INFN SoUP 20|21

The 1st INFN School on Underground Physics: Theory & Experiments

INFN

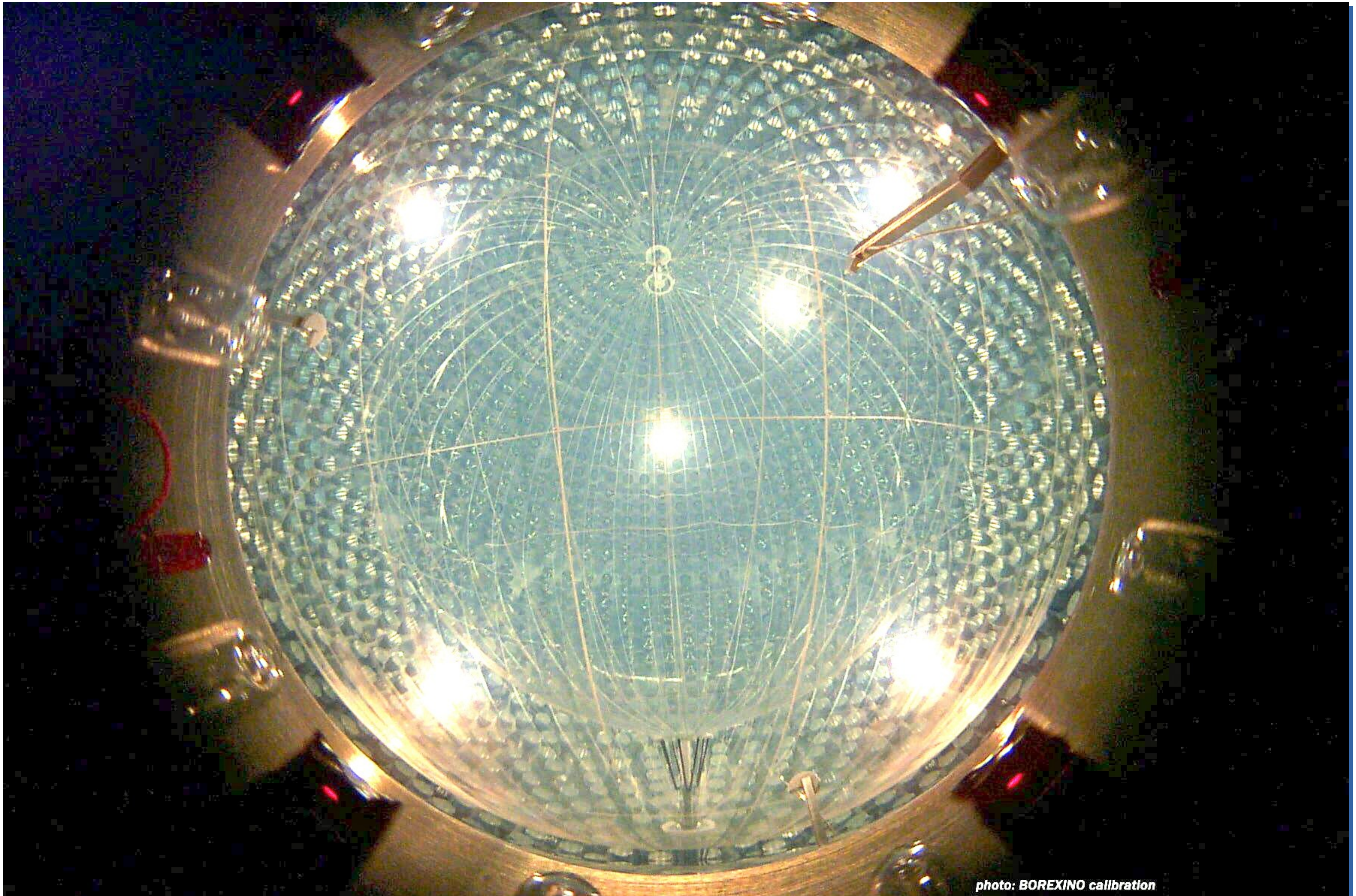

photo: BOREXINO calibration

Semiconductor Detectors

Alessandro Razeto
Laboratori Nazionali del Gran Sasso

photo: BOREXINO calibration

References

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- Radiation Detection & Measurement – G. Knoll
- Solid State Physics – A. Mermin
  - Chapter 8-9 & 28
- http://ecee.colorado.edu/~bart/book/book/contents.htm
  - Chapter 2 & 4
- http://www.ioffe.ru/SVA/NSM/Semicond/ ← tables of semiconductor properties
- https://www-physics.lbl.gov/~spieler/
  - Semiconductor Detector Systems – H. Spieler
- Semiconductor Radiation Detectors – G. Lutz
- Passage of Particles Through Matter

DETECT RESIST

INFN LNGS

Detection of physical quantities

- Light
- Particles
- Sound
- Humidity
- Accelerations
- Temperature

Detection of physical quantities

- Light
- Particles
- Sound
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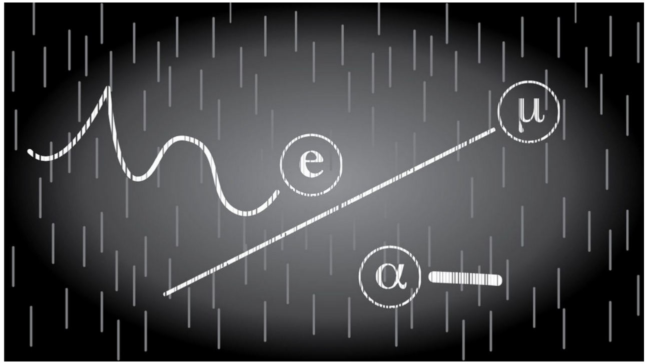
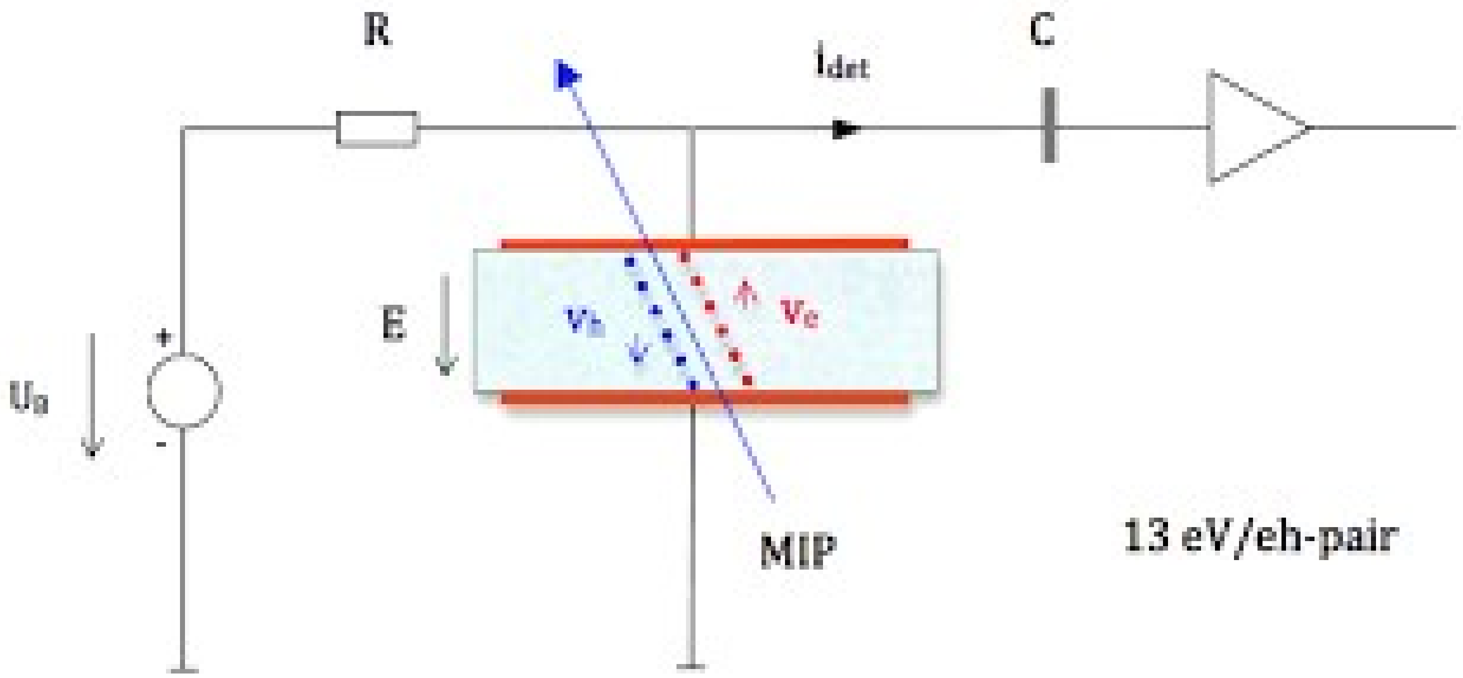
- Temperature

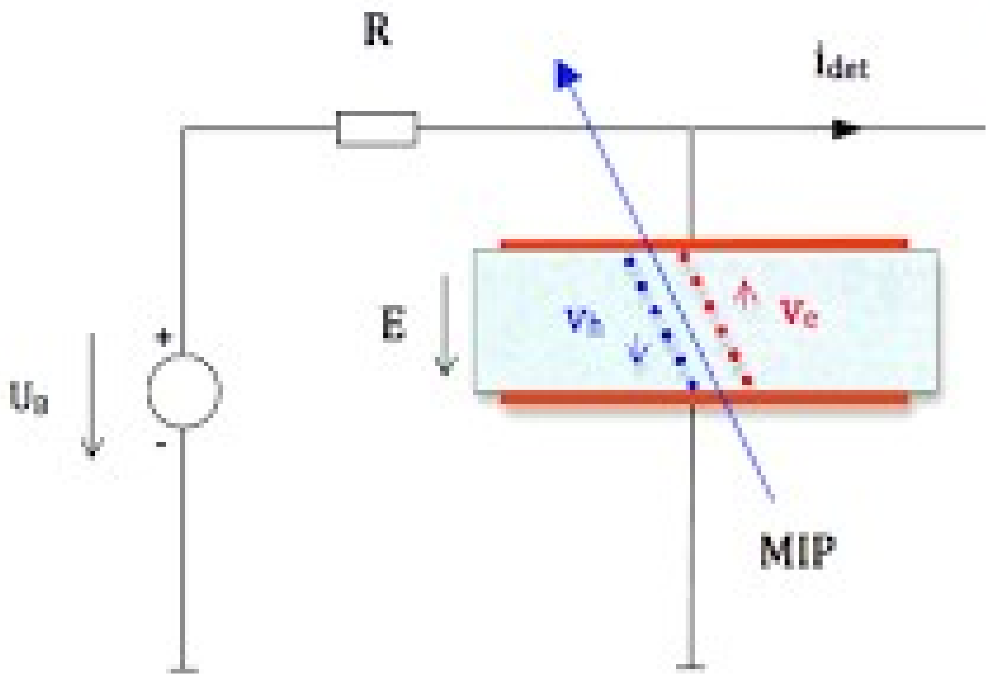


Base design



13 eV/eh-pair

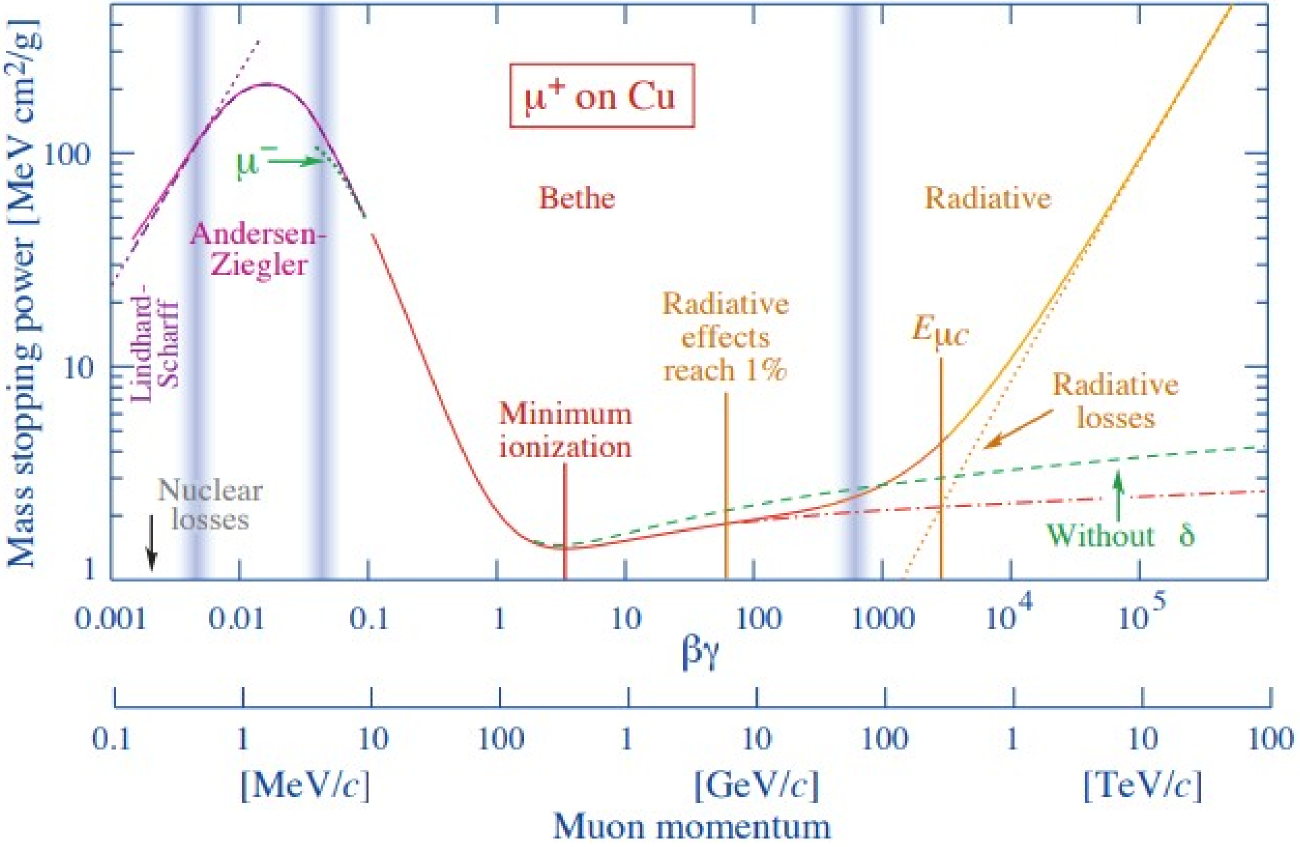
Base design



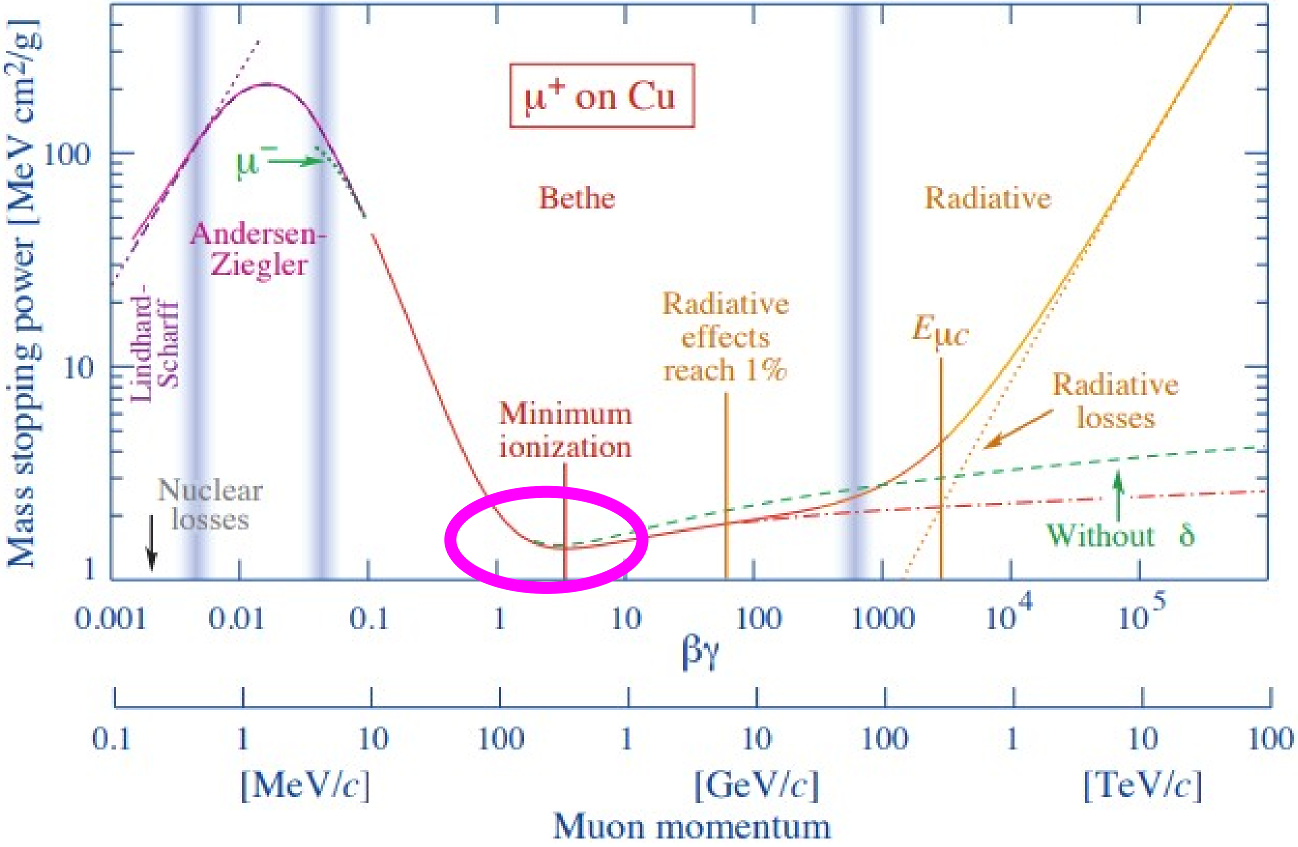
- Non conductive target + field
- A particle releases charge
- The charge is drifted
  - Amplified and acquired

