Semiconductor Detectors
(Solid State Detectors)

energy, position
particles & photons

↓

energy loss

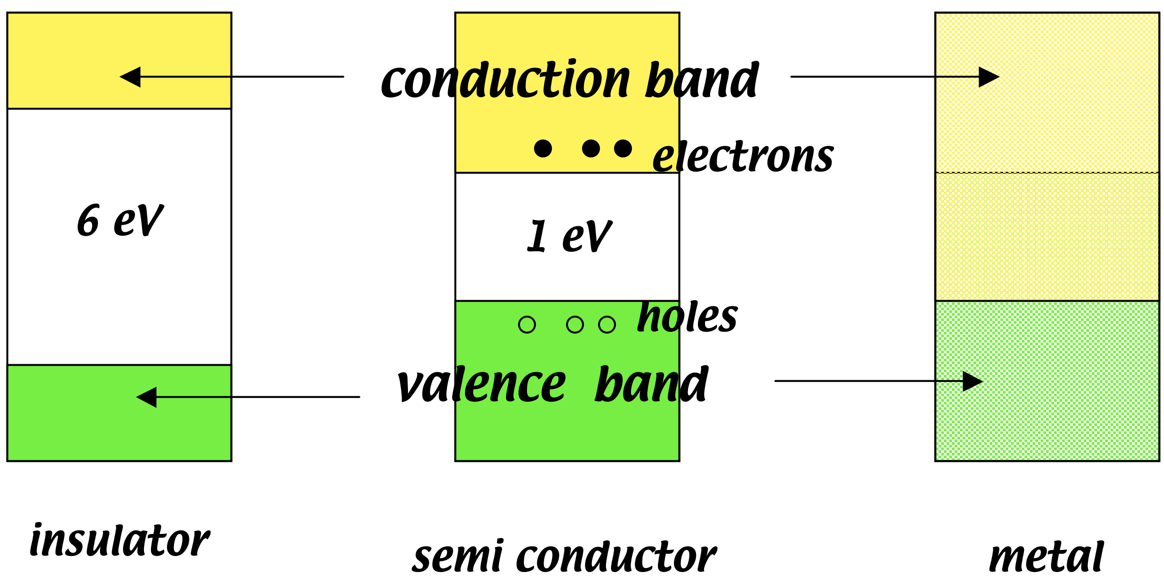
↓

conversion
electron-hole pairs

↓

energetic “cheap”
improved resolution

Semiconductor Detectors
(Solid State Detectors)

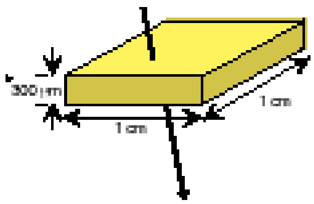


$$n_i = \sqrt{N_c N_v}\,\exp\left(-\frac{E_g}{2kT}\right) = AT^{3/2}\exp\left(-\frac{E_g}{2kT}\right)$$

$N_{C,v}$	number of states conduction,valence band
E_g	gap at 0 K
A	constant independent from T

for pure Si: $n_i = 1.45 \times 10^{10}\ cm^{-3}$

Semiconductor Detectors
how to get a signal ?



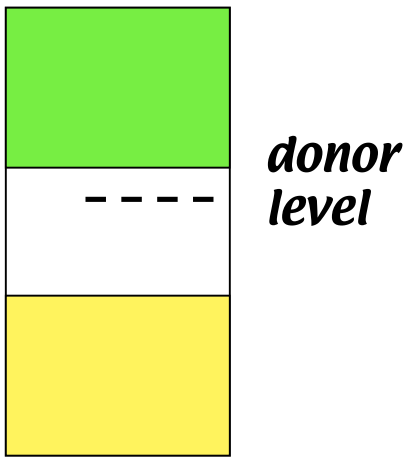
particle passing through
a thin layer of Si:
300 m

mimimum ionizing particle will produce:
about $3.2x10^4$ e-h pairs

but $4.5x10^8$ free charge carriers in the same volume !

reduce number of free charge carriers,
i.e. deplete material !

