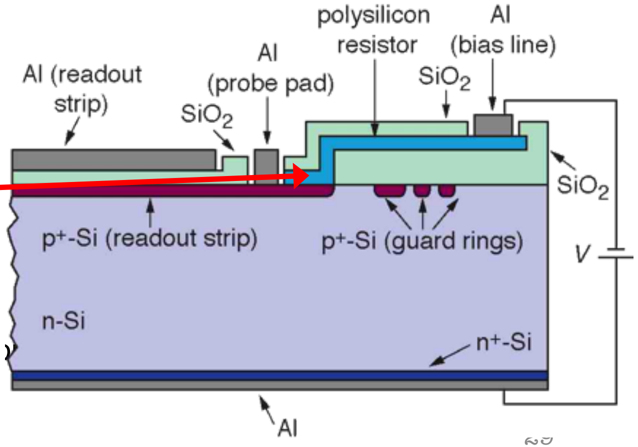
- Using modern microfabrication technology developed for electronics (planar process) one can segment the junction readout electrode in various ways → position sensitive detectors
  - Readout pitch can be as small as $50\mu m$
- Each electrode must have its own amplifier → need for miniaturized integrated circuits
- Signal to noise ratio requires careful optimization



Coupling and bias

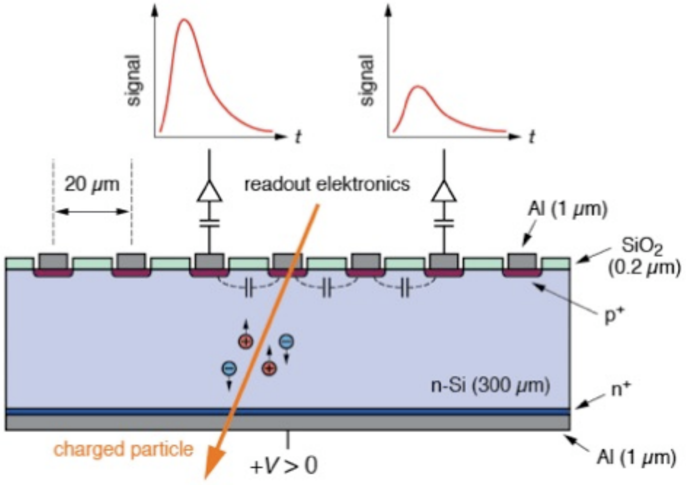
- It is desirable that leakage current does NOT flow into amplifier → AC coupling of strips
  - Integrate capacitors along the strip
  - SiO_2/Si_3N_4 deposition (100-200 nm)
  - Issues with defects of oxide (pinholes)
  - Order of 30pF/cm
- To apply voltage to the substrate a bias resistor is required
  - Can also be integrated on the detector surface
  - Deposition of polycrystalline silicon
  - Sheet resistance of order 250 $k\Omega/\square$ leading to a $R \sim 10-20\ M\Omega$
  - Drawback: more fabrication complexity





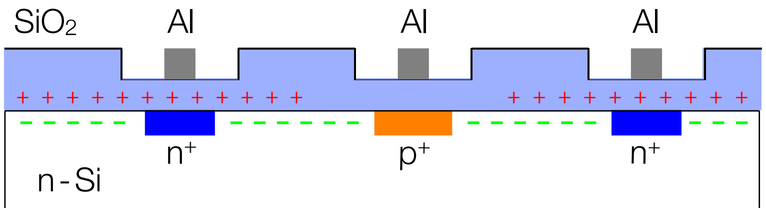
Point resolution

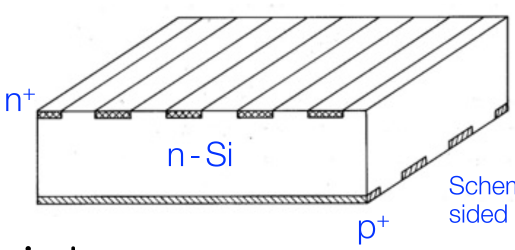
- Segmented detectors provide space information on the point x of passage of the particle
  - The distance between strips is called pitch p
- Point resolution depends on the readout mode and on the angle. For perpendicular tracks.
- Threshold readout (digital yes/no):
  - One strip is over threshold at position x_1.
  - Position estimator $x = x_1$
  - Flat probability between $x_1 - \frac{p}{2}$ and $x_1 + \frac{p}{2}$.
  - Resolution $\sigma_x = \frac{p}{\sqrt{12}}$
- Charge readout (analog)
  - Signals h_1, h_2 on strips at positions x_1, x_2
  - Position estimator center of gravity $x = \frac{x_1 h_1 + x_2 h_2}{h_1 + h_2}$
  - Resolution $\sigma_x \propto \frac{p}{\text{signal/noise}}$
  - Can take advantage of charge division through capacitive coupling