- Leakage is the current with no particle
  - Leakage << signal

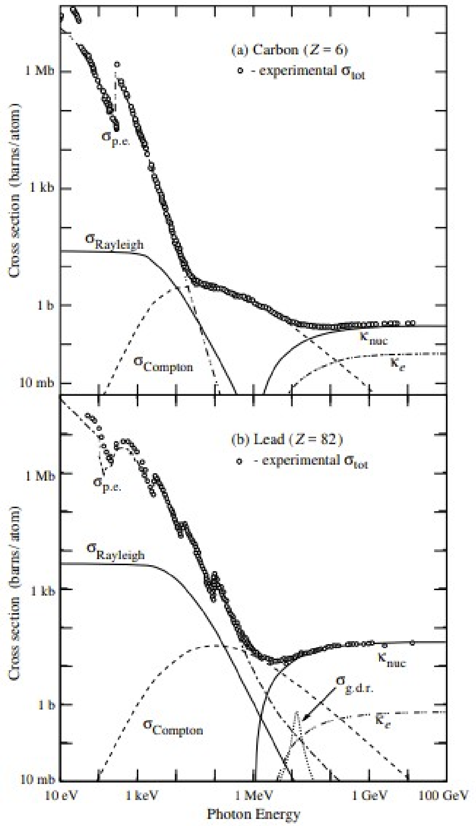
Interaction with matter

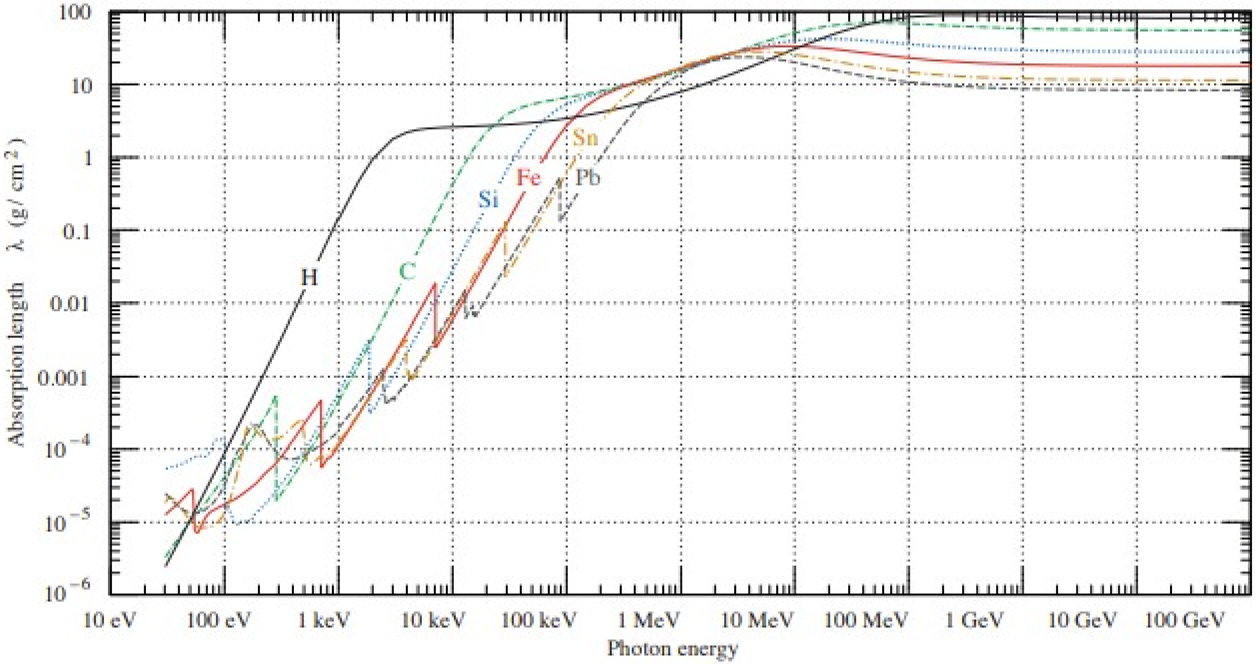


Interaction with matter



Photon in matter





Target

- Non conductive
  - Diamond
  - Selenium
  - Other high purity crystals
  - Silicon & Germanium
- High mobility of carriers
  - High carrier lifetime

Target

- Non conductive
  - Diamond
  - Selenium
  - Other high purity crystals
  - ~~Silicon & Germanium~~ ← High resistivity 10 kΩ/cm (50 Ω/cm)
- High mobility of carriers
  - High carrier lifetime

Target

- Non conductive
  - Diamond
  - Selenium
  - Other high purity crystals
  - ~~Silicon & Germanium~~
- High mobility of carriers
  - High carrier lifetime

Sat. velocity: 10 cm/μs
Lifetime: few ns
→ thickness sub-mm

Target

- Non conductive
  - Diamond
  - Selenium
  - Other high purity crystals
  - ~~Silicon & Germanium~~
- High mobility of carriers
  - High carrier lifetime

Sat. velocity: 10 cm/μs
Lifetime: few ns
→ thickness sub-mm

Sat. velocity: 1 cm/μs
Lifetime: few μs
→ thickness sub-cm

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DETECT RESIST

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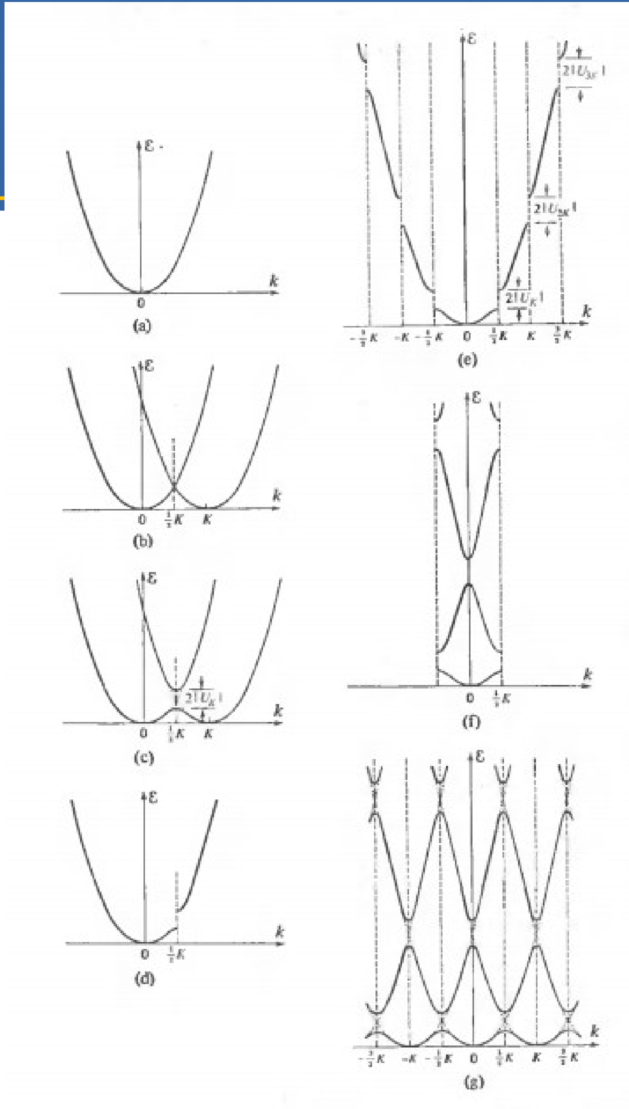
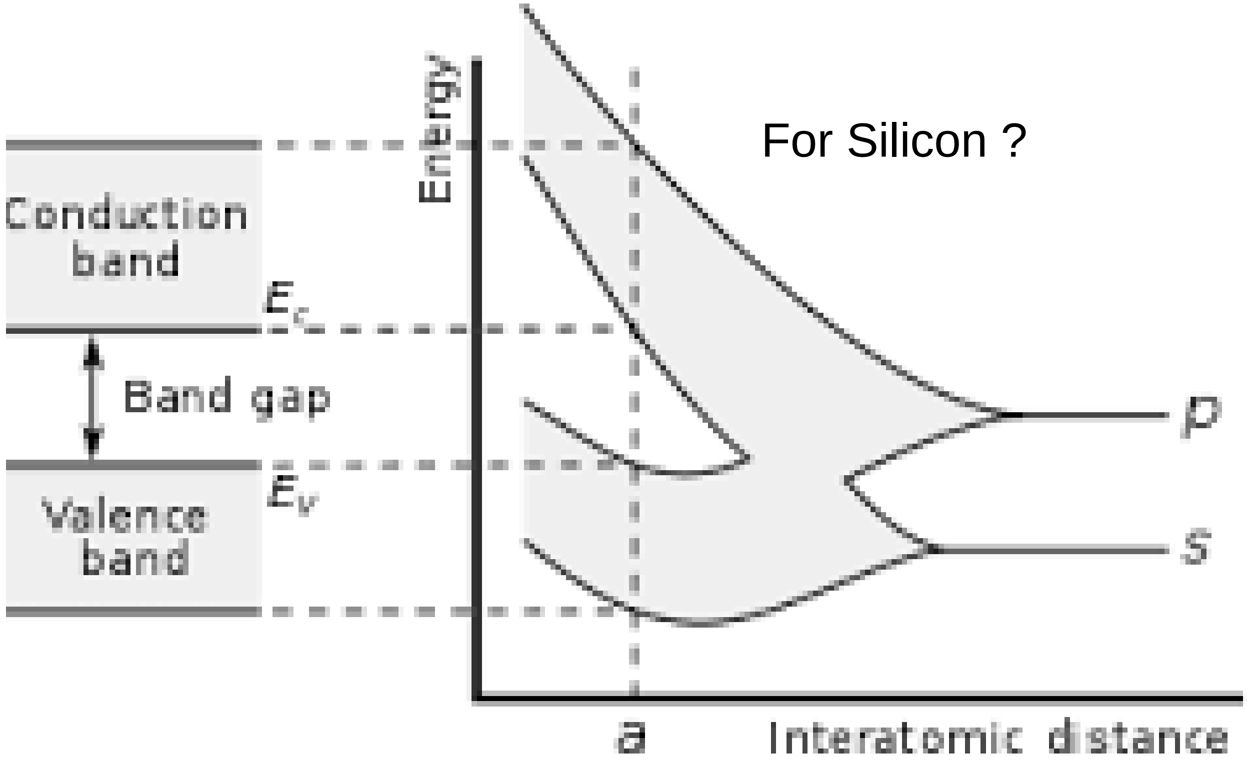
Band structure



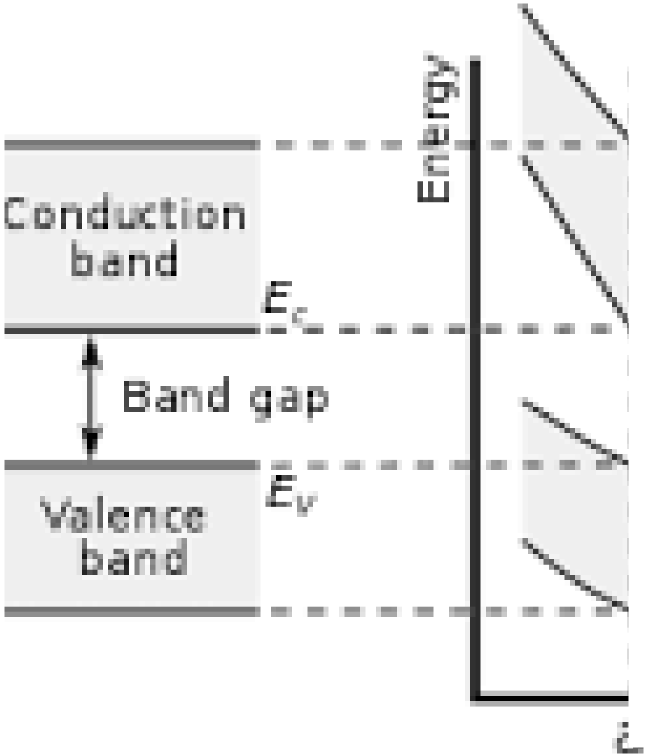
- Simple model with atoms connected by springs
- Periodicity implies the band structure

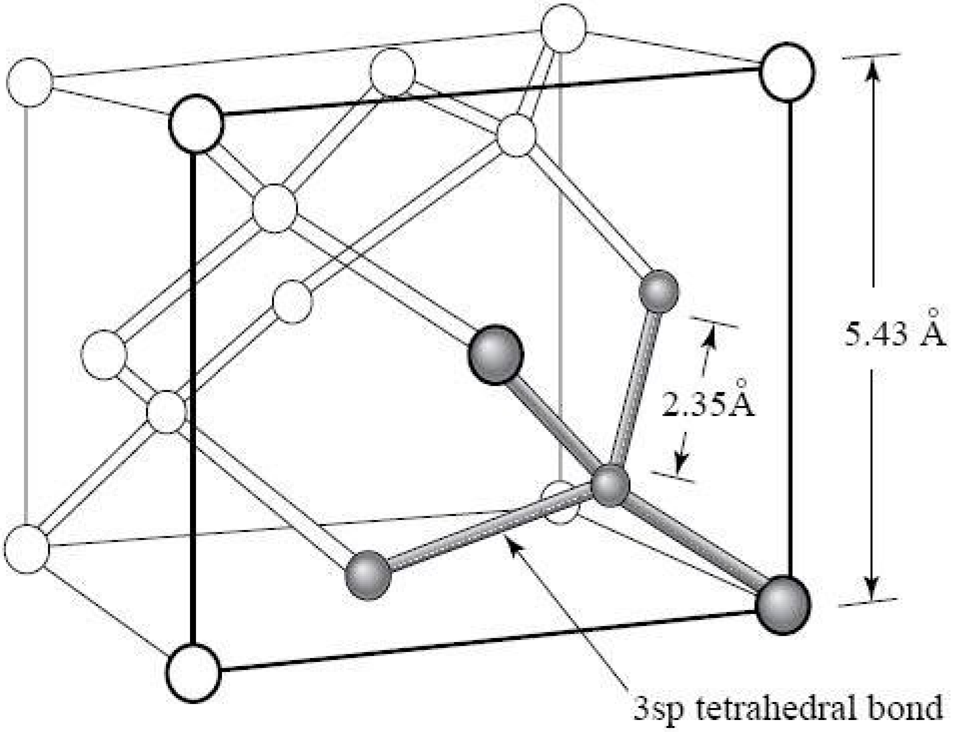
Band structure



For Silicon ?

Band structure





Semiconductors

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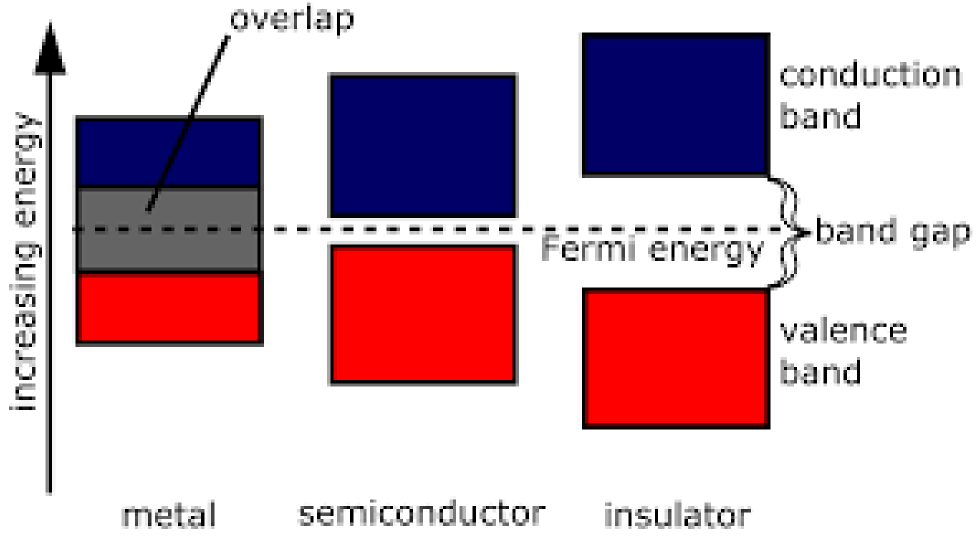
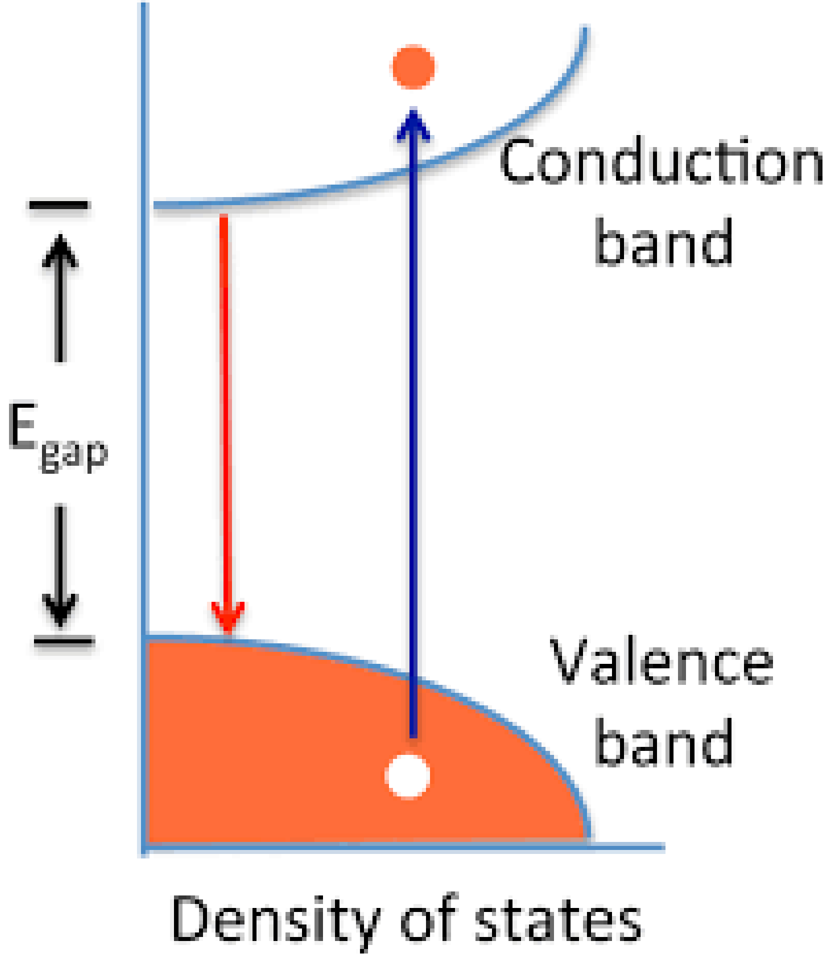


- The band gap has to be compared with the $k_B T$
  - 1/40 eV at 300 K
  - Si 1.1 eV
  - Ge 0.6 eV
  - Diamond 5.5 eV
- Typ. the band-gap $\propto$ -T
  - Increasing lattice spacing

Carriers for semi-conductors



- At T << E_g/k_B all electrons are in the valence band
  - No conduction at all
- For T < E_g/k_B electrons can jump to the conduction band
  - Creating a hole in the valence band ← hole
- For intrinsic semiconductors **$n_h = n_e := n_i$**