Semiconductor Detectors
"doped" n-type



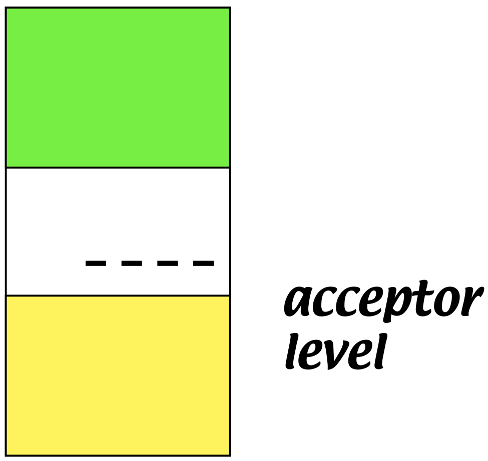
n-type
+ e^-

add donor elements: V^{th} group elements like P, As, Sb

extra electrons resides at discrete energy level in the energy gap, close to the CB (separated 0.01 - 0.05 eV)

conductivity enhanced by electrons
=> n-type semiconductors

Semiconductor Detectors
"doped" p-type



p-type
+ holes

add acceptor elements: IIIrd group elements like Ga, B, In

extra electron states close to the VB, electrons easily excited into these states, creating hole states in the VB.

conductivity enhanced by holes states
=> p-type semiconductors

Semiconductor Detectors
"doped"

Typical doping levels for detector silicon:

10^{12} atoms/cm^{-3}

which has to be compared with
10^{22} atoms/cm^{-3} density Ge & Si

heavily doped semiconductors:
("+" sign after the material)

10^{20} atoms/cm^{-3}

Semiconductor Detectors
Si, characteristics

band gap: Eg =1.12 V.

E(e^--hole pair) = 3.6 eV
(~30 eV for gas detectors)

high specific density (2.33 g/cm^3)

ΔE/track length
for M.I.P.'s.: 390 eV/mm, ~108 e-h/ μm (average)

high mobility
m_e=1450 cm^2/Vs, m_h = 450 cm^2/Vs

small dimensions
fast charge collection (<10 ns)

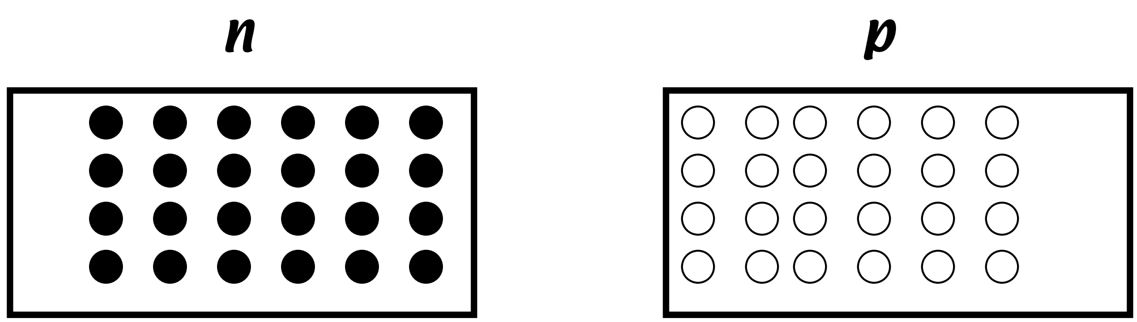
rigidity of silicon
thin self supporting structures
typical thickness 300 μm
~3.2 x10^4 e-h (average)

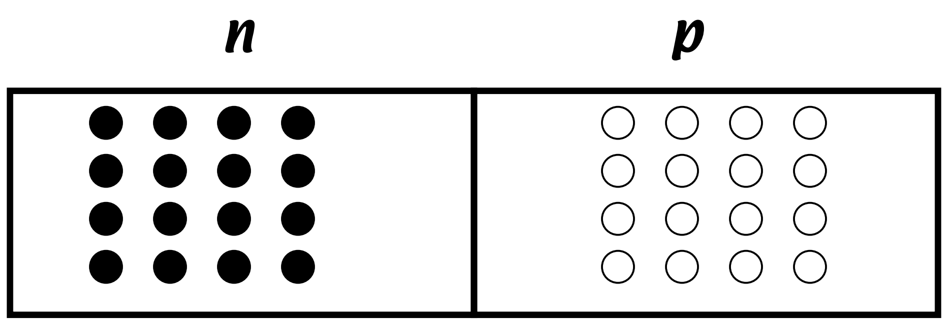
PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 (269, 273)	111 (272)	112 (277)						

Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)

Semiconductor Detectors
"np-junction"





