INFN SoUP 20|21

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

INFN

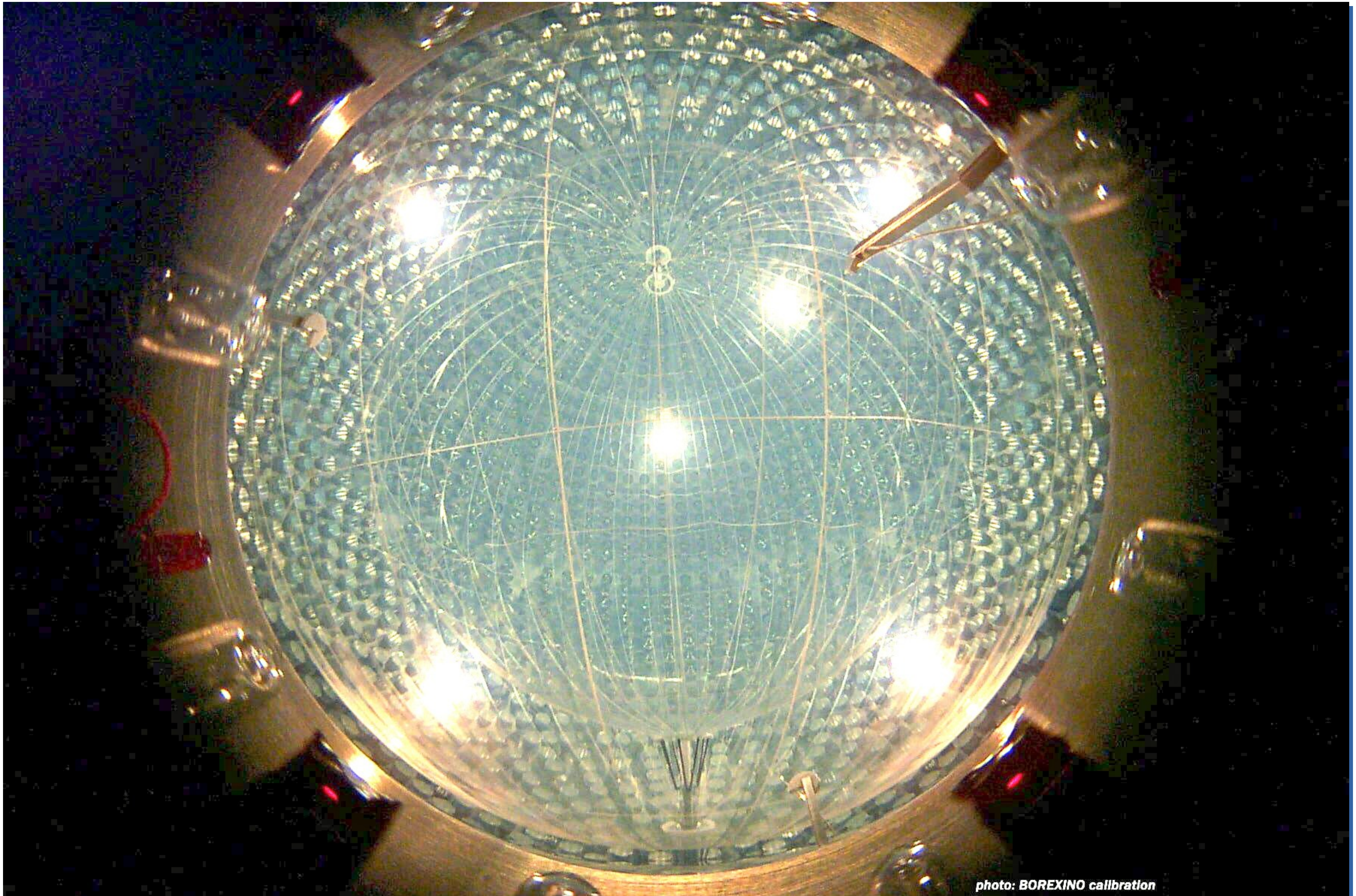

photo: BOREXINO calibration

Semiconductor detectors

Alessandro Razeto
Laboratori Nazionali del Gran Sasso

photo: BOREXINO calibration

References

- 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

Detection of physical quantities

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

Detection of physical quantities

- Light
- Particles
- Sound
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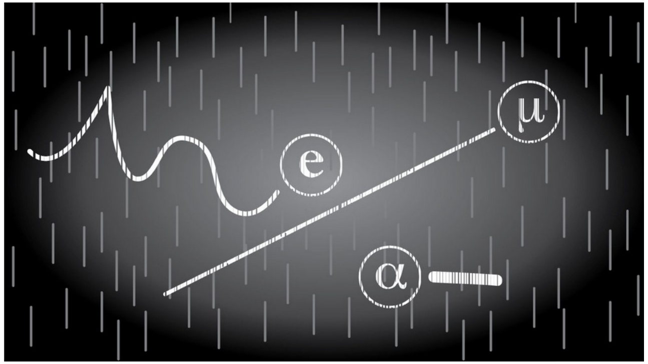
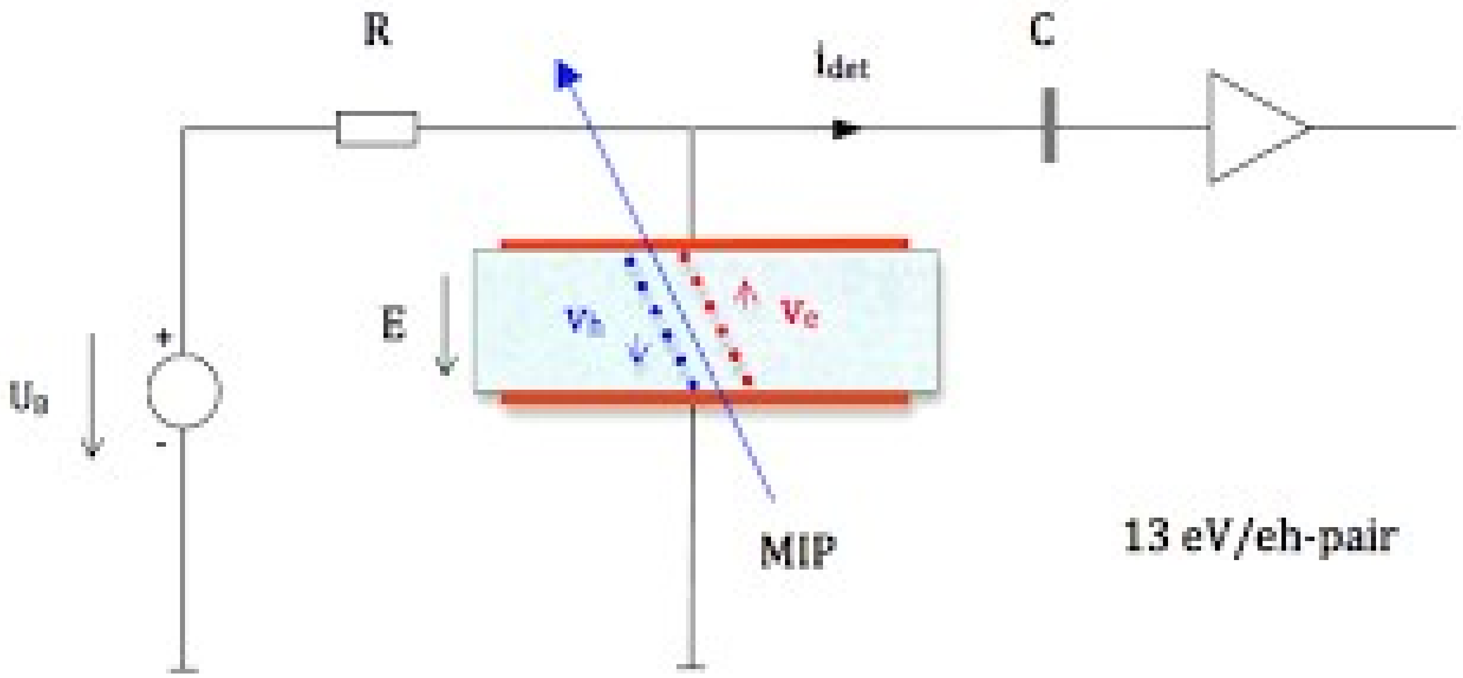
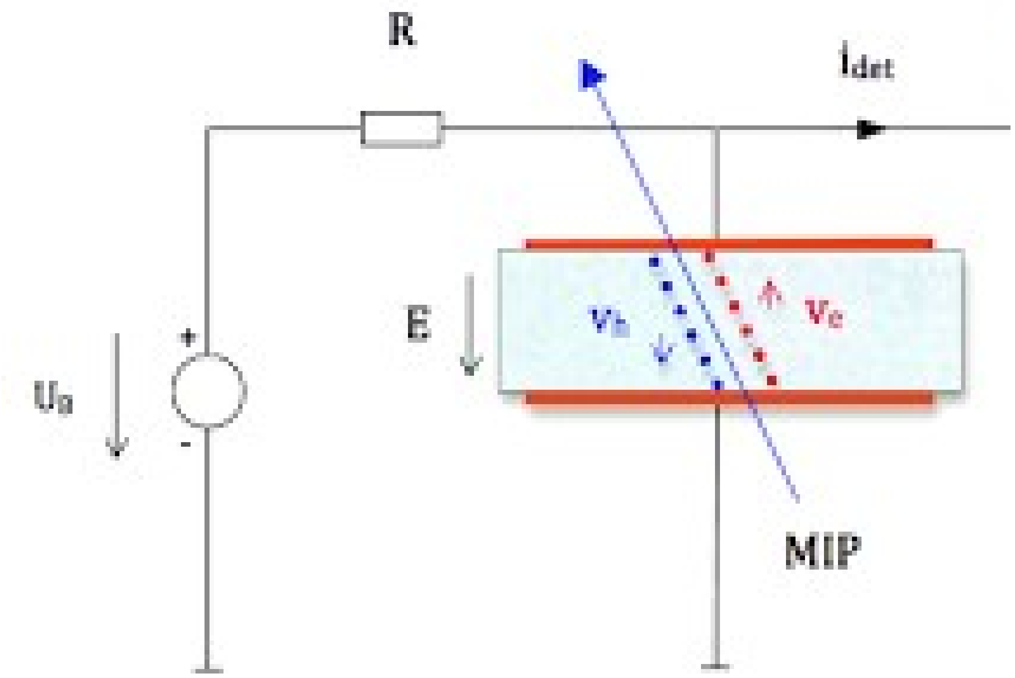
- Accelerations
- Temperature



Base design



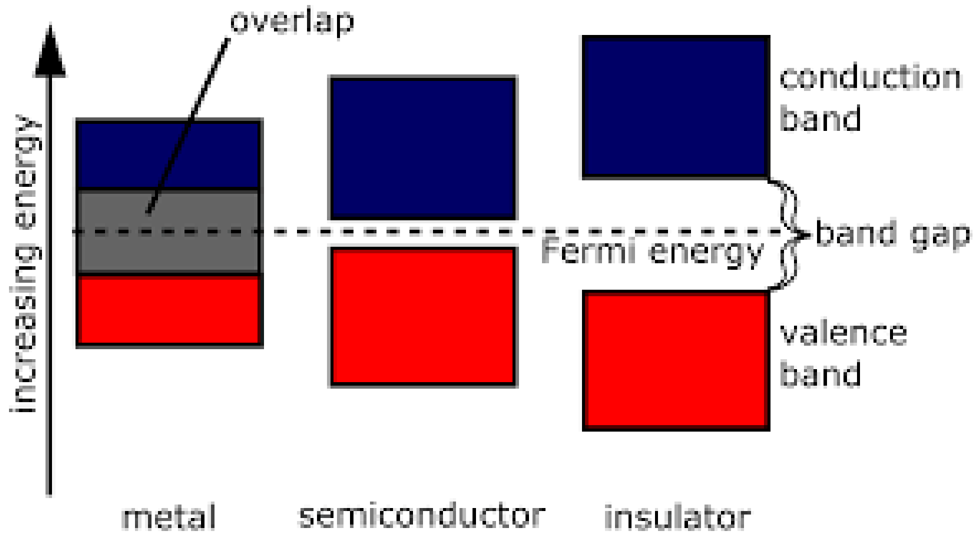
Base design



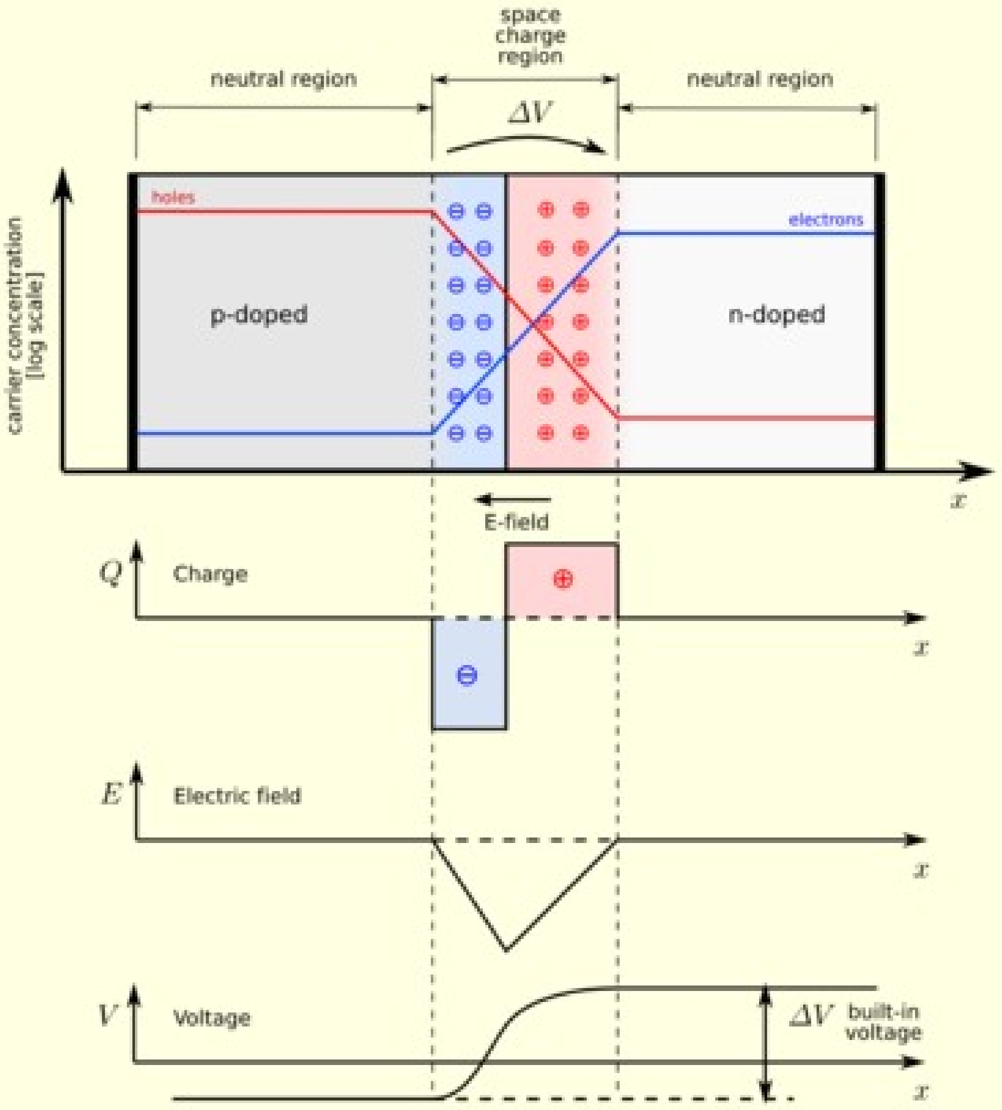
- Non conductive target + field
- A particle releases charge
- The charge is drifted
  - Amplified and acquired

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

Semiconductors



- 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

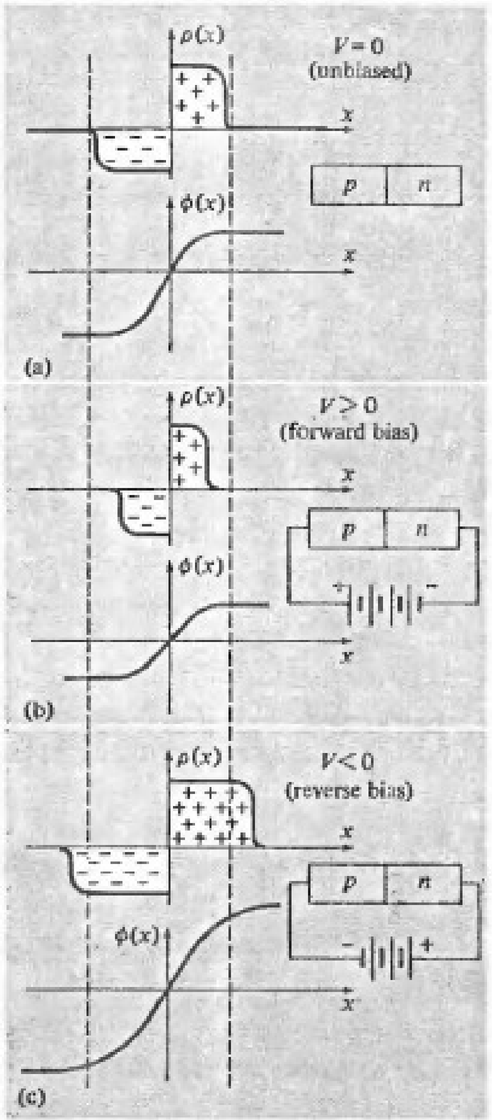


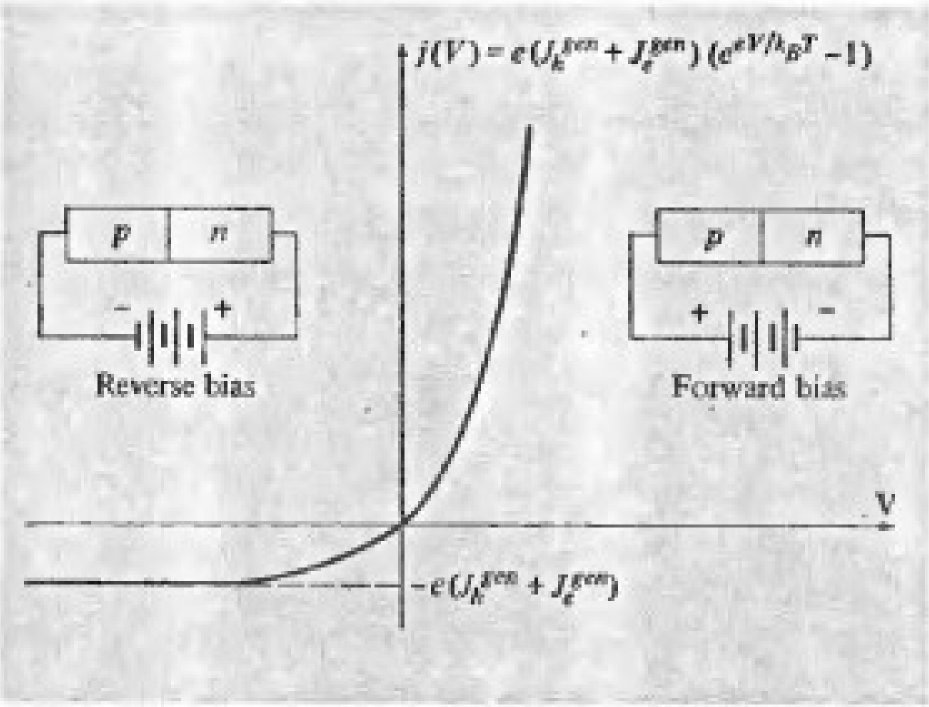
- Majority carriers diffusing on the other side of the junction recombine
  - Depletion layer
    - Capacitance

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

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

Shockley equation

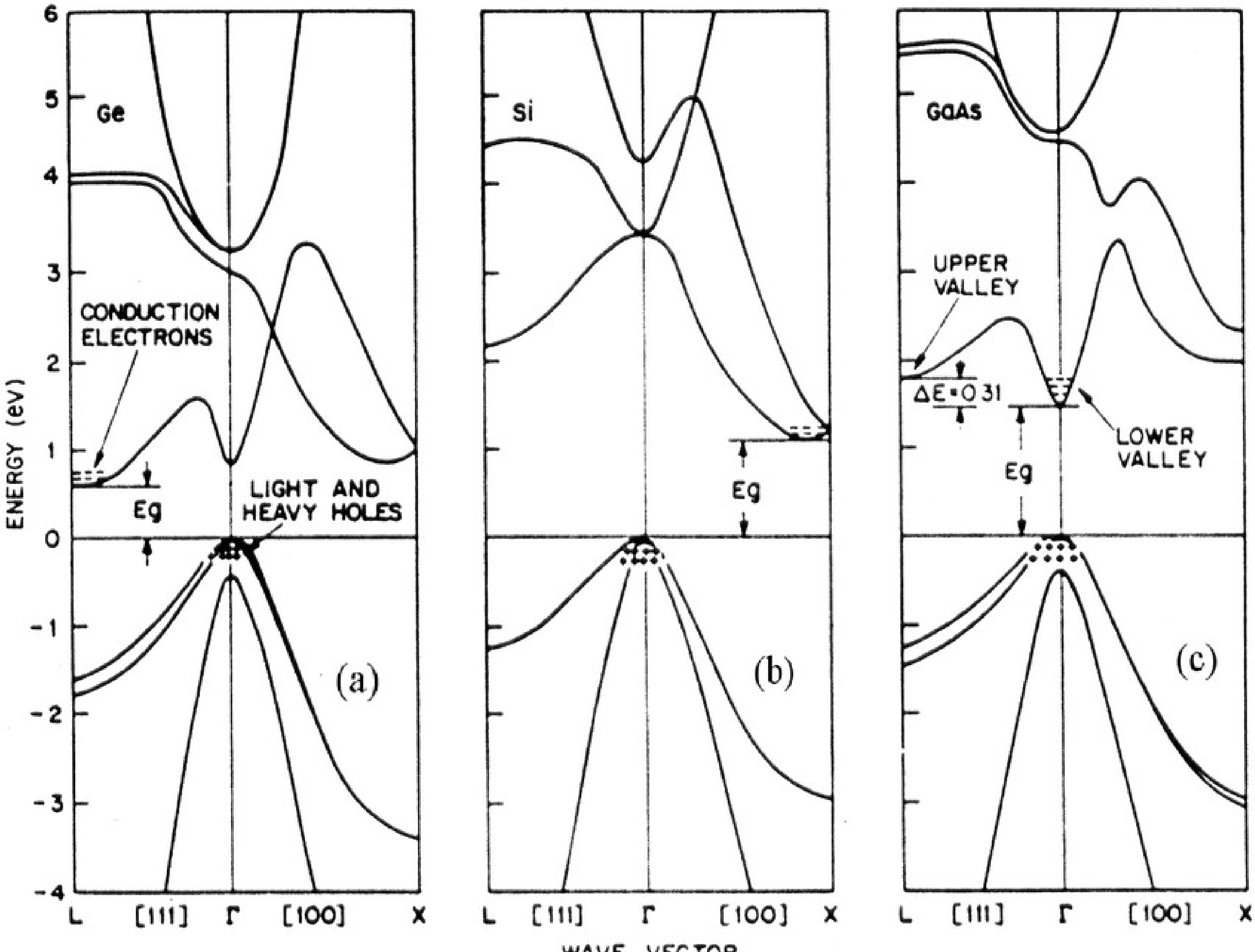




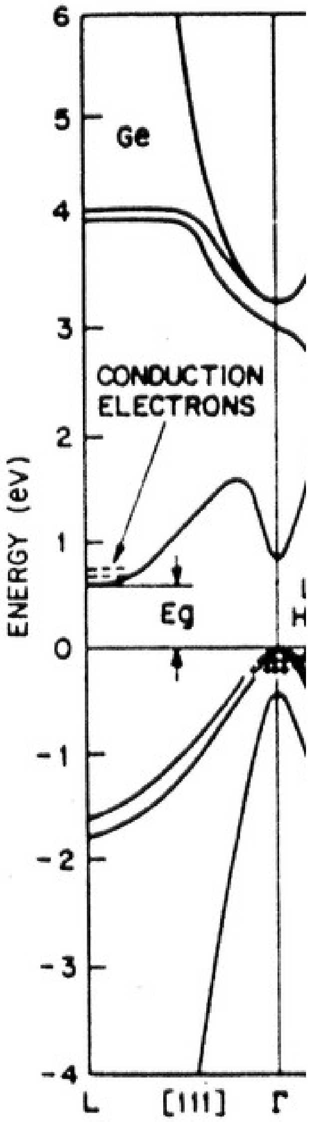
$$I = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