Carriers for semiconductors

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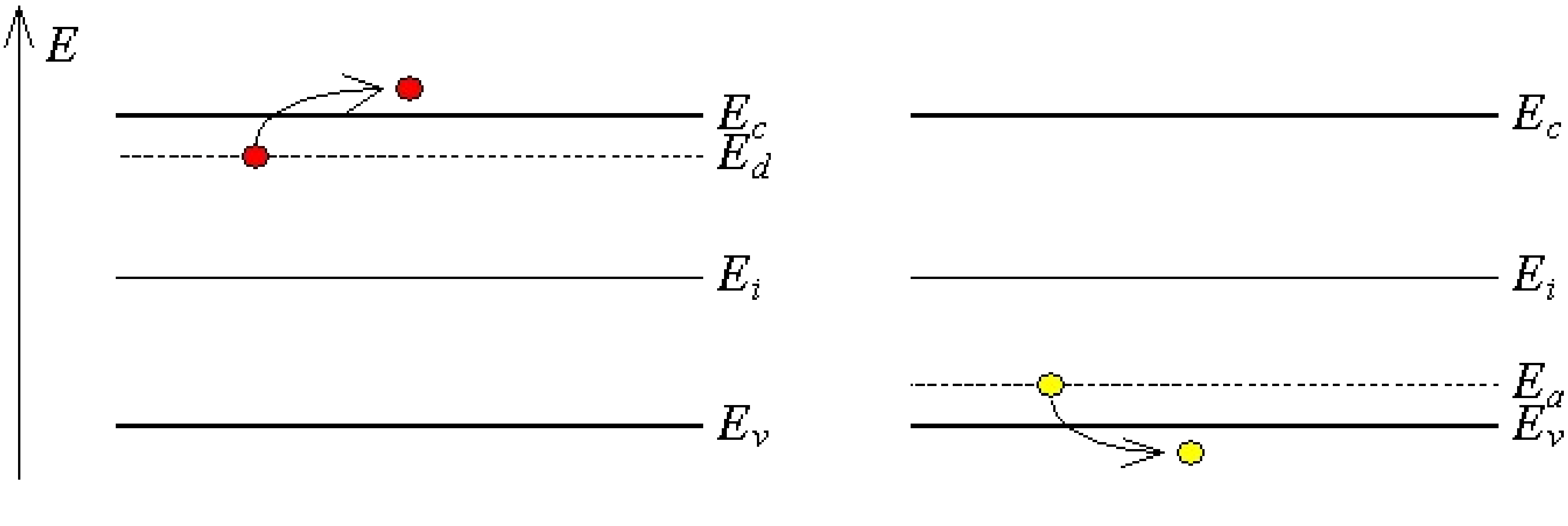
$$n_i(T) = \frac{1}{4}\left(\frac{2k_BT}{\pi\hbar^2}\right)^{3/2}(m_c m_v)^{3/4} e^{-E_g/2k_BT}$$
$$= 2.5\left(\frac{m_c}{m}\right)^{3/4}\left(\frac{m_v}{m}\right)^{3/4}\left(\frac{T}{300\ \mathrm{K}}\right)^{3/2} e^{-E_g/2k_BT} \times 10^{19}/\mathrm{cm}^3.$$

For intrinsic semiconductors

For Si ~ 10^{10} /cm^3
For Ge ~ 10^{13} /cm^3

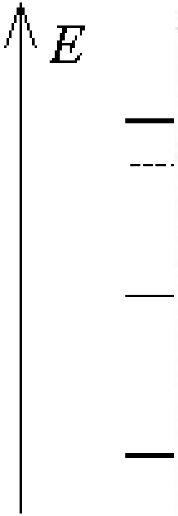
$$n_c p_v = N_c P_v e^{-(\varepsilon_c - \varepsilon_v)/k_BT}$$
$$= N_c P_v e^{-E_g/k_BT}.$$

Dopants

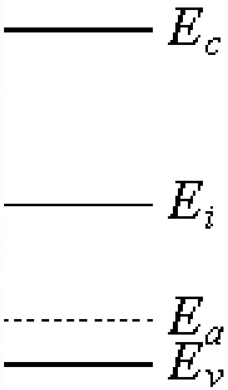


(a) (b)

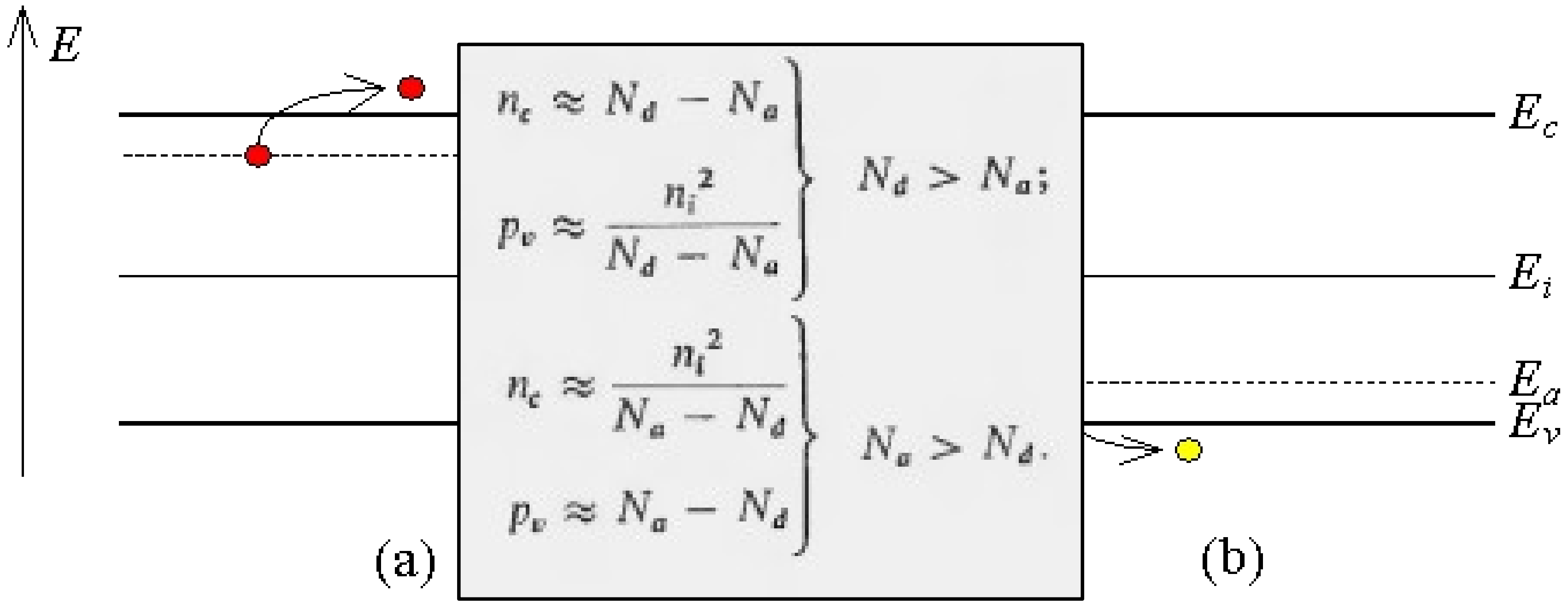
Dopants



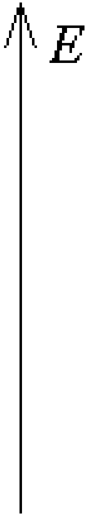
GROUP III ACCEPTORS (TABLE ENTRY IS $\mathcal{E}_a - \mathcal{E}_v$)					
	B	Al	Ga	In	Tl
Si	0.046 eV	0.057	0.065	0.16	0.26
Ge	0.0104	0.0102	0.0108	0.0112	0.01
GROUP V DONORS (TABLE ENTRY IS $\mathcal{E}_c - \mathcal{E}_d$)					
	P	As	Sb	Bi	
Si	0.044 eV	0.049	0.039	0.069	
Ge	0.0120	0.0127	0.0096	—	
ROOM TEMPERATURE ENERGY GAPS ($E_g = \mathcal{E}_c - \mathcal{E}_v$)					
Si	1.12 eV				
Ge	0.67 eV				



Dopants


E
$n_c \approx N_d - N_a$
$p_v \approx \frac{n_i^2}{N_d - N_a}$
$N_d > N_a;$
$n_c \approx \frac{n_i^2}{N_a - N_d}$
$p_v \approx N_a - N_d$
$N_a > N_d.$
E_c
E_i
E_a
E_v
(a)
(b)

Dopants



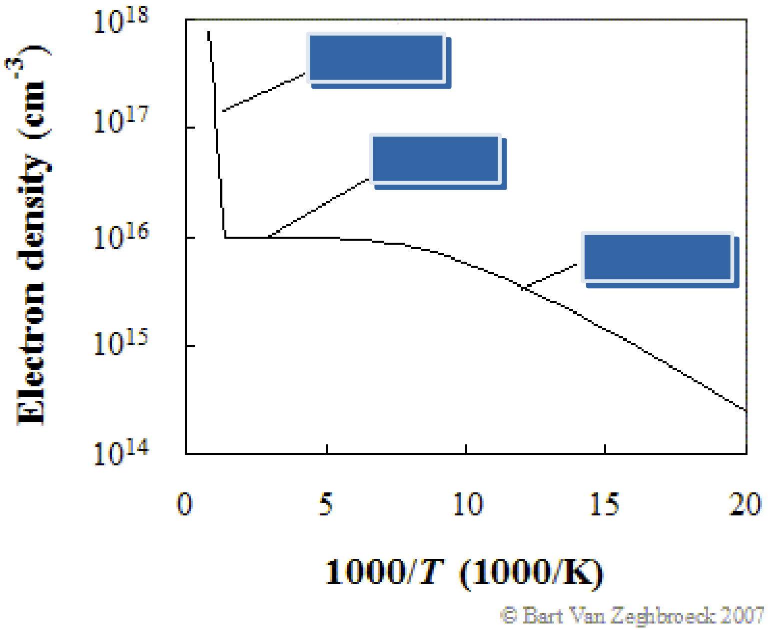
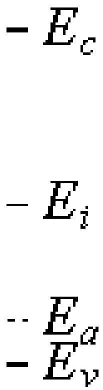
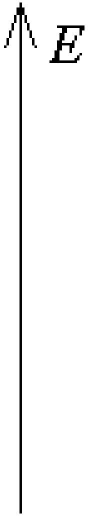
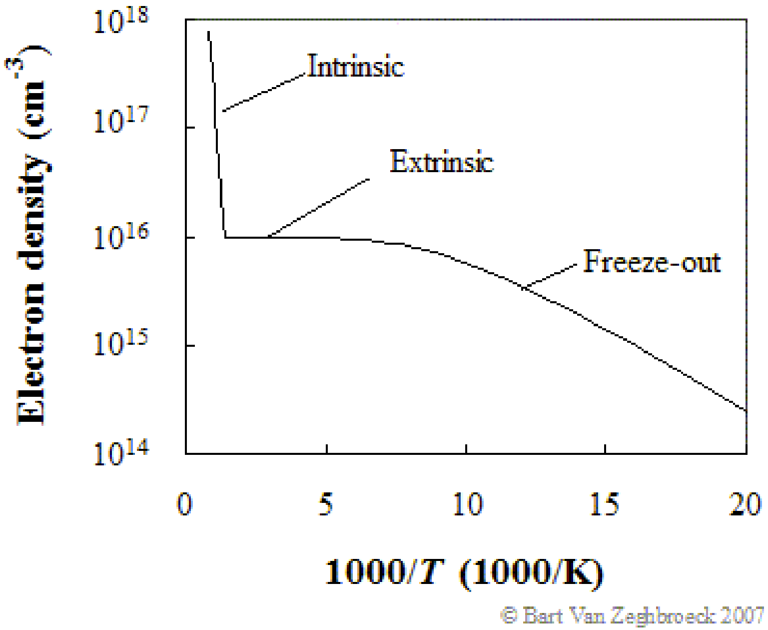


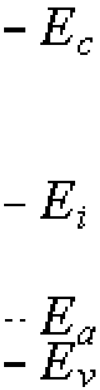
Figure 2.6.9: Electron density and Fermi energy as a function of temperature in silicon with $N_d = 10^{16}$ cm^{-3}, $N_a = 10^{14}$ cm^{-3} and $E_c - E_d = E_a - E_v = 50$ meV. The activation energy at 70 K equals 27.4 meV.



Dopants







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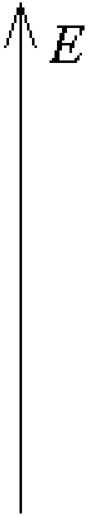