2-D detectors

- One needs to measure two coordinates of passage of a particle
- In principle can use two strips detectors with orthogonal orientation
  - Twice the material → bad impact on multiple scattering
- Development of double-side strip detectors
  - Need special insulating structures between n type strips (ohmic contact side)





Schematics of a double sided micro-strip detector

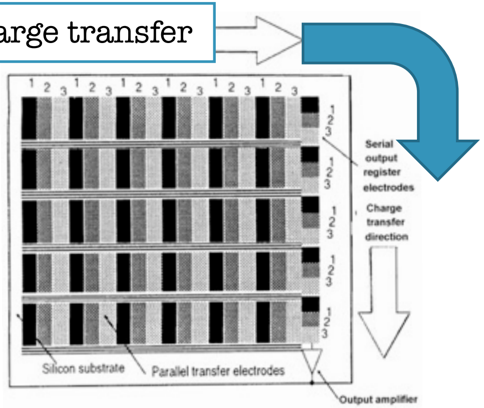
- Same material as single sided, but 2D point
  - Ambiguity if more than particle crosses the detector: multiple combinations of the two views

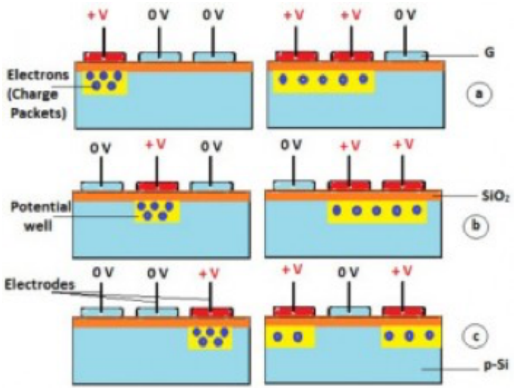
Used in Belle II experiment

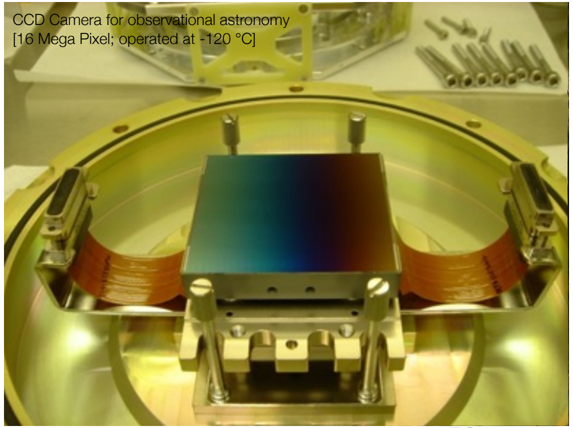
Pixel detectors

- Electrodes can also be segmented in pixels
  - Pro: no ambiguity in point determination
  - Con: added complexity, huge number of channels
- Strong technology connection with digital cameras
- First development: Charged Coupled Devices (CCD)
  - Charged stored under metal gates, individually switchable. Slow readout
  - Pixel dimension down to $20\mu m$