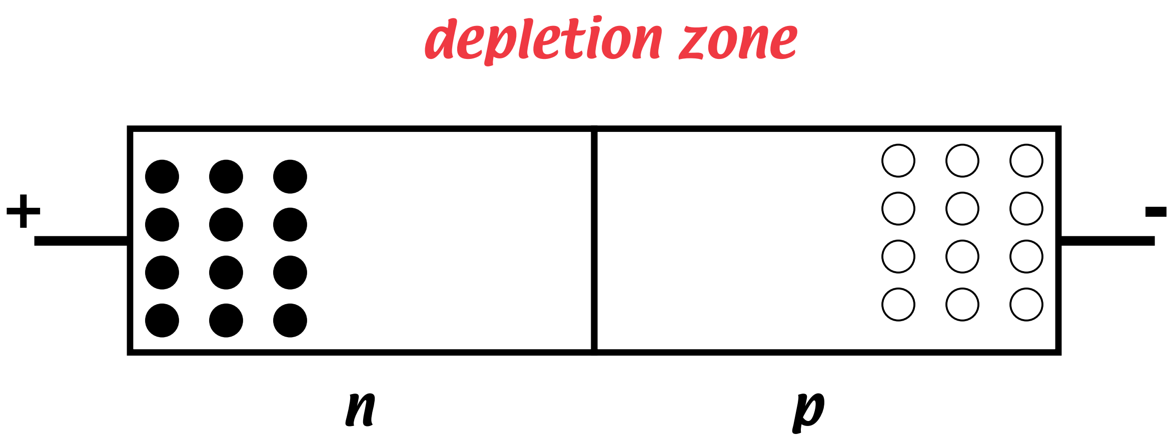
initial diffusion:
holes -> n-region, electrons -> p-region

charge building up:
n-region-> positive, p-region -> negative

emerging electric field (contact potential)
stops diffusion

region of changing potential:
depletion zone, space charge region

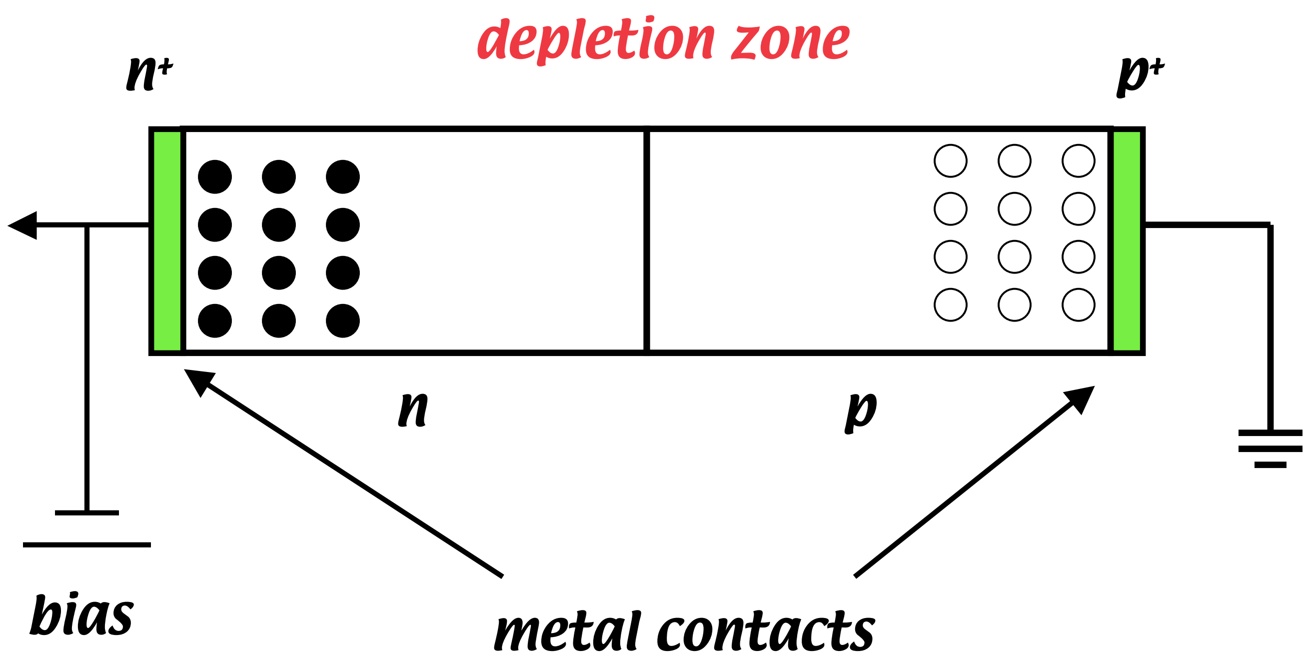
Semiconductor Detectors
increasing depletion



reversed bias junction
(bias voltage about 100 V)
apply negative voltage to p-side
-> attract holes
apply positive voltage to n-side
-> attract electrons