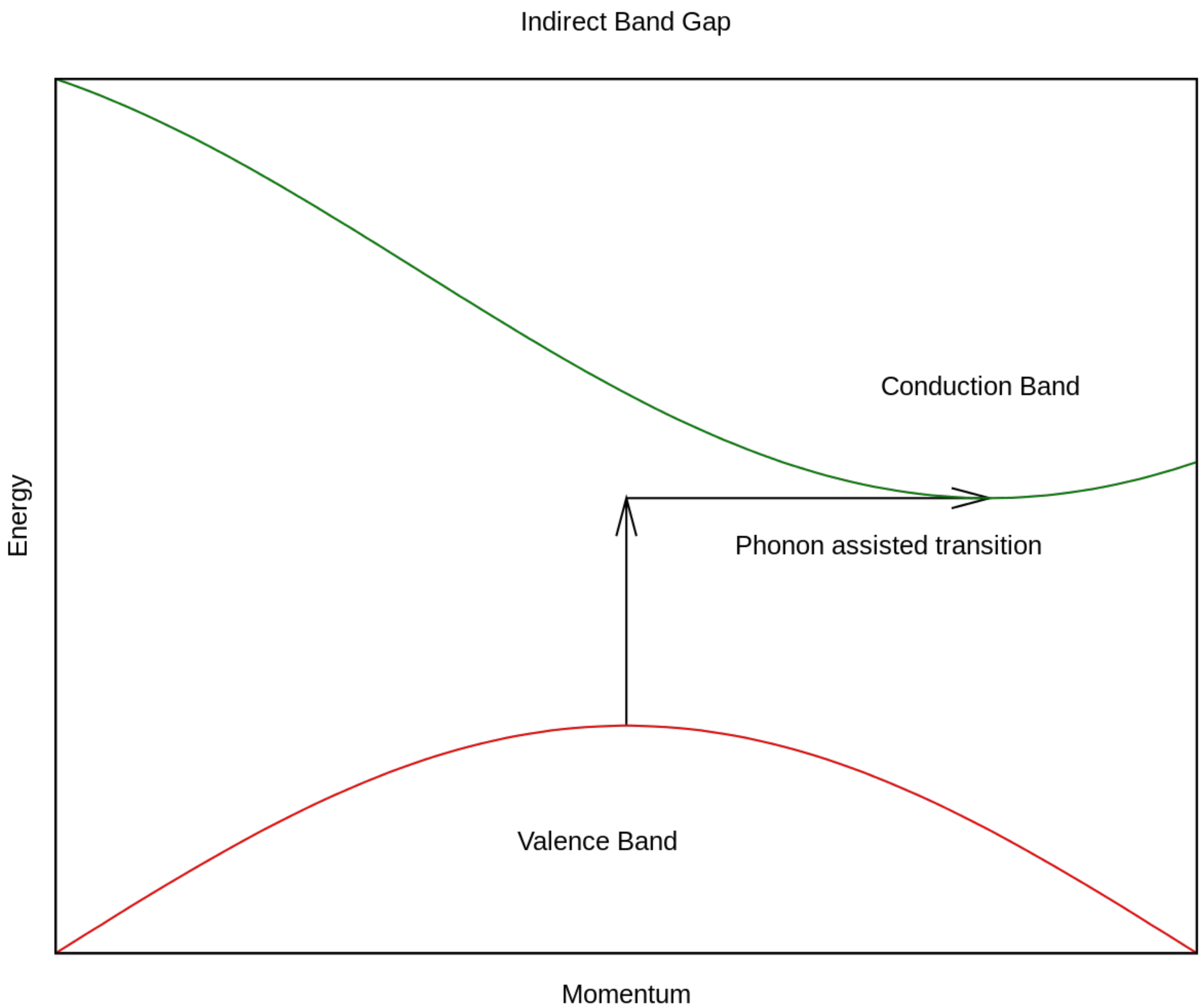
I_s ∝ # minority carriers ∝ exp(-1/T) * 1/doping

Band structure



$$E_{ev} = 1.24/L_{um}$$



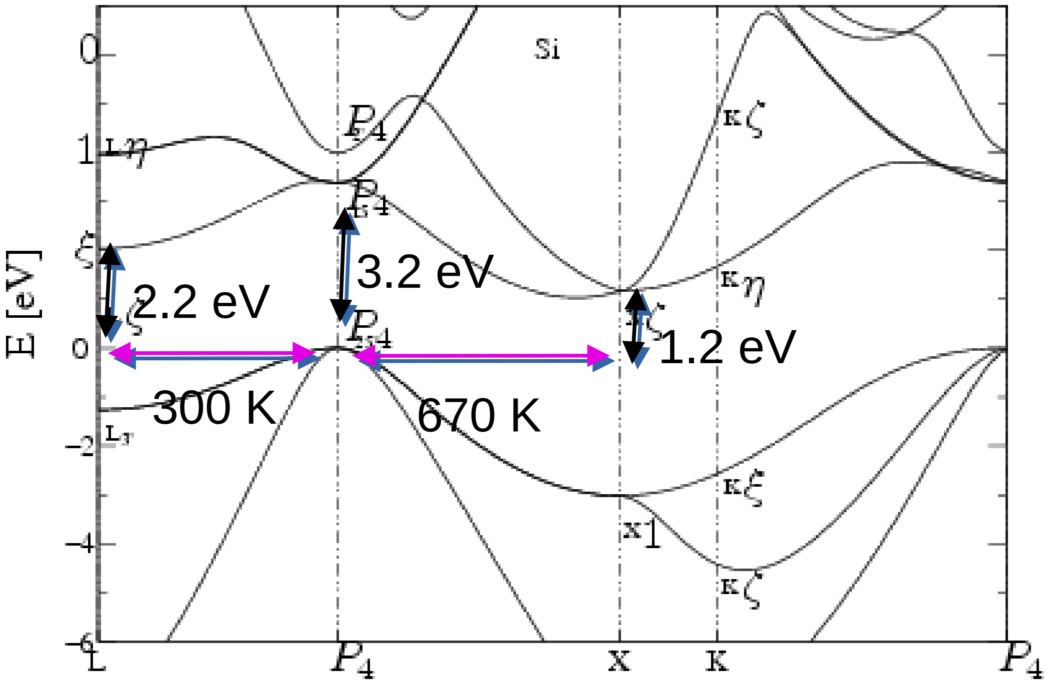


hool on Underground Physics

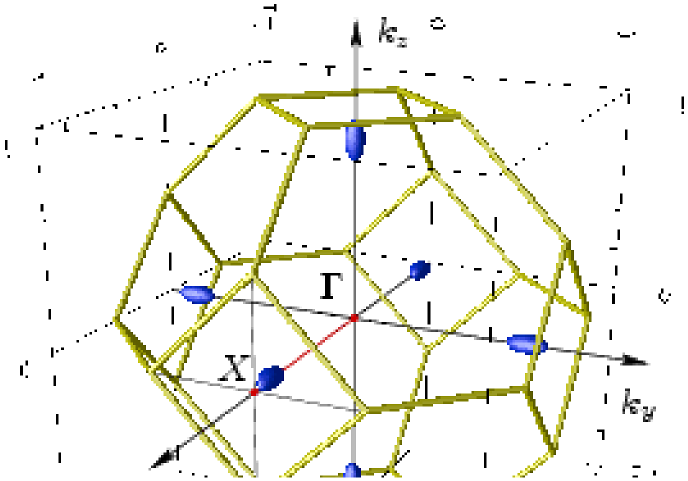
ucture

.24/Lum

Si structure



(a) Band diagram of silicon.

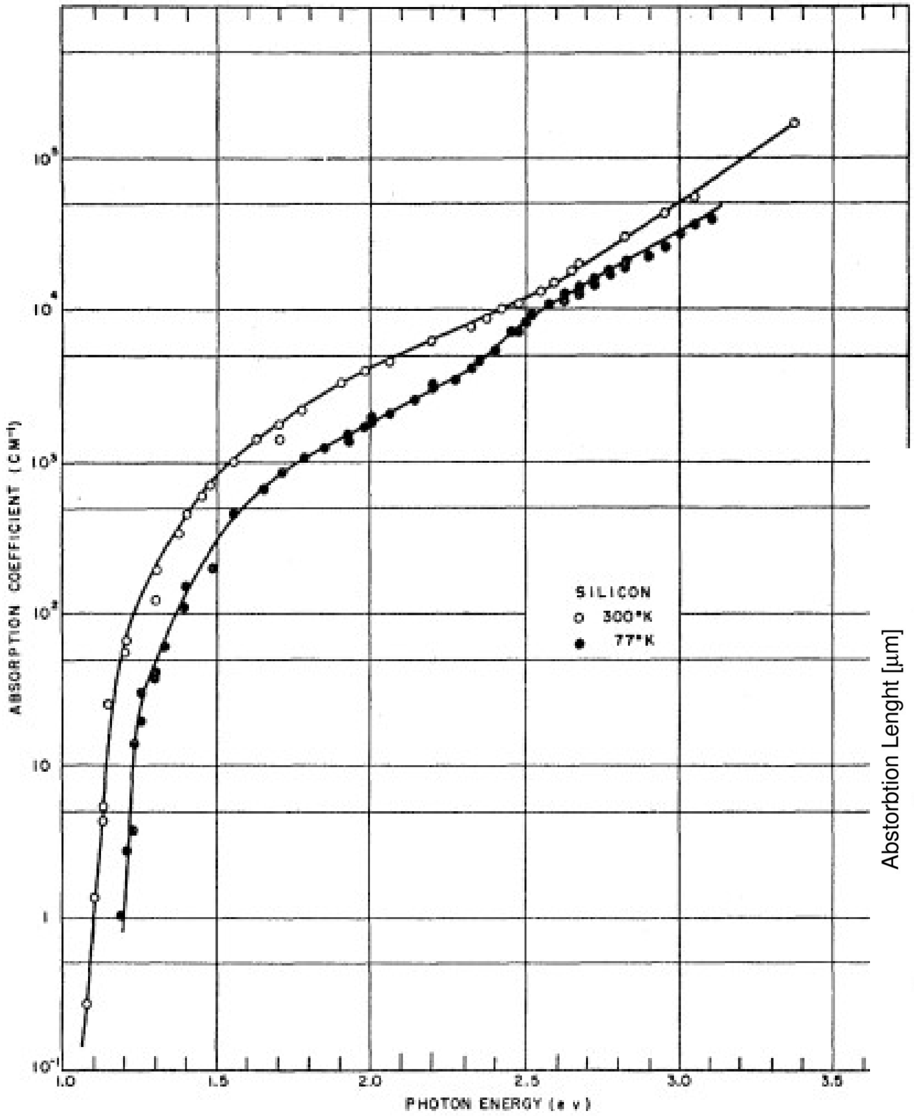


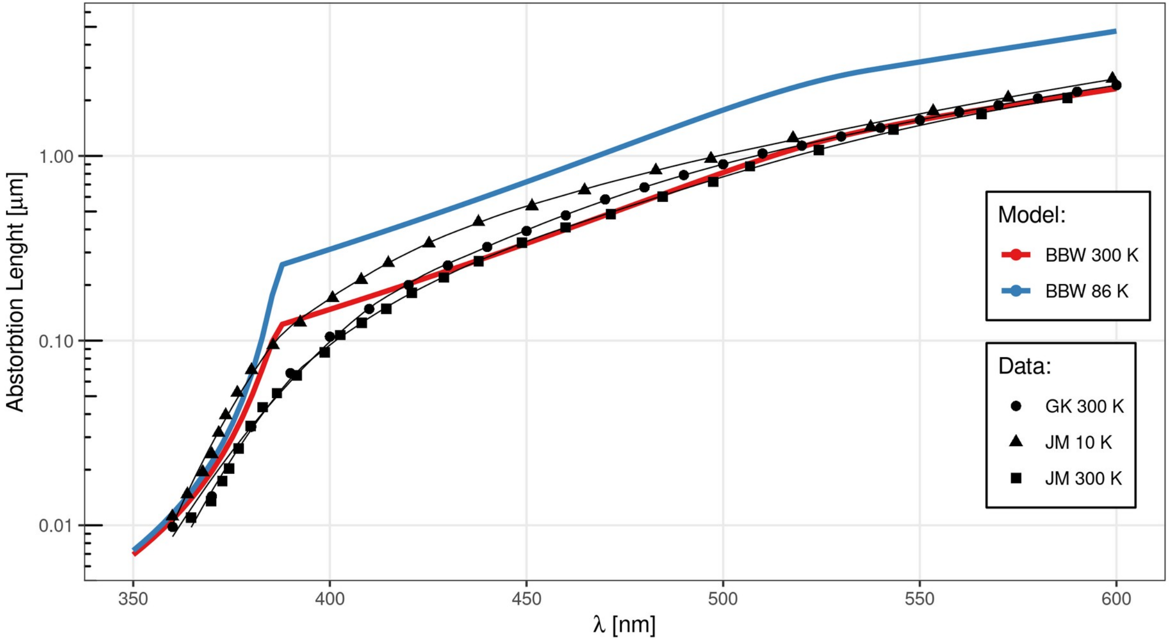
$$\alpha(T)=\sum_{\substack{i=\text{phonon }1,2\\ j=\text{band gap }1,2}} A_j C_i \frac{[h\nu-E_{g,j}(T)+E_{\text{ph},i}]^2}{\exp(E_{\text{ph},i}/kT)-1} + \frac{[h\nu-E_{g,j}(T)-E_{\text{ph},i}]^2}{1-\exp(-E_{\text{ph},i}/kT)} + \frac{A_d(h\nu-E_{g,d})^{3/2}}{h\nu}, \quad (4)$$

https://doi.org/10.1063/1.356496

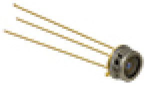
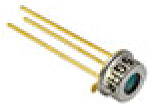
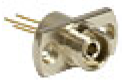
α in silicon

$E_{ev} = 1.24/L_{um}$



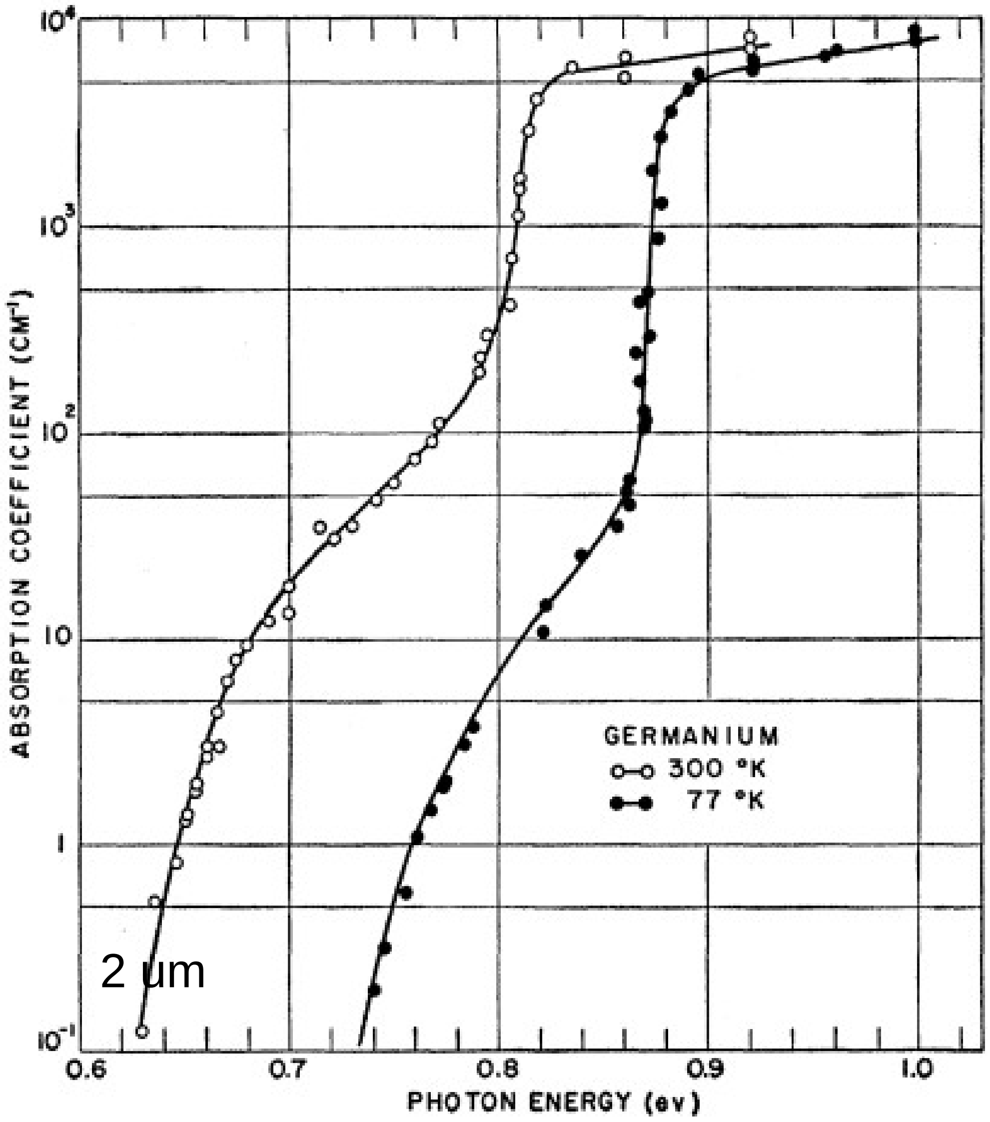


Si Photodiodes - VIS Wavelengths

Click Image for Details								
Item #	FDS010	FD11A	FDS10X10	FDS100	FDS1010	FDS015	FDS02	FDS025
Key Feature	High Speed, UV Grade Fused Silica Window to Provide Sensitivity Down to 200 nm	Lowest Dark Current in TO-18 Can with a Window	Low Dark Current in 10 mm x 10 mm Ceramic Package	High Speed, Largest Sensor in a TO-5 Can	High Speed, Large Active Area and Mounted on an Insulating Ceramic Substrate	Highest Speed and Lowest Capacitance in a TO-46 Can with an AR-Coated Window	High Speed and Low Capacitance in a Direct Fiber-Coupled FC/PC Package	High Speed and Low Capacitance in a TO-46 Can with a Ball Lens
Info	i	i	i	i	i	i	i	i
Wavelength Range	200 - 1100 nm[a]	320 - 1100 nm	340 - 1100 nm	350 - 1100 nm	350 - 1100 nm	400 - 1100 nm	400 - 1100 nm	400 - 1100 nm
Active Area	0.8 mm^2 (Ø1.0 mm)	1.21 mm^2 (1.1 mm x 1.1 mm)	100 mm^2 (10 mm x 10 mm)	13 mm^2 (3.6 mm x 3.6 mm)	100 mm^2 (10 mm x 10 mm)	0.018 mm^2 (Ø150 µm)	0.049 mm^2 (Ø0.25 mm)	0.049 mm^2 (Ø0.25 mm)
Rise/Fall Time[b]	1 ns / 1 ns @ 830 nm, 10 V	400 ns[c,d] @ 650 nm, 0 V	150 ns / 150 ns[d] @ 5 V	10 ns / 10 ns[d] @ 632 nm, 20 V	65 ns / 65 ns[d] @ 632 nm, 5 V	35 ps / 200 ps @ 850 nm, 5 V	47 ps / 246 ps @ 850 nm, 5 V	47 ps / 246 ps @ 850 nm, 5 V
NEP ($W/Hz^{1/2}$)	5.0×10^{-14} @ 830 nm, 10 V	6.8×10^{-16} @ 960 nm, 0 V	1.50×10^{-14} @ 960 nm	1.2×10^{-14} @ 900 nm, 20 V	2.07×10^{-13} @ 970 nm, 5 V	8.60×10^{-15} @ 850 nm, 5 V	9.29×10^{-15} @ 850 nm, 5 V	9.29×10^{-15} @ 850 nm, 5 V
Dark Current	0.3 nA (Typ.) @ 10 V	2.0 pA (Max) @ 10 mV	200 pA @ 5 V	1.0 nA (Typ.) @ 20 V	600 nA (Max) @ 5 V	0.03 nA (Typ.) @ 5 V	35 pA (Typ.) @ 5 V	35 pA (Typ.) @ 5 V
Junction Capacitance	6 pF (Typ.) @ 10 V	140 pF (Typ.) @ 0 V	380 pF @ 5 V	24 pF (Typ.) @ 20 V	375 pF (Typ.) @ 5 V	0.65 pF (Typ.) @ 5 V	0.94 pF (Typ.) @ 5 V	0.94 pF (Typ.) @ 5 V
Package	TO-5	TO-18	Ceramic	TO-5	Ceramic	TO-46	TO-46, FC/PC Bulkhead	TO-46
Compatible Sockets	STO5S STO5P	STO46S STO46P	Not Available	STO5S STO5P	Not Available	STO46S STO46P	STO46S STO46P	STO46S STO46P

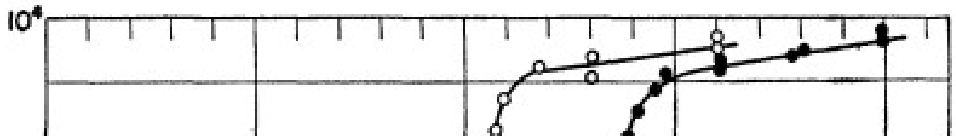
PHOTON ENERGY (e v)

& Ge?



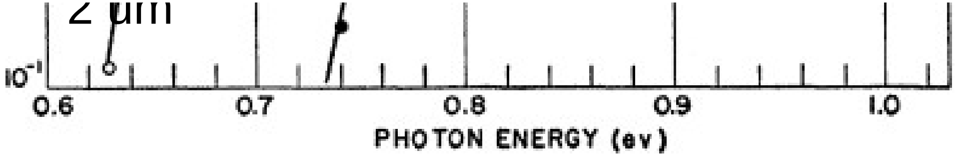
ABSORPTION COEFFICIENT (CM⁻¹)
PHOTON ENERGY (ev)
GERMANIUM
300 °K
77 °K
0.6
0.7
0.8
0.9
1.0
2 um

& Ge?



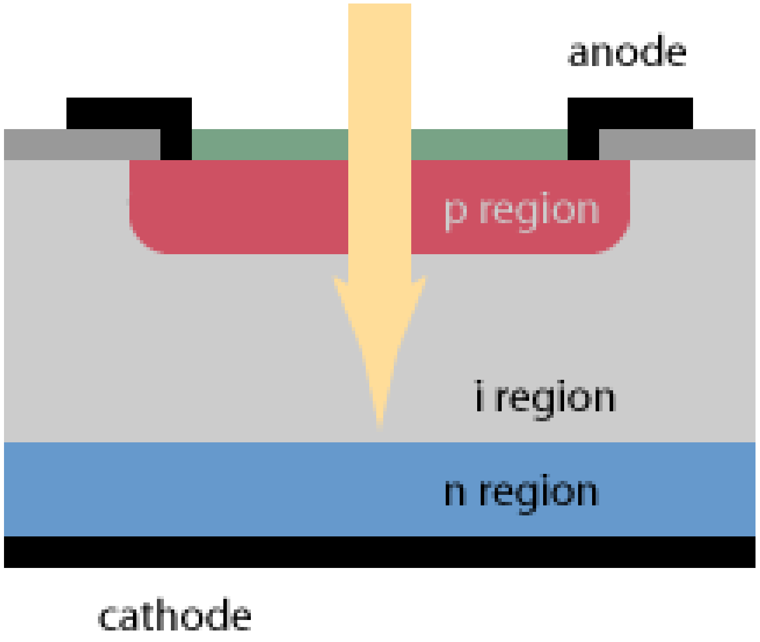
Ge Photodiodes - NIR Wavelengths

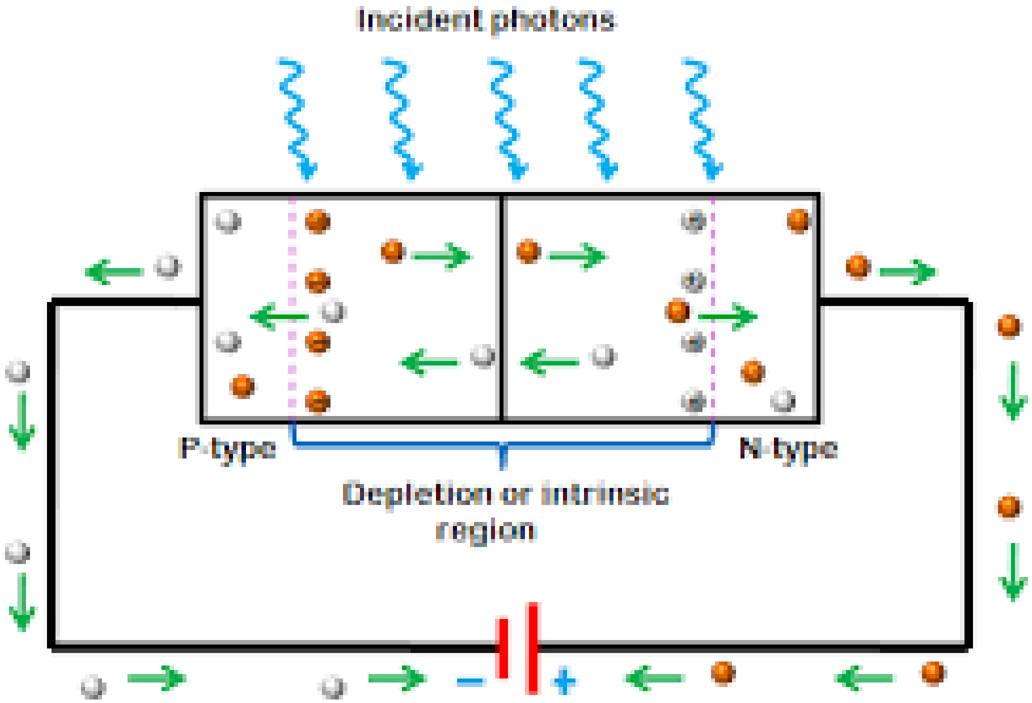
Click Image for Details				
Item #	FDG03	FDG05[a]	FDG50	FDG10X10
Key Feature	Large Active Area in a TO-5 Can	High Speed on a Ceramic Substrate	Large Active Area in a TO-8 Can	Largest Active Area
Info	i	i	i	i
Wavelength Range	800 - 1800 nm	800 - 1800 nm	800 - 1800 nm	800 - 1800 nm
Active Area	7.1 mm^2 (Ø3 mm)	19.6 mm^2 (Ø5 mm)	19.6 mm^2 (Ø5 mm)	100 mm^2 (10 mm x 10 mm)
Rise/Fall Time[b]	600 ns / 600 ns @ 3 V	220 ns / 220 ns @ 3 V	220 ns / 220 ns (Typ.) @ 10 V	10 µs (Typ.) @ 1 V
NEP	2.6 x 10^{-12} $W/Hz^{1/2}$ @ 1550 nm	4.0 x 10^{-12} $W/Hz^{1/2}$ @ 1550 nm	4.0 x 10^{-12} $W/Hz^{1/2}$ @ 1550 nm	4.0 x 10^{-12} $W/Hz^{1/2}$ @ 1550 nm[c]
Dark Current	4.0 µA (Max) @ 1 V	40 µA (Max) @ 3 V	60 µA (Max) @ 5 V	50 µA (Max) @ 0.3 V
Junction Capacitance	6 nF (Typ.) @ 1 V 4.5 nF (Typ.) @ 3 V	3000 pF (Typ.) @ 3 V	1800 pF (Max) @ 5 V 16000 pF (Max) @ 0 V	80 nF (Typ.) @ 1 V 135 nF (Typ.) @ 0 V
Shunt Resistance	25 kΩ (Min)	-	4 kΩ (Typ.)	2 kΩ (Min)
Package	TO-5	Ceramic	TO-8	Ceramic
Compatible Sockets	STO5S STO5P	Not Available	STO8S STO8P	Not Available