Charge transfer

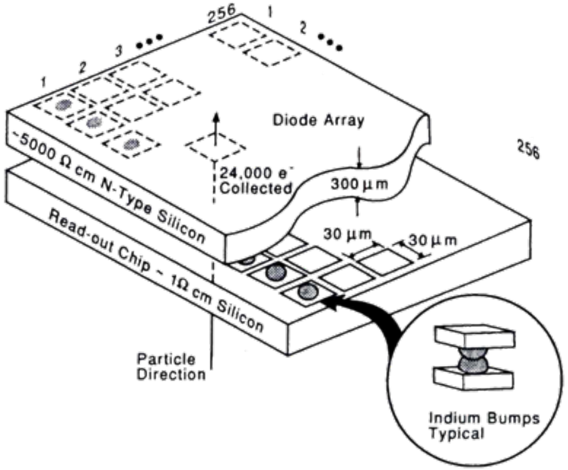




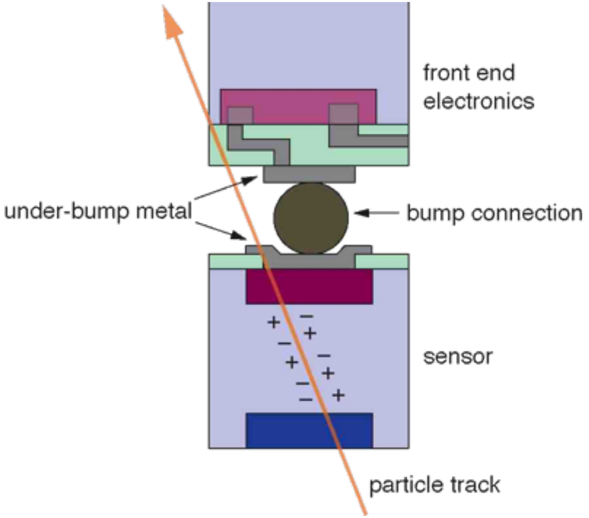


Flip-chip pixel detectors

- Sensor pixels are connected 1-to-1 to amplifier channels, organized with a matching geometry on the readout IC.
- Bump bonding technology: use soft material (like Indium) to perform vertical connection

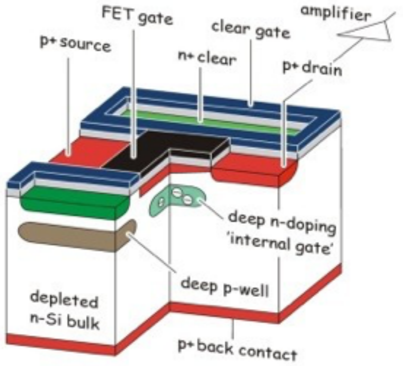


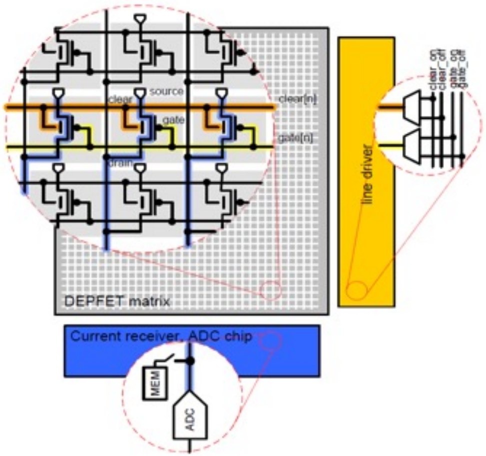
S.L. Shapiro et al., *Si PIN Diode Array Hybrids for Charged Particle Detection*, Nucl. Instr. Meth. A **275**, 580 (1989)



L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

DEPFETs





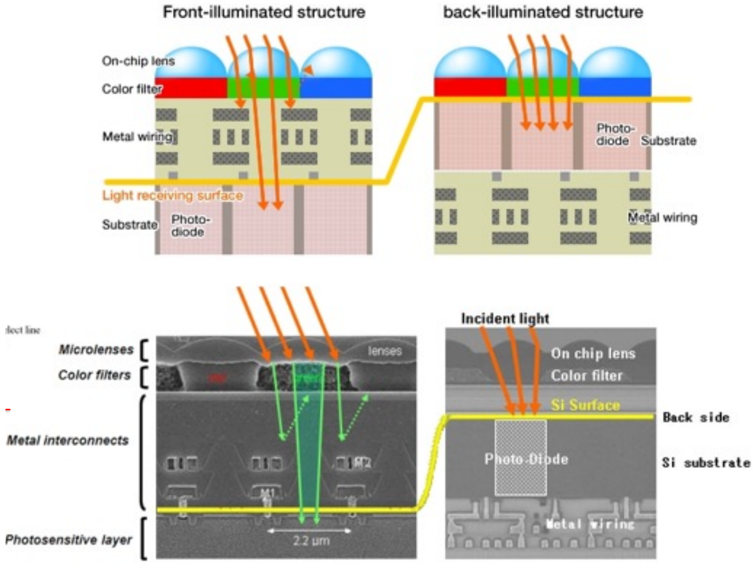
- **fully depleted sensitive volume**
  - fast signal rise time (~ns), small cluster size
- In-house fabrication at MPS Semiconductor Lab
  - **Wafer scale devices possible**
  - **Thinning to (almost) any desired thickness**
  - no stitching, 100% fill factor
- no charge transfer needed
  - faster read out
  - better radiation tolerance
- **Charge collection in "off" state, read out on demand**
  - potentially low power device
- **internal amplification**
  - charge-to-current conversion
  - r/o cap. independent of sensor thickness
  - **Good S/N for thin devices ~40nA/μm for mip**