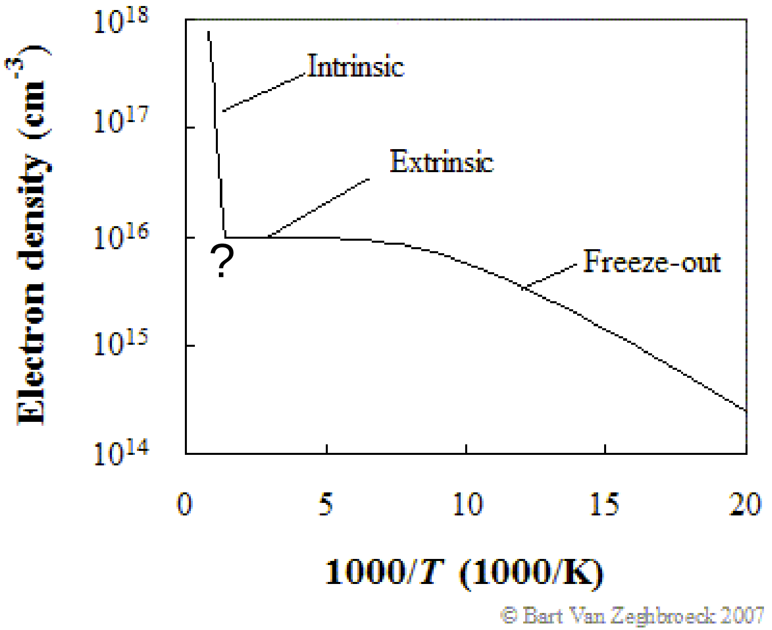

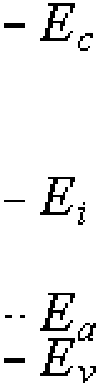

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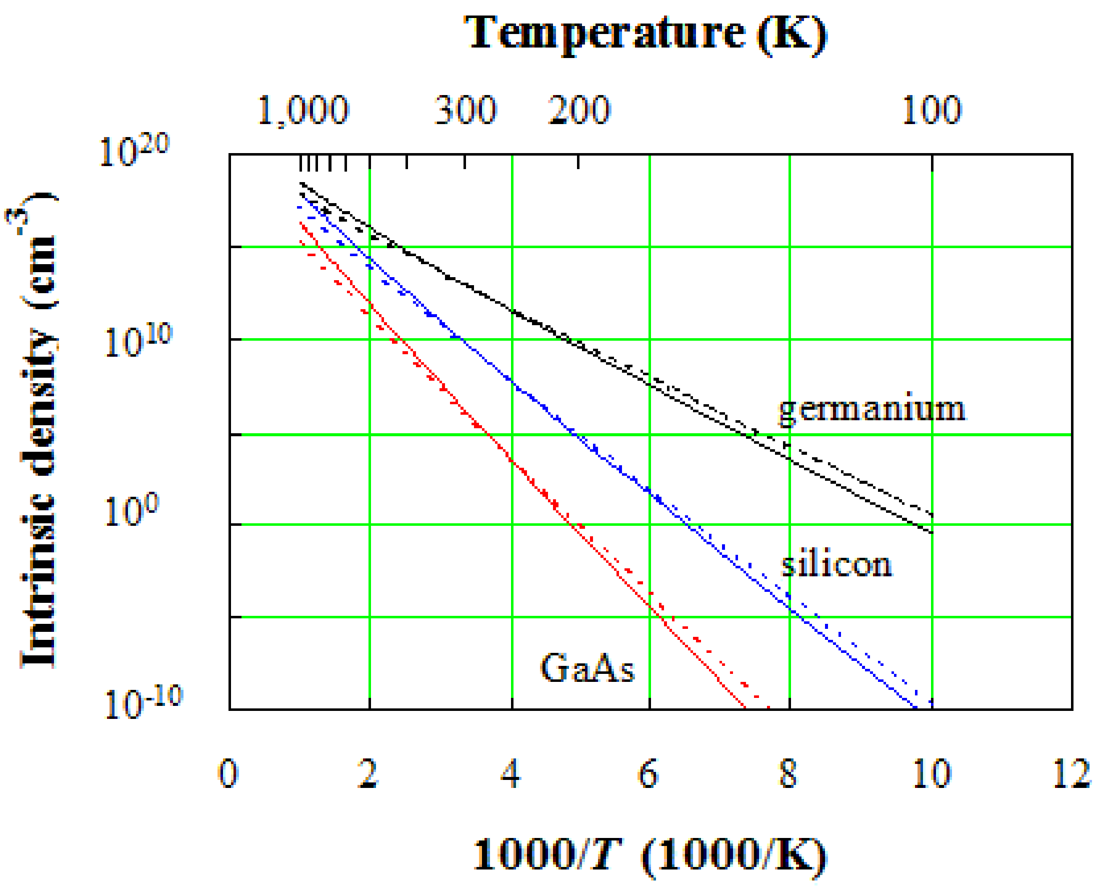
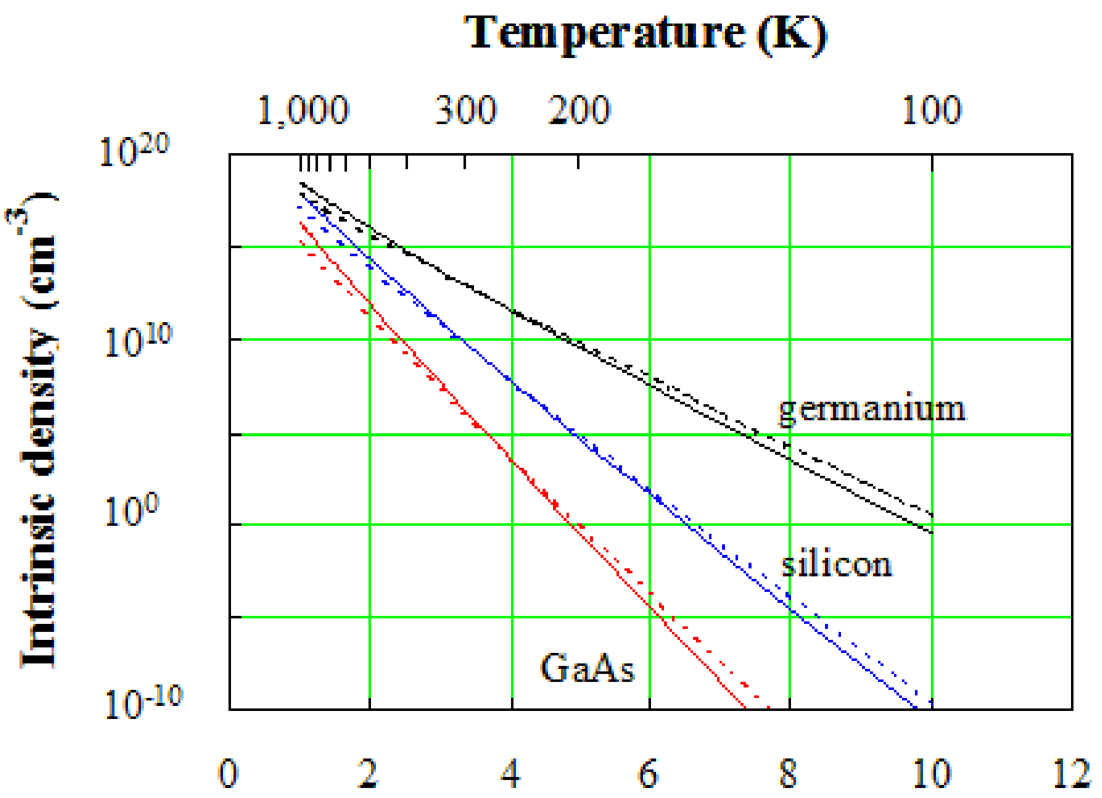
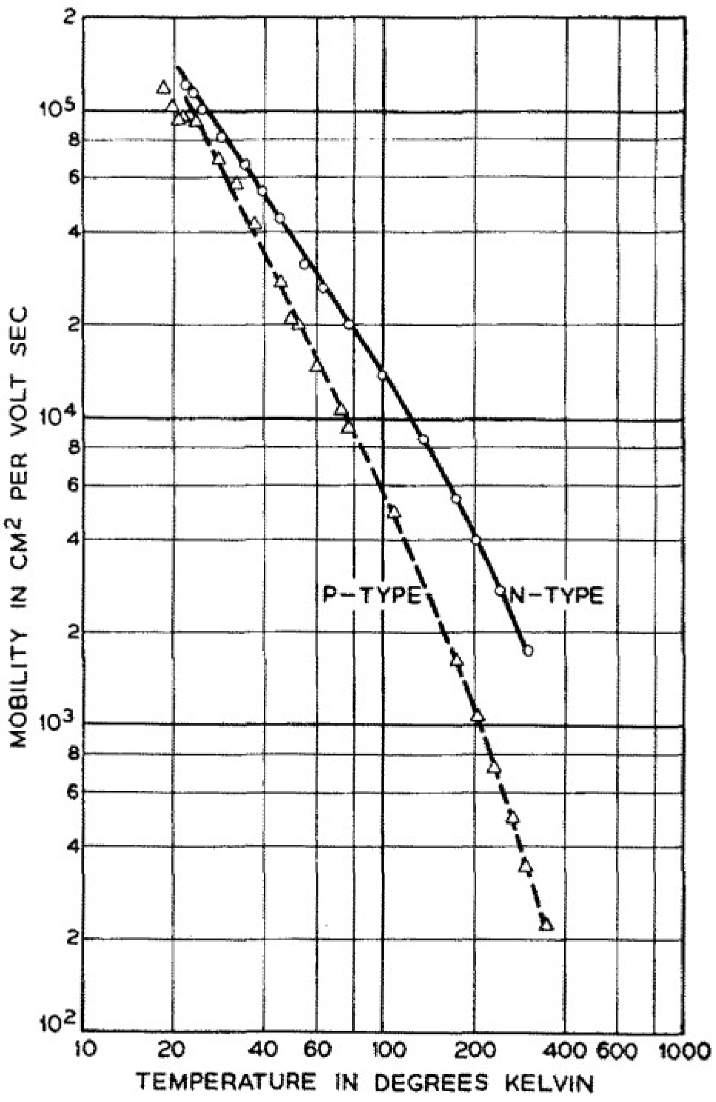
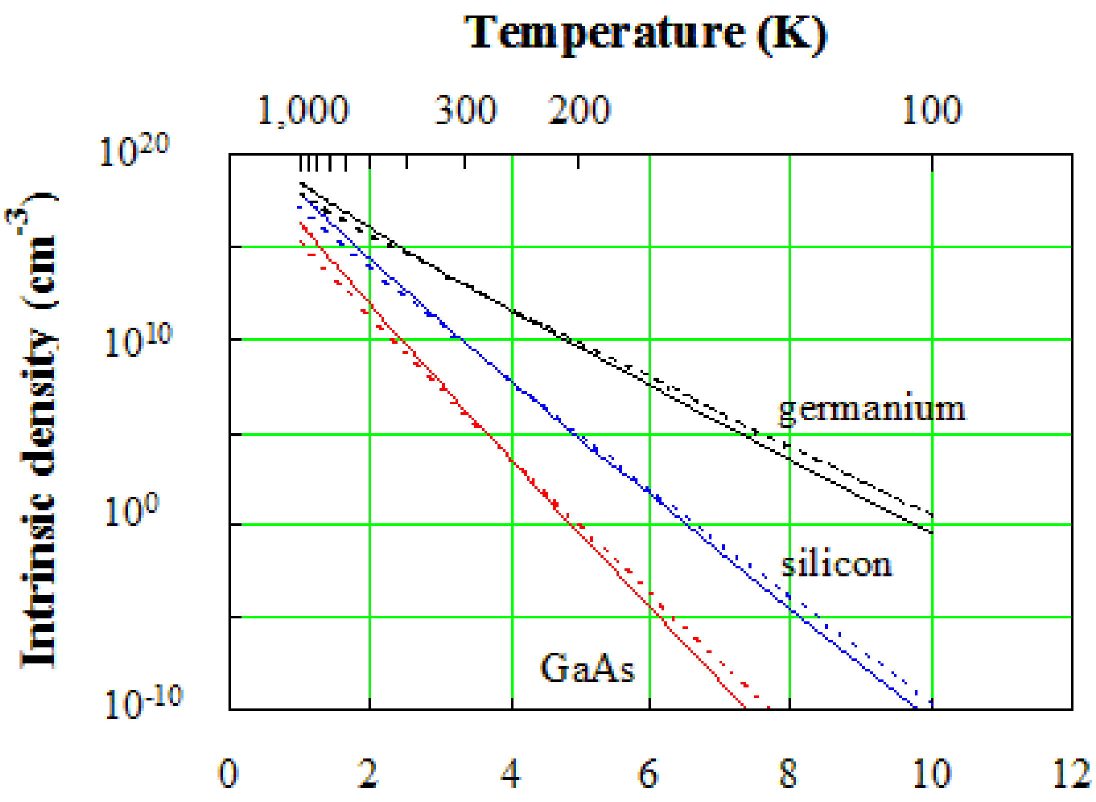
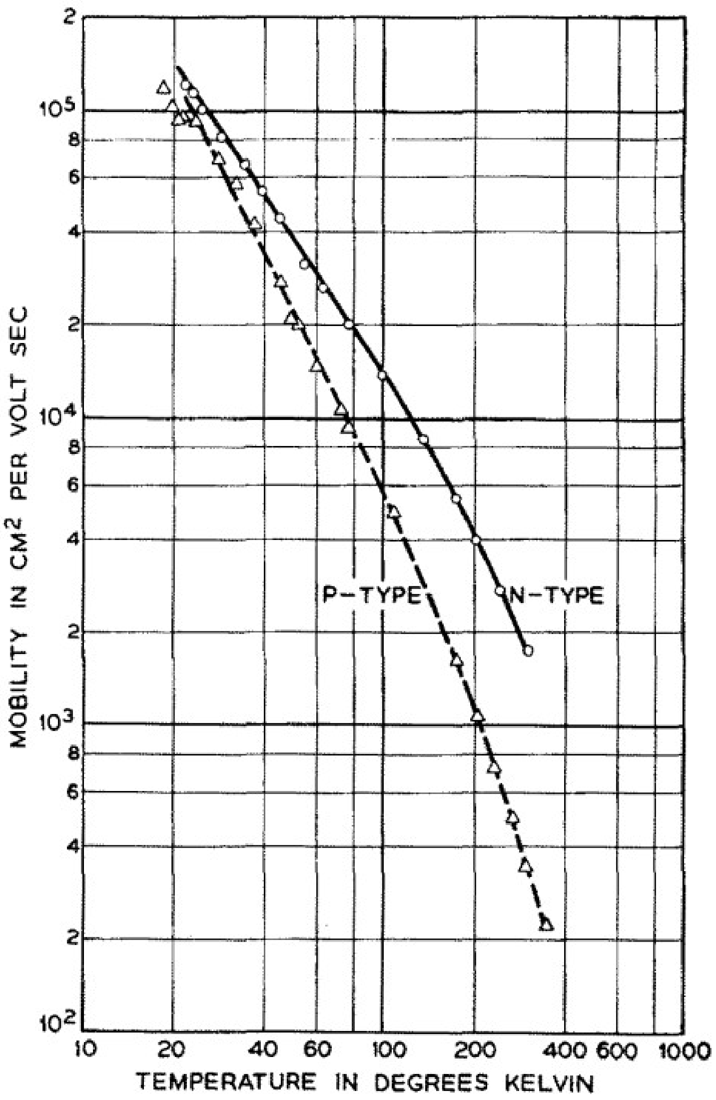

Temperature (K)
1,000
300
200
100
10^{20}
10^{10}
10^{0}
10^{-10}
Intrinsic density (cm^{-3})
germanium
silicon
GaAs
0
2
4
6
8
10
12
1000/*T* (1000/K)



R = 1/(e- μ N_i) → For Si ?

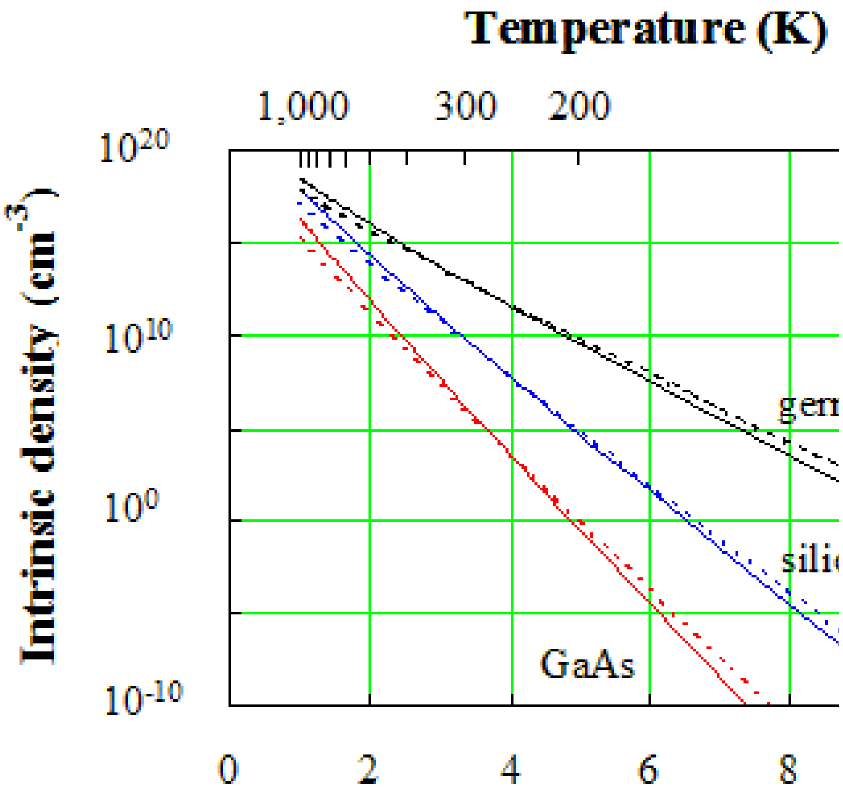


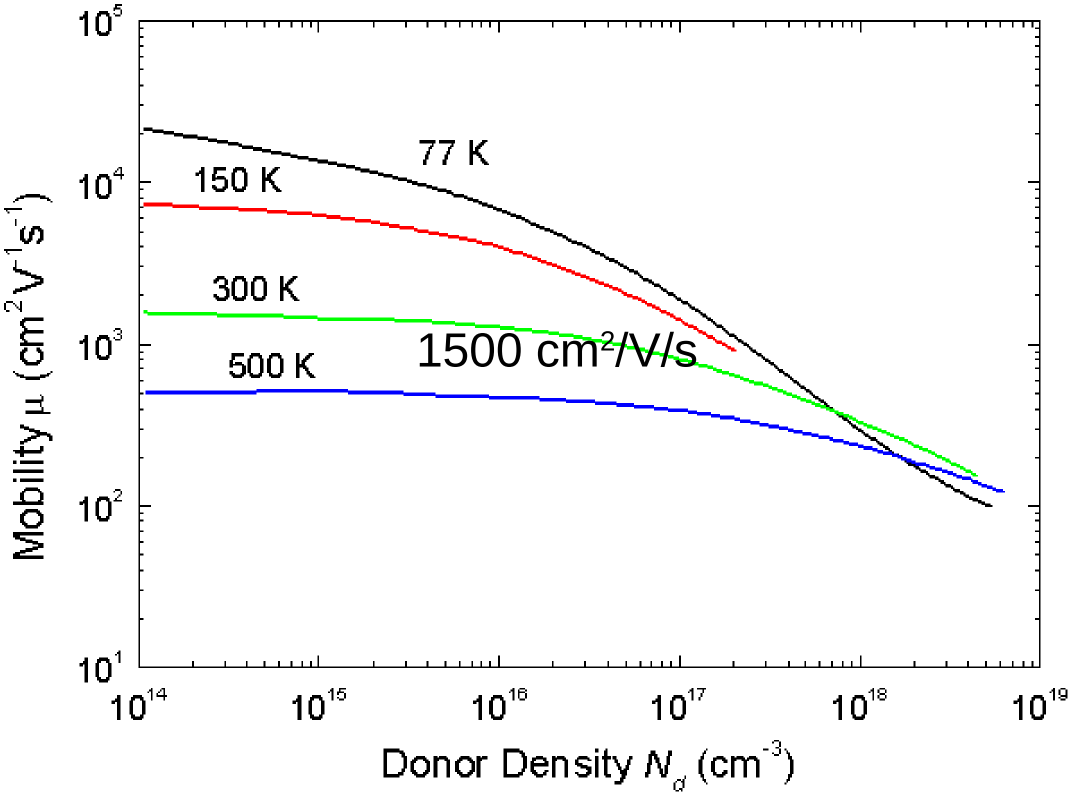




$R = 1/(e\text{-}\ \mu\ N_i) \rightarrow$ For Si ½ MΩ/cm

commercially available Si ~ 10 kΩ/cm





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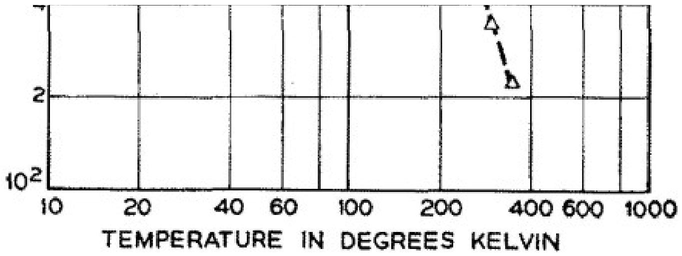
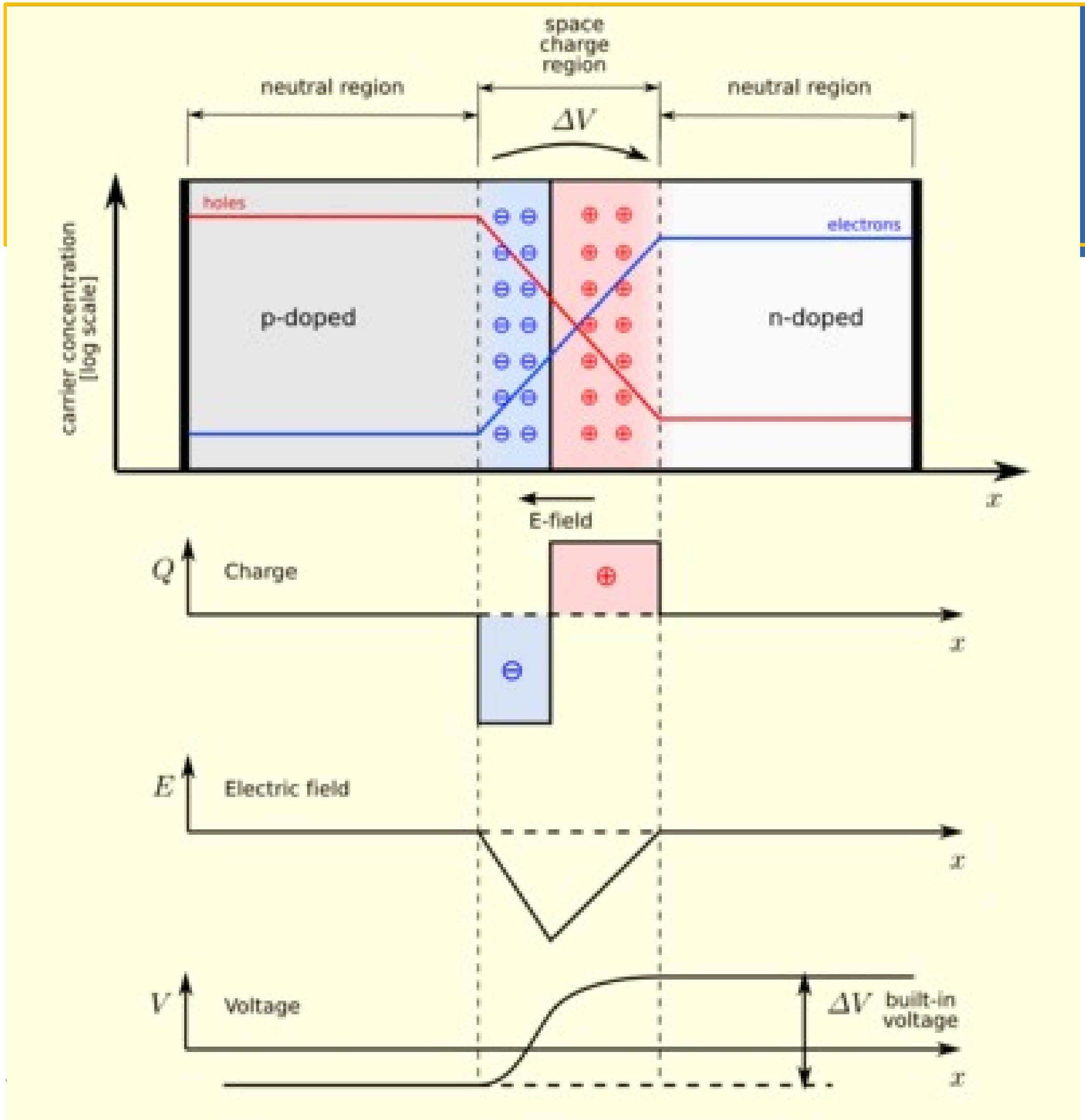


https://order.universitywafer.com/default.aspx?cat=Silicon&dopant=undoped

Qty	ID	Diam	Type	Dopant	Orien	Res (Ohm-cm)	Thick (um)	Polish	Grade	Lead Time	Quantity	1 Unit Price	5 Unit Price	10 Unit Price	25 Unit Price	50 Unit Price	100 Unit Price
25	2313	25.4mm	Undoped	Undoped	<111>	>2000	280um	SSP	Test	In Stock	152	$45.90	$25.90	$17.90	$16.90		
100	2018	50.8mm	Undoped	Undoped	<100>	>10000	280um	DSP	Prime	In Stock	974	$59.50	$39.90	$32.90	$23.90	$22.90	$20.90
82	3635	50.8mm	Undoped	Undoped	<100>	>10,000	280um	SSP	Prime	In Stock	82	$54.90	$36.90	$30.90	$21.90	$21.90	
20	3678	50.8mm	Undoped	Undoped	<100>	>5000	500um	SSP	Test	In Stock	20	$39.90	$29.90	$22.90	$19.9	$18.90	
100	3685	76.2mm	Undoped	Undoped	<100>	>10,000	380um	SSP	Prime	5 WEEKS	100		$49.90	$39.90	$29.90	$27.90	$26.90
1	3696	76.2mm	Undoped	Undoped	<100>	>10000	380um	DSP	Prime	In Stock	1	$65.90	$55.90	$45.90	$38.9		
131	3193	100mm	Undoped	Undoped	<100>	>10,000	525um	DSP	Prime	In Stock	131	$145.90	$99.90	$79.90	$65.9	$61.90	$59.90
100	3328	100mm	Undoped	Undoped	<100>	>20,000	525um	SSP	Prime	In Stock	505	$110.90	$92.90	$77.90	$68.9	$66.90	$61.90

