Modern Particle Physics Detectors I

Theory
Applications
Practice

Lesson 3: Silicon Photo-Detectors (part b)
Silicon Photo-Multipliers

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http://dpnc.unige.ch/PhD

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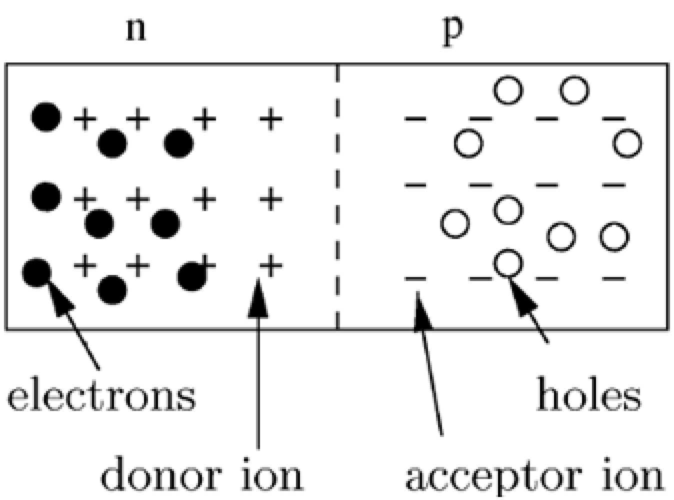
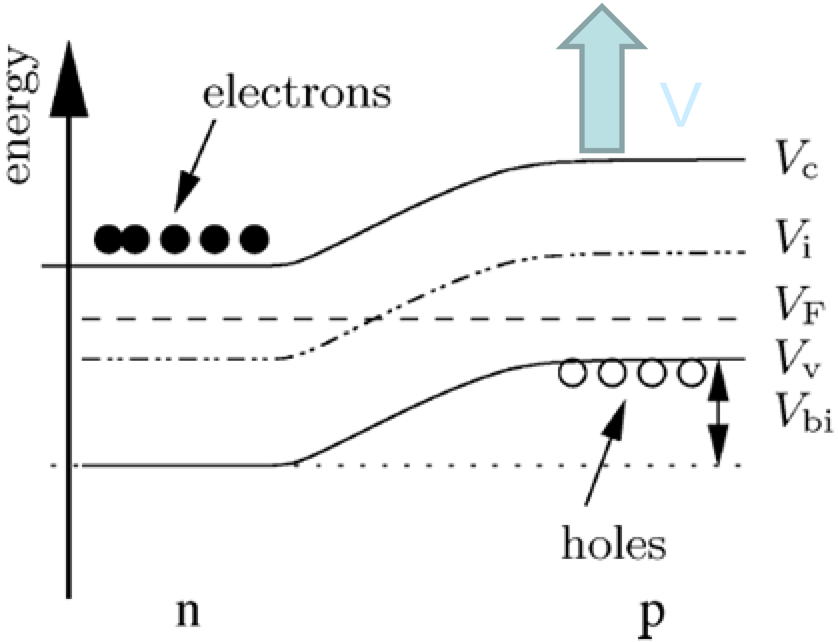
Photo-Diodes

Diodes (*pn* Junctons)

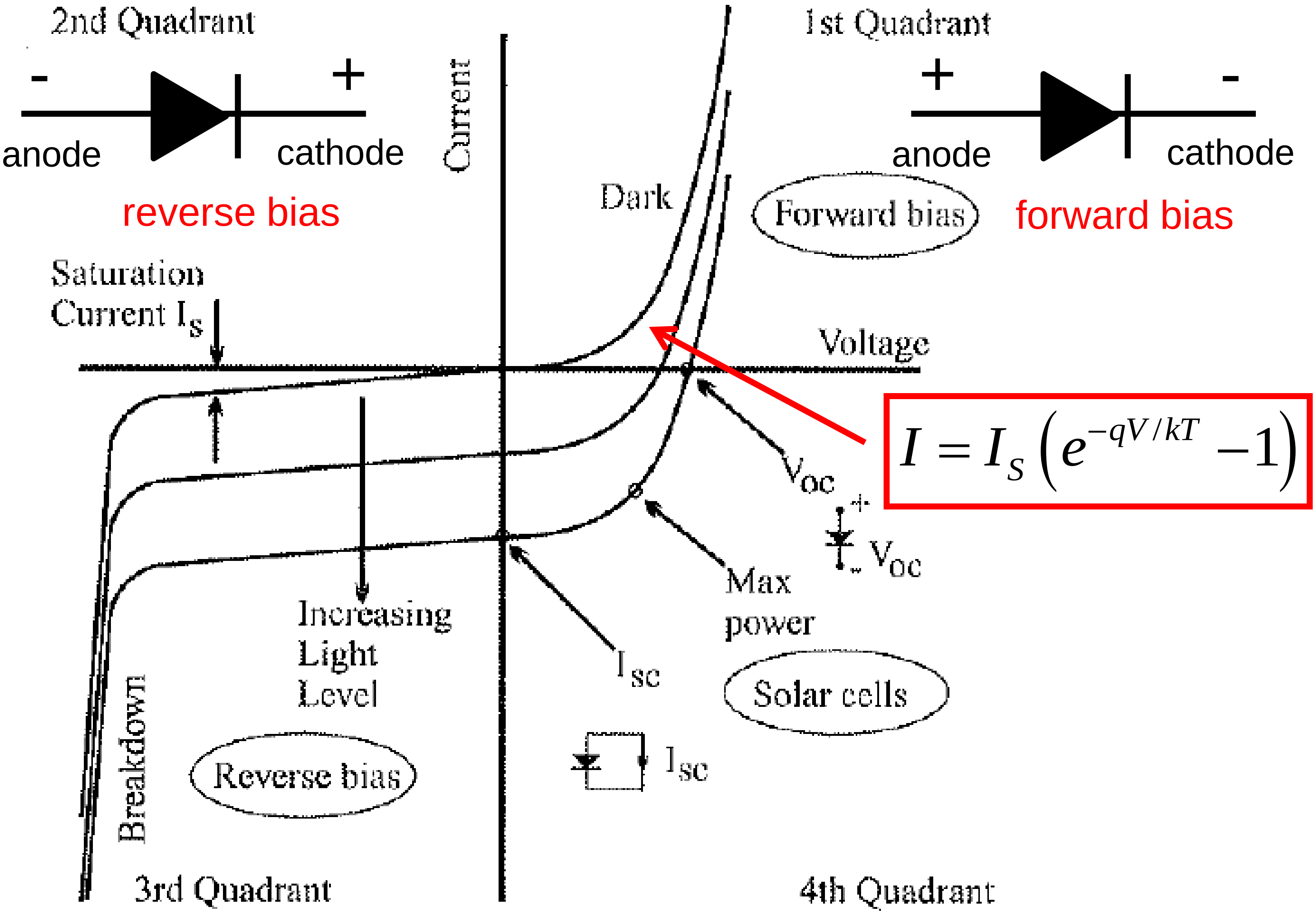
The reversely biased p-n junction is the building block of silicon sensors.
It builds-up an electric field that can be used to extract the signal charge and suppresses the noise resulting from the leakage current.