Used in Belle II experiment

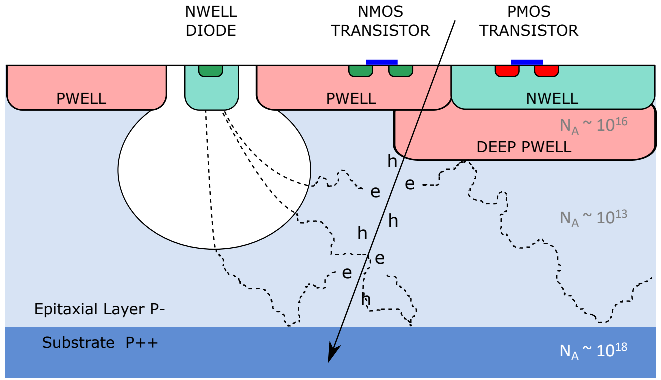
CMOS sensors

- Idea: use the CMOS Image Sensor (CIS) technology for particle detection. Electronics and sensor on the same substrate

Basic CIS technology



CMOS radiation sensor



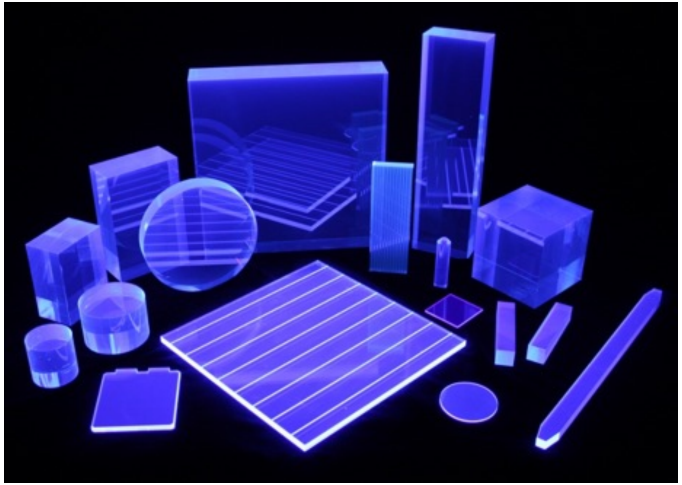
pixel capacitance ≈5 fF (@ V_{bb} = -3 V)

Very active development of many different structures

Scintillators

Scintillators

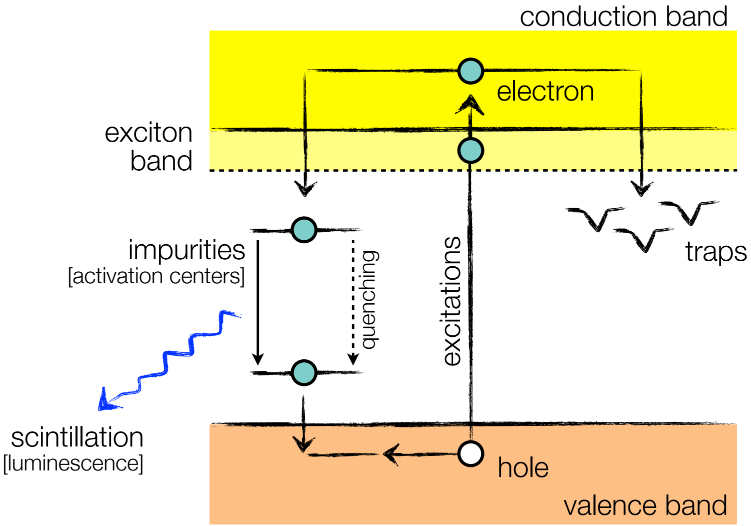
- Principle: released energy converted into light
  - Detection via photosensor for instance photomultipliers.
- Requirements
  - High efficiency for conversion of excitation energy
  - Transparency to allow transmission of light
  - Spectral range detectable by photosensors
  - Short decay time to allow fast response



- Material:
  - Solid or liquid. Typically transparent plastic plates
  - Doped with molecules that emit light (visible or UV) when excited through ionization energy loss. Can be organic or inorganic.
  - Rest of material must be transparent to that wavelength
  - Wavelength shifting technique to avoid re-absorption
- Typically 10k photons/MeV deposited