INFN LNGS

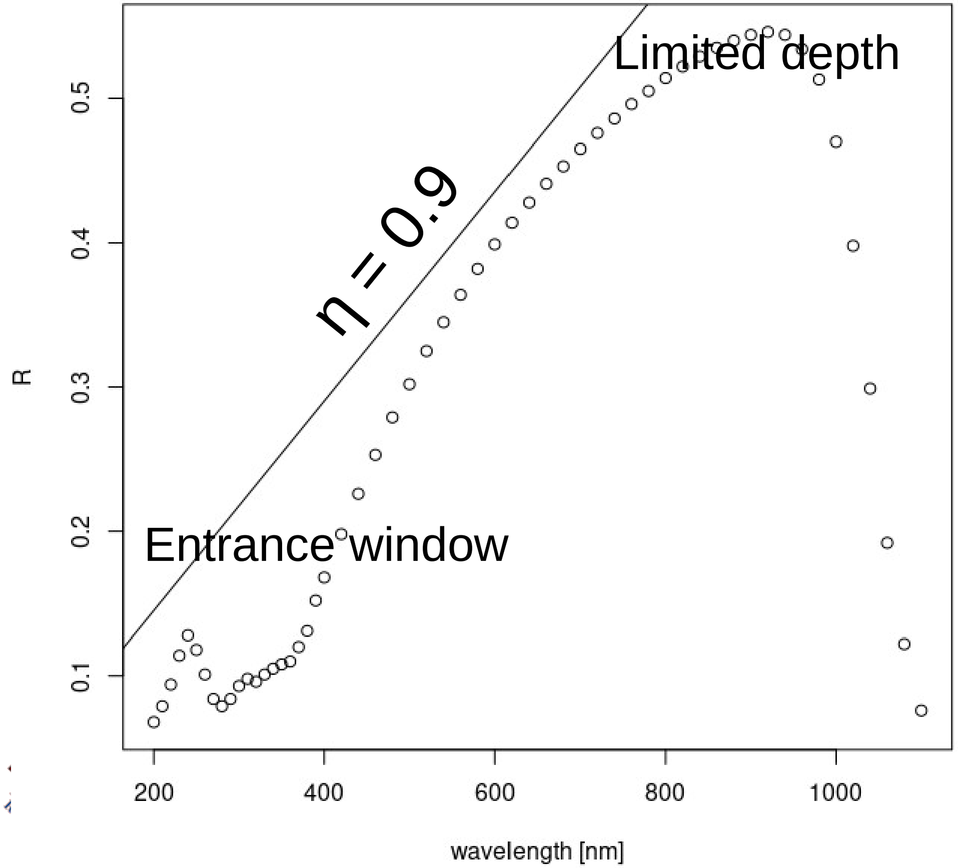
Photodiode structure

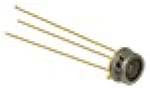




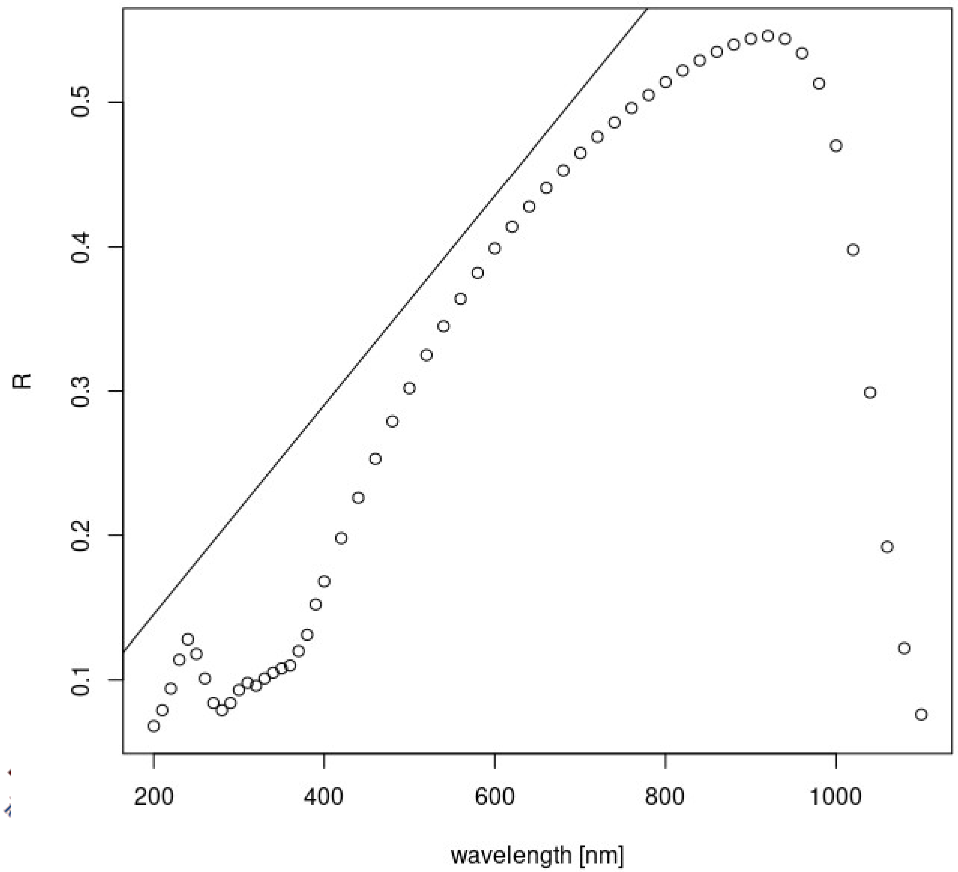
I = *R* * P = η q / h ν * P = η λ[um] / 1.24 * P

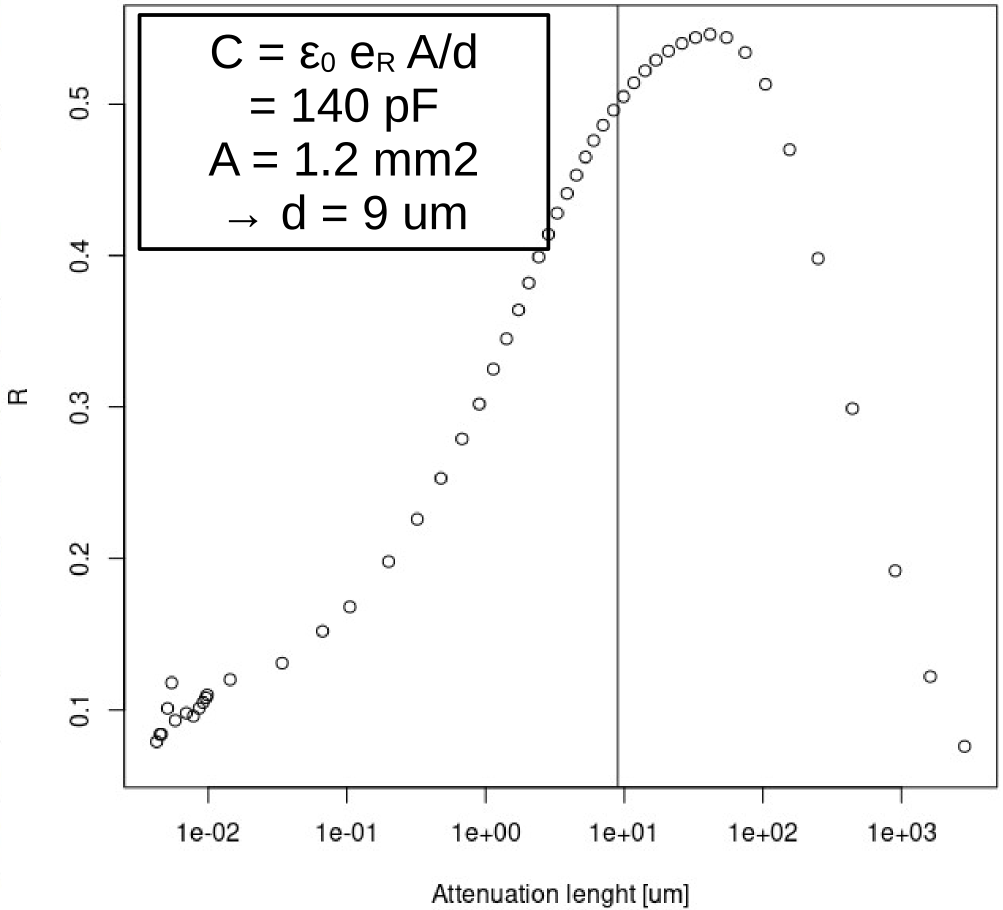
Responsivity



Click Image for Details		
Item #	FDS010	FD11A
Key Feature	High Speed, UV Grade Fused Silica Window to Provide Sensitivity Down to 200 nm	Lowest Dark Current in TO-18 Can with a Window
Info		
Wavelength Range	200 - 1100 nm[a]	320 - 1100 nm
Active Area	0.8 mm^2 (Ø1.0 mm)	1.21 mm^2 (1.1 mm x 1.1 mm)
Rise/Fall Time[b]	1 ns / 1 ns @ 830 nm, 10 V	400 nsc[c,d] @ 650 nm, 0 V
NEP ($W/Hz^{1/2}$)	5.0 x 10^{-14} @ 830 nm, 10 V	6.8 x 10^{-16} @ 960 nm, 0 V
Dark Current	0.3 nA (Typ.) @ 10 V	2.0 pA (Max) @ 10 mV
Junction Capacitance	6 pF (Typ.) @ 10 V	140 pF (Typ.) @ 0 V
Package	TO-5	TO-18
Compatible Sockets	STO5S STO5P	STO46S STO46P

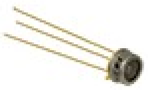
Responsivity





Dark Current & NEP

- Couples are generated spontaneously
  - I_{gen} in PN junction
- Then there is the leakage current
  - Surface effects
  - Bulk effects
- NEP = noise power density
  - Minimum power that can be detected
  - NEP > shot noise of the dark current
    - $\sim \sqrt{(2 e^{-} I\, BW)} / R$
  - If you want to see a signal at 10 kHz $\rightarrow P_n$ = 70 aW
    = 0.2 Mph/s

Click Image for Details		
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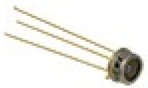
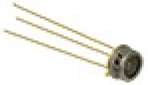
Rise/Fall Time[b]	1 ns / 1 ns @ 830 nm, 10 V	400 ns[c,d] @ 650 nm, 0 V
NEP (W/Hz$^{1/2}$)	5.0 x 10^{-14} @ 830 nm, 10 V	6.8 x 10^{-16} @ 960 nm, 0 V
Dark Current	0.3 nA (Typ.) @ 10 V	2.0 pA (Max) @ 10 mV
Junction Capacitance	6 pF (Typ.) @ 10 V	140 pF (Typ.) @ 0 V
Package	TO-5	TO-18
Compatible Sockets	STO5S STO5P	STO46S STO46P

Dark Current & NEP

- Couples are genera
  - I_{gen} in PN junction
- Then there is the lea
  - Surface effects
  - Bulk effects
- NEP = noise power
  - Minimum power th
  - NEP > shot noise
    - ~ $\sqrt{(2 e^- I\ BW)}$ / R
  - If you want to see

Click Image for Details			
Item #	FDS010	FD11A	FDS10X10
Key Feature	High Speed, UV Grade Fused Silica Window to Provide Sensitivity Down to 200 nm	Lowest Dark Current in TO-18 Can with a Window	Low Dark Current in 10 mm x 10 mm Ceramic Package
Info	i	i	i
Wavelength Range	200 - 1100 nm[a]	320 - 1100 nm	340 - 1100 nm
Active Area	0.8 mm^2 (Ø1.0 mm)	1.21 mm^2 (1.1 mm x 1.1 mm)	100 mm^2 (10 mm x 10 mm)
Rise/Fall Time[b]	1 ns / 1 ns @ 830 nm, 10 V	400 ns[c,d] @ 650 nm, 0 V	150 ns / 150 ns[d] @ 5 V
NEP ($W/Hz^{1/2}$)	5.0 x 10^{-14} @ 830 nm, 10 V	6.8 x 10^{-16} @ 960 nm, 0 V	1.50 x 10^{-14} @ 960 nm
Dark Current	0.3 nA (Typ.) @ 10 V	2.0 pA (Max) @ 10 mV	200 pA @ 5 V
Junction Capacitance	6 pF (Typ.) @ 10 V	140 pF (Typ.) @ 0 V	380 pF @ 5 V
Package	TO-5	TO-18	Ceramic
Compatible Sockets	STO5S STO5P	STO46S STO46P	Not Available

Click Image for Details		
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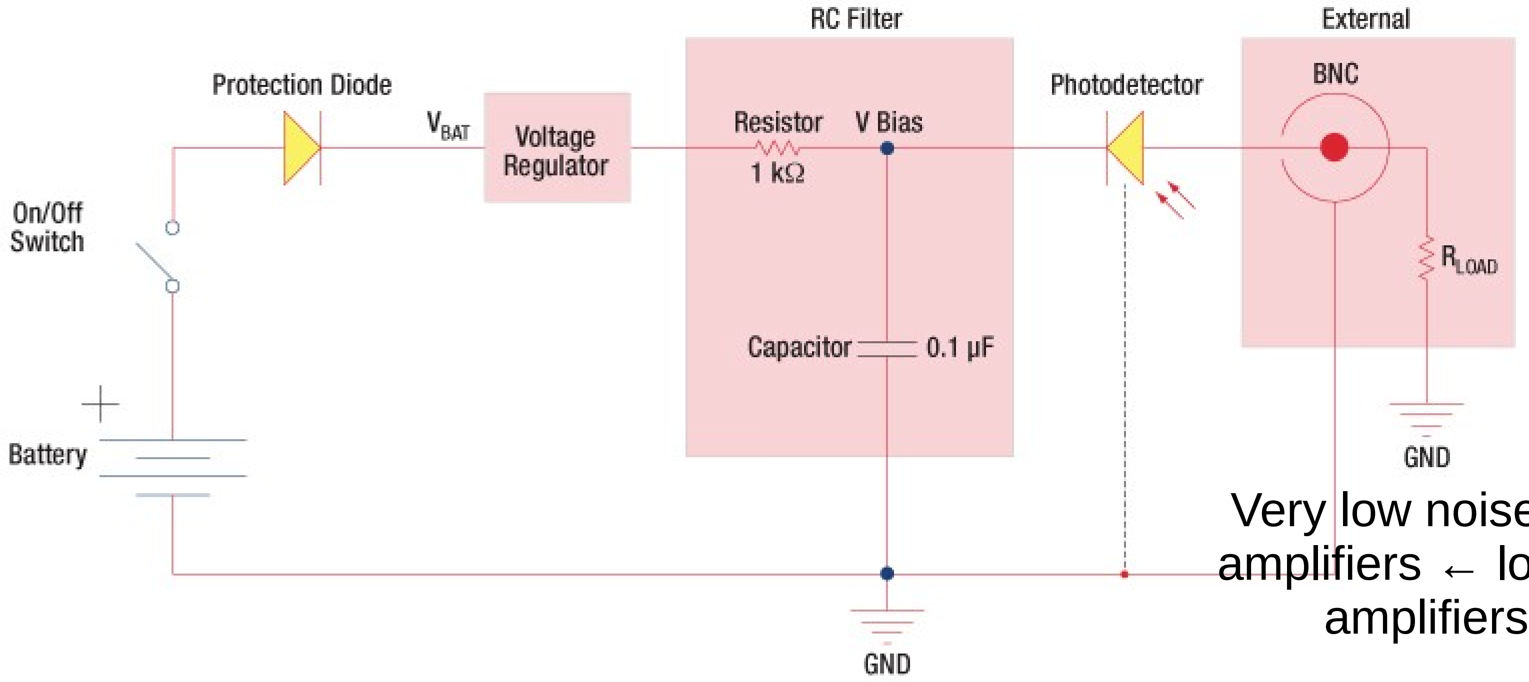
Junction Capacitance	6 pF (Typ.) @ 10 V	140 pF (Typ.) @ 0 V
Package	TO-5	TO-18
Compatible Sockets	STO5S STO5P	STO46S STO46P

Linearity & Speed

The 1st INFN School on Underground Physics

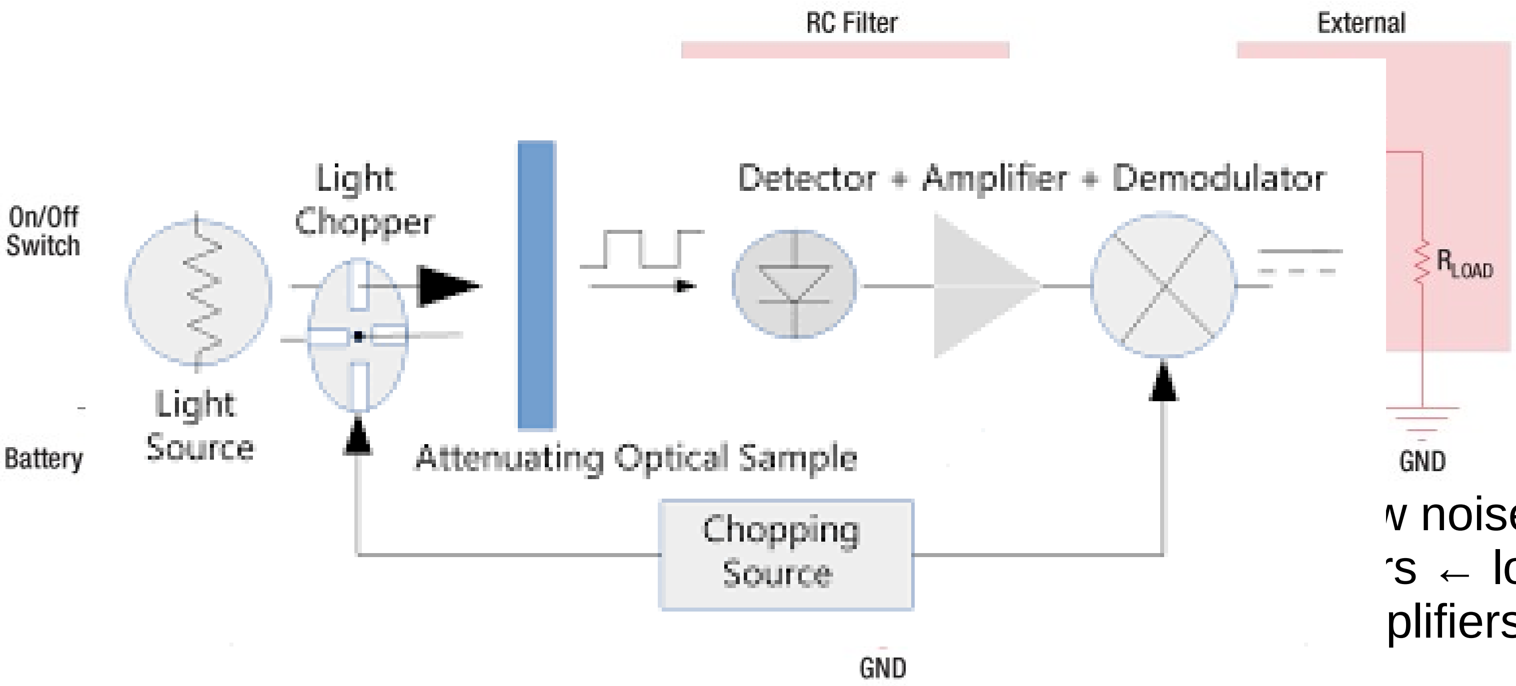
- PN/PIN photo-diodes are the most linear device we know
  - From pW to W
    - Just remember to keep the temperature constant
- In telecommunication and for many particle detector speed is important
  - Up to sub-ps

Read-out – DC circuit



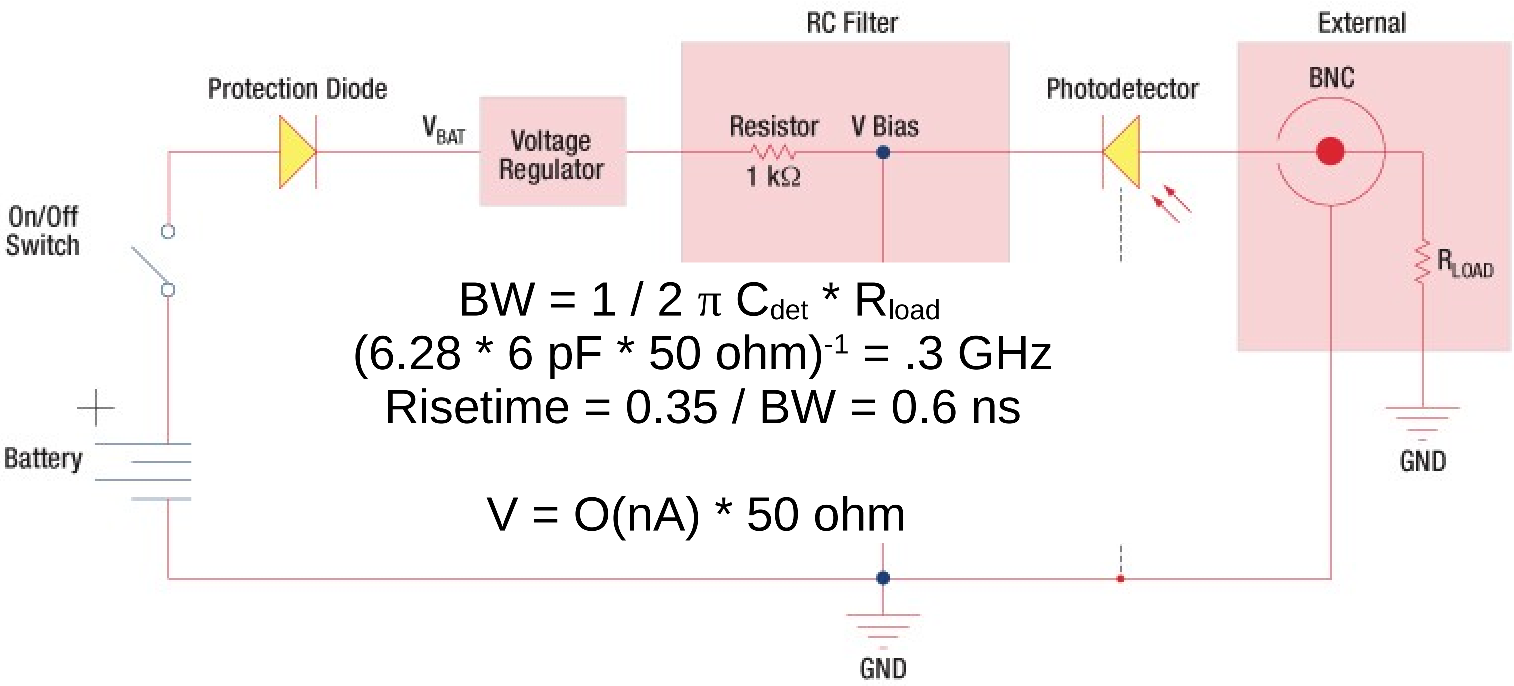
Very low noise DC amplifiers ← lock-in amplifiers

Read-out – DC circuit



v noise DC
rs ← lock-in
plifiers

Read-out – DC circuit



$$BW = 1 / 2\pi C_{det} * R_{load}$$

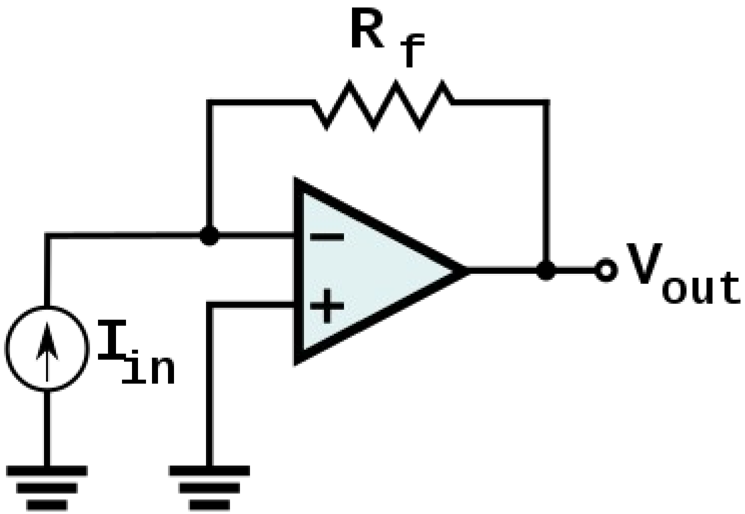
$$(6.28 * 6\ pF * 50\ ohm)^{-1} = .3\ GHz$$

$$Risetime = 0.35 / BW = 0.6\ ns$$

$$V = O(nA) * 50\ ohm$$

Charge Amplifier for AC ?