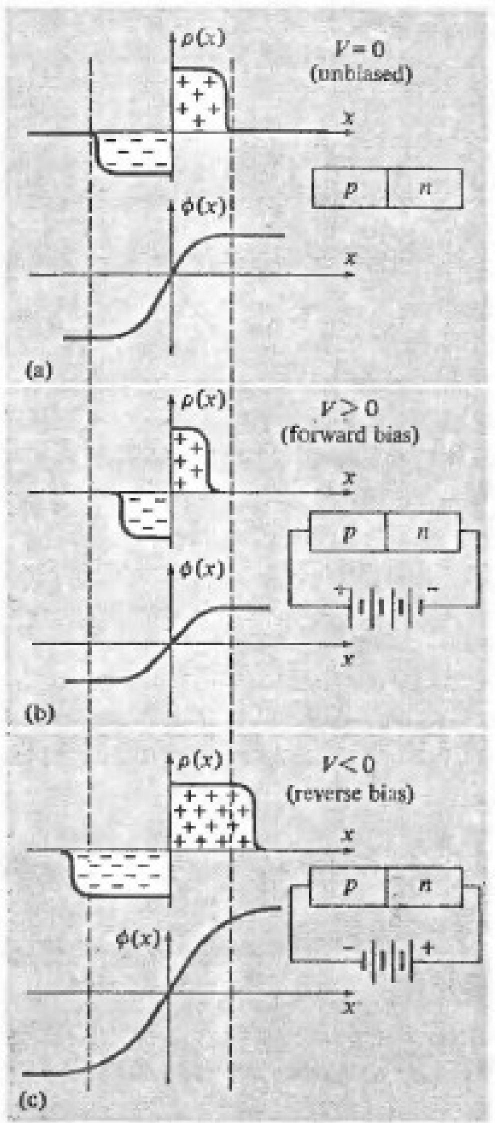


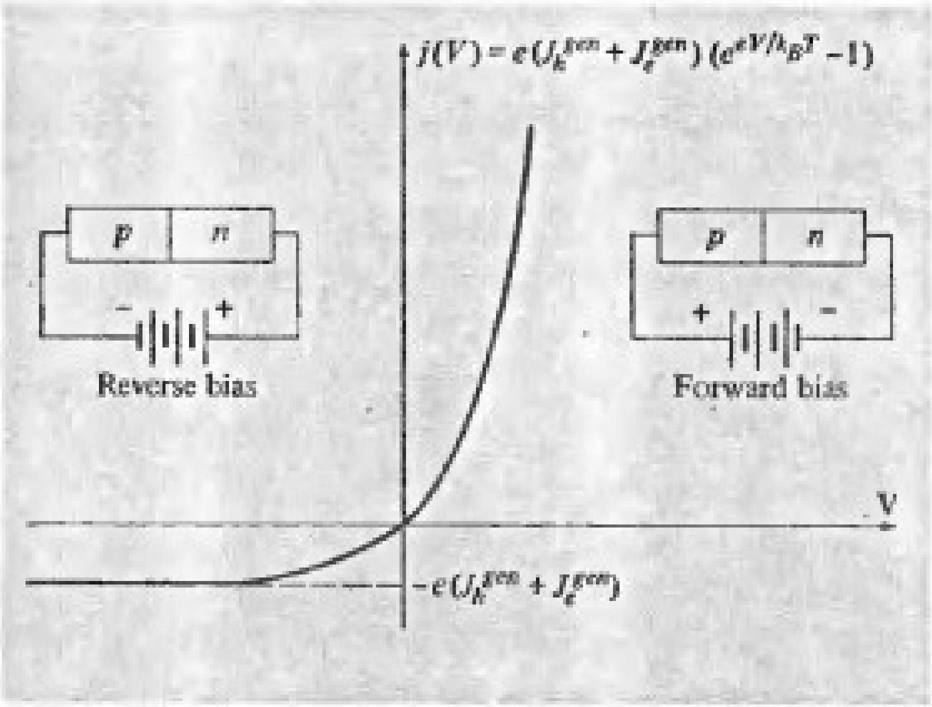
- Majority carriers diffusing on the other side of the junction recombine
  - Depletion layer
    - Capacitance

$$C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$$

  - $V = k_B T/e^{-}\ ln\left(\frac{n_a n_d}{n_i^2}\right)$

Shockley equation



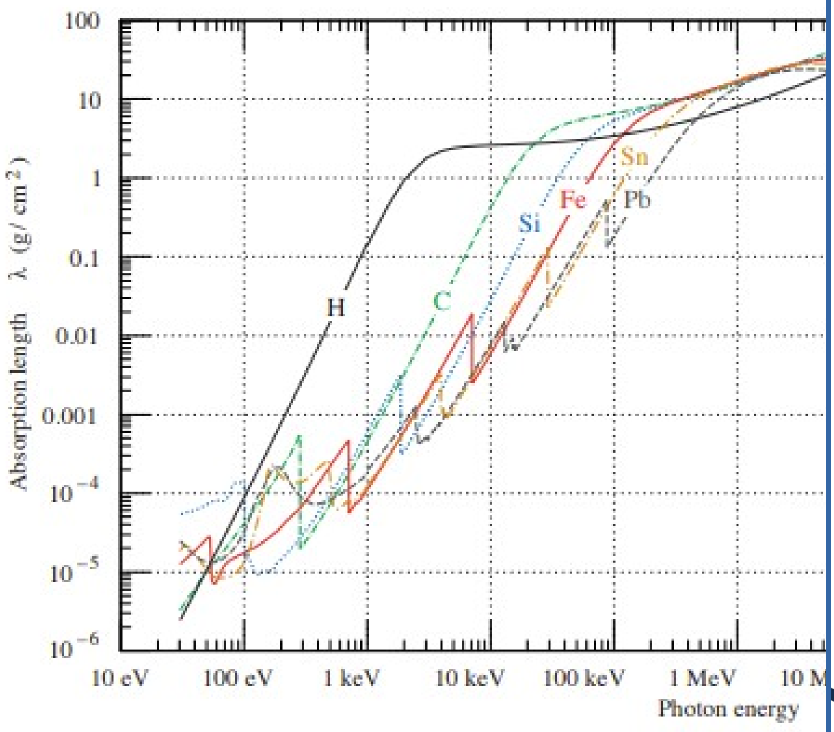


$$I = I_S \left(e^{\frac{V_D}{n V_T}} - 1 \right)$$

I_s ∝ # minority carriers ∝ exp(-1/T) * 1/doping

Gamma spectroscopy

- For spectroscopy the gamma has to be fully contained in the detector
  - Silicon density ~ 2.3 g/cm^3
    - Absorption length 10 cm ~ 1 MeV
  - Germanium density ~ 5.5 g/cm^3
    - Absorption length 5 cm ~ 1 MeV
- Typically germanium junctions are used:
  - Cryogenic temperature
    - limit the leakage current
    - Increase the carrier lifetime
  - High purity germanium is required



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ORTEC » PRODUCTS » Radiation Detectors » *High Purity Germanium (HPGe) Radiation Detectors*

Radiation Detectors

- **High Purity Germanium (HPGe) Radiation Detectors**
  - HPGe Radiation Detector Types and How to Choose
  - HPGe Radiation Detector Cooling
  - HPGe Radiation Detector Electronics
  - HPGe Radiation Detector Options and Accessories
  - HPGe Radiation Detector Stock List
- Silicon Charged Particle Radiation Detectors
- Scintillation Radiation Detectors
- Exempt Quantity Radioactive Sources

High Purity Germanium (HPGe) Radiation Detectors

Semiconductor based photon radiation detectors have been evolving for over half a century, with ORTEC pioneering commercial availability for a majority of that time. Initial offerings were based around lithium-drifted germanium Ge(Li) and lithium-drifted silicon Si(Li). Ge(Li) was later replaced with more advanced, high purity germanium (HPGe) detectors. ORTEC provides a comprehensive suite of HPGe detector solutions covering an extensive range of energies and for a variety of applications.

Cryogenic cooling is required for germanium semiconductor radiation detectors. In order to support various counting geometries, ORTEC offers a wide range of cooling options ranging from standard LN2 systems, to advanced electro-mechanical cryocoolers such as the ICS™.

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Detector response

$$\sigma = \sqrt{a + bN + cN^2}$$

- a ← electronic noise
- b ← Fano factor → $\sigma/N = \sqrt{a/N^2 + b/N + c}$
- c ← disuniformities (in gain, field, …)
- In poissonian approximation a=c=0, b=1

detectors

	Gap [eV]	ev/couple	Fano
Si	1.12	3.86	0.115
Ge	0.67	2.96	0.12
SiC	2.5-3.5	7.6	0.04

- How many couples for 30 keV x-ray in Ge?

detectors

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- Energy resolution?

detectors

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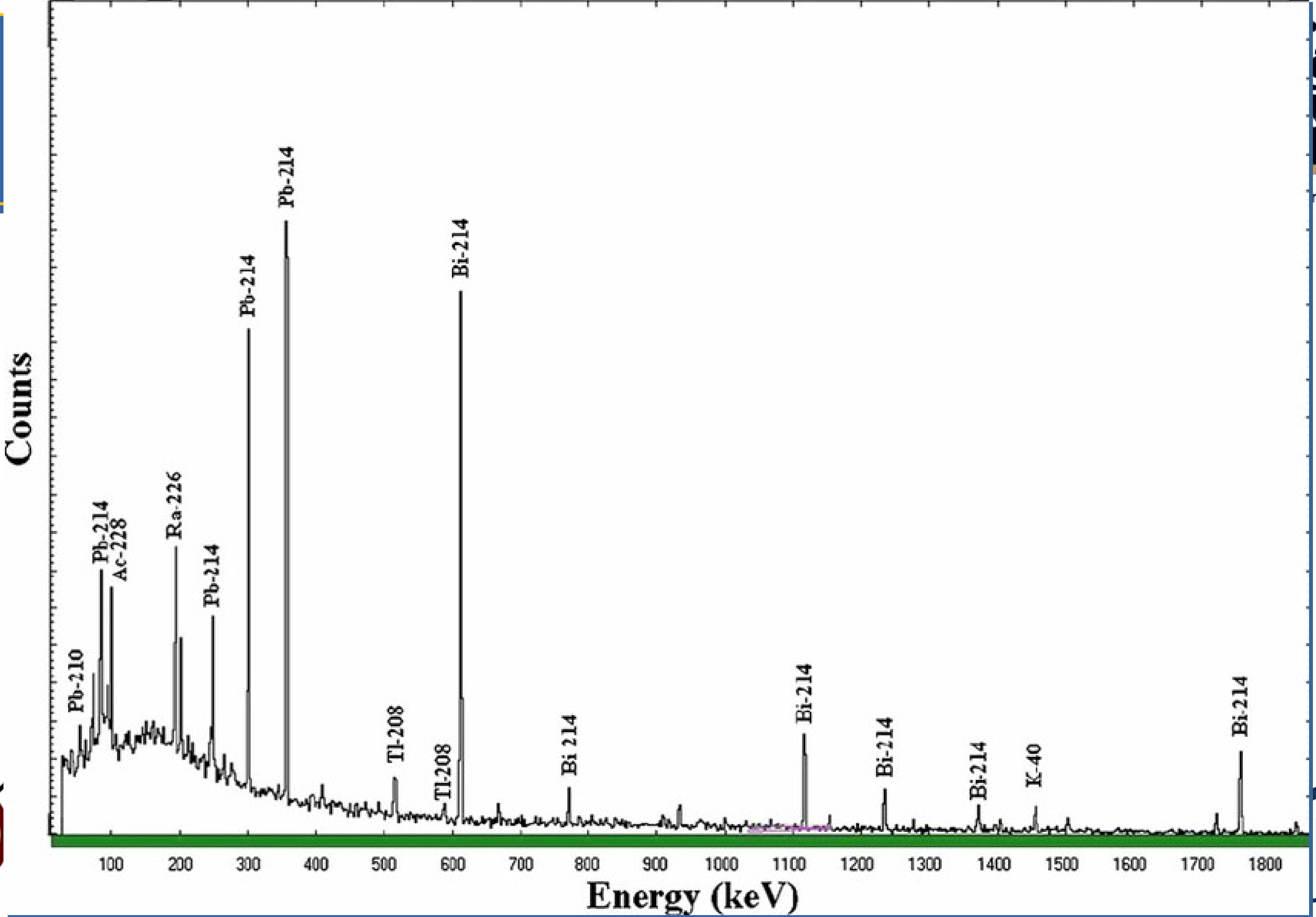
- How many couples for 30 keV x-ray in Ge?
  - 30 keV / 3 eV = 10000 e/h
- Energy resolution?
  - 2.355 * sqrt(0.12 / 10000) = 0.8 %

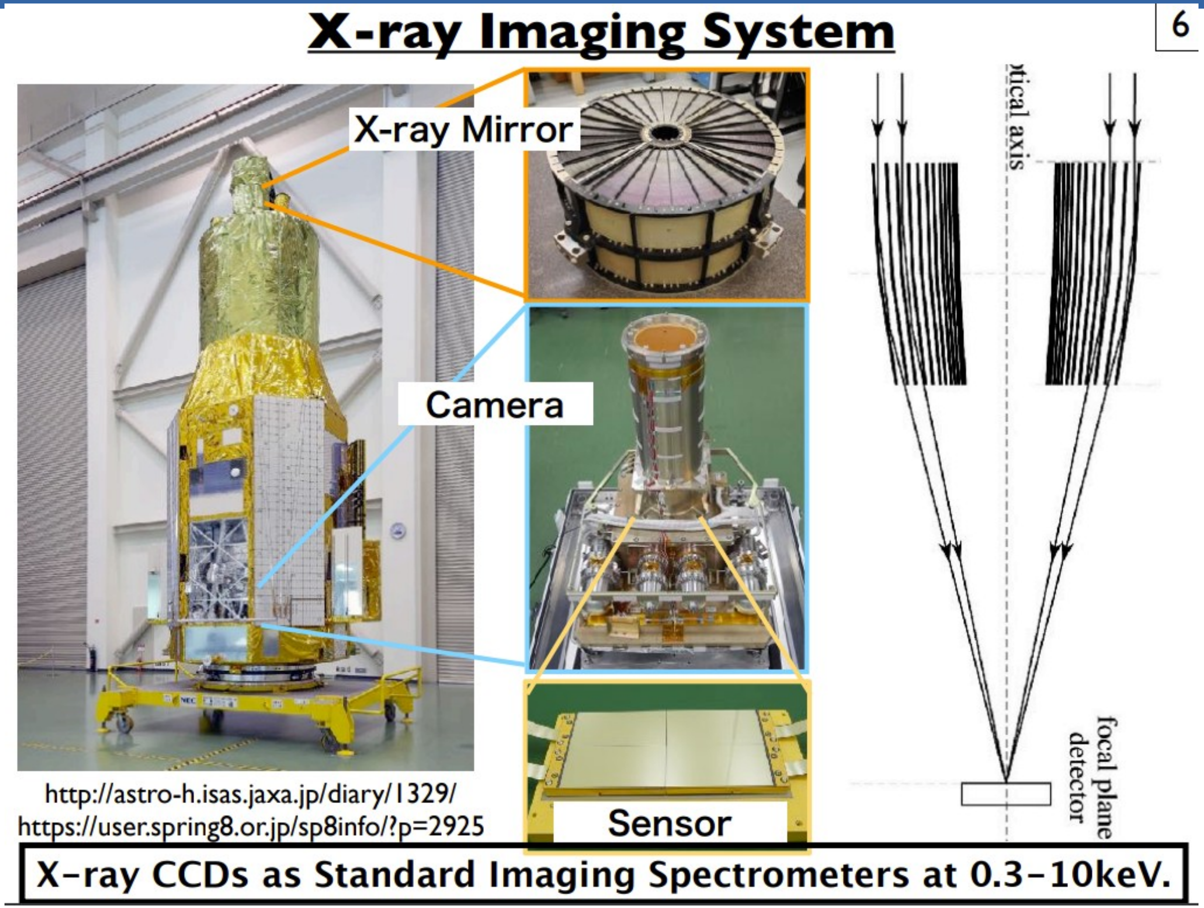


Counts
Energy (keV)
Pb-210
Pb-214
Ac-228
Ra-226
Pb-214
Pb-214
Pb-214
Tl-208
Tl-208
Bi-214
Bi 214
Bi-214
Bi-214
Bi-214
K-40
Bi-214
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800

And Silicon?

- Silicon is used for almost everything else
  - Alpha detectors
  - X-ray detectors
  - Pixel and strip detectors
- Silicon requires no cooling
  - I_{gen} ~ O(nA / cm^2) @ 300 K

X-ray imaging

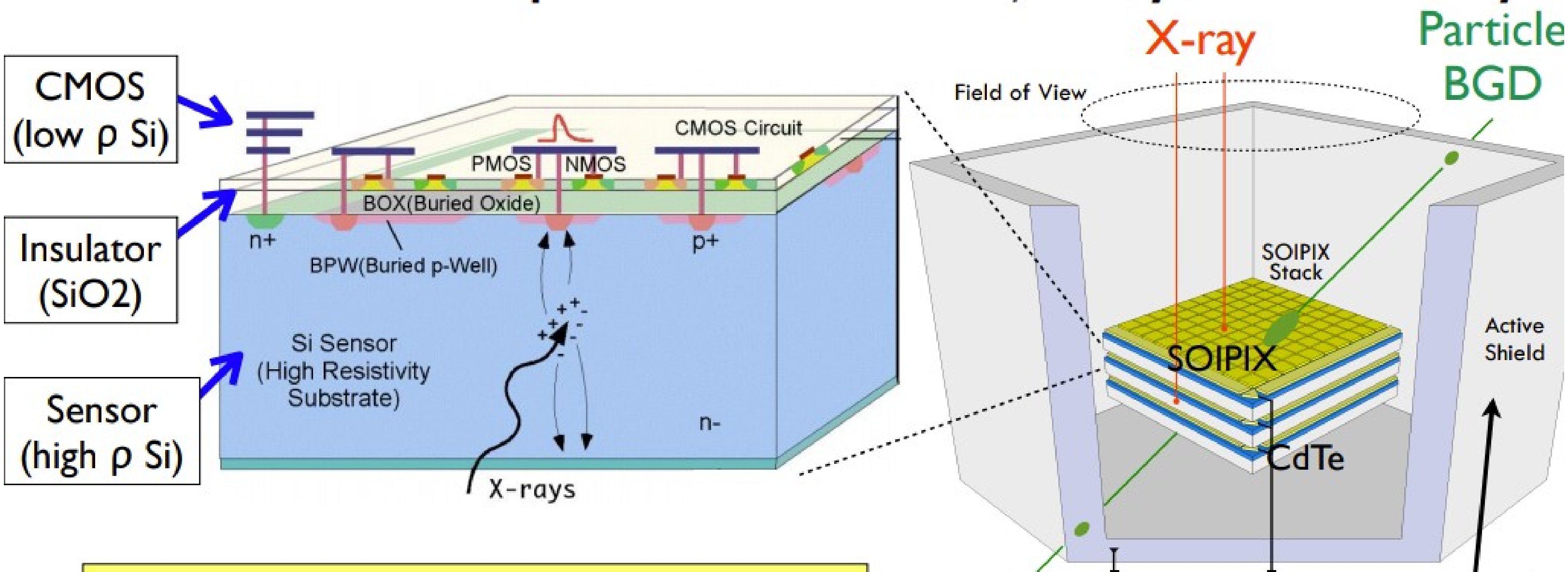


https://tinyurl.com/ydkarju5

Integrated sensor

"XRPIX" = SOI pixel sensor for X-ray Astronomy

9



<u>Each pixel</u> has its own trigger logic and analogue readout CMOS circuit.