Inorganic crystals

- Materials:
  - Sodium iodide (NaI)
  - Cesium iodide (CsI)
  - Barium fluoride (BaF_2)
- Mechanism
  - Energy deposition by ionization
  - Energy transfer to impurities
  - Radiation of scintillation photons
- Different time constants
  - Fast: recombination from activation centers [ns … µs]
  - Slow: recombination due to trapping [ms … s]

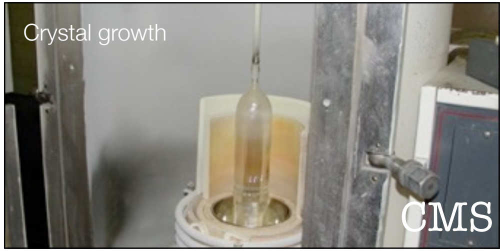


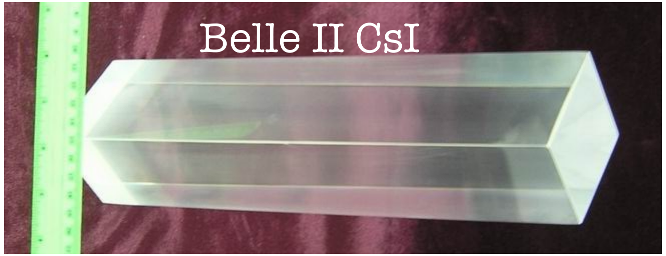
Energy bands in impurity activated crystal

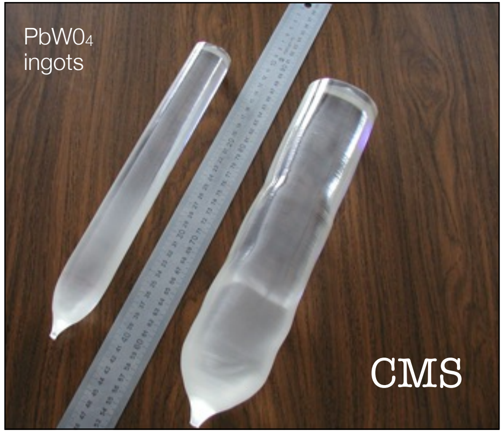
showing excitation, luminescence, quenching and trapping

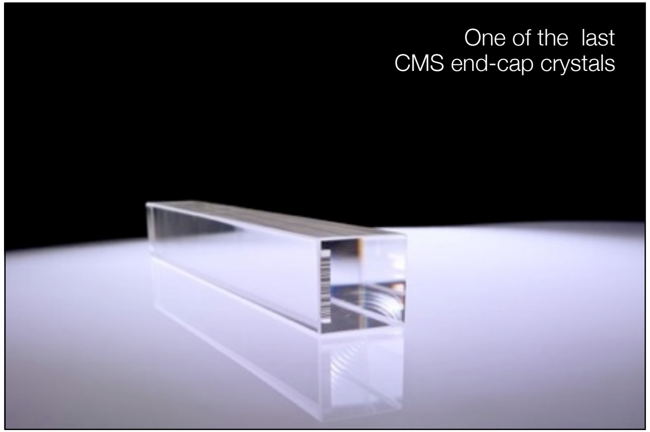
Note: crystal is substantially transparent to the scintillation light

Crystal pictures







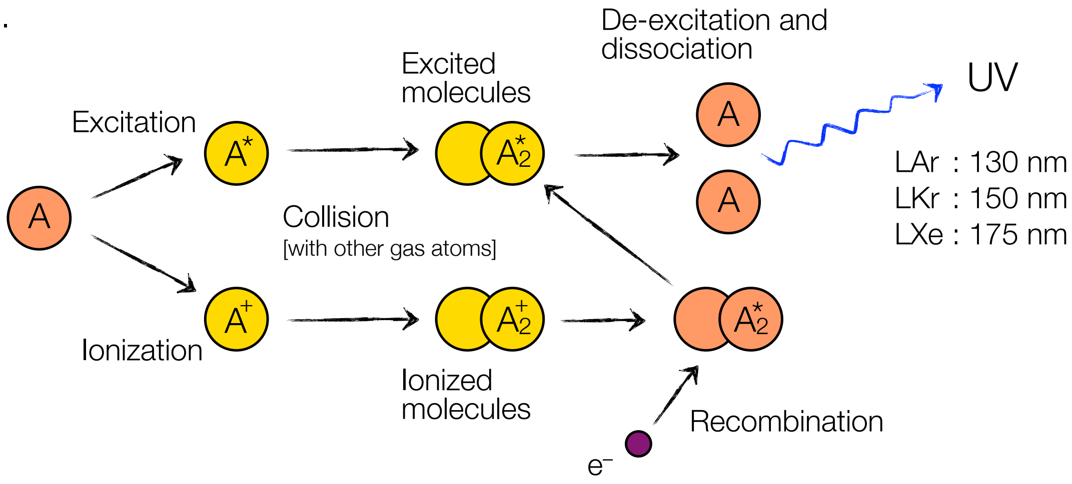


Liquid Nobel Gases

- Materials:
  - Helium (He)
  - Liquid Argon (LAr)
  - Liquid Xenon (LXe)