-> increase depletion zone

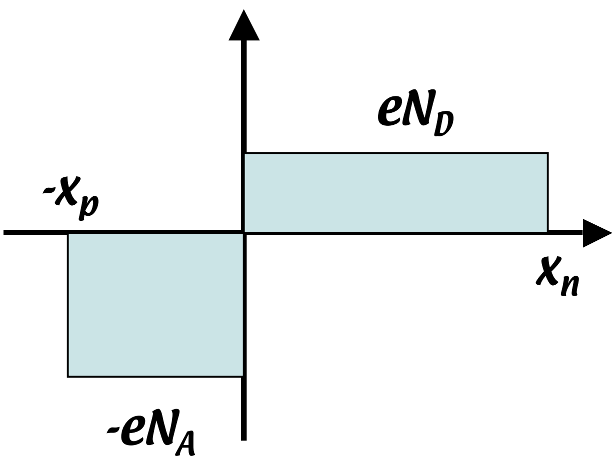
Semiconductor Detectors signal read out

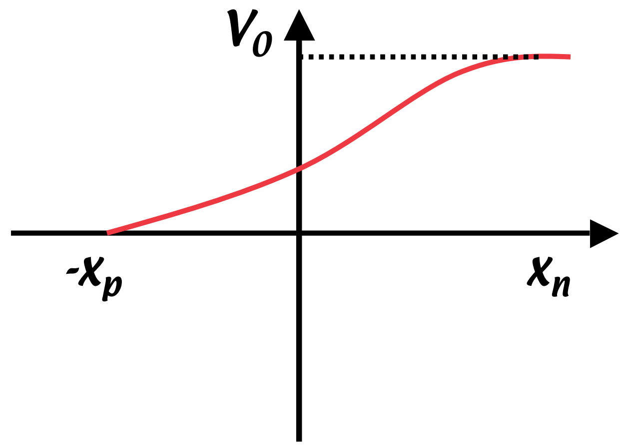


to prevent depletion zone between metal and semi conductor
-> layer of highly doped material

Semiconductor Detectors characteristics

depletion depth





Poissons' s equation : $$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

charge density : $$\rho(x) = eN_D \qquad 0 < x < x_n$$
$$= -eN_A \qquad -x_p < x < 0$$

charge conservation : $$N_A x_p = N_D x_n$$

Semiconductor Detectors characteristics

depletion depth d

integration yields V(x):

$$0 < x < x_n$$

$$V(x) = -\frac{eN_D}{\varepsilon}\left(\frac{x^2}{2} - x_n x\right) + C$$

$$-x_p < x < 0$$

$$V(x) = \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + x_p x\right) + C'$$

matching at x = 0 =>

$$C = C'$$

$$C = \frac{eN_A}{2\varepsilon} x_p^2$$

Semiconductor Detectors characteristics

depletion depth d

integration yields contact potential $V(x_n)=V_0$:

$$V_0 = \frac{e}{2\varepsilon}\left(N_D x_n^2 + N_A x_p^2\right)$$

and

$$x_n = \sqrt{\frac{2\varepsilon V_0}{eN_D\left(1 + N_D / N_A\right)}}$$

$$x_p = \sqrt{\frac{2\varepsilon V_0}{eN_A\left(1 + N_A / N_D\right)}}$$

depletion zone extends farther into the lighter-doped side

Semiconductor Detectors characteristics

depletion depth d

under assumption $N_A >> N_D$:

$$d = x_n + x_p \approx \sqrt{\frac{2\varepsilon V_0}{eN_D}}$$

resistivity of n-type material:

$$\rho_n \approx \frac{1}{eN_D \mu_e}$$

μ_e ***electron mobility*** $[cm^2/Vs]$

$$d \approx \sqrt{2\varepsilon \rho_n \mu_e V_0}$$

Semiconductor Detectors characteristics “an application”

Assume □=20 k□ cm for heavily doped n-type Si and

V_0=100 V. The dielectric constant □/$□_0$=12
and
$□_e$ (300K)=1350 cm^2/Vs.

How thick is the depletion zone ?