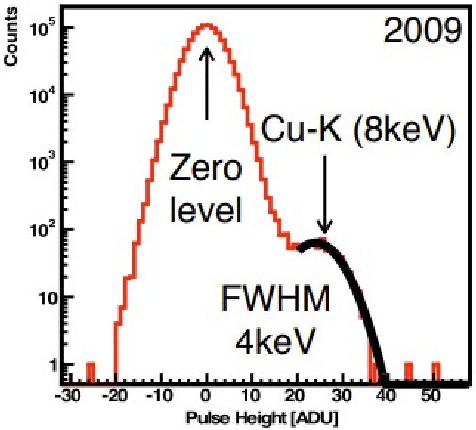
Anti-coincidence Shield by Scintillators
Rate ~10kHz

Target Specification of the Device

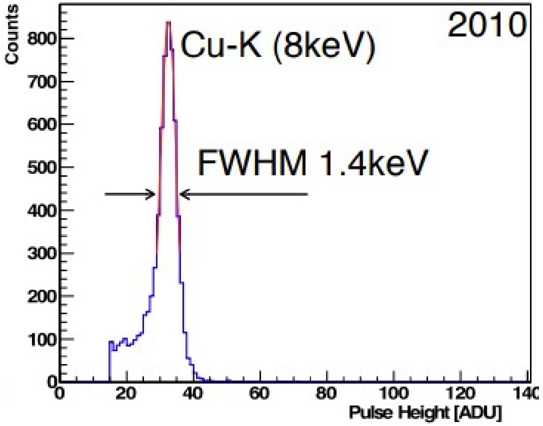
same performance as CCD

Imaging	area ~ 15x45mm^2 pixel ~ 30-60μm□ (1" @ F=10m)
Energy Band	Req. 1-40 keV, Goal 0.5-40 keV Backside Illumination Req. <1μm, Goal 0.1μm Full Depletion Req. >250μm
Spectroscopy	ΔE : Req. < 300eV, Goal < 140eV @ 6keV ENC: Req. <10e-, Goal < 3e- ← **Most Difficult**
Time Resolution	< 10μsec for the anti-coincidence with the rate of ~10kHz

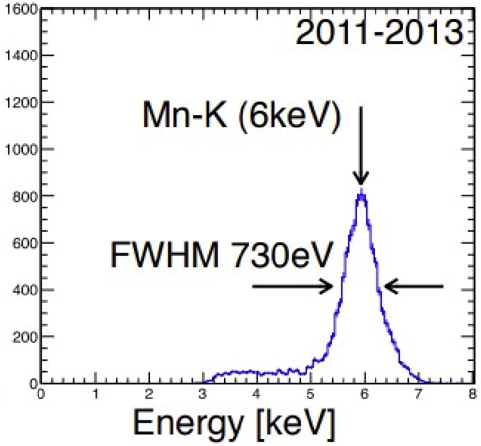
Improvement of Spectral Performance in Frame Mode



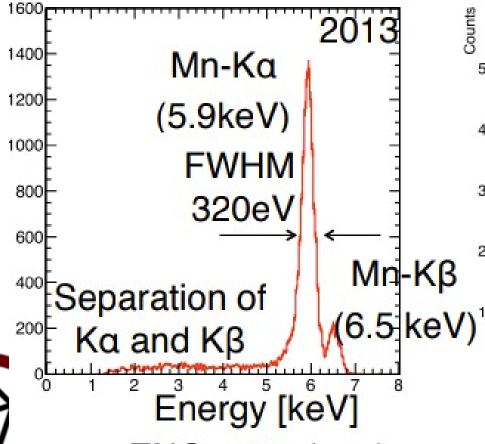
ENC ~600e (rms)



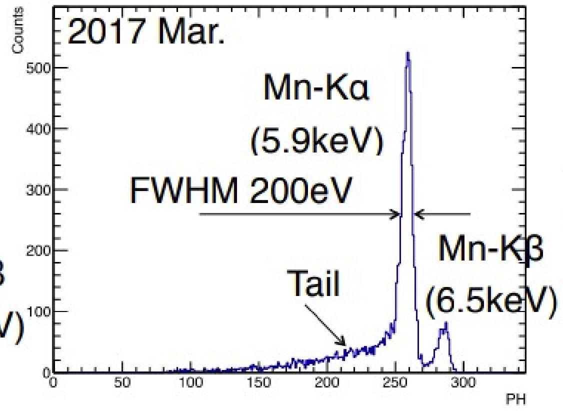
ENC ~130e (rms)



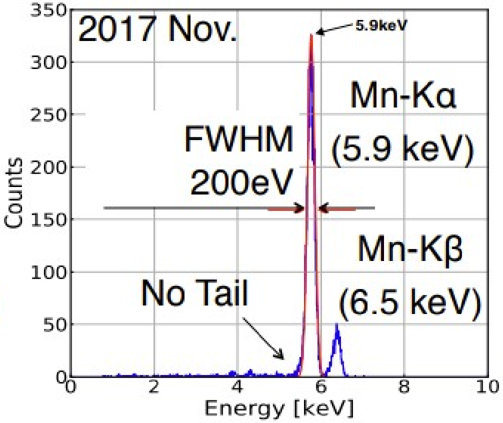
ENC ~68e (rms)



ENC ~35e (rms)



ENC ~16e (rms)



ENC ~10e (rms)

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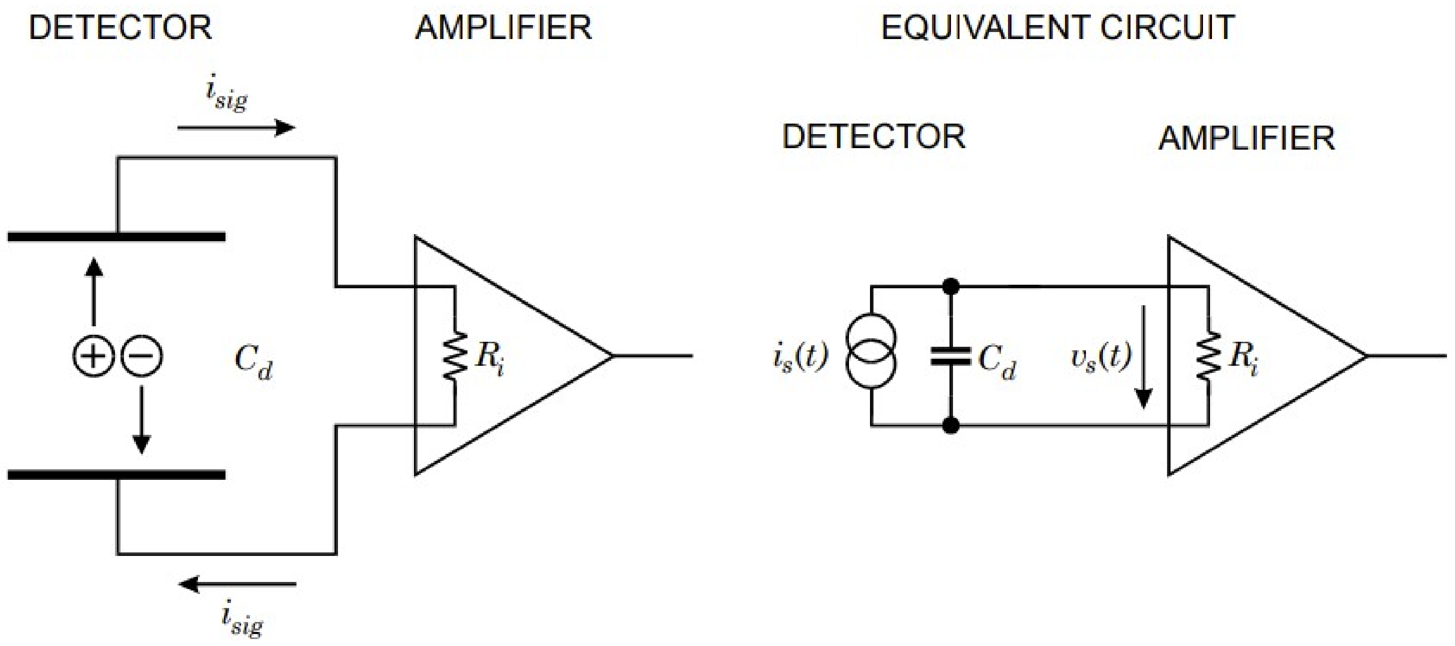
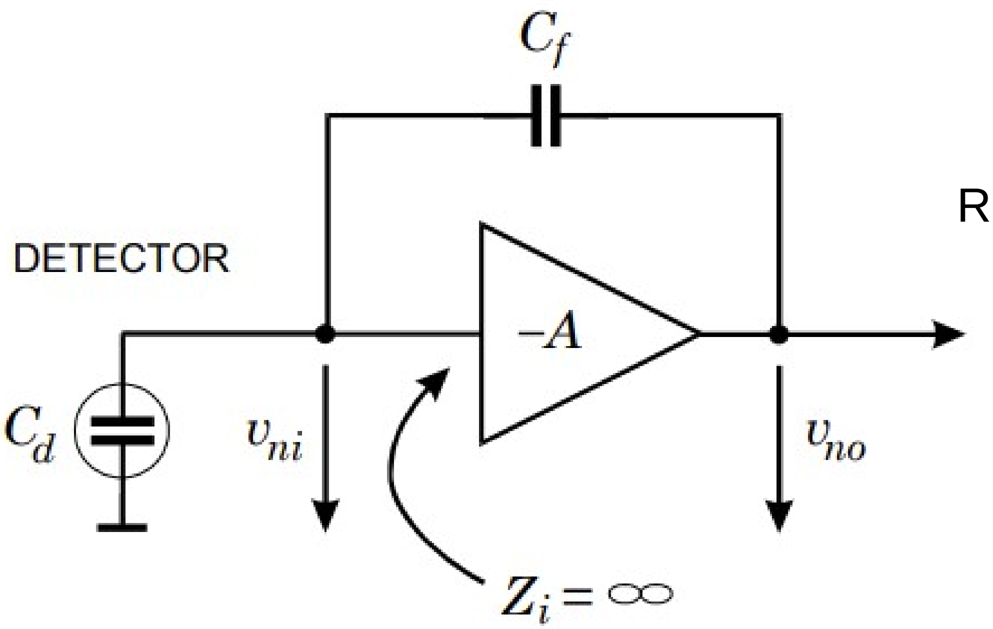
Detecting pulses



Charge[-sensitive] pre-amplifier

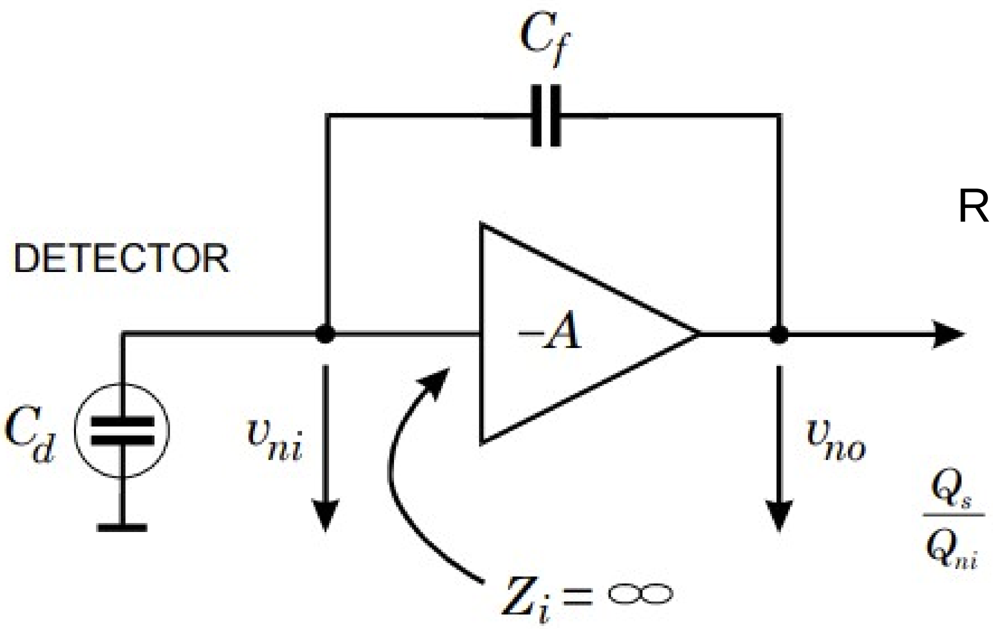


Signal = Q / C_f

$C_f \ll C_d$

Risetime $\propto C_d/(C_f\,GBP)$

Charge[-sensitive] pre-amplifier



Signal = Q / C_f

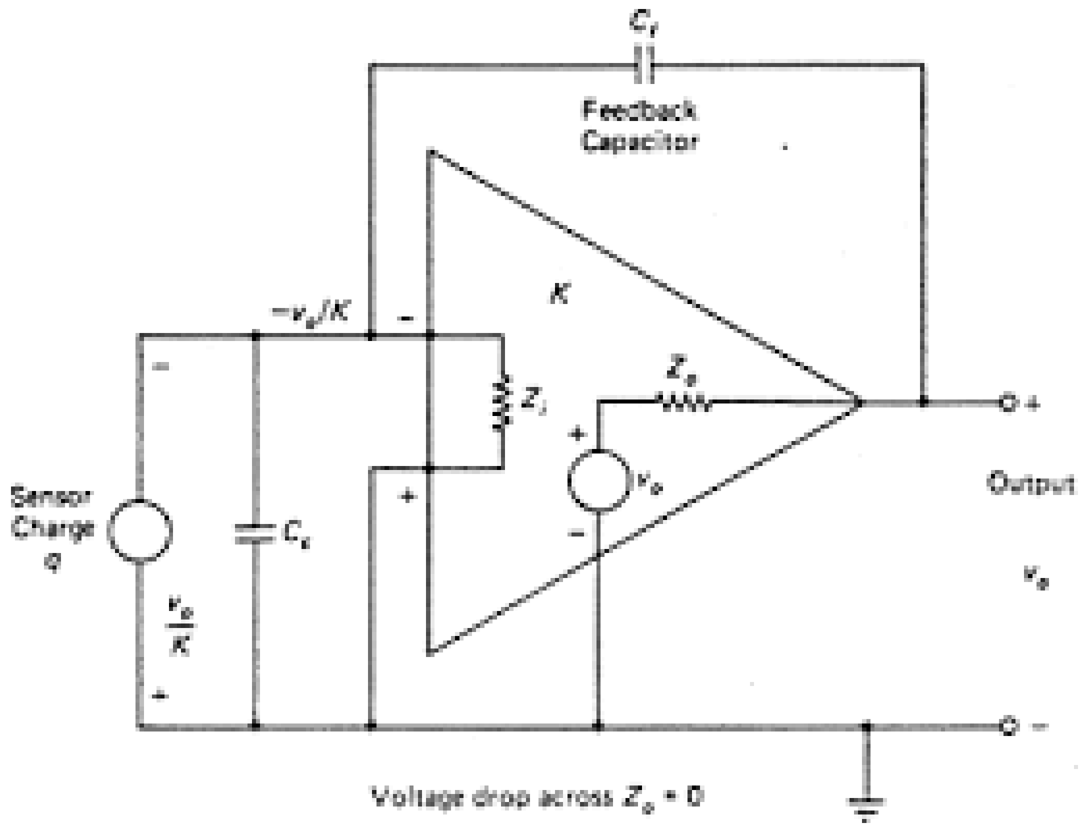
$C_f \ll C_d$

Risetime $\propto C_d/(C_f\, GBP)$

SNR

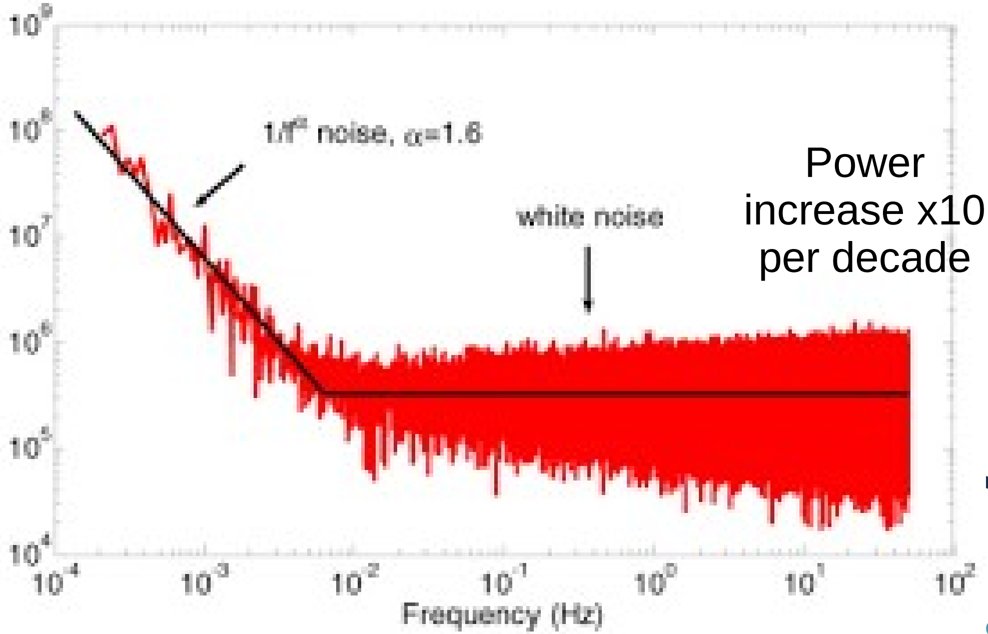
$$\frac{Q_s}{Q_{ni}} = \frac{Q_s}{v_{ni}(C_d + C_f)} = \frac{1}{C}\frac{Q_s}{v_{ni}}$$