  …

- Decay time constant
  - Helium: $\tau_1 = 0.02\mu s, \tau_2 = 3\mu s$
  - Argon: $\tau_1 \leq 0.02\mu s$



Note: also in this case material is transparent to the scintillation light

Properties of inorganic scintillators

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29 *	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60 *	150	0.003/0.02	$4 \cdot 10^4$

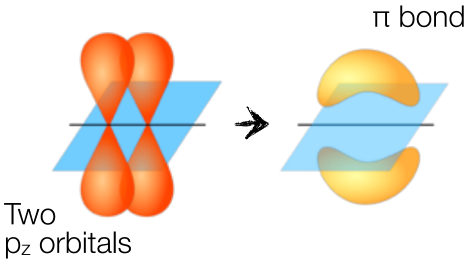
* at 170 nm

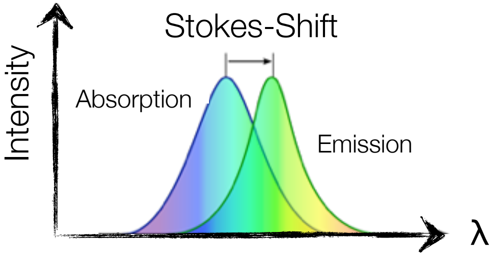
Organic scintillators

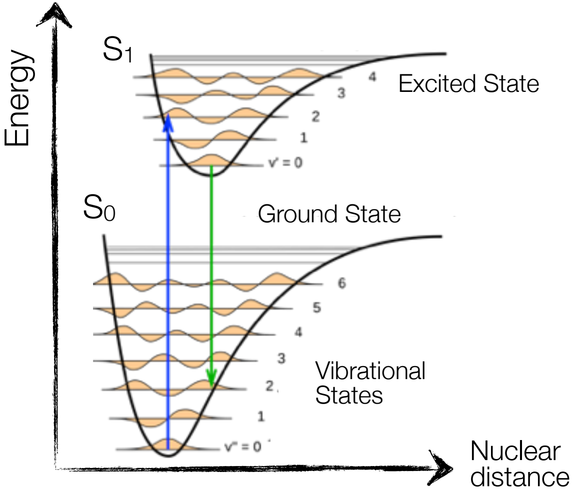
- Materials:
  - aromatic hydrocarbon compounds.
  - Naphtalene $[C_{10}H_8]$
  - Antracene $[C_{14}H_{10}]$
  - Stilbene $[C_{14}H_{12}]$
  - …
- Very fast
  - Decay times of O(ns)
  - Scintillation light arises from delocalized electrons in π-orbitals

Scintillation is based on electrons of the C=C bond …

…







Note: also in this case material is transparent to the scintillation light

Properties of inorganic scintillator

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Photon detection

- Emitted light must be converted into an electronic signal
- Principle: use photo-electric effect to convert photons to photo-electrons (p.e.)
- Requirement:
  - High photon detection efficiency (PDE), also called Quantum Efficiency: $Q.E.=N_{pe}/N_{photons}$
- Example of devices:

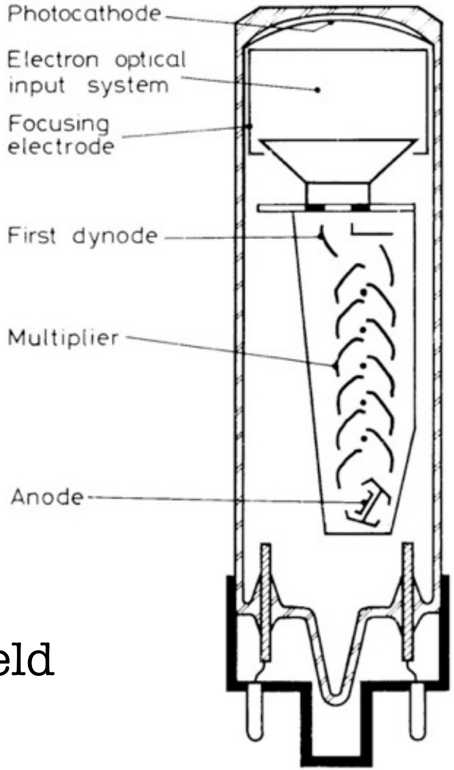
Photomultipliers (PMT)	HybridPhoto Diodes (HPD)
Micro Channel Plates (MCP)	Visible Light Photon Counters (VLPC)
Photo Diodes (PD)	Silicon Photomultipliers (SiPM)