Trans-impedance amplifier



- The standard for telecommunication
- Can be very very fast
  - Used for > 100 gbit/s optical transmissions
- Simpler idea than charge amp
  - At first view the design is the same
  - But the implications and the problems are very different
    - Except for detector capacitance

OPA855 8-GHz Gain Bandwidth Product, Gain of 7-V/V Stable, Bipolar Input Amplifier

1 Features

- High Gain Bandwidth Product: 8 GHz
- Decompensated, Gain ≥ 7 V/V (Stable)
- Low Input Voltage Noise: 0.98 nV/√Hz
- Slew Rate: 2750 V/µs
- Low Input Capacitance:
  - Common-Mode: 0.6 pF
  - Differential: 0.2 pF
- Wide Input Common-Mode Range:
  - 0.4 V from Positive Supply
  - 1.1 V from Negative Supply
- 3 V_{PP} Total Output Swing
- Supply Voltage Range: 3.3 V to 5.25 V
- Quiescent Current: 17.8 mA
- Package: 8-Pin WSON
- Temperature Range: –40 to +125°C

2 Applications

- High-Speed Transimpedance Amplifier
- Laser Distance Measurement
- CCD Output Buffer
- High-Speed Buffer
- Optical Time Domain Reflectometry (OTDR)
- High-Speed Active Filter
- 3D Scanner
- Silicon Photomultiplier (SiPM) Buffer Amplifier
- Photomultiplier Tube Post Amplifier

3 Description

The OPA855 is a wideband, low-noise operational amplifier with bipolar inputs for wideband transimpedance and voltage amplifier applications. When the device is configured as a transimpedance amplifier (TIA), the 8-GHz gain bandwidth product (GBWP) enables high closed-loop bandwidths at transimpedance gains of up to tens of kΩs.

The graph below shows the bandwidth and noise performance of the OPA855 as a function of the photodiode capacitance when the amplifier is configured as a TIA. The total noise is calculated along a bandwidth range extending from dc to the calculated frequency, f, on the left-hand scale. The OPA855 package has a feedback pin (FB) that simplifies the feedback network connection between the input and the output.

The OPA855 is optimized to operate in optical time-of-flight (ToF) systems where the OPA855 is used with time-to-digital converters, such as the TDC7201. Use the OPA855 to drive a high-speed analog-to-digital converter (ADC) in high-resolution LIDAR systems with a differential output amplifier, such as the THS4541 or LMH5401.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
OPA855	WSON (8)	2.00 mm × 2.00 mm

(1) For all available packages, see the package option addendum at the end of the data sheet.

Product Folder | Order Now | Technical Documents | Tools & Software | Support & Community

TEXAS INSTRUMENTS

OPA855

SBOS622A – JULY 2018 – REVISED OCTOBER 2018

OPA855 8-GHz Gain Bandwidth Product, Gain of 7-V/V Stable, Bipolar Input Amplifier

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1 Features

- High Gain Bandwidth Product: 8 GHz
- Decompensated, Gain ≥ 7 V/V (Stable)
- Low Input Voltage Noise: 0.98 nV/√Hz
- Slew Rate: 2750 V/µs
- Low Input Capacitance:
  - Common-Mode: 0.6 pF
  - Differential: 0.2 pF
- Wide Input Common-Mode Range:
  - 0.4 V from Positive Supply
  - 1.1 V from Negative Supply
- 3 V_{PP} Total Output Swing
- Supply Voltage Range: 3.3 V to 5.25 V
- Quiescent Current: 17.8 mA
- Package: 8-Pin WSON
- Temperature Range: –40 to +125°C

2 Applications

- High-Speed Transimpedance Amplifier
- Laser Distance Measurement
- CCD Output Buffer
- High-Speed Buffer
- Optical Time Domain Reflectometry (OTDR)
- High-Speed Active Filter
- 3D Scanner
- Silicon Photomultiplier (SiPM) Buffer Amplifier
- Photomultiplier Tube Post Amplifier

3 Description

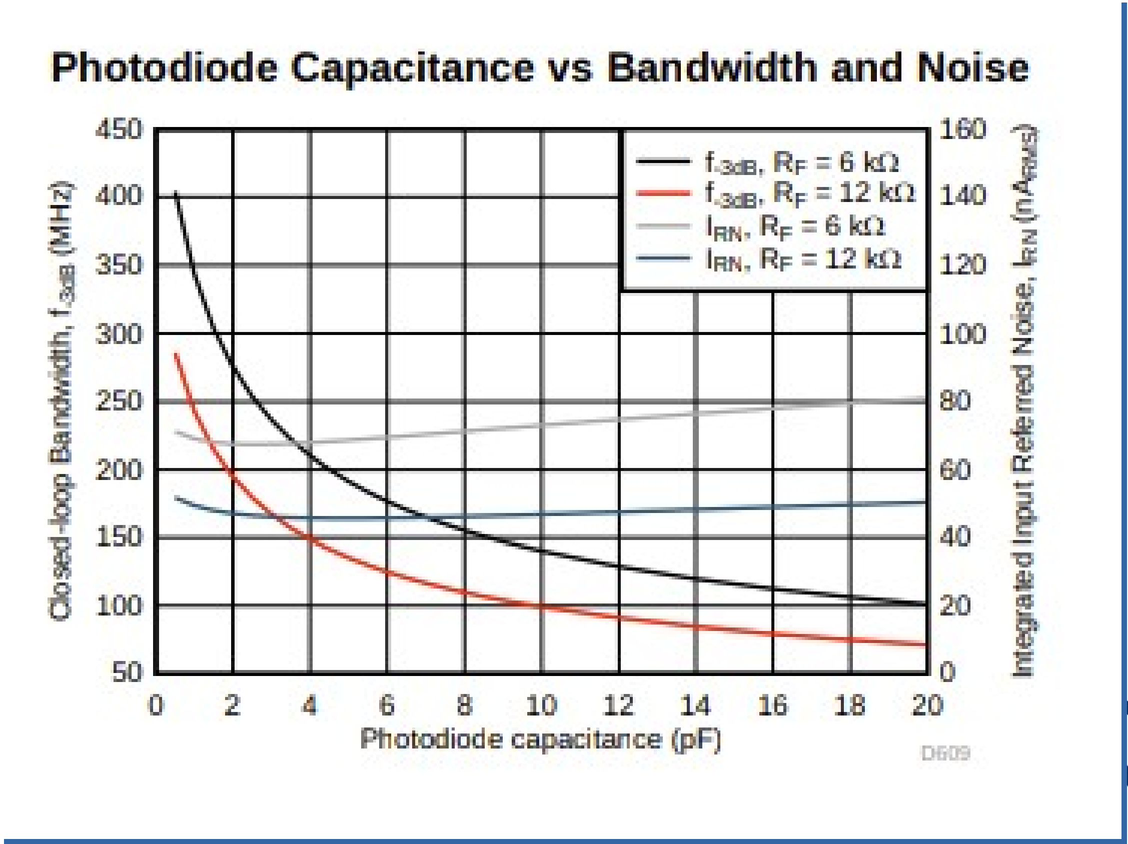
The OPA855 is a wideband, low-noise operational amplifier with transimpedance When the devic amplifier (TIA), (GBWP) enabl transimpedance

The graph belo performance of photodiode ca configured as a along a bandwi calculated frequ OPA855 packa simplifies the fe the input and th

The OPA855 is of-flight (ToF) s with time-to-digi Use the OPA8 digital converte systems with a the THS4541 or

PART NUMBER
OPA855

(1) For all availabl at the end of th



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Texas Instruments

OPA855

SBOS622A – JULY 2018 – REVISED OCTOBER 2018

Stable, Bipolar Input Amplifier

tion

is a wideband, low-noise operational

SoUP 2021

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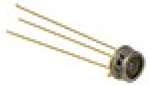
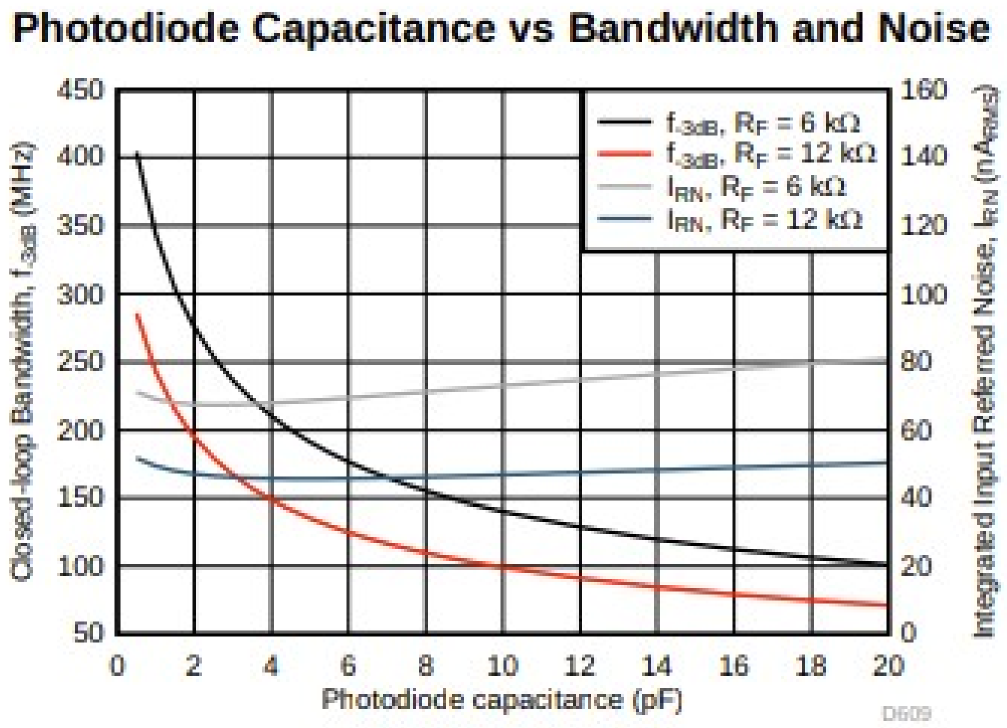
Click Image for Details			
Item #	FDS010	FD11A	FDS10X10
Key Feature	High Speed, UV Grade Fused Silica Window to Provide Sensitivity Down to 200 nm	Lowest Dark Current in TO-18 Can with a Window	Low Dark Current in 10 mm x 10 mm Ceramic Package
Info	i	i	i
Wavelength Range	200 - 1100 nm[a]	320 - 1100 nm	340 - 1100 nm
Active Area	0.8 mm^2 (Ø1.0 mm)	1.21 mm^2 (1.1 mm x 1.1 mm)	100 mm^2 (10 mm x 10 mm)
Rise/Fall Time[b]	1 ns / 1 ns @ 830 nm, 10 V	400 ns[c,d] @ 650 nm, 0 V	150 ns / 150 ns[d] @ 5 V
NEP ($W/Hz^{1/2}$)	5.0×10^{-14} @ 830 nm, 10 V	6.8×10^{-16} @ 960 nm, 0 V	1.50×10^{-14} @ 960 nm
Dark Current	0.3 nA (Typ.) @ 10 V	2.0 pA (Max) @ 10 mV	200 pA @ 5 V
Junction Capacitance	6 pF (Typ.) @ 10 V	140 pF (Typ.) @ 0 V	380 pF @ 5 V
Package	TO-5	TO-18	Ceramic
Compatible Sockets	STO5S STO5P	STO46S STO46P	Not Available

- Silicon Photomultiplier (SiPM) Buffer Amplifier
- Photomultiplier Tube Post Amplifier



TIA equations

- BW = $\sqrt{GBP/(4 \pi R_f C_d)}$
  - GBP is the BW at gain 1 for the amplifier
    - can be 10 GHz
- The noise:

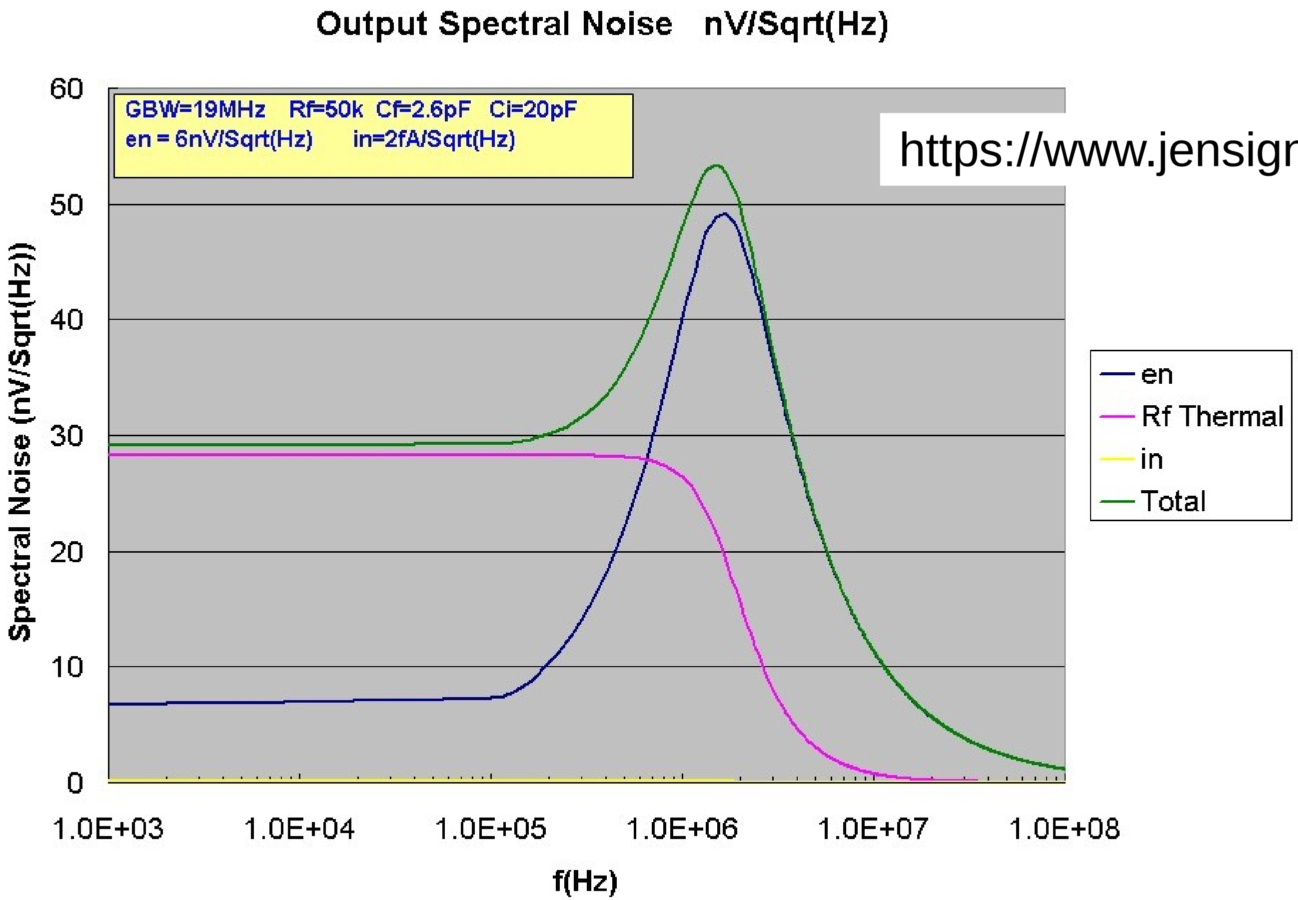
$$V_n^{out} = \sqrt{\left(e_n^2 + i_n^2 R_p^2 + 4K_b T R_p\right) N0^2 F0 \frac{\pi}{2} Q \left(1 + \frac{BW}{F_z}\right) + \left(i_n^2 R_f^2 + 4K_b T R_f N0\right) F0 \frac{\pi}{2} Q}$$

$$\propto \sqrt{C_d}$$

https://www.jensign.com/inoutnoise

TIA equations

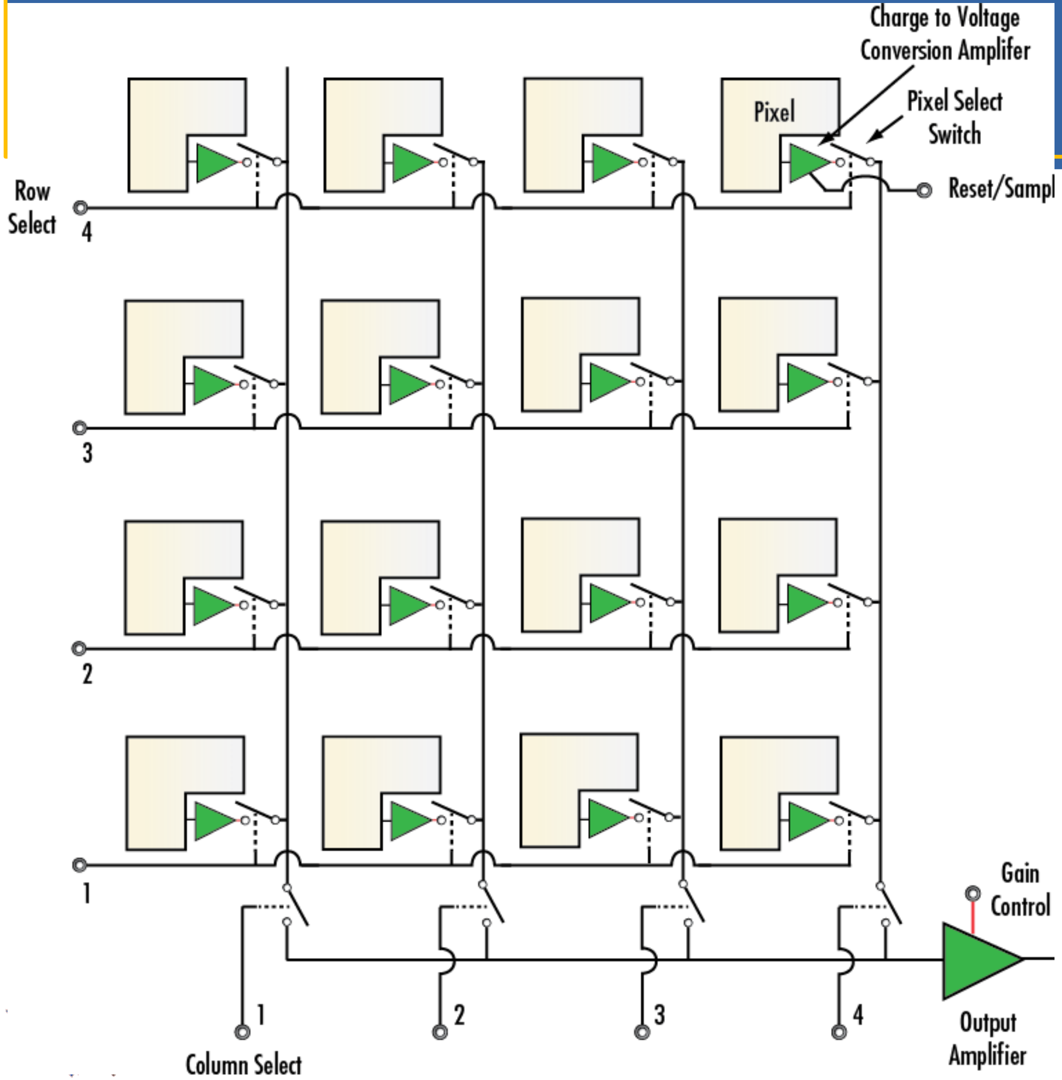
https://www.jensign.com/noisegain/index.html



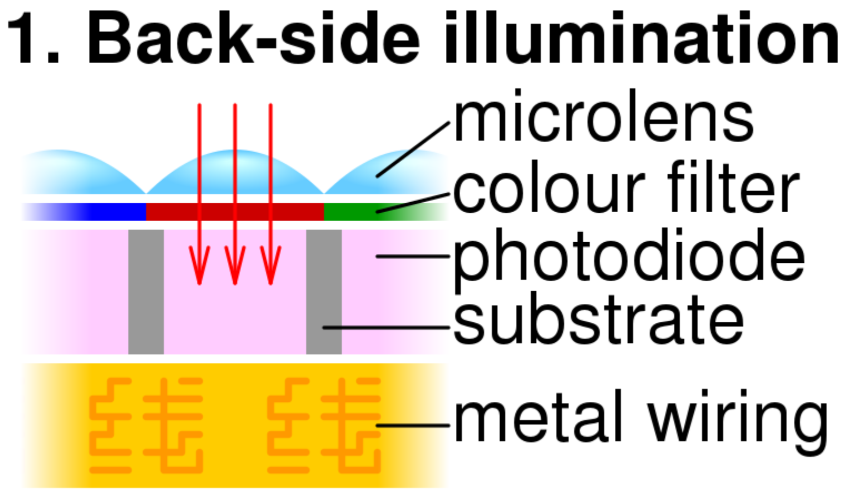
$$\ldots R_f^{\,2} + 4K_bTR_fN0\big)F0\frac{\pi}{2}Q$$

/inoutnoise

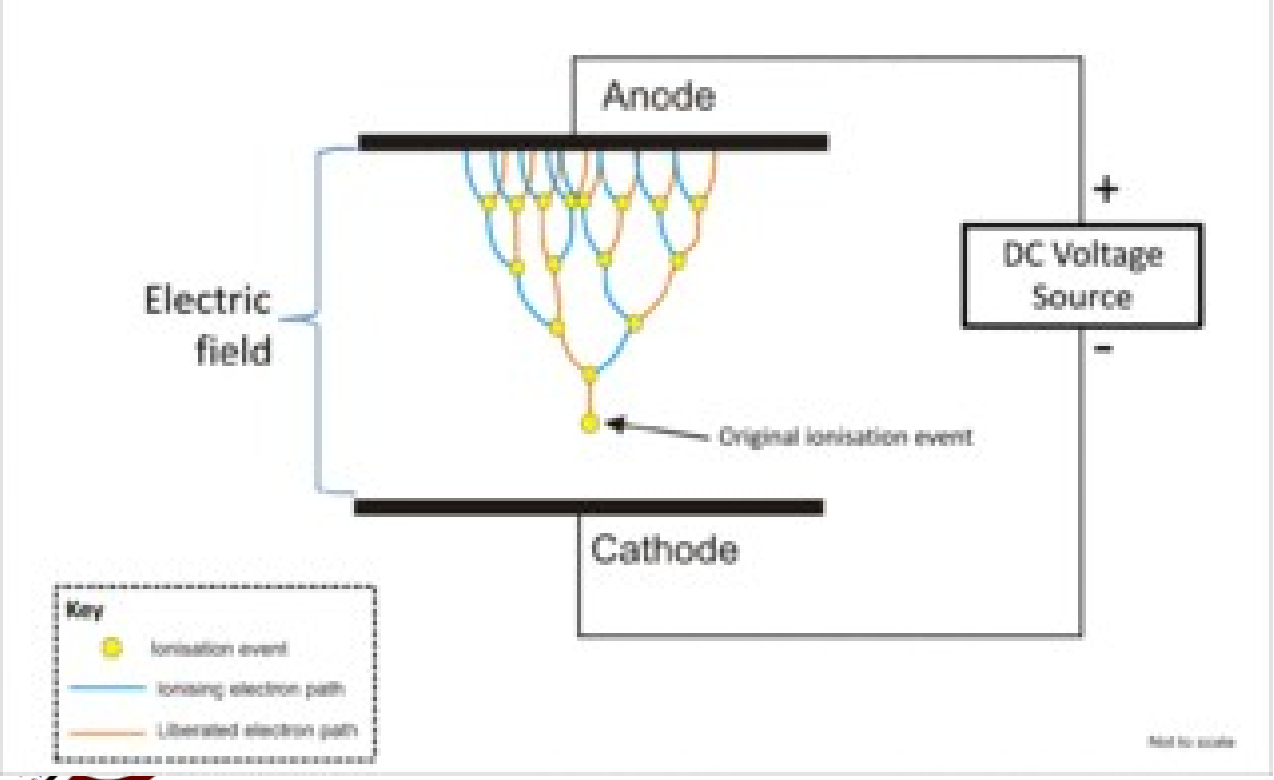
CMOS sensors



- Each pixel is few um
  - Capacitance ~ fF
    - Resolution ~ sub-e-
- Modern sensors are back-illuminated



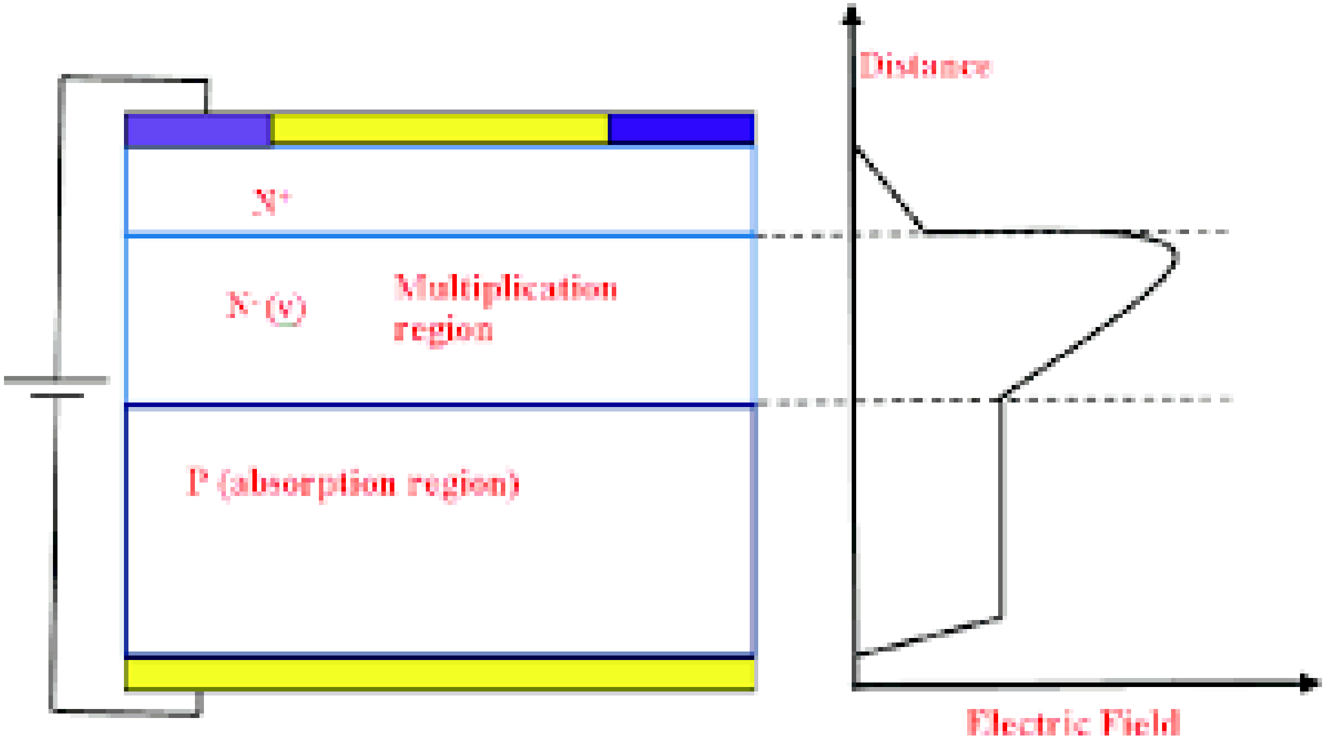
Avalanches



- In semi-conductors impurities act as scattering centers
  - If a carrier is hot enough it ionizes further the impurity
  - New carriers drift until a new scattering center is hit
- Exponential progression