Charge amplifier



Electronic noise

- Intrinsic
  - Thermal noise, shot noise
  - 1/f noise
- External
  - Pick-up
  - Ground loops



Power increase x10 per decade

Electronic noise

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  - Thermal noise, shot noise
  - 1/f noise
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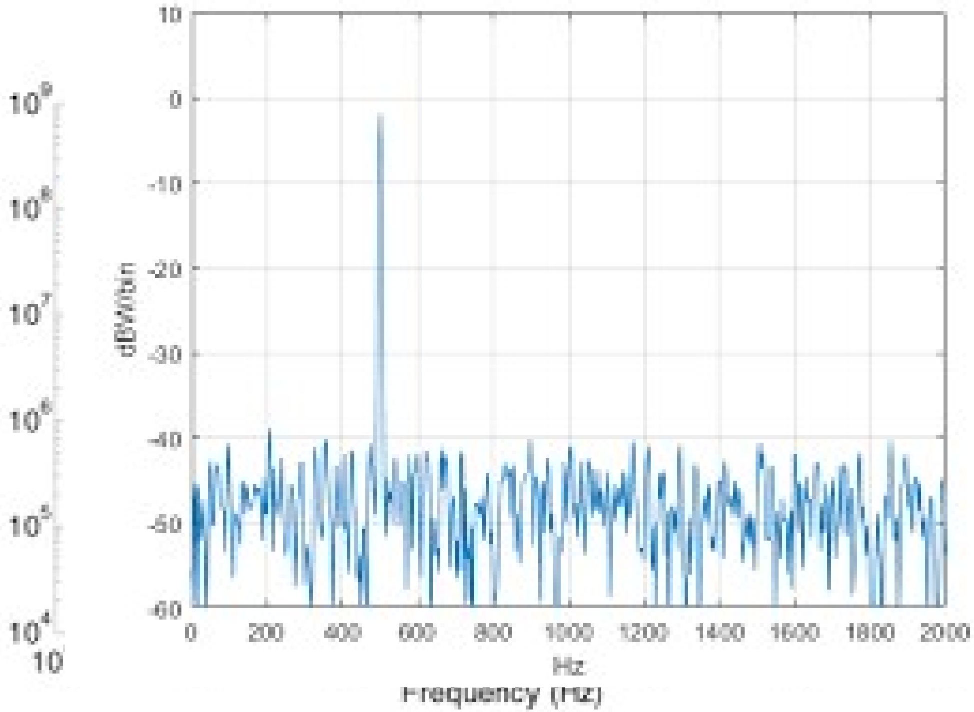
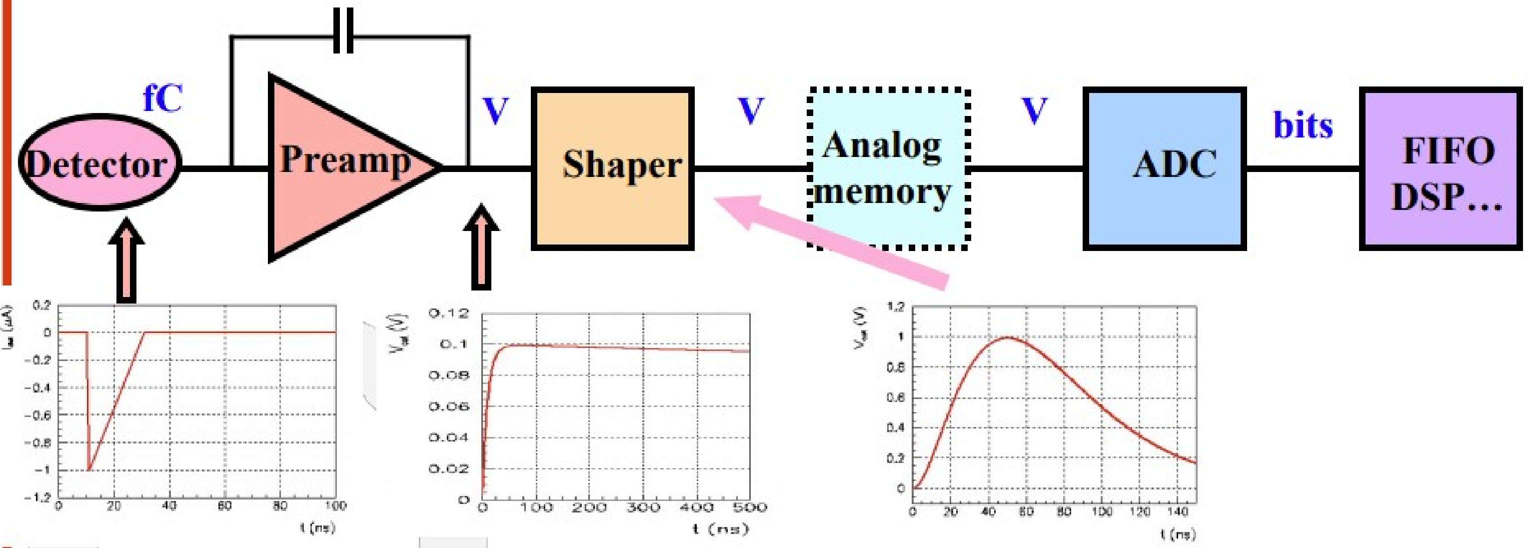
  - Ground loops



Overview of readout electronics

- Most front-ends follow a similar architecture



- Very small signals (fC) -> need amplification
- Measurement of amplitude and/or time (ADCs, discris, TDCs)
- Several thousands to millions of channels

https://tinyurl.com/yflynbe7

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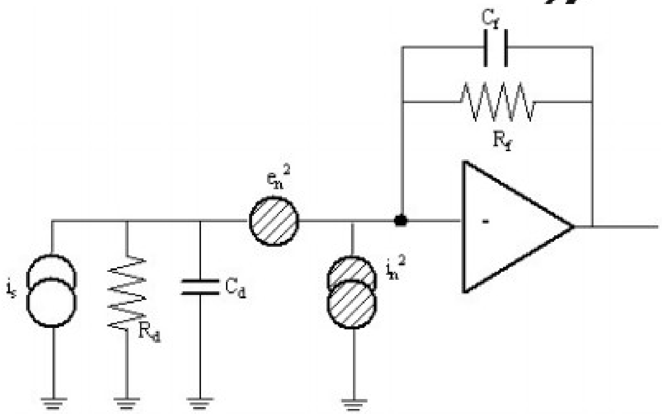
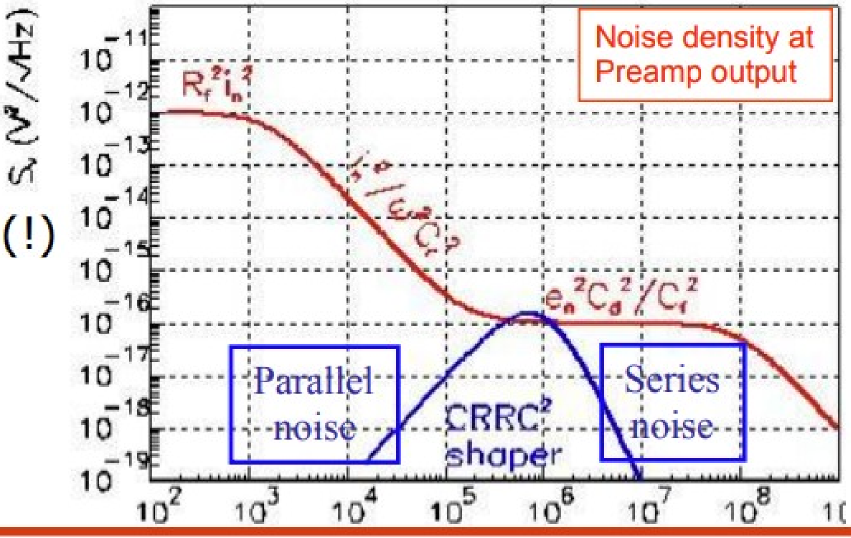
Noise in charge pre-amplifiers

- 2 noise generators at the input
  - Parallel noise : (i_n^2) (leakage currents)
  - Series noise : (e_n^2) (preamp)
- Output noise spectral density :
  - $Sv(\omega) = (i_n^2 + e_n^2/|Z_d|^2) / \omega^2 C_f^2$
    $= i_n^2 / \omega^2 C_f^2 + e_n^2 C_d^2/C_f^2$
  - Parallel noise in $1/\omega^2$
  - Series noise is flat, with a « noise gain » of C_d/C_f
- *rms* noise V_n
  - $V_n^2 = \int Sv(\omega)\, d\omega/2\pi \to \infty$ (!)
  - Benefit of shaping…



Noise generators in charge preamp



Equivalent Noise Charge (ENC) after CRRC^n

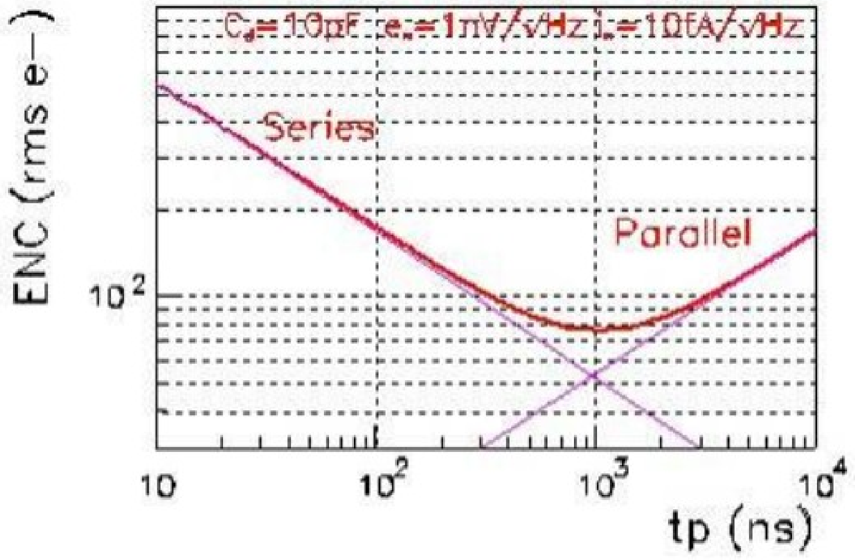
- A useful formula : **ENC (e- rms) after a CRRC² shaper :**

$$ENC = 174\ e_n C_{tot}/\sqrt{t_p}\ (\delta) \oplus 166\ i_n \sqrt{t_p}\ (\delta)$$

  - e_n in nV/ √Hz, i_n in pA/ √Hz are the preamp noise spectral densities
  - C_{tot} (in pF) is dominated by the detector (C_d) + input preamp capacitance (C_{PA})
  - t_p (in ns) is the shaper peaking time (5-100%)

Noise minimization

- Minimize source capacitance
- Operate at optimum shaping time
- Preamp series noise (en) best with high trans-conductance (g_m) in input transistor
  => large current, optimal size



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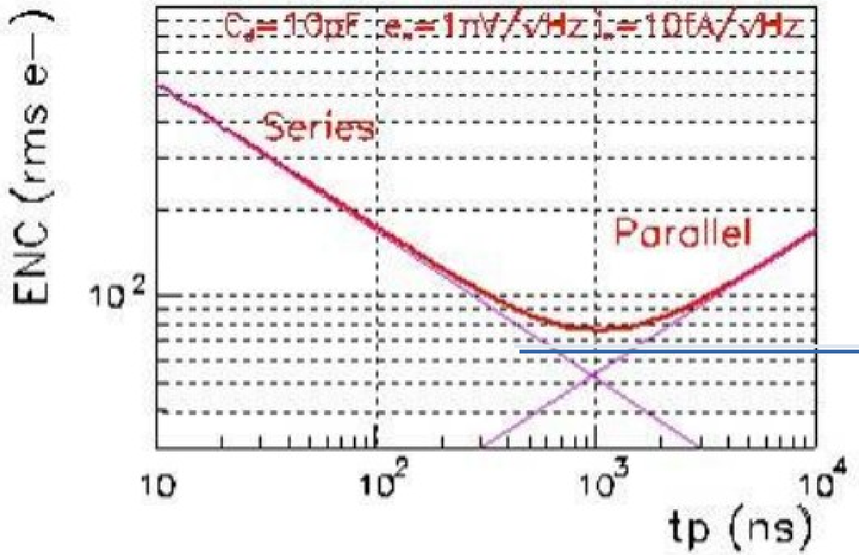

1/f noise

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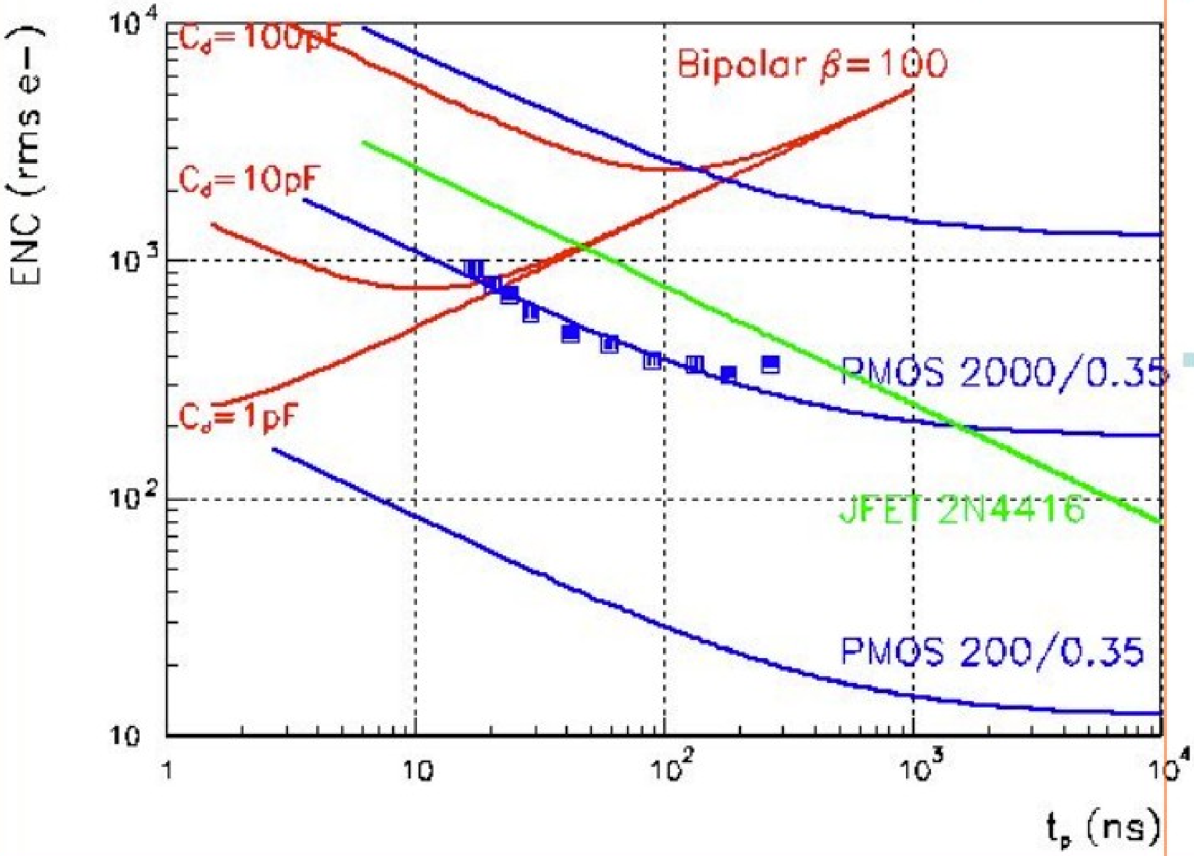
ENC for various technologies

- ENC for Cd=1, 10 and 100 pF at I_D = 500 uA
  - MOS transistors best between 20 ns – 2 µs



- **Parameters**
- Bipolar :
  - g_m = 20 mA/V
  - $R_{BB'}$=25 Ω
  - e_n= 1 nV/√Hz
  - I_B=5uA
  - i_n = 1 pA/√Hz
  - C_{PA}=100fF
- **PMOS 2000/0.35**
  - g_m = 10 mA/V
  - e_n = 1.4 nV/√Hz
  - C_{PA} = 5 pF
  - 1/f :

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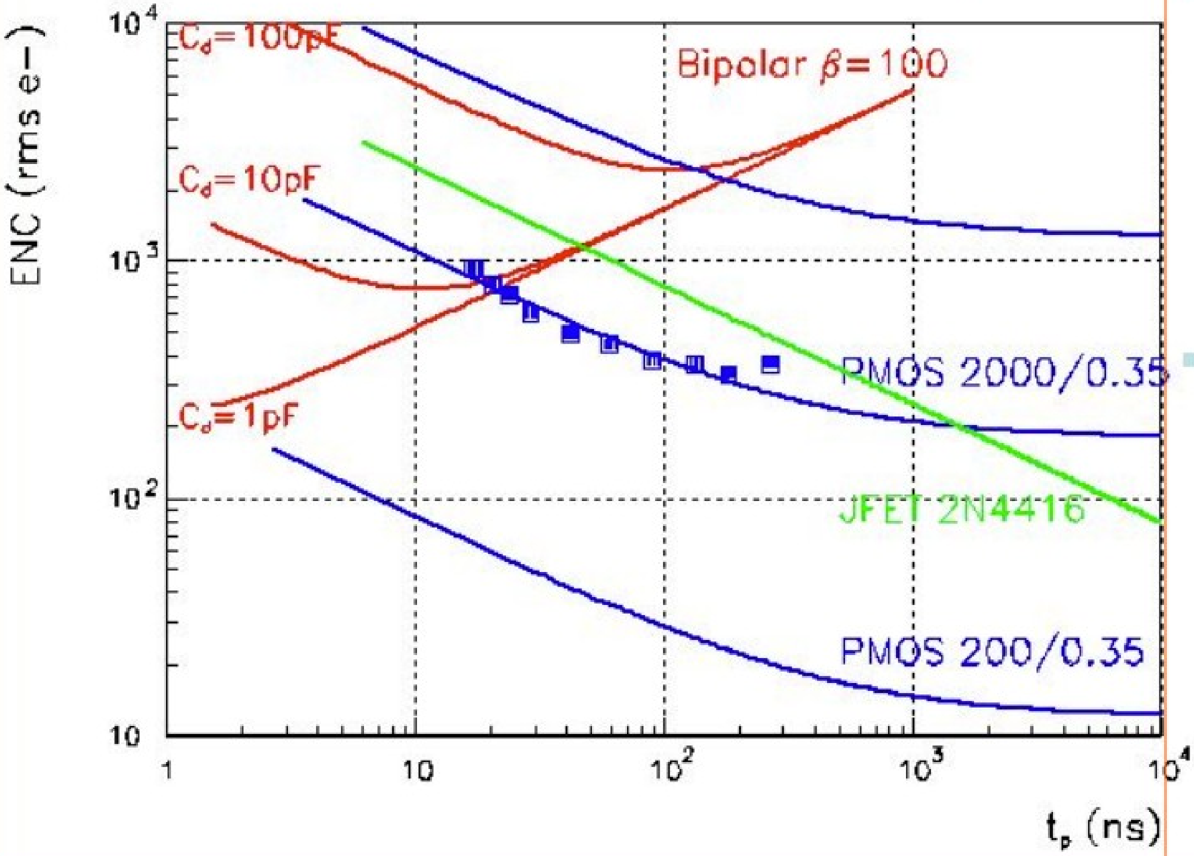
ENC for various technologies