Photomultipliers

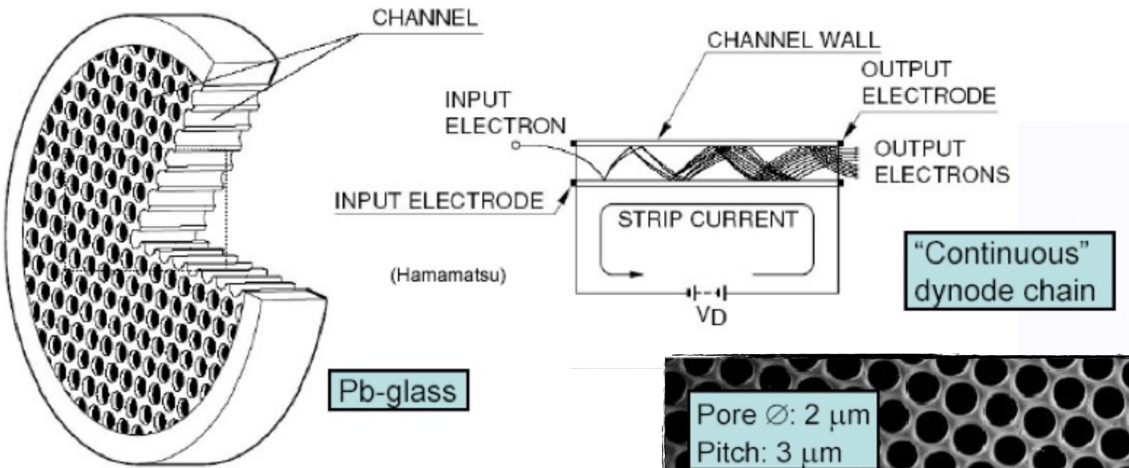
- Principle:
  - Electron emission from photocathode
  - Secondary emission from dynodes
  - Single dynode gain: 3-50
- Typical overall gain > 10^6
  - PMT can see single photons !

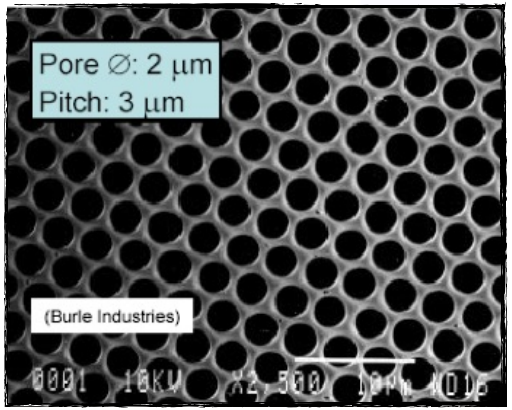
PMT Collection

Sensitive to magnetic field



Micro Channel Plate





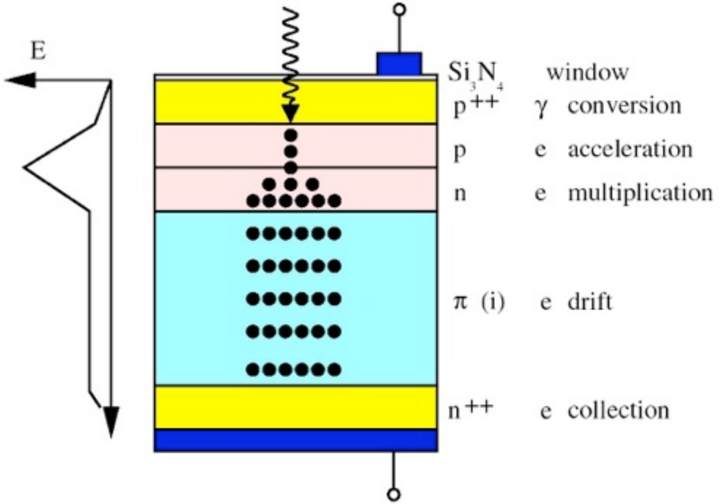
"2D Photomultiplier"