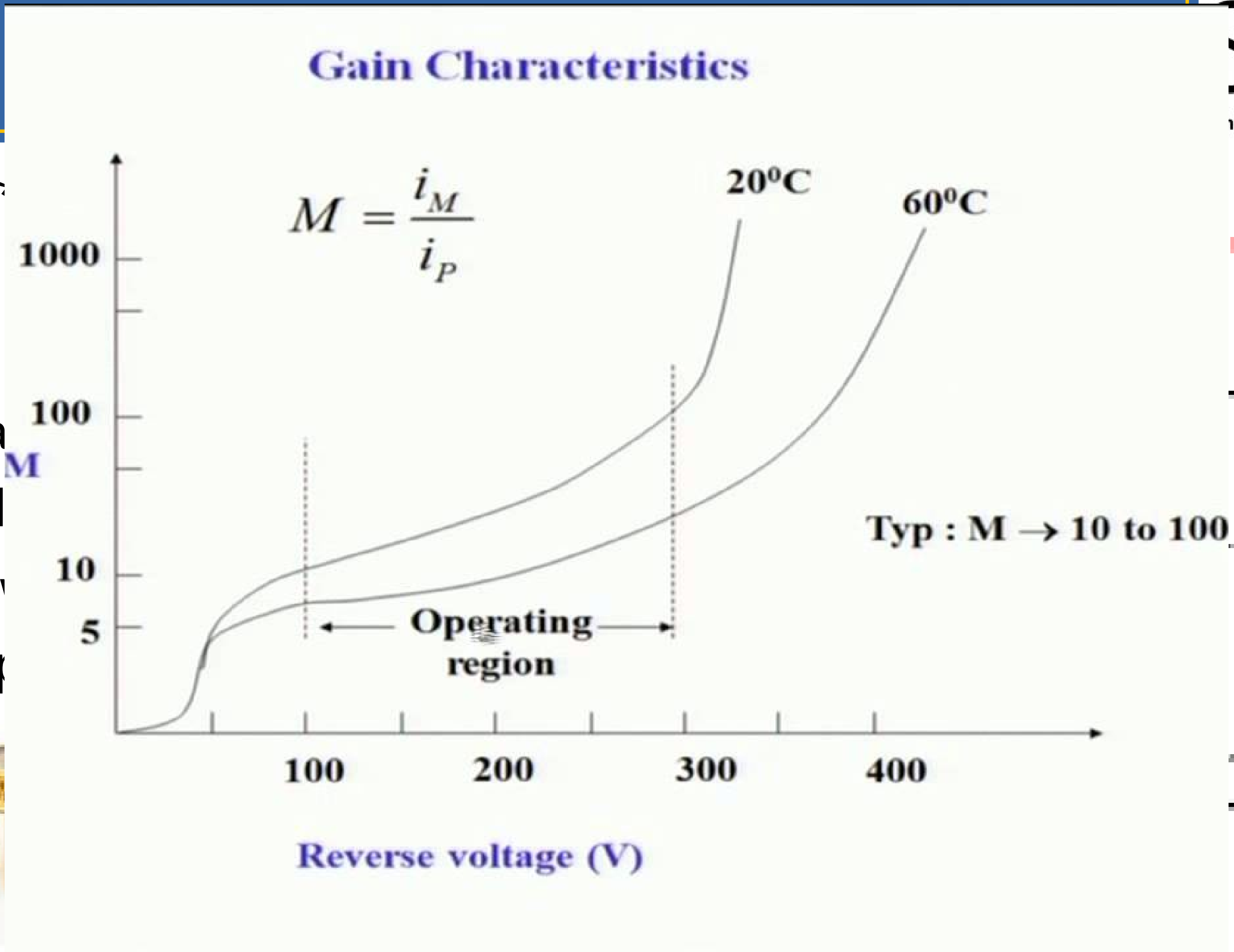
APD

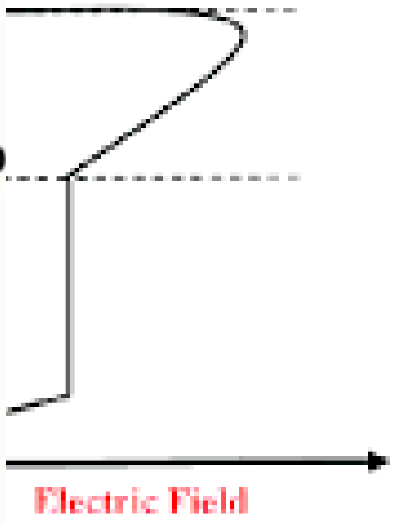
- I = P * **M** * R
  - M → 10 – 100
- ENF
  - Gain noise
- Small size
  - Few mm²
- With pre-amplifier



APD

- I = P *
  - M
- ENF
  - Ga
- Small
  - Fe
- With p





Electrical and optical characteristics (Typ. Ta=25 °C, unl

Type no.	Spectral response range λ (nm)	Peak[*5] sensitivity wavelength λp (nm)	Photo-sensitivity S M=1 λ=800 nm (A/W)	Quantum efficiency QE M=1 λ=800 nm (%)	Breakdown voltage V_{BR} I_D=100 µA Typ. (V)	Breakdown voltage V_{BR} I_D=100 µA Max. (V)	Temp co-efficie of V_B (V/°C
S12023-02							
S12023-05							
S12051							
S12086							
S12023-10	400 to 1000	800	0.5	75	150	200	0.65
S12023-10A[*3]							
S3884							
S2384							
S2385							

*5: Values measured at a gain listed in the characteristics table

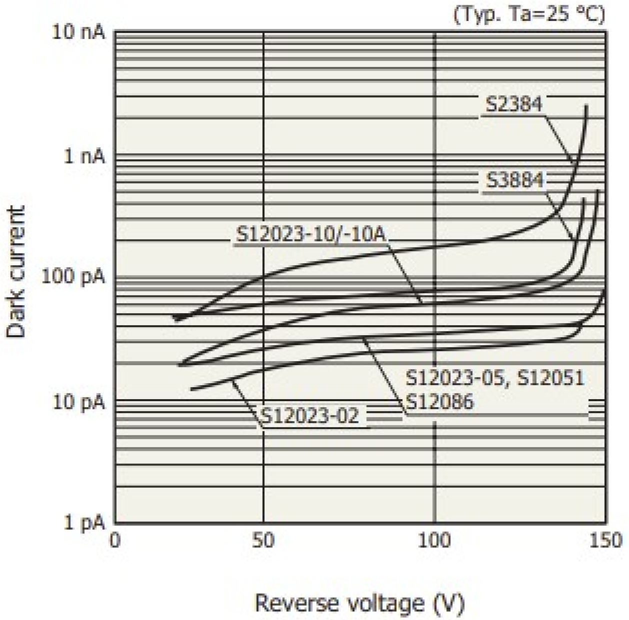
Note: Breakdown voltage can be specified by using the suffix of type number a

S12023-02-01: 80 to 120 V

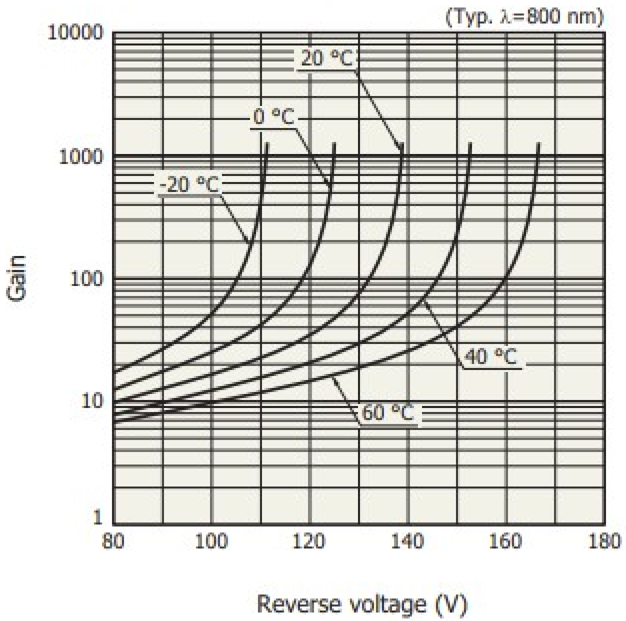
S12023-02-02: 120 to 160 V

S12023-02-03: 160 to 200 V

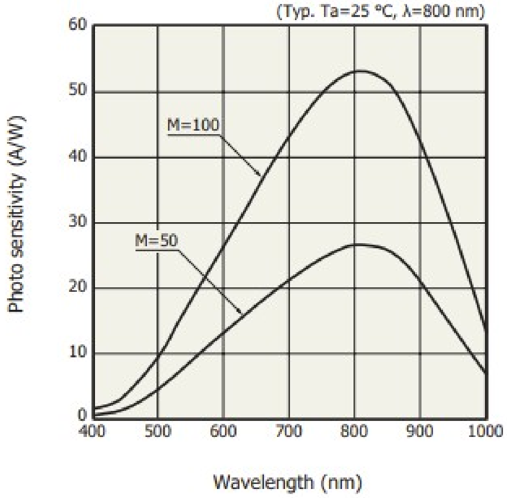
Dark current vs. reverse voltage



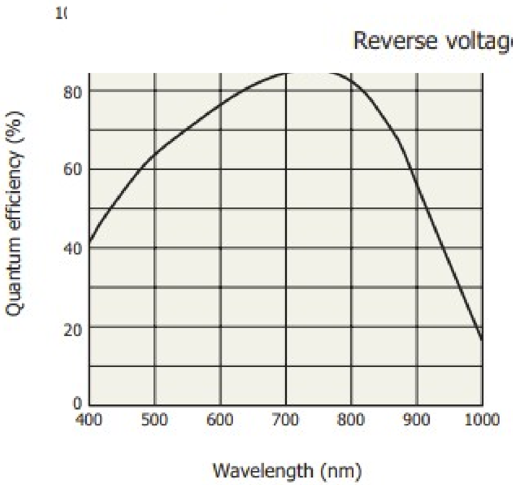
Gain vs. reverse voltage



Spectral response



Quan



Electrical and optical characteristics (Typ. Ta=25 °C, unl

Type no.	Spectral response range λ (nm)	Peak[5] sensitivity wavelength λp (nm)	Photo-sensitivity S M=1 λ=800 nm (A/W)	Quantum efficiency QE M=1 λ=800 nm (%)	Breakdown voltage V_{BR} I_D=100 µA Typ. (V)	Max. (V)	Temp co-efficie of V_B (V/°C
S12023-02	400 to 1000	800	0.5	75	150	200	0.65
S12023-05							
S12051							
S12086							
S12023-10							
S12023-10A[3]							
S3884							
S2384							
S2385							

*5: Values measured at a gain listed in the characteristics table

Note: Breakdown voltage can be specified by using the suffix of type number a

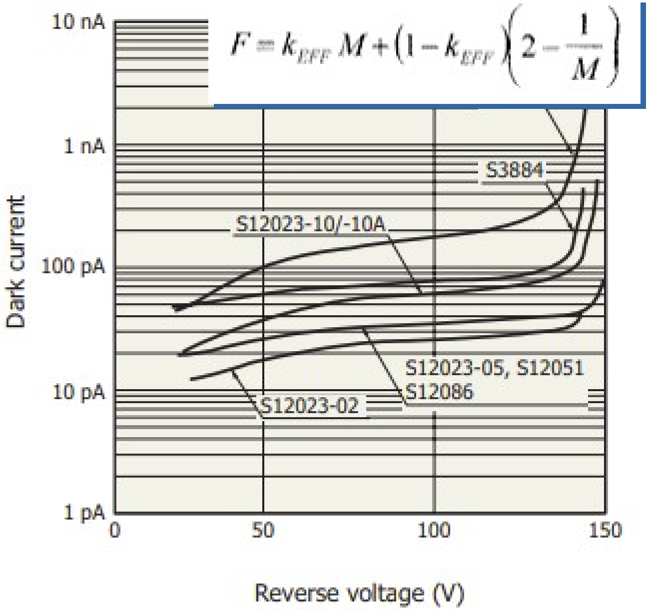
S12023-02-01: 80 to 120 V

S12023-02-02: 120 to 160 V

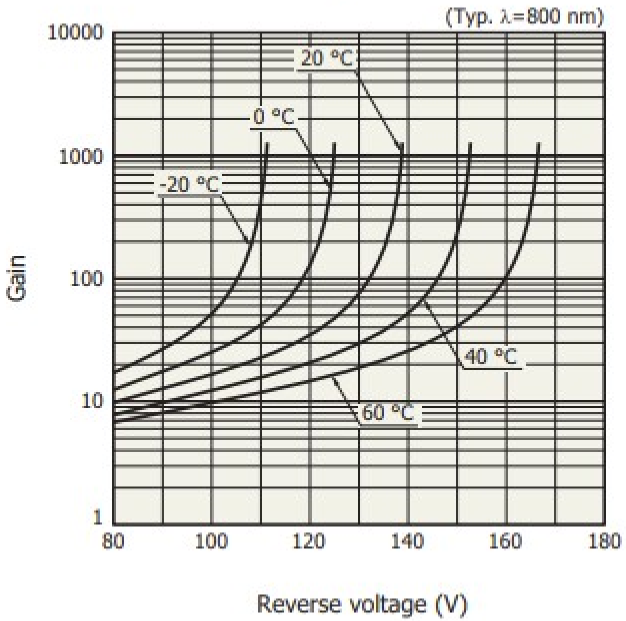
S12023-02-03: 160 to 200 V

Dark current vs. reverse voltage

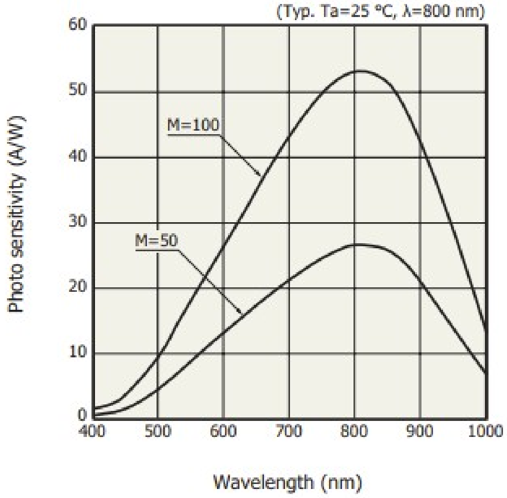
$$F = k_{EFF} M + (1 - k_{EFF})\left(2 - \frac{1}{M}\right)$$



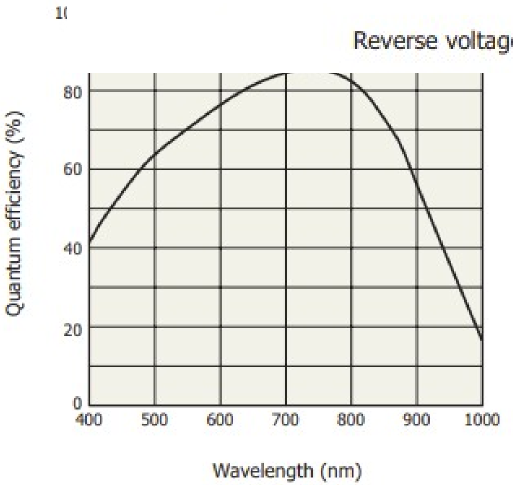
Gain vs. reverse voltage



Spectral response

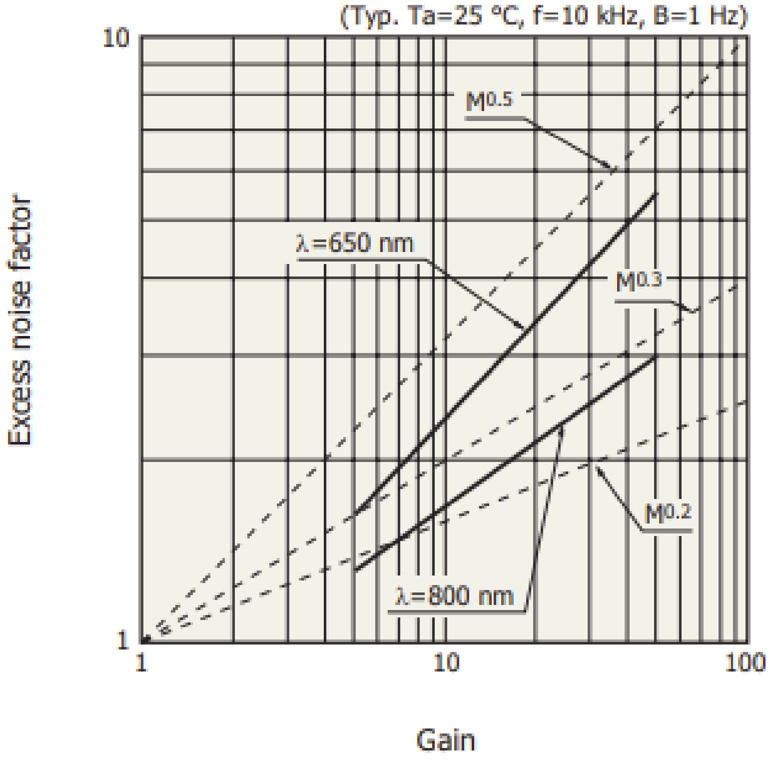


Quan



ENF

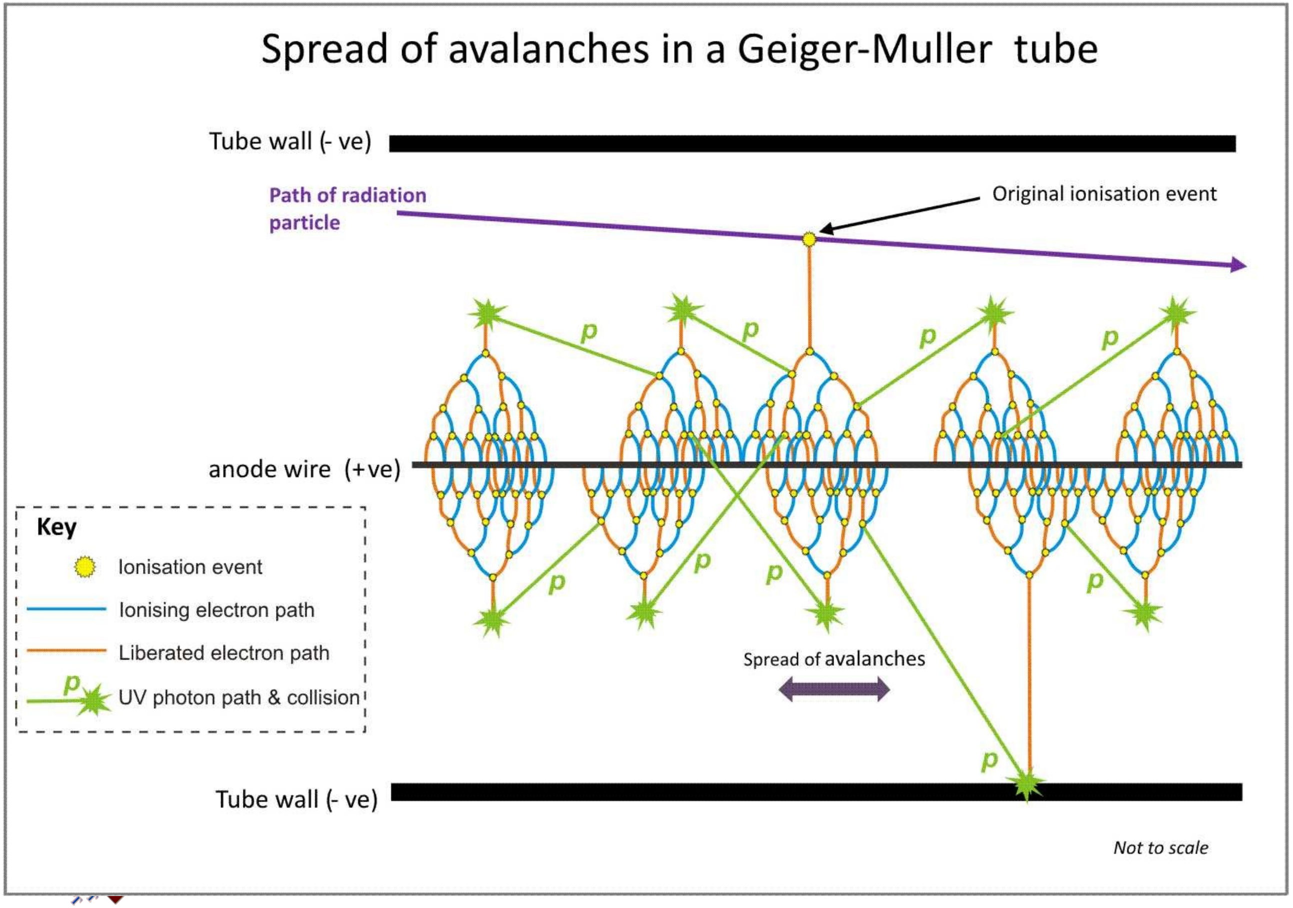
Excess noise factor vs. gain



$$F = k_{EFF} M + (1 - k_{EFF})\left(2 - \frac{1}{M}\right)$$

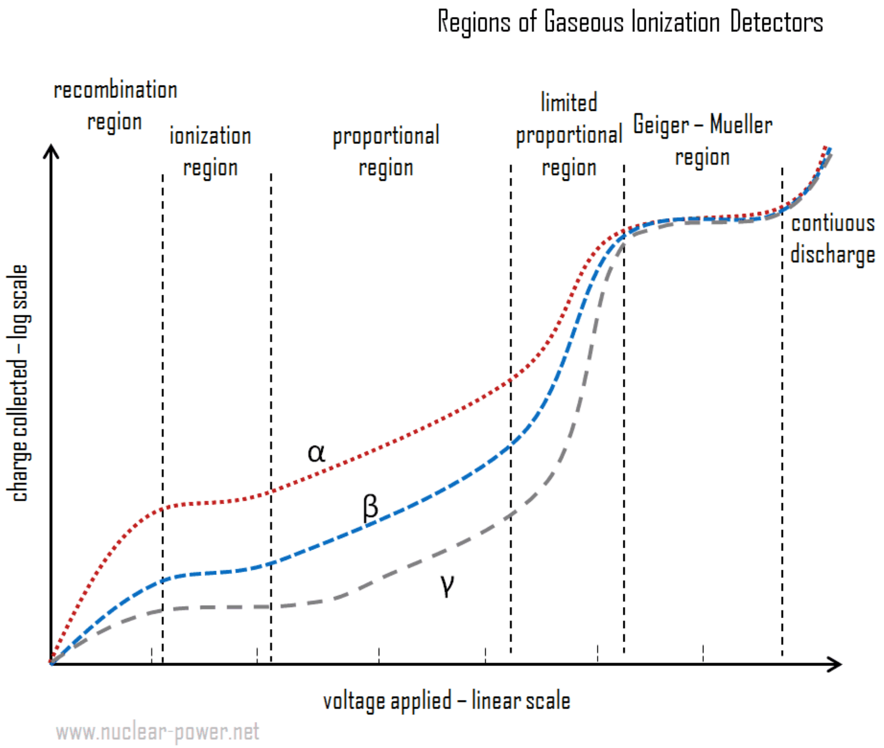
$K = P_h/P_e$

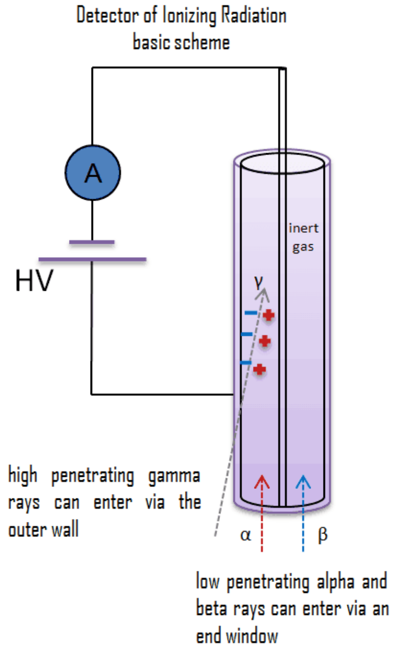
Geiger mode



- The avalanche is self-sustaining
  - Until an external process stops it
  - Passive or active quenching
- The signal is no more proportional to the initial event