- ENC for Cd=1, 10 and 100 pF at I_D = 500 uA
  - MOS transistors best between 20 ns – 2 µs



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  - i_n = 1 pA/√Hz
  - C_{PA}=100fF
- **PMOS 2000/0.35**
  - g_m = 10 mA/V
  - e_n = 1.4 nV/√Hz
  - C_{PA} = 5 pF
  - 1/f :

Shot noise

$$\sigma_i = \sqrt{2\,q\,I\,\Delta f}$$

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ORCA-FusionBT
CAMERA SPECS

LOW NOISE AND EXCEPTIONAL READOUT NOISE UNIFORMITY WITH HIGH QE

LOW READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan

HIGH QE
95 % @550 nm
Gen III Back-illuminated sCMOS

HIGH SPEED
89.1 fps
@ 2304 x 2304 (16 bit)

HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

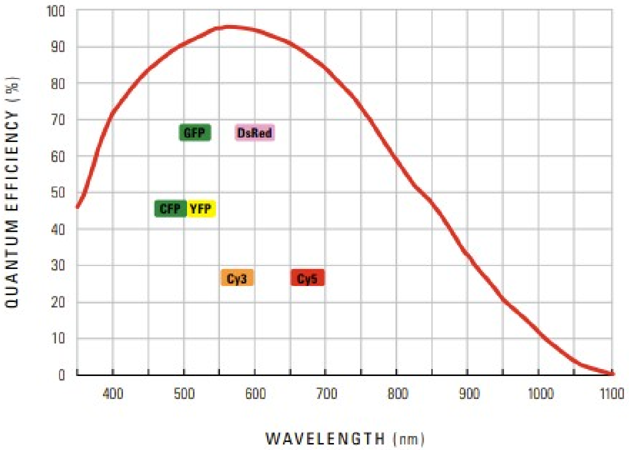
PRNU
0.06 % rms
@ 7500 electrons

PIXEL SIZE
6.5 µm × 6.5 µm

DYNAMIC RANGE
21 400:1
Ultra-quiet Scan

DSNU
0.06 electrons rms
Ultra-quiet Scan

Back-thin Boosted QE for Maximum Photon Collection



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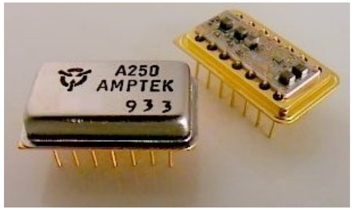
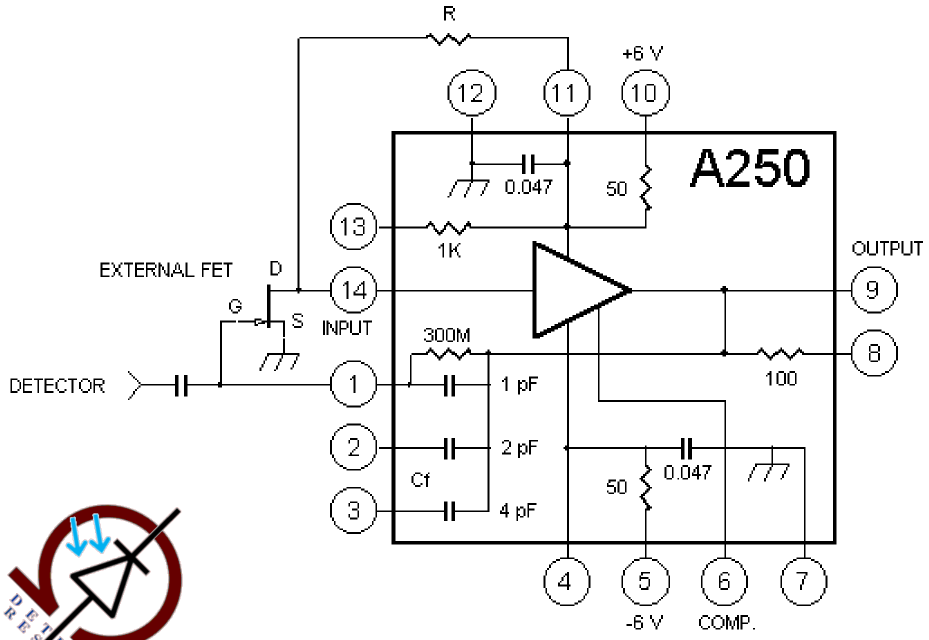
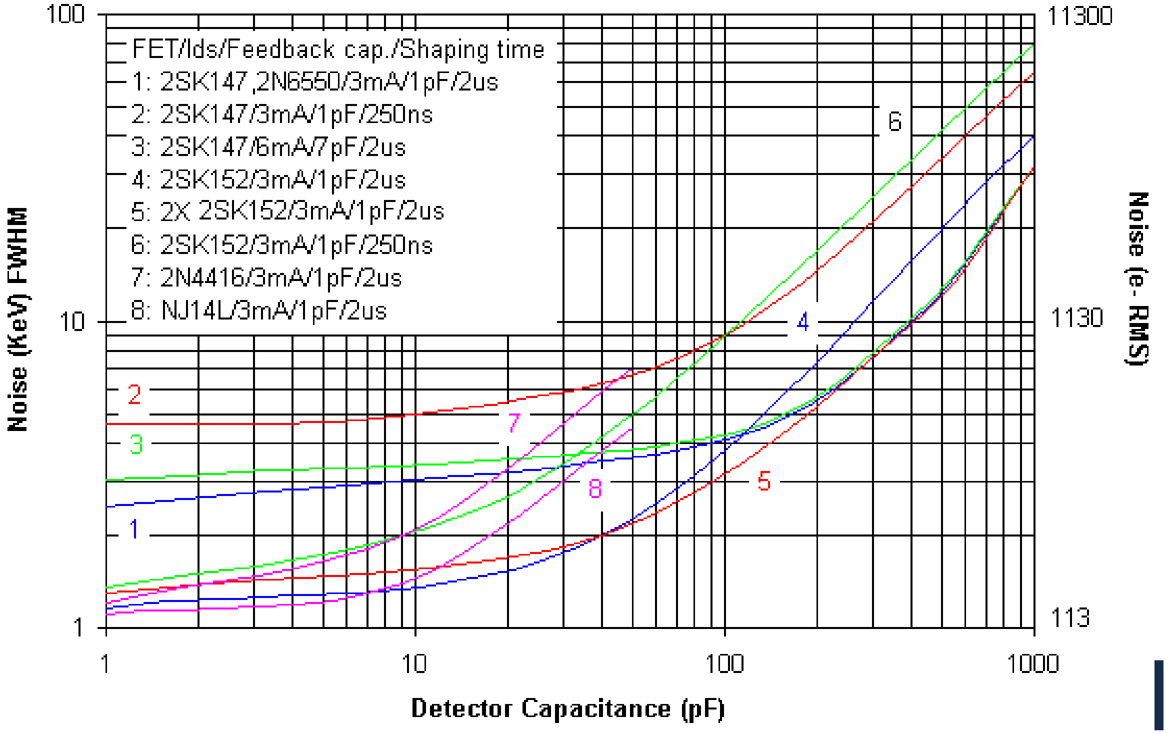
Continuous reset Charge amplifier

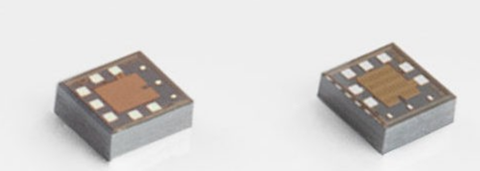


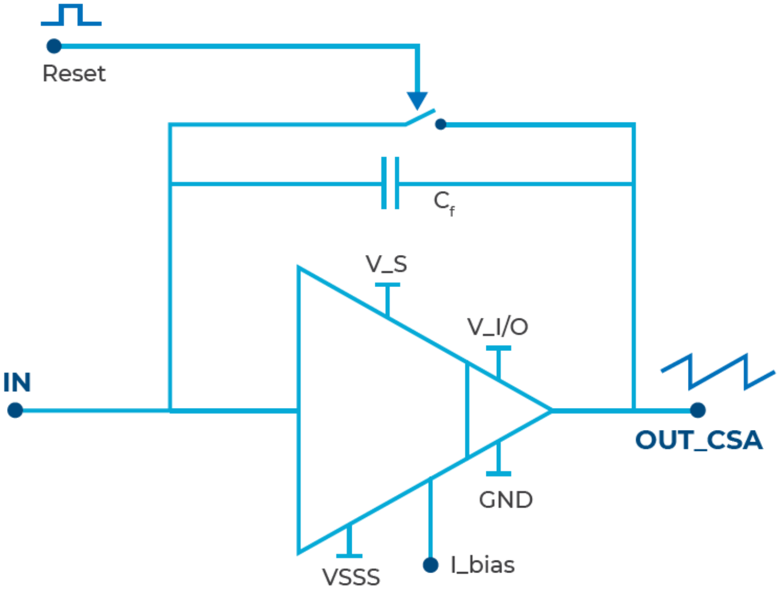
https://www.amptek.com/





Pulsed reset Charge amplifier

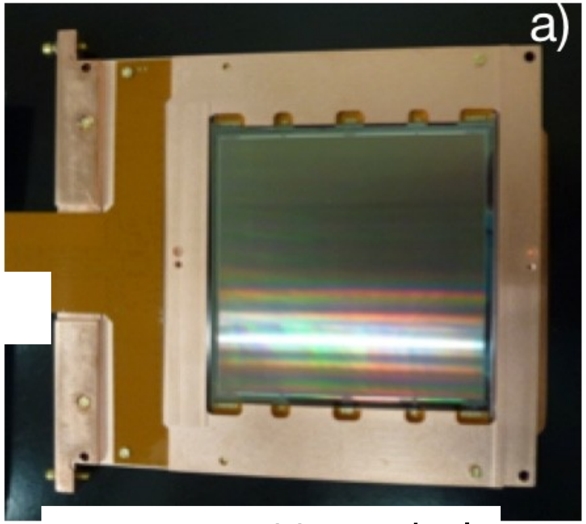




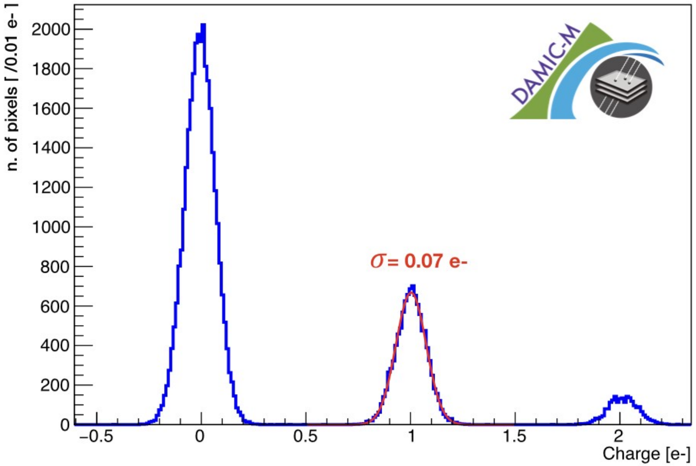
CUBE Version	Polarity	Detector capacitance [pF]	Feedback capacitance [fF]	ENC (CUBE only, 3.6 eV/e)
PRE_016	Negative (electrons)	< 0.25	25	3.3 e- @ 1 µs
PRE_031	Negative (electrons)	< 0.5	25	3.3 e- @ 1 µs
PRE_033	Negative (electrons)	<0.25	25	2.4e- @ 1us
PRE_037	Positive (holes)	< 0.70	25	4.0e- @1us
PRE_038	Positive (holes)	0.50 - 3.00	50	12.3 e- @1us
PRE_039	Positive (holes)	3.00-10.00	50	20.2e- @1us
PRE_040	Negative (electrons)	0.50-3.00	50	12.4e- @1us
PRE_041	Both (selectable)	3.00-10.00	500	57 e- @1us
PRE_042	Both (selectable)	0.50-3.00	500	35.5 e- @1us

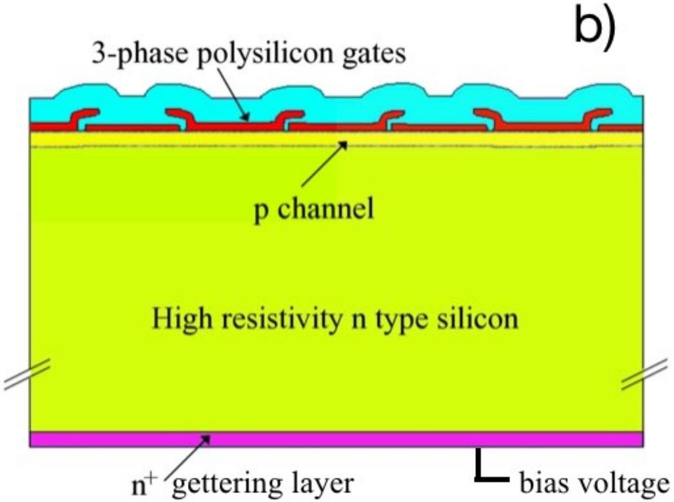
DAMIC

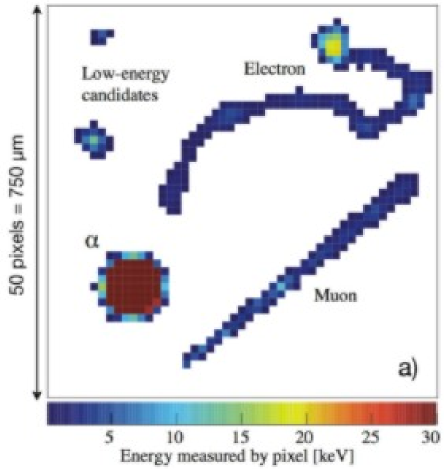
https://damic.uchicago.edu/detector.php

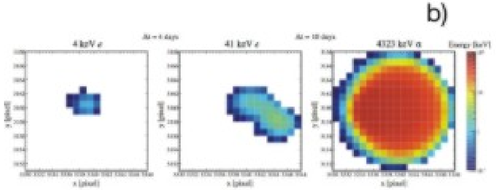


15 x 15 x 500 um pixel
Fully depleted









DAMIC

https://damic.uchicago.edu/c

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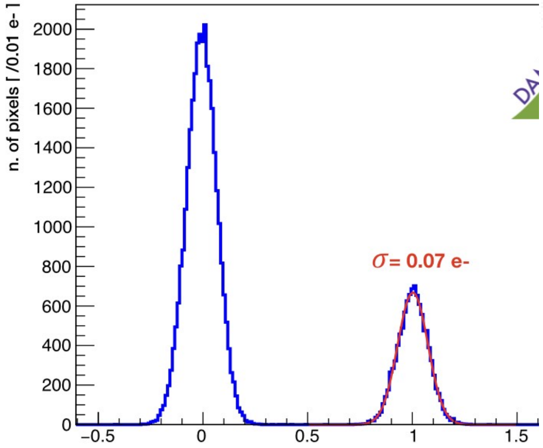

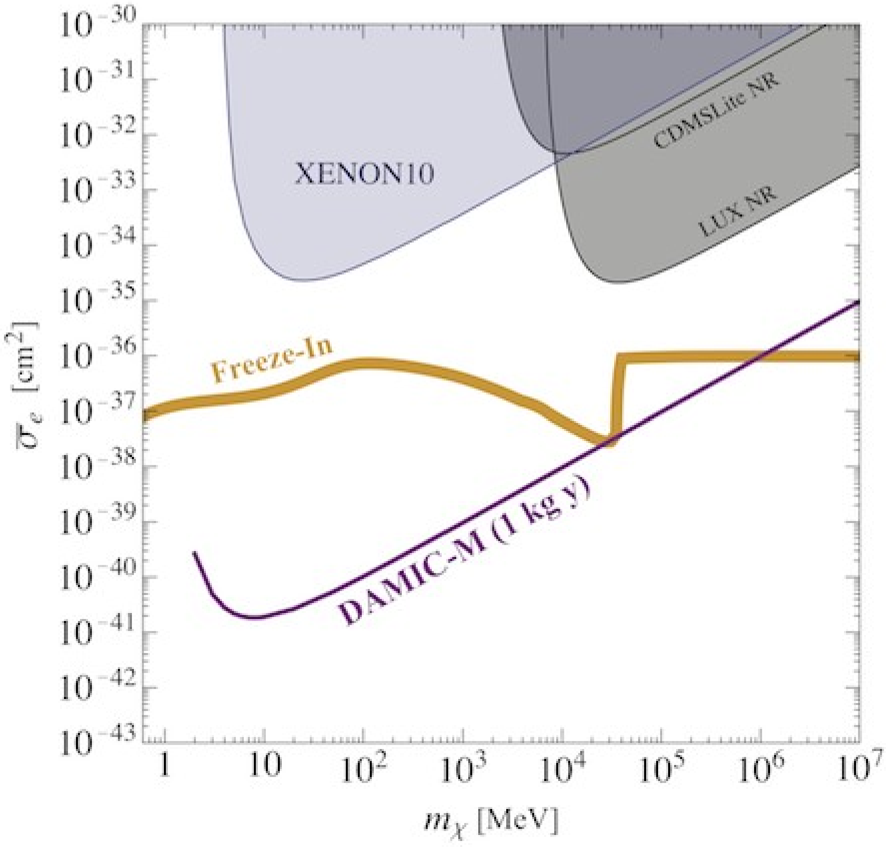

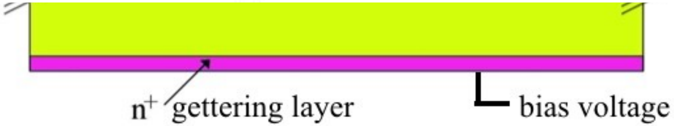

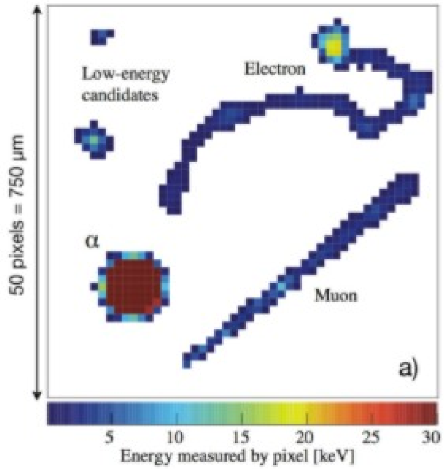

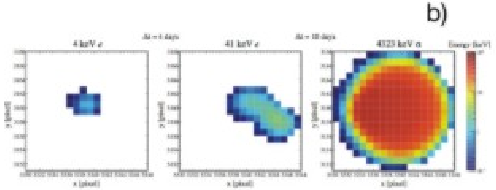

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