Gain: $5 \cdot 10^4$
Fast signal [time spread ~ 50 ps]
B-Field tolerant [up to 0.1T]

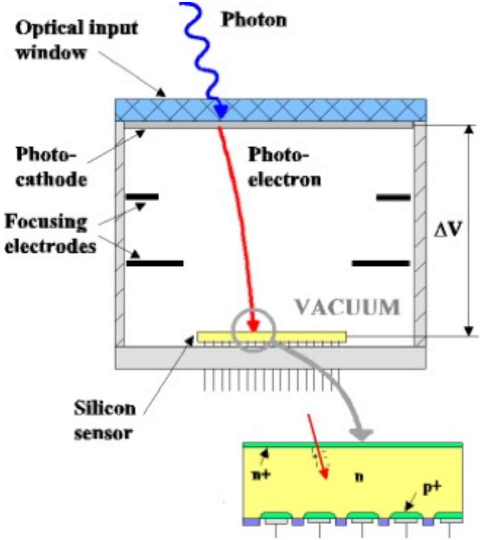
But: limited life time/rate capability

Avalanche and Hybrid Photo Diodes

- Avalanche Photo Diode (APD)
- Reverse voltage (100-500 V) leads to avalanche
- Gain 100-1000

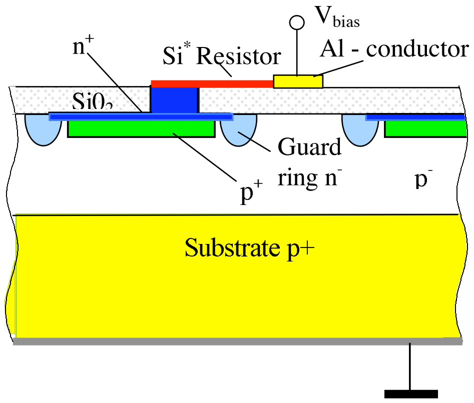


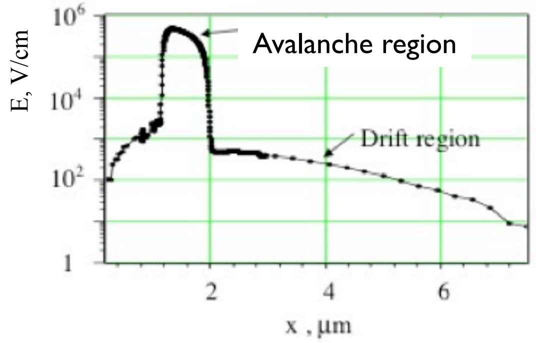
- Hybrid Photo Diodes (HPD)
- Photocathode like in PMT
- Acceleration in vacuum of e⁻ (10-20kV, super high vacuum)
- Silicon detector to measure e⁻



Silicon Photomultipliers

- Principle:
  - Pixelized photo diodes operated in Geiger mode
  - Single pixel works as a binary device
  - Energy = #photons seen by summing over all pixels
- Features:
  - Granularity : 10^3 pixels/mm2
  - Gain : 10^6
  - Bias voltage : < 100 V
  - Efficiency : ca. 30%
- Insensitive to magnetic field





Comparison of photo detectors

	PMT	APD	HPD	SiPM
Photon detection efficiency:				
blue	20%	50%	20%	12%
green - yellow	a few %	60-70%	a few %	15%
red	<1%	80%	<1%	15%
Gain	10^6-10^7	100-200	10^3	10^6
High voltage	1-2 kV	100-500 V	20 kV	25 V
Operation in the magnetic field	problematic	OK	OK	OK
Threshold sensitivity S/N≫1	1 ph.e.	~10 ph.e.	1 ph.e.	1 ph.e.
Timing /10 ph.e.	~100 ps	a few ns	~100 ps	30 ps
Dynamic range	$\sim10^6$	large	large	$\sim10^3/\text{mm}^2$
Complexity	high (vacuum, HV)	medium (low noise electronics)	very high (hybrid technology, very HV)	relatively low

Take away message

- Ionization charge can be readout with an electric field
- Gas, liquid, solid materials can be used, as long as charge can be collected
- Photons must be converted to electrical signal to be recorded.
- Detector technologies are many, and complex, taking advantage of often sophisticated chemical and physical mechanisms.

End of Part 02