Semiconductor Detectors characteristics

junction capacitance

for planar geometry:

$$C = \varepsilon \frac{A}{d}$$

for $N_D >> N_A$ or $N_A >> N_D$, respectively

Si:

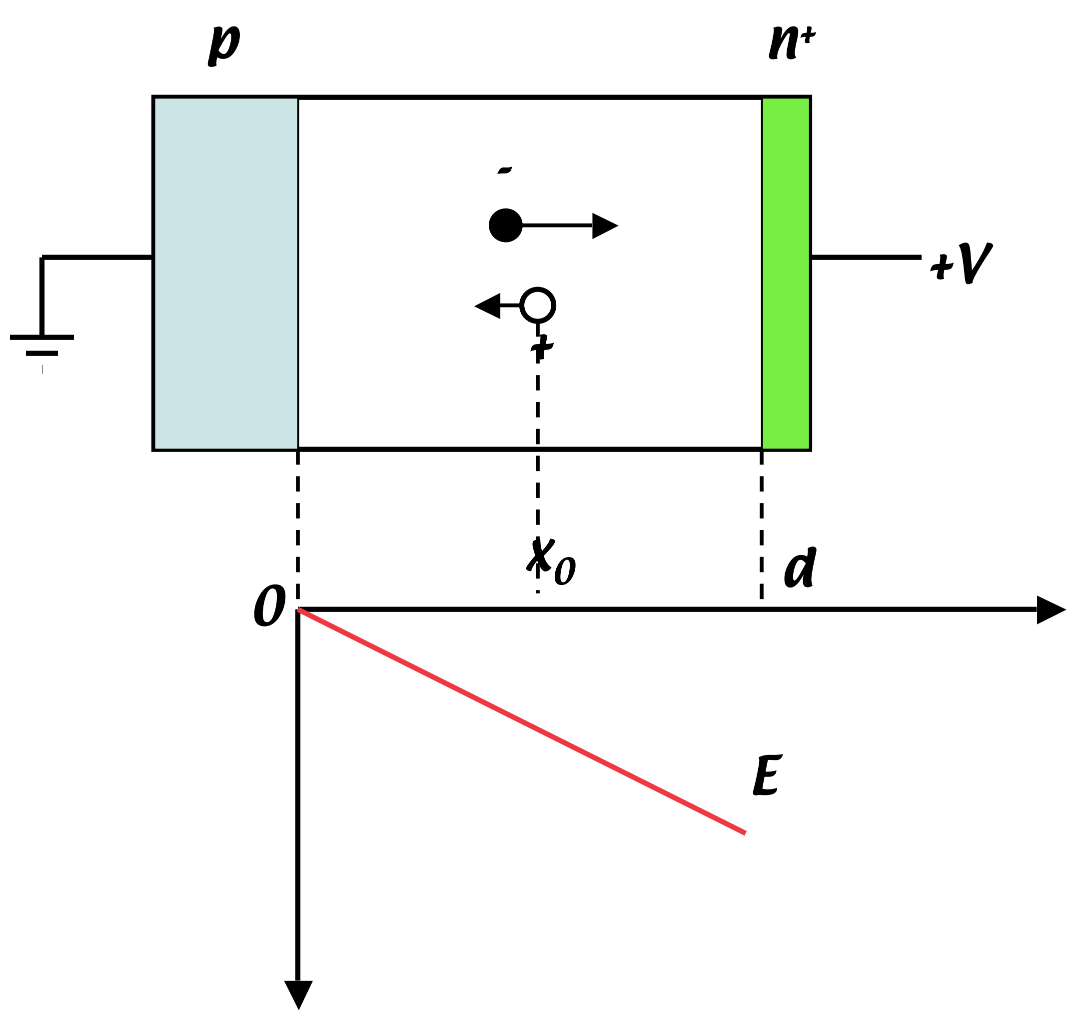
$$C/A = \frac{2.2}{\sqrt{\rho_N V_0}}\, pF/mm^2 \qquad \textbf{n - type}$$

$$C/A = \frac{3.7}{\sqrt{\rho_N V_0}}\, pF/mm^2 \qquad \textbf{p - type}$$

Semiconductor Detectors characteristics

pulse shape, rise time
charge collection time

for planar geometry, heavily doped p-type



Semiconductor Detectors characteristics

pulse shape, rise time
charge collection time

for planar geometry, heavily doped p-type:

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

integration of Poisson' s equation :

$$\frac{dV}{dx} = E = -\frac{eN_A}{\varepsilon}x = -\frac{x}{\mu_h \tau}$$

$\tau = \varepsilon\rho$ ***with*** $1/\rho = eN_A\mu_h$

Semiconductor Detectors characteristics

$$v_e = \frac{dx_e}{dt} = \square\square_e E = \frac{\square_e}{\square_h}\frac{x}{\square}$$

if mobility independent of E

$$x_e(t) = x_0 \exp\left(\frac{\square_e t}{\square_h \square}\right)$$

electron reaches eletrode at x = d :

$$t = \square\frac{\square_h}{\square_e}\ln\frac{d}{x_0}$$

Semiconductor Detectors characteristics

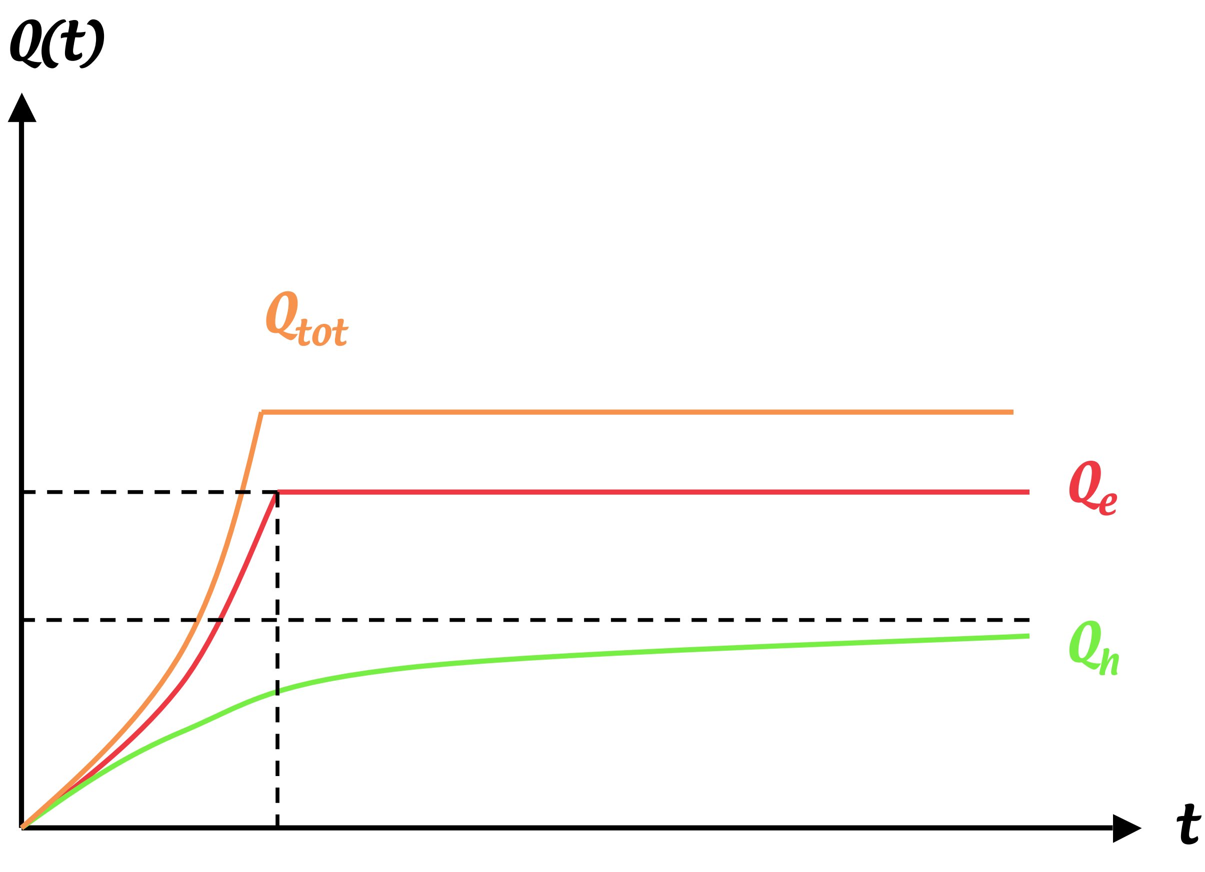
$$Q_e(t) = -\int \frac{e}{d}\,\frac{dx}{dt}\,dt = \frac{e}{d}x_0\left[1-\exp\left(\frac{\mu_e t}{\tau_h}\right)\right]$$

analogue for holes, with

$$v_h = \mu_h E = -\frac{x}{\tau}$$

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

Semiconductor Detectors characteristics



Semiconductor Detectors characteristics "an application"

Estimate the rise time of the solid state detector discussed above !