Geiger mode





- The avalanche is self-sustaining
  - Until an external process stops it
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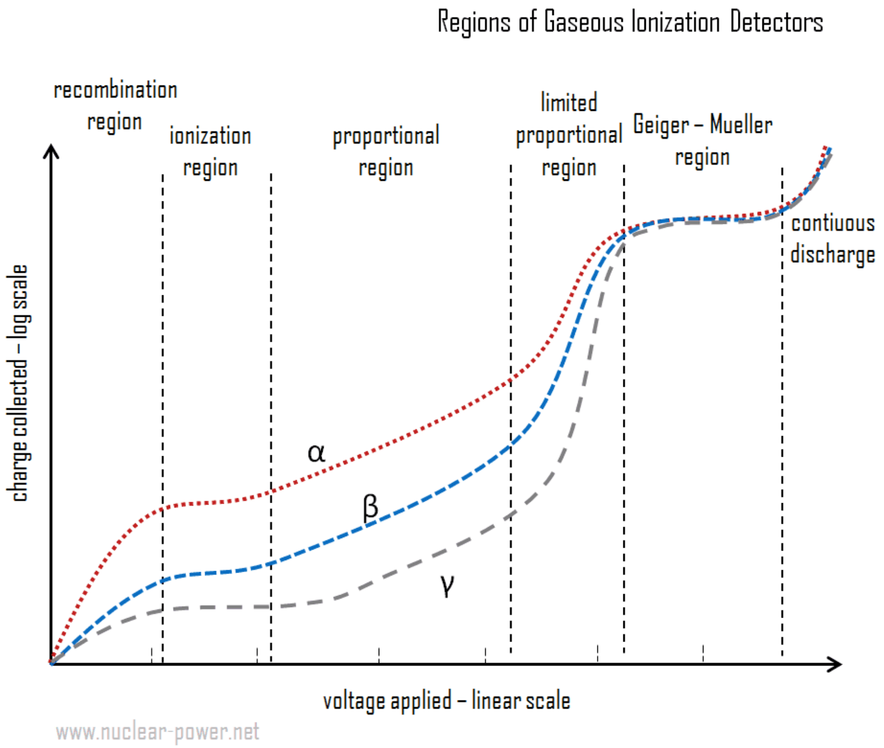
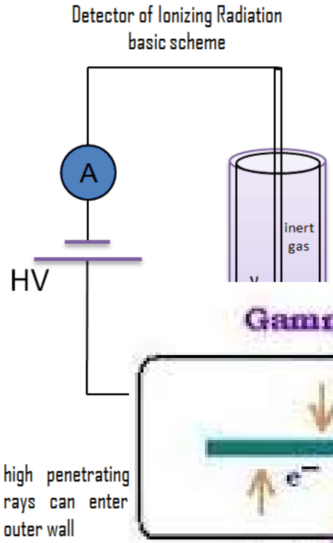
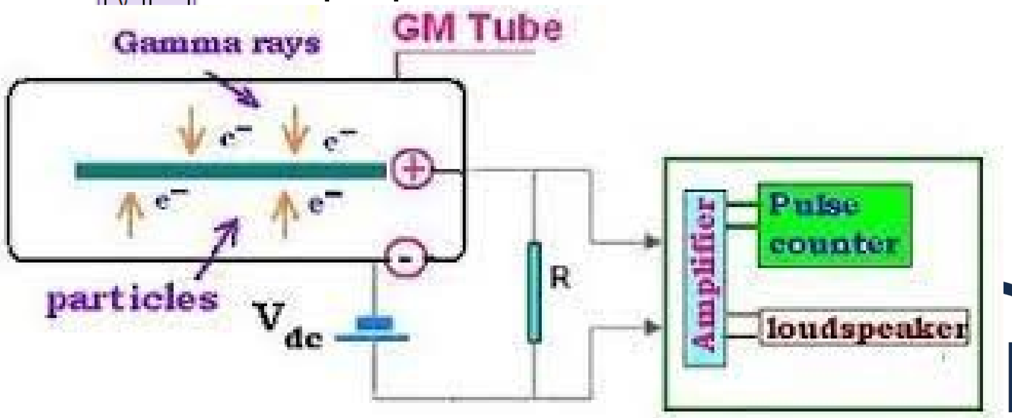
- The signal is no more proportional to the initial event

Geiger mode

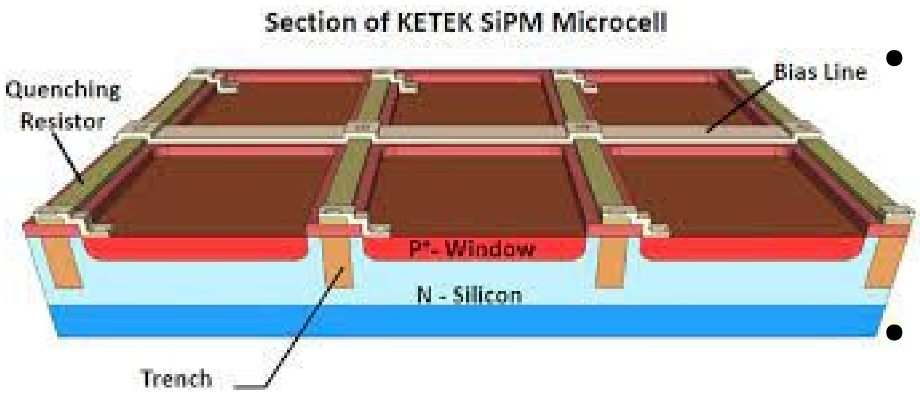






- The avalanche is self-sustaining
  - Until an external process stops it
  - Passive or active quenching
- The signal is no more proportional to the initial event

SiPM

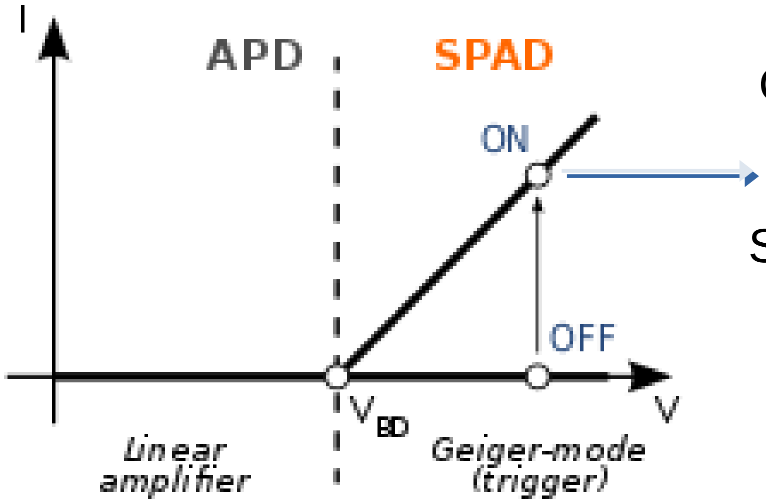


- Silicon PM are a collection of SPADs
- SPAD 5-50 µm

Single-Photon Avalanche Diode

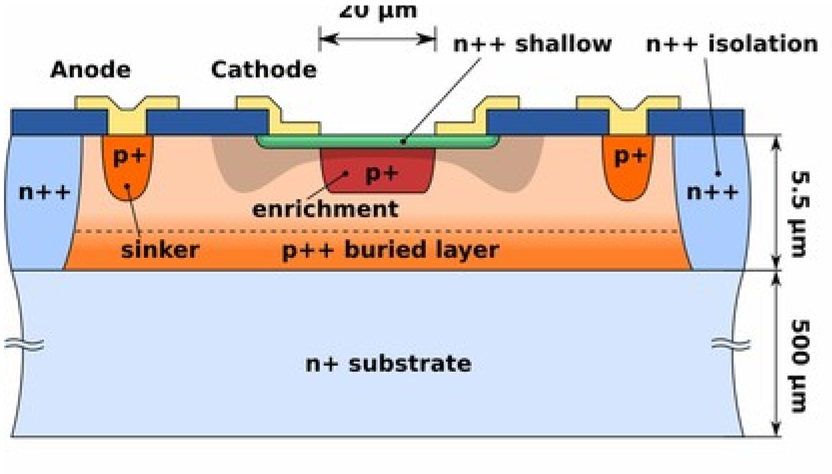
  - Operating in geiger mode
  - Include a quenching resistor
- SiPMs can be found between 1x1 mm^2 to 10x10 mm^2
- The PDE of SiPMs ~ 30-60 %
- A set of noises is present

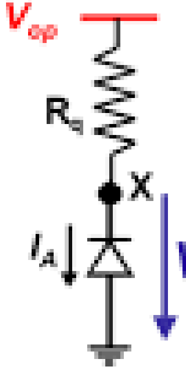
Geiger mode



Current defined by the (thermally) generated couples
Amplified by G ~ 10^6
Since SPAD are sensitive to single carriers we speak of dark rate

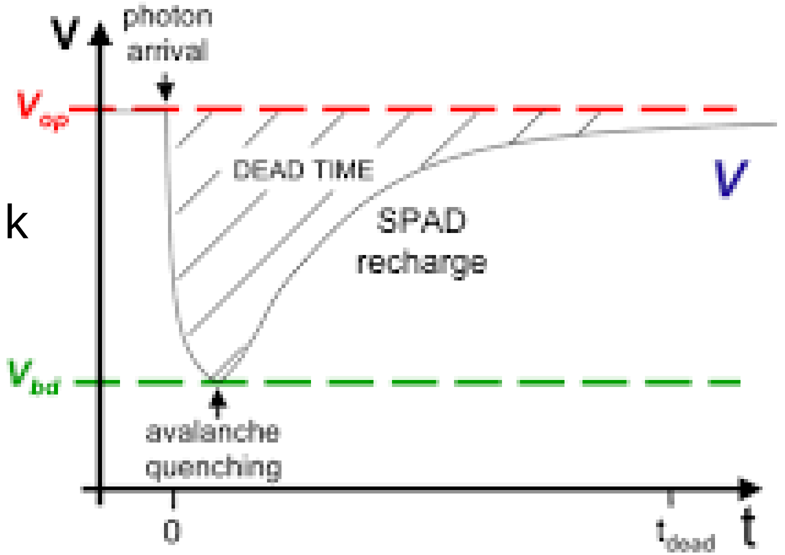
SPAD





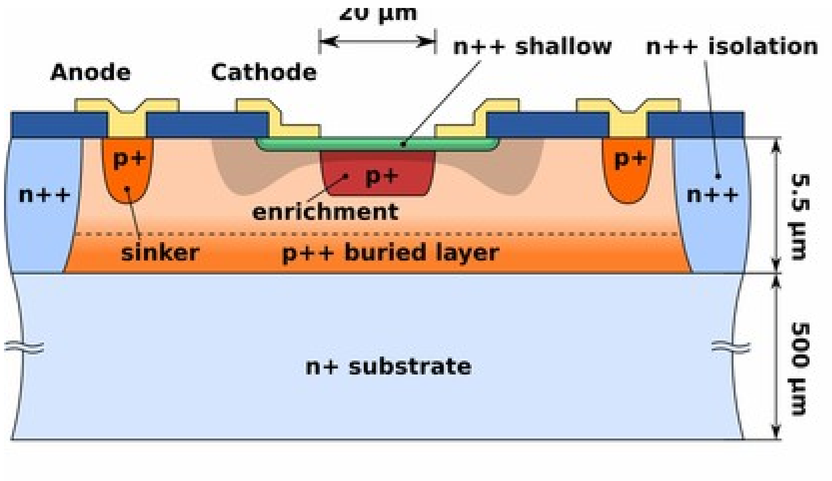
Rq ~100 k

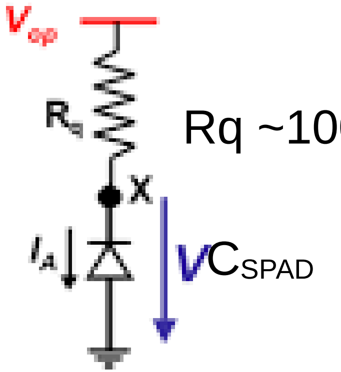
C_{SPAD}



Which is the maximum SPAD size?

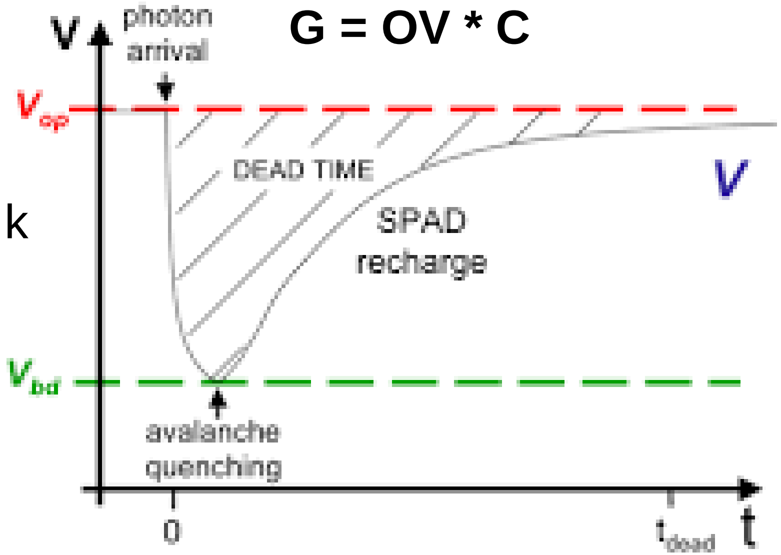
SPAD





Rq ~100 k

G = OV * C



The dead-time is dominated by the recharge time

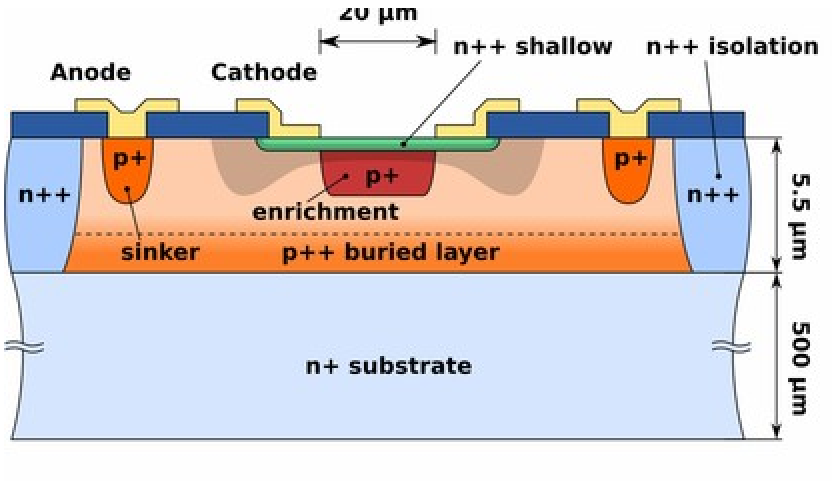
$R_q * C_{SPAD}$ = 50 ns – 500 ns

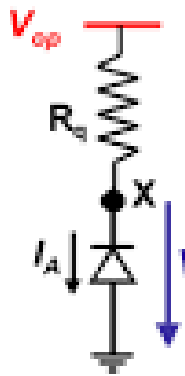
DCR ~ 1 Mcps/mm2

500 ns * 1 MHz = 50% of dead-time

PDE <= dead time

SPAD



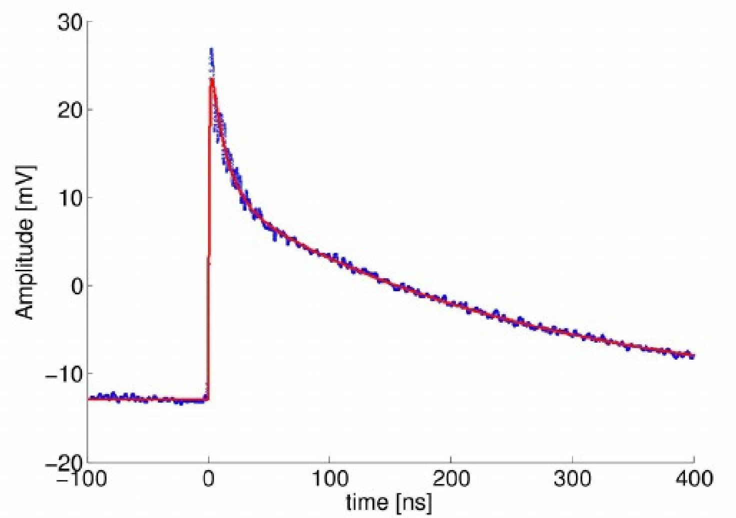


Rq ~100 k

C_{SPAD}

Which is the gain?

G = ∫ I dt



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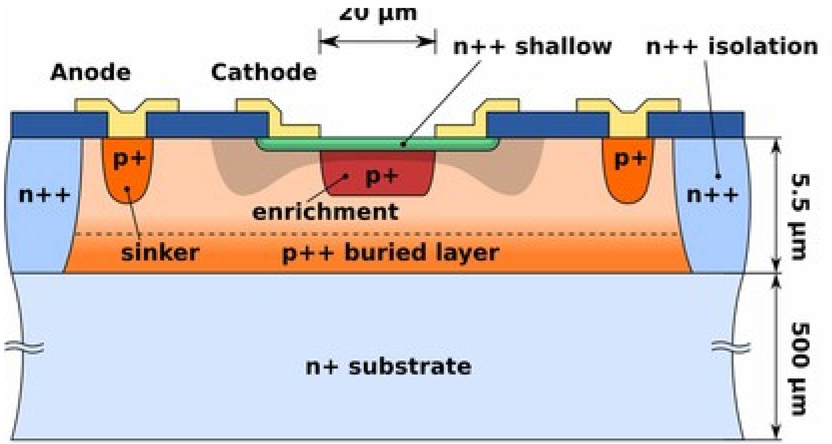
SPAD

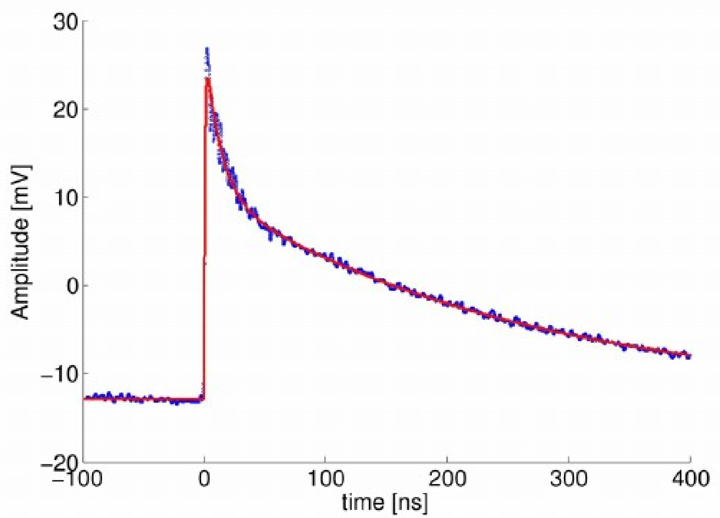


Rq ~100 k

VCSPAD

We are depleting C_{SPAD}

G = OV * C_{SPAD}



The dead-time is dominated by the recharge time

$R_q * C_{SPAD}$ = 50 ns – 500 ns

DCR ~ 1 Mcps/mm2

500 ns * 1 MHz = 50% of dead-time

PDE <= dead time

DCR

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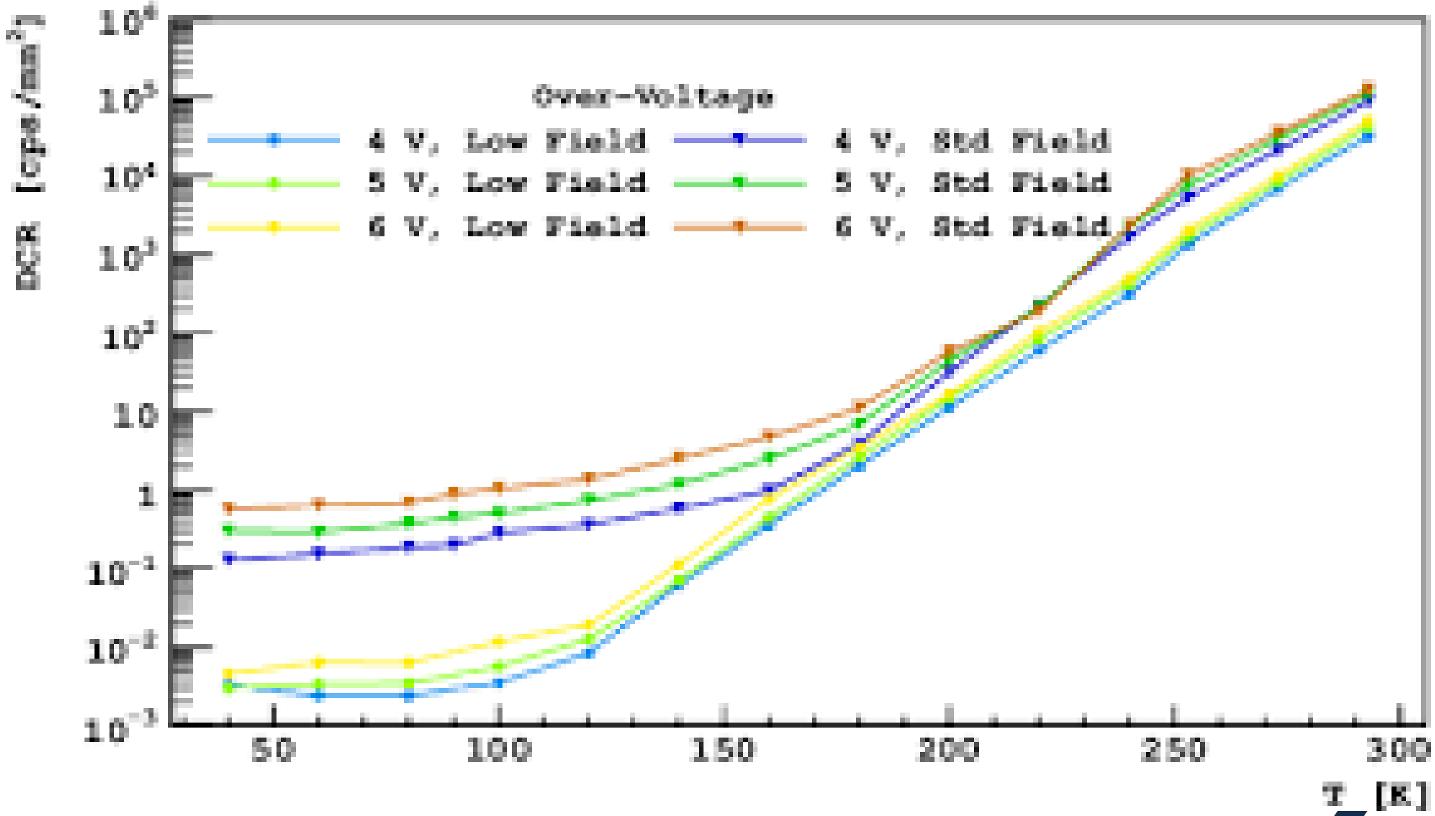
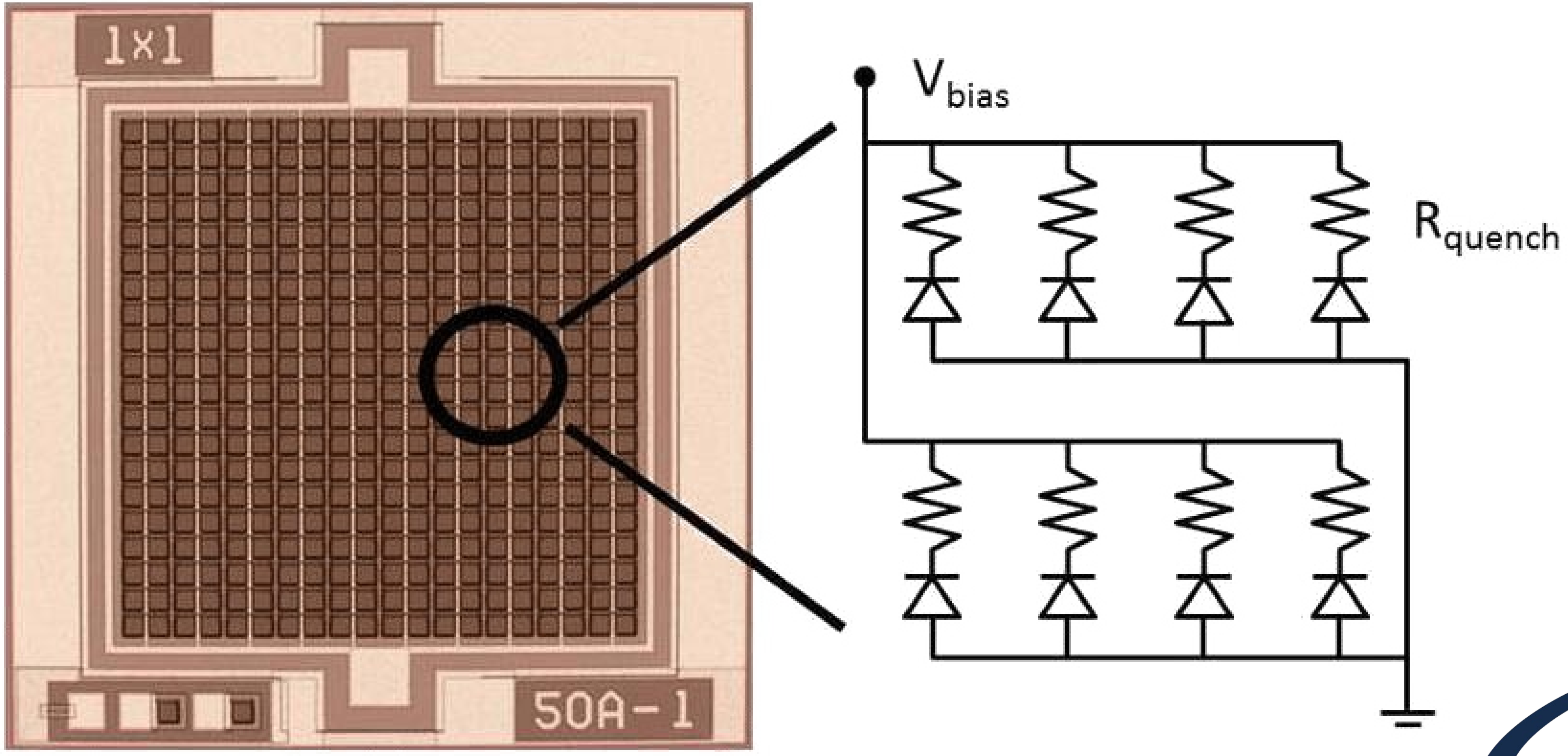
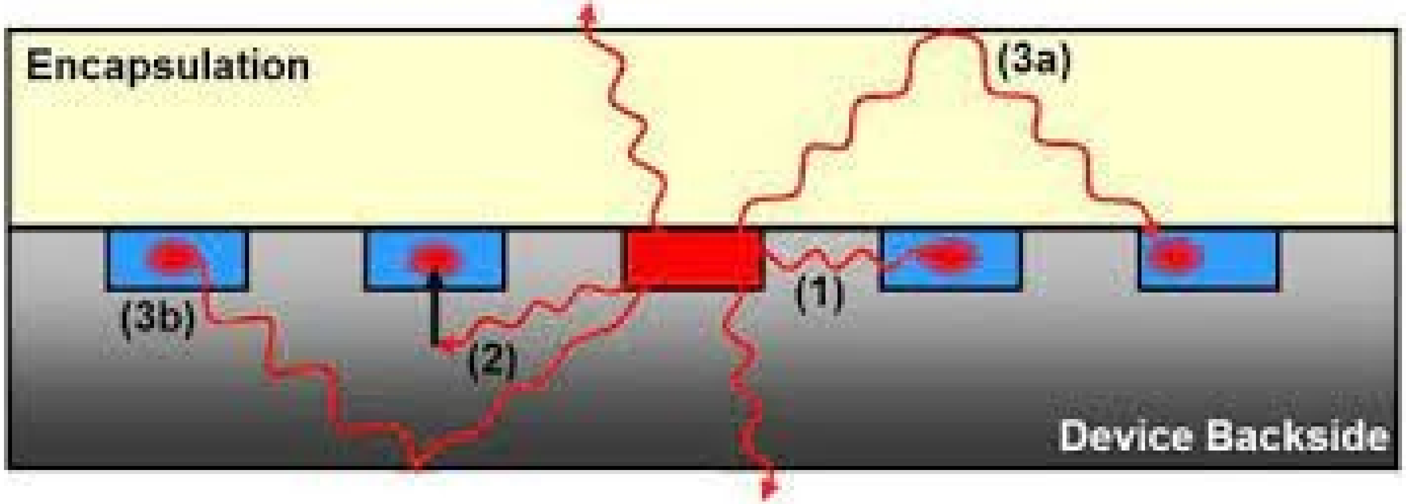


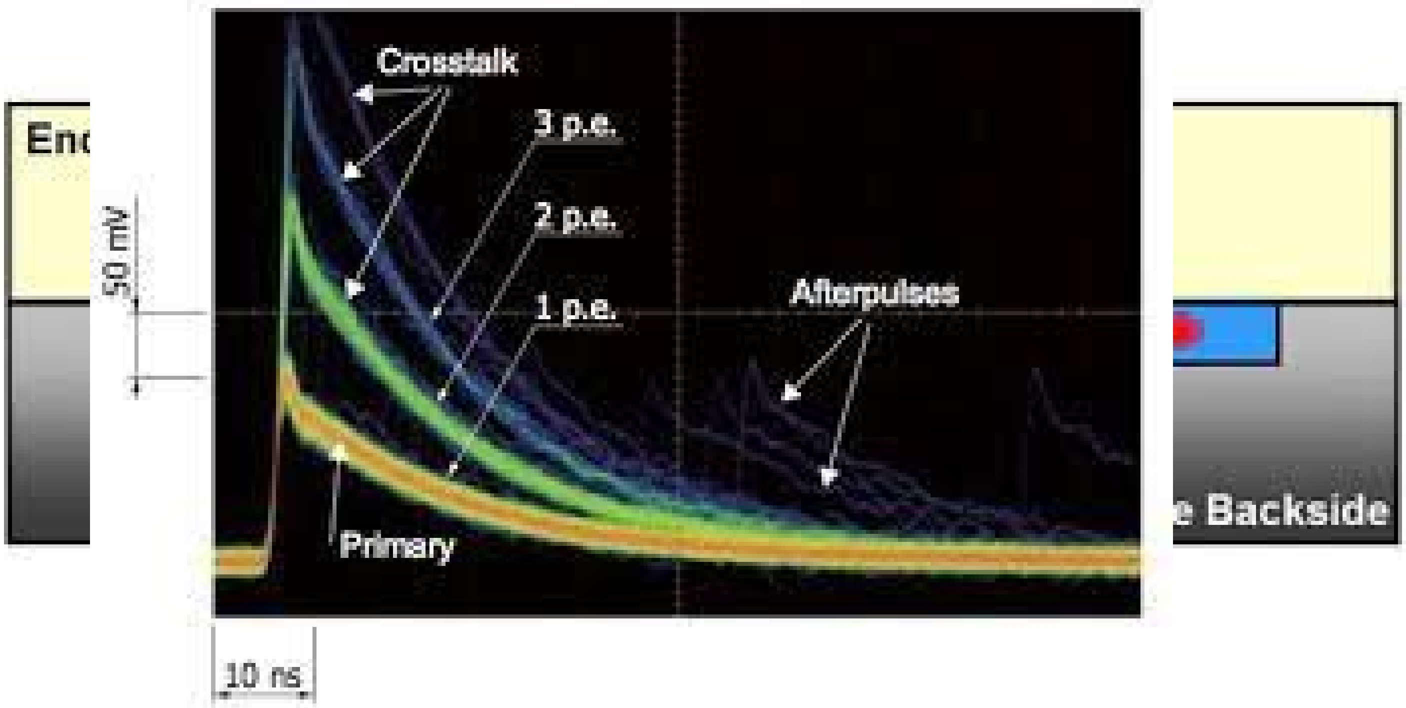
Building SiPMs



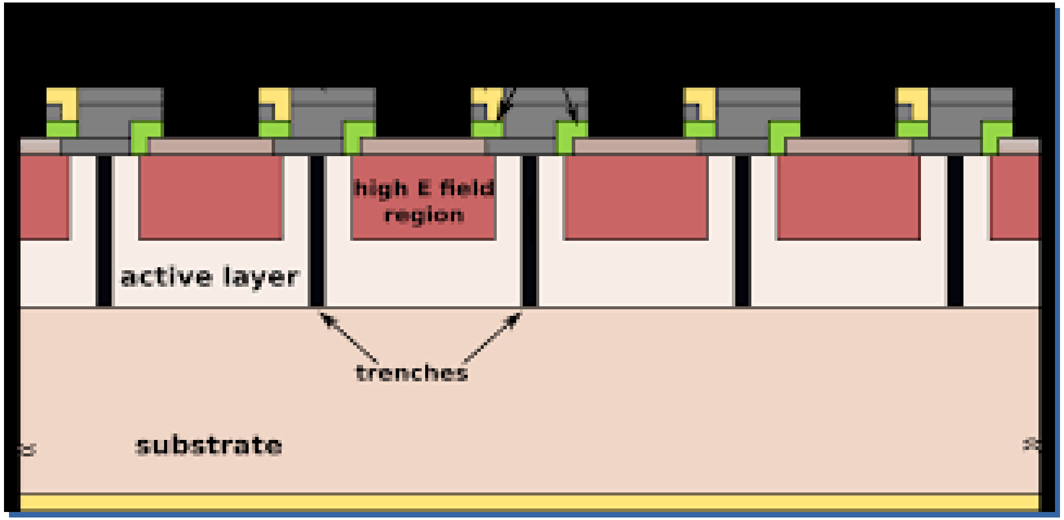
Cross-talk



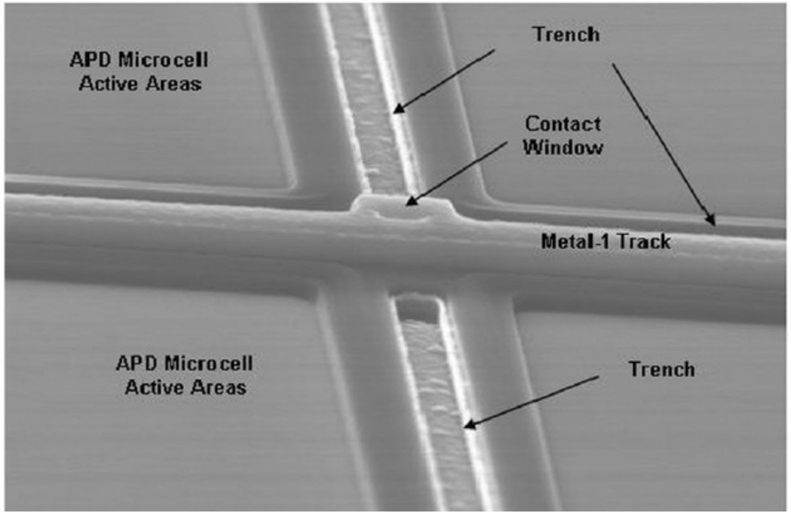
Cross-talk


Crosstalk
3 p.e.
2 p.e.
1 p.e.
Afterpulses
Primary
50 mV
10 ns
e Backside

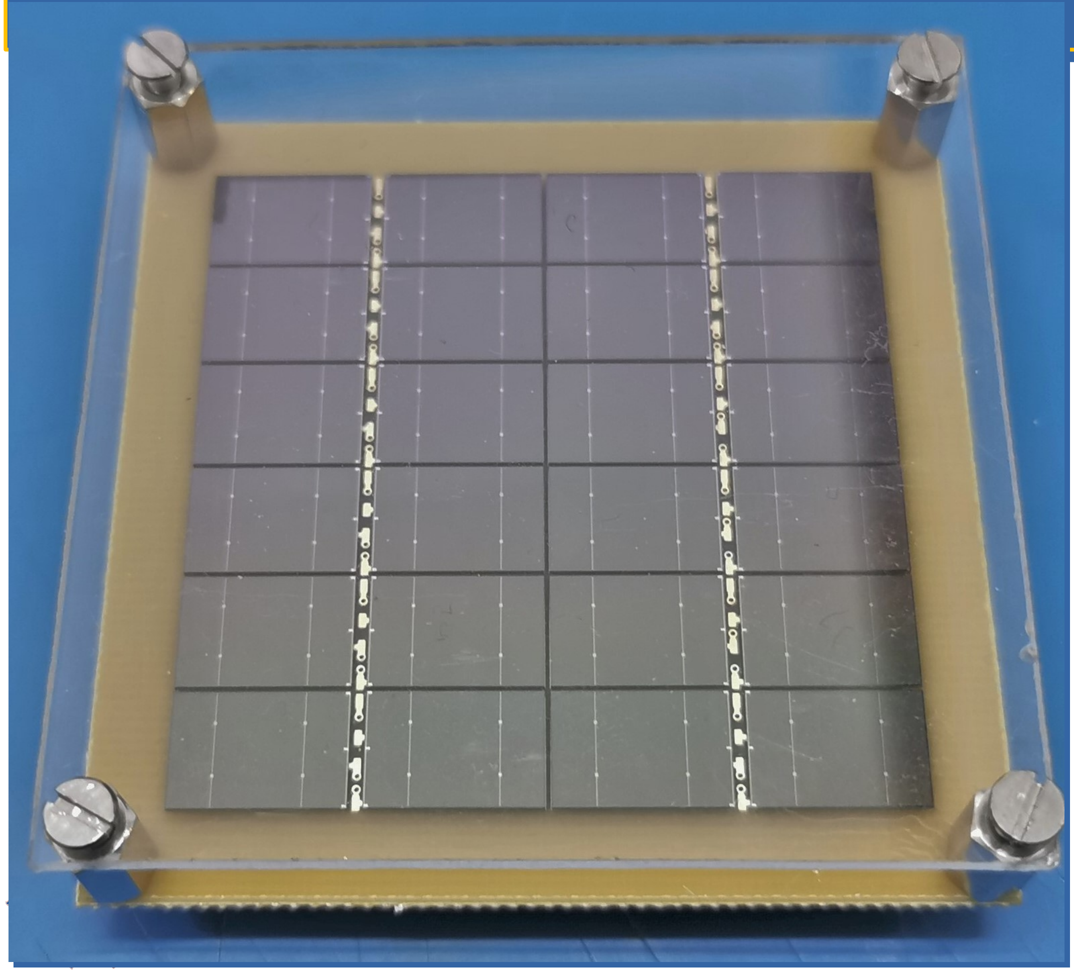
Trenches

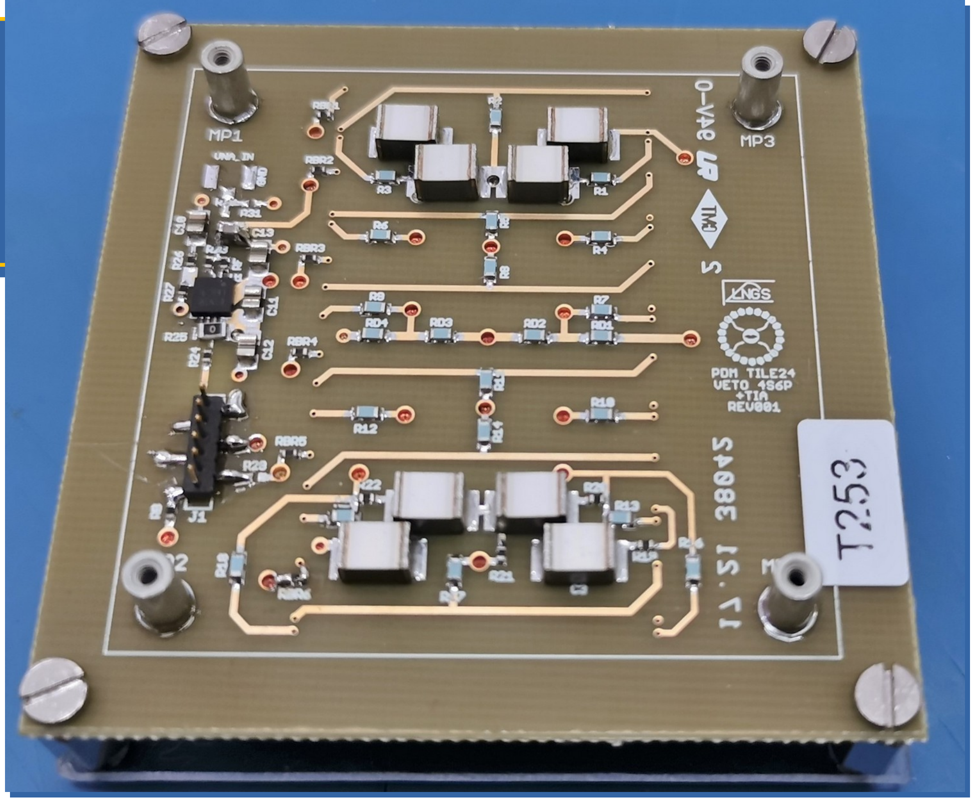

high E field region
active layer
trenches
substrate

(a)


APD Microcell Active Areas
Trench
Contact Window
Metal-1 Track
APD Microcell Active Areas
Trench

Use case: DarkSide



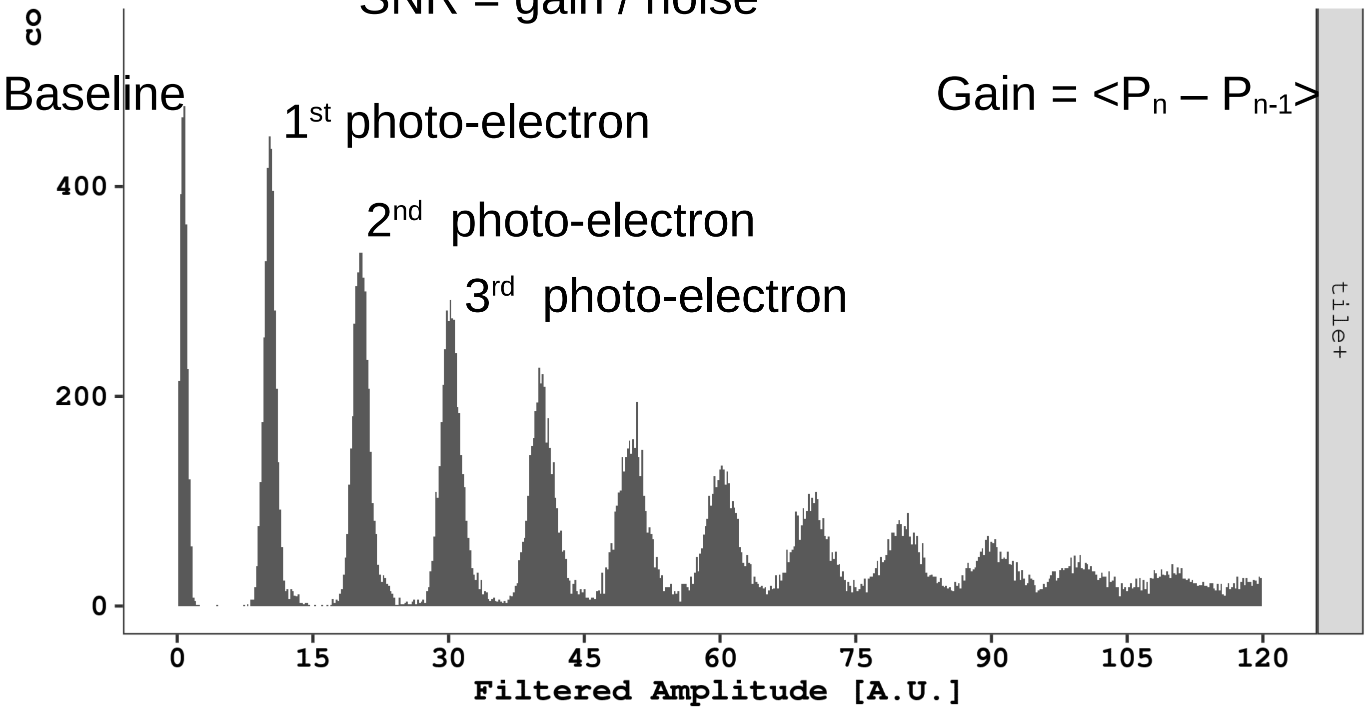


24x 1 cm2 SiPMs → 2.4 10^6 SPAD
On a radio-pure PCB
With electronics on the back
(40 mW)
DCR ~ 10 cps/tile

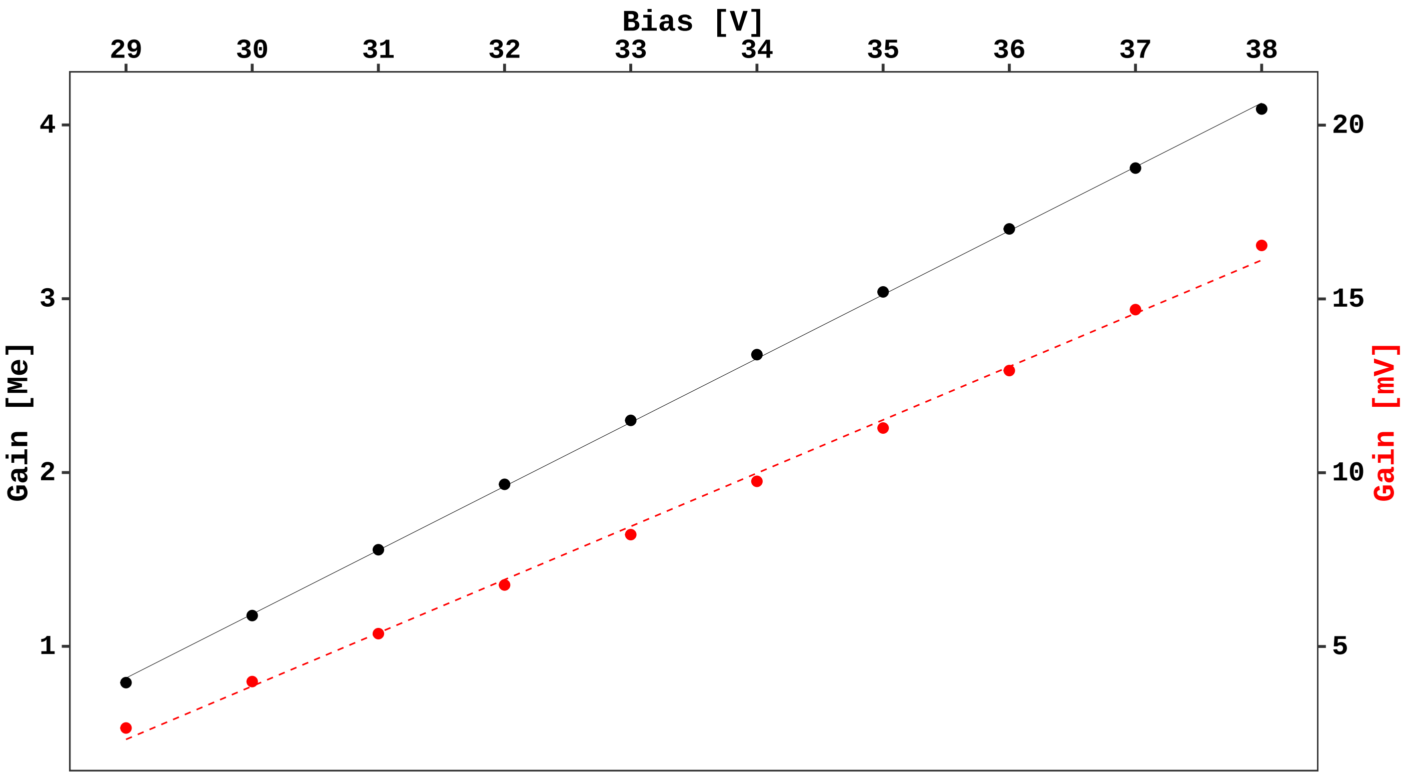
INFN
LNGS

Finger plot

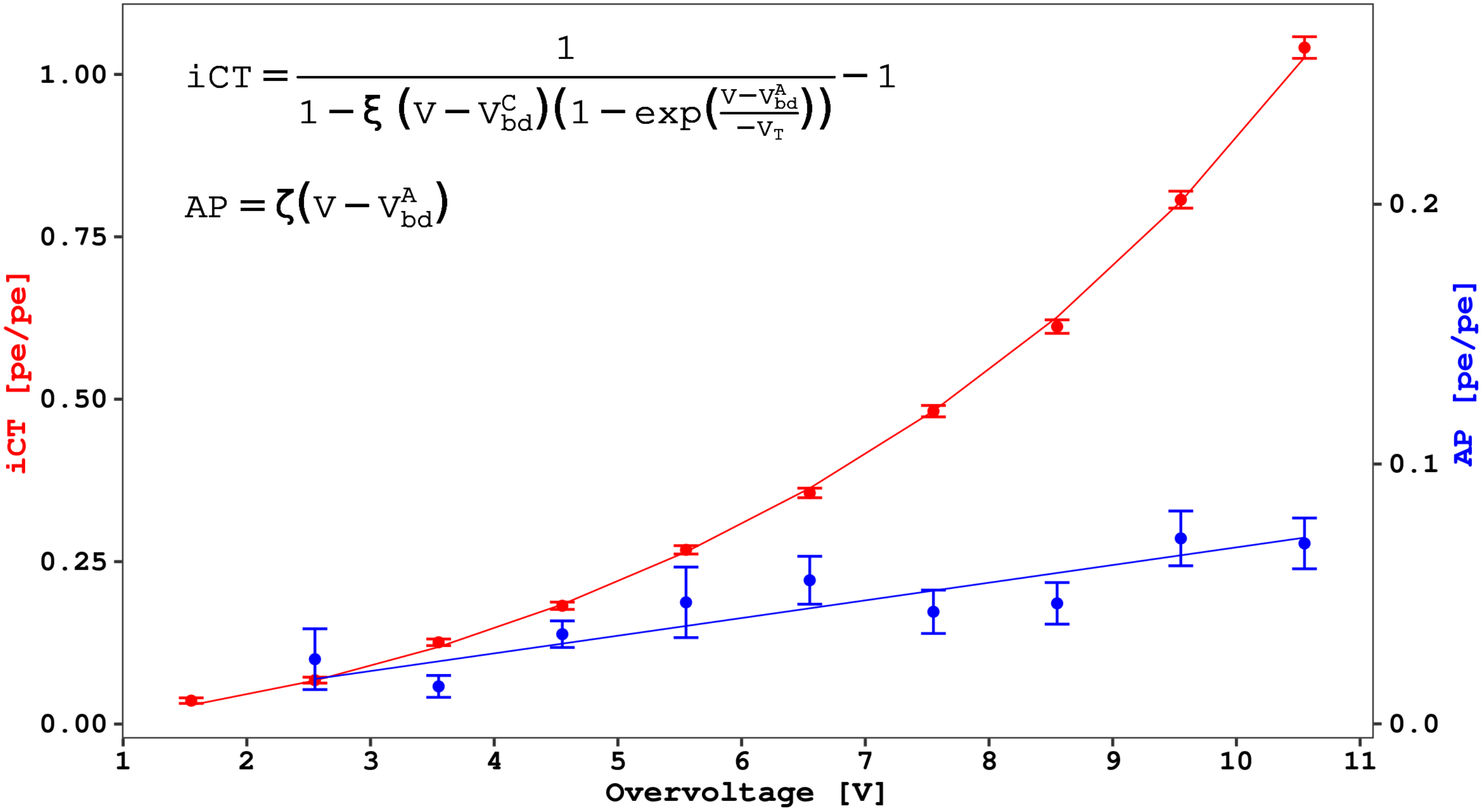
SNR = gain / noise



Gain

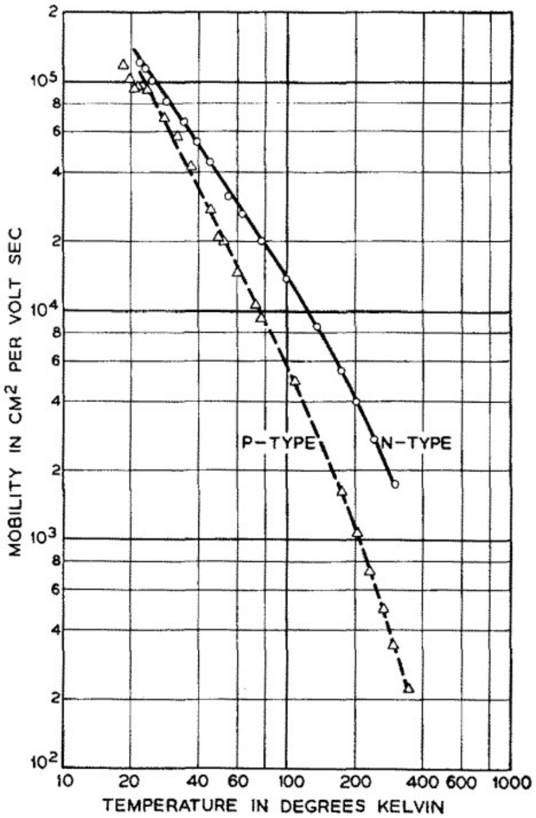


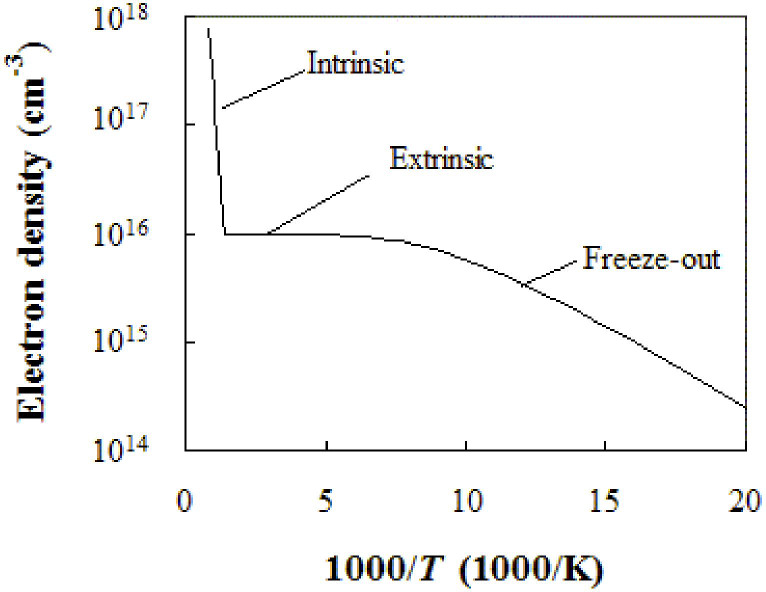
iCT & AP factor

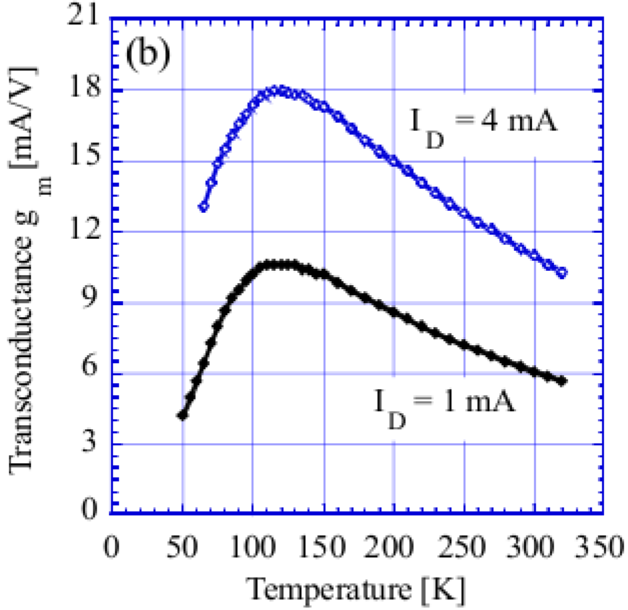


$\#_{iCT} = 1/(1 - P_{iCT})$

Going cold





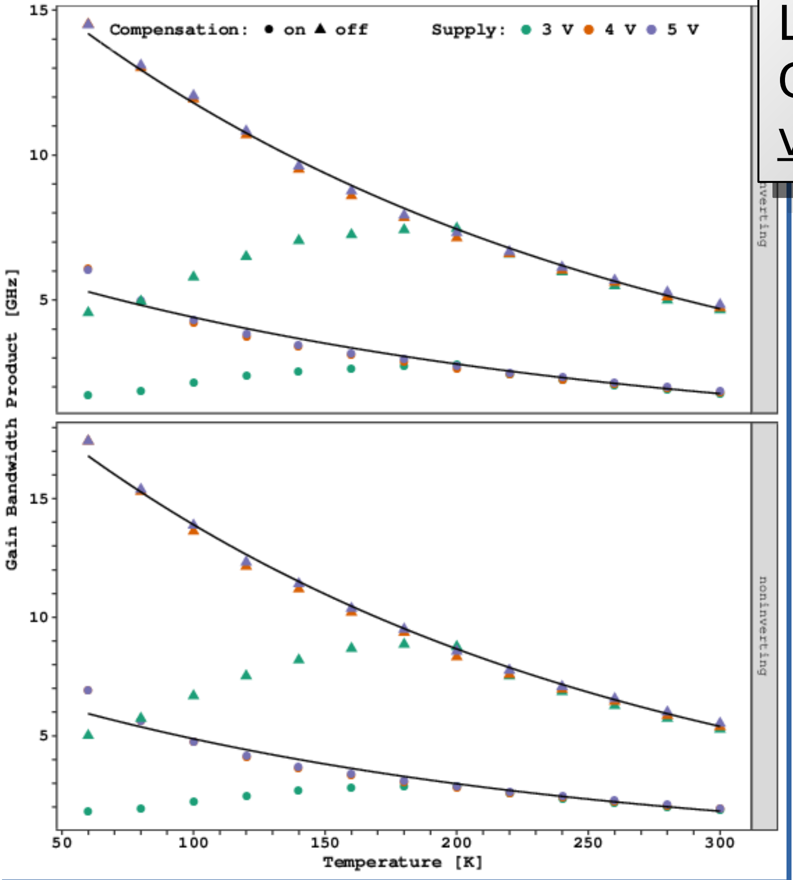


$R = 1/(e\text{-}\ \mu\ N_i) \rightarrow \frac{1}{2}\ M\Omega/cm$

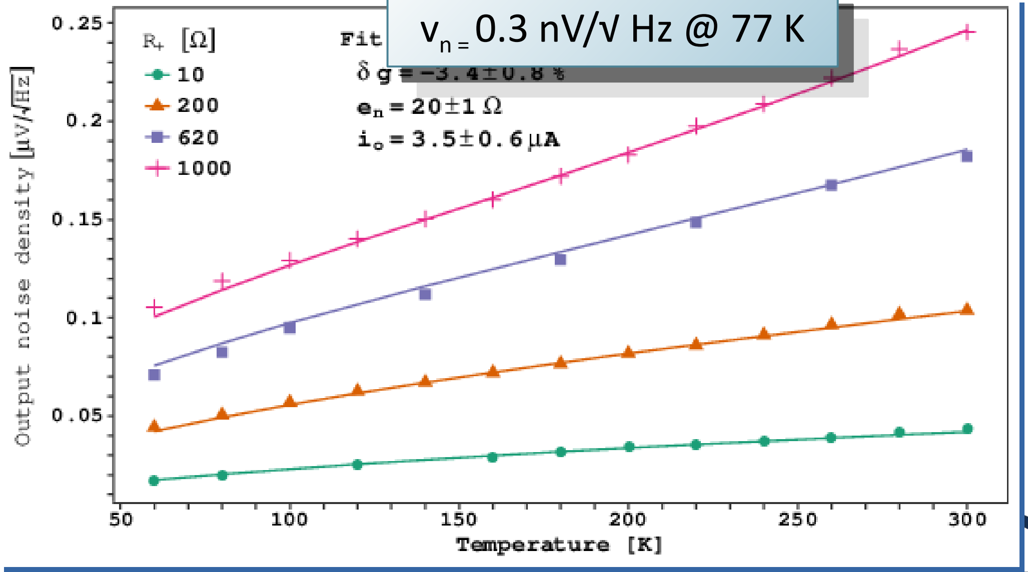
$$g_m|_{V_G=0}^{JFET} \simeq \frac{W}{L}\,\mu(T)\,N_{ch}(T)\,d$$

DarkSide pre-amplifier

LMH6629 from Texas Instruments
GBP reach 18 GHz at 60 K
v_n behaves like a 20 Ω resistor



$v_n = 0.3$ nV/√ Hz @ 77 K



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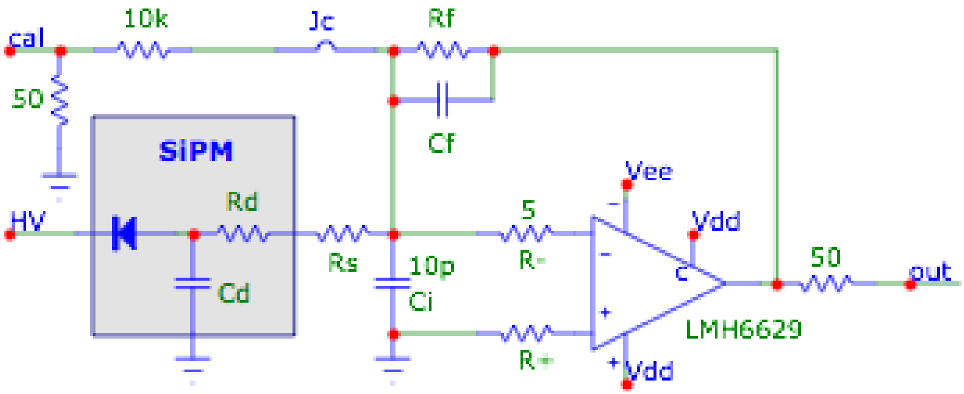
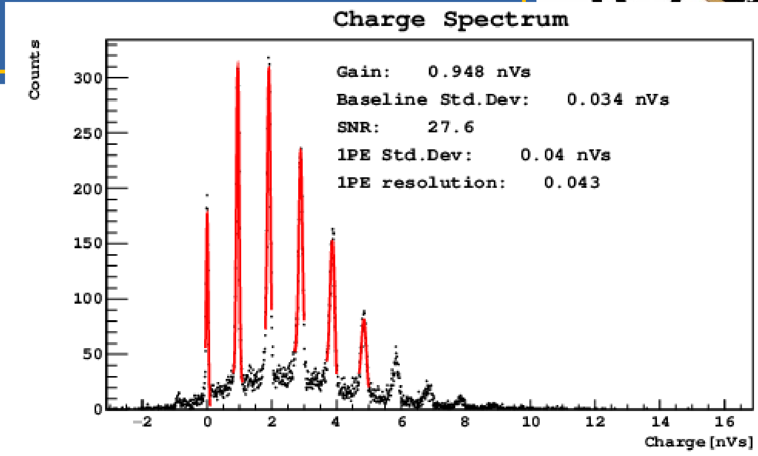
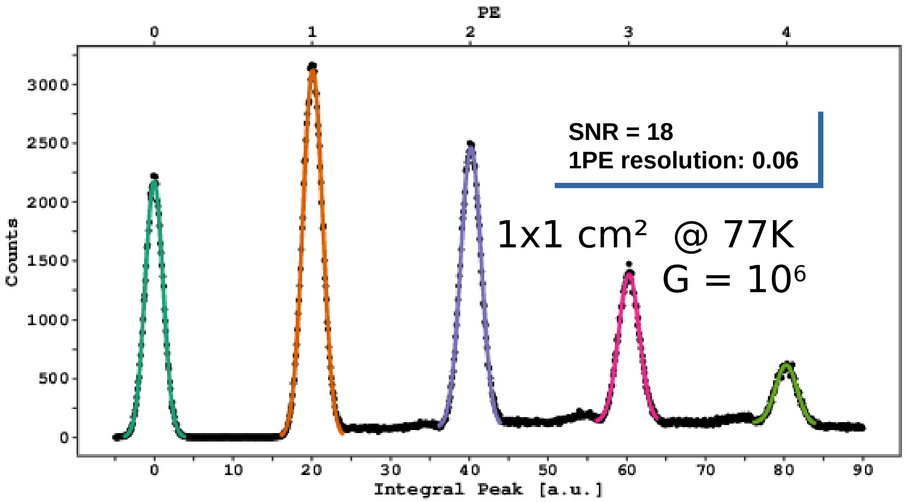
DarkSide



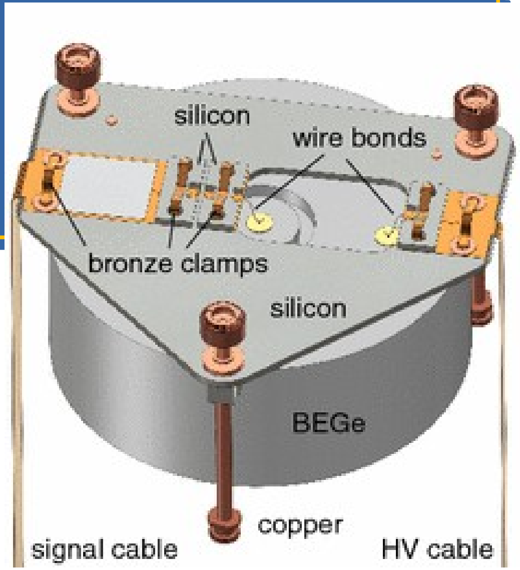


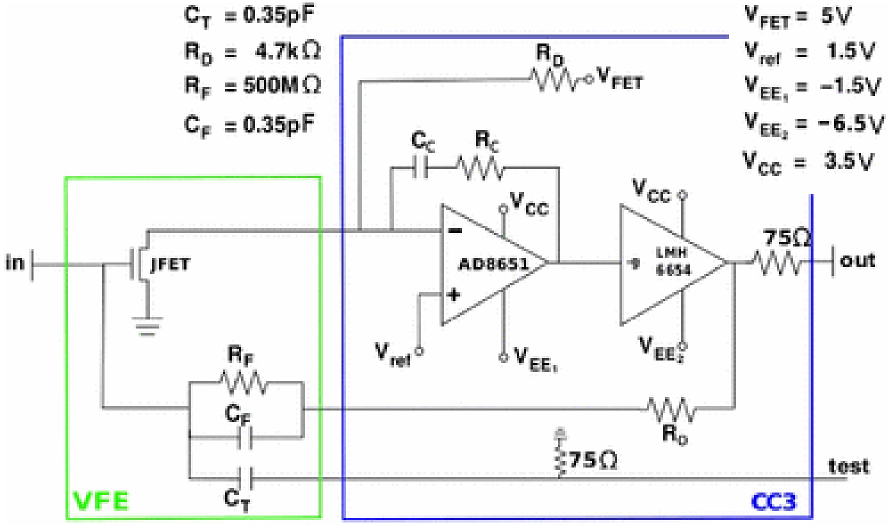


Noise = 50 nA(rms)

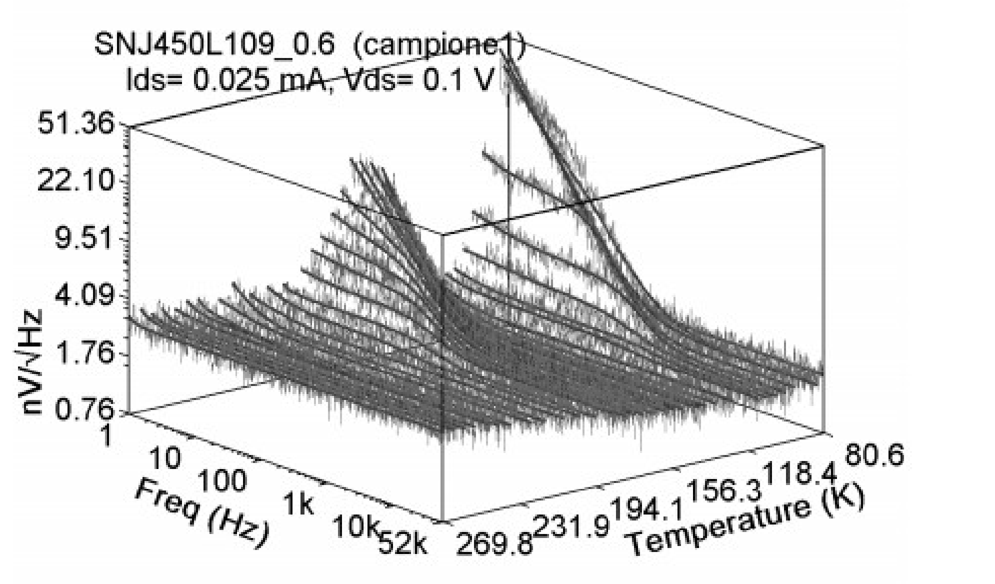
GERDA

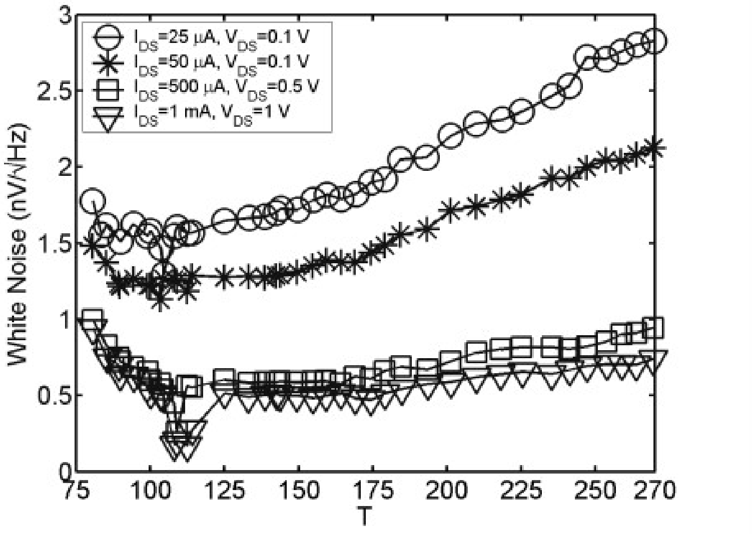
- ~ 300 e- resolution
- 60 mW
- Using radio-clean components





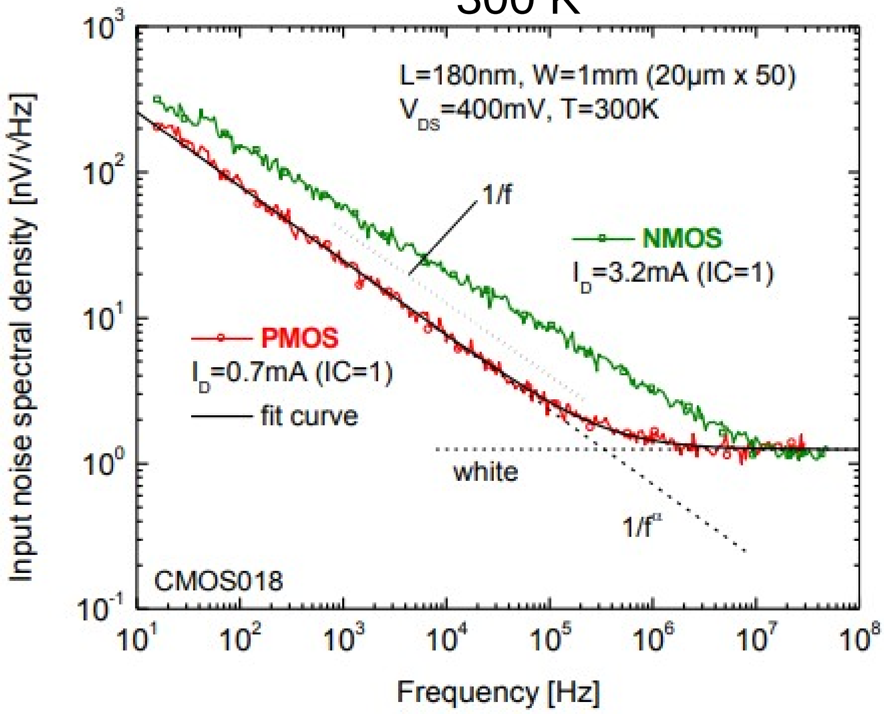
Noise in jFET



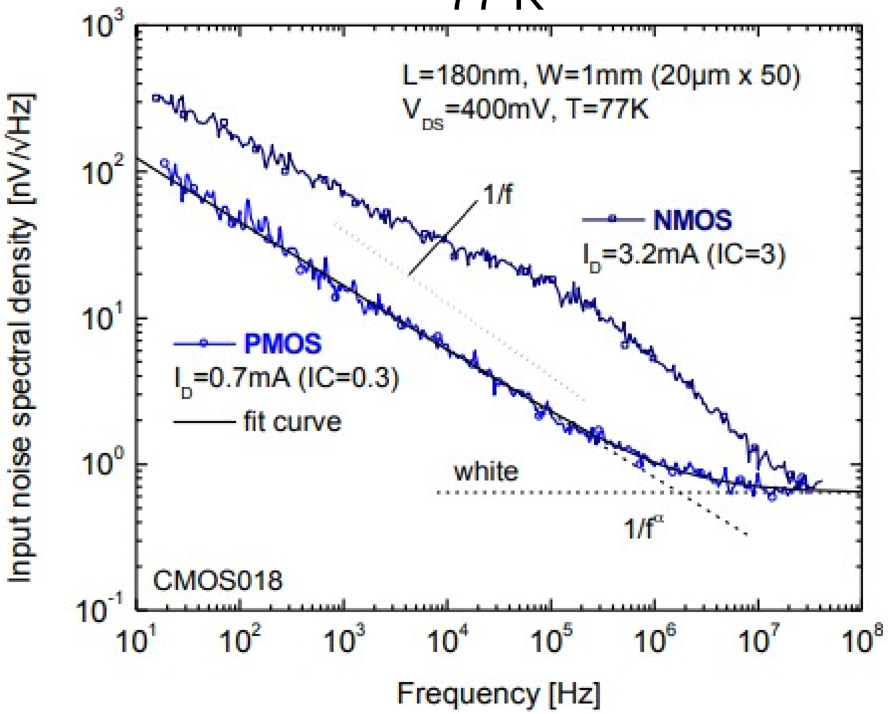


CMOS electronics

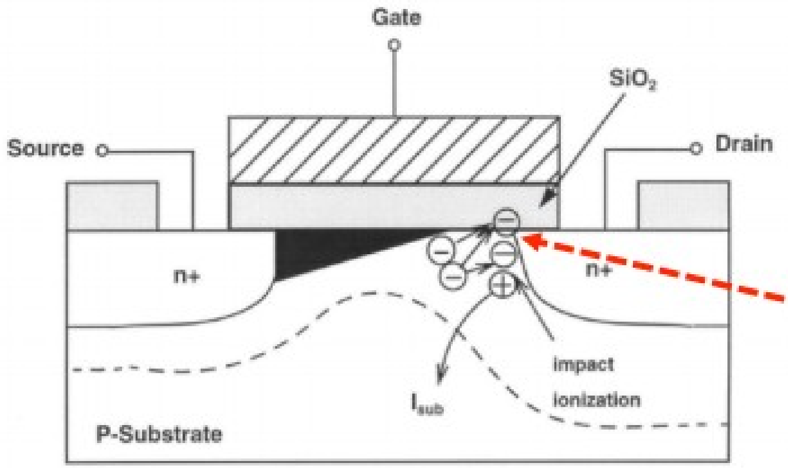
300 K



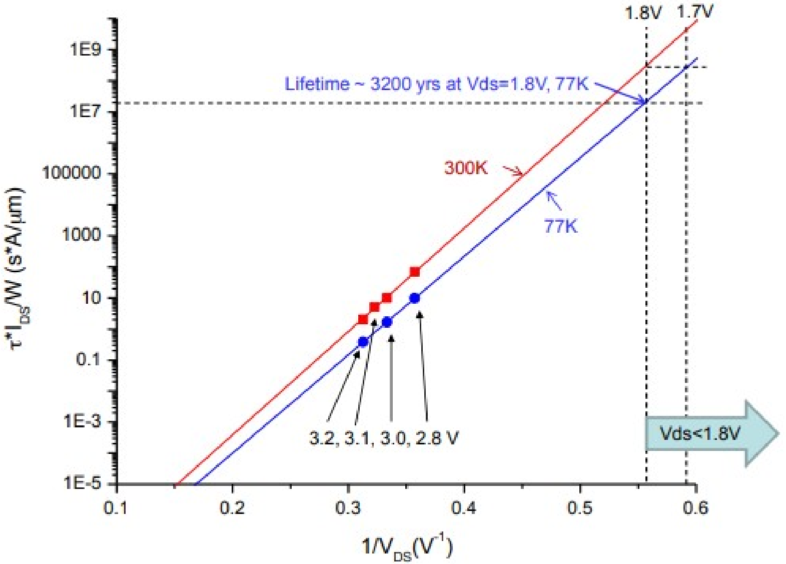
77 K



Lifetime



Strong electric
field @ drain



For NMOS:
L=180nm,
W=10um;