In the transition *pn* region, some of the majority carriers on one side diffuse in the opposite side due to the concentration difference and recombine with the majority carriers on the other side, leaving a *charge free* zone (*depletion zone*, where acceptor and donor ions are left without their reversely charged free carriers).
This region is then electrically charged (*space charge region*) and generates an E-field that counteracts the continuation of the diffusion, with a built-in voltage V_{bi} (O ~ 1 V).





Current – Voltage Curve



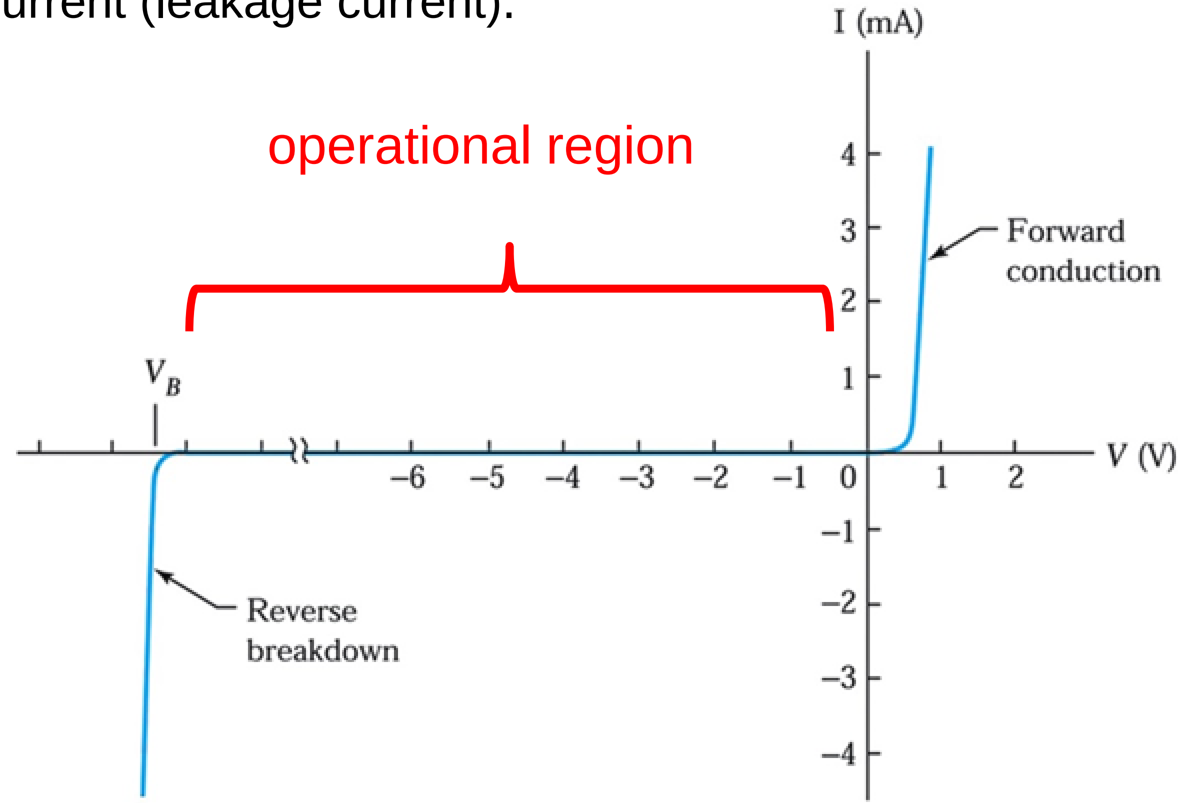
$$I = I_S\left(e^{-qV/kT} - 1\right)$$

Current – Voltage Characteristics

Exponential current increase in forward bias.

Avalanche current increase when reverse breakdown is reached
(with possible device damage if current is not limited).

Large operational region (with different depletion depths up to full depletion)
with very small current (leakage current).



Junction Capacitance

The depleted junction volume is free of mobile charges and thus forms a capacitor with capacitance C, (i.e. a parallel plate capacitor of area A and thickness W):

$$\boxed{C = \varepsilon_{Si}\frac{A}{W} = A\sqrt{\frac{\varepsilon q N_B}{2(V_{bias}+V_{bi})}}}$$

→ capacitance decreases with the applied voltage V_{bias}.

The capacitance per unit area for a typical Si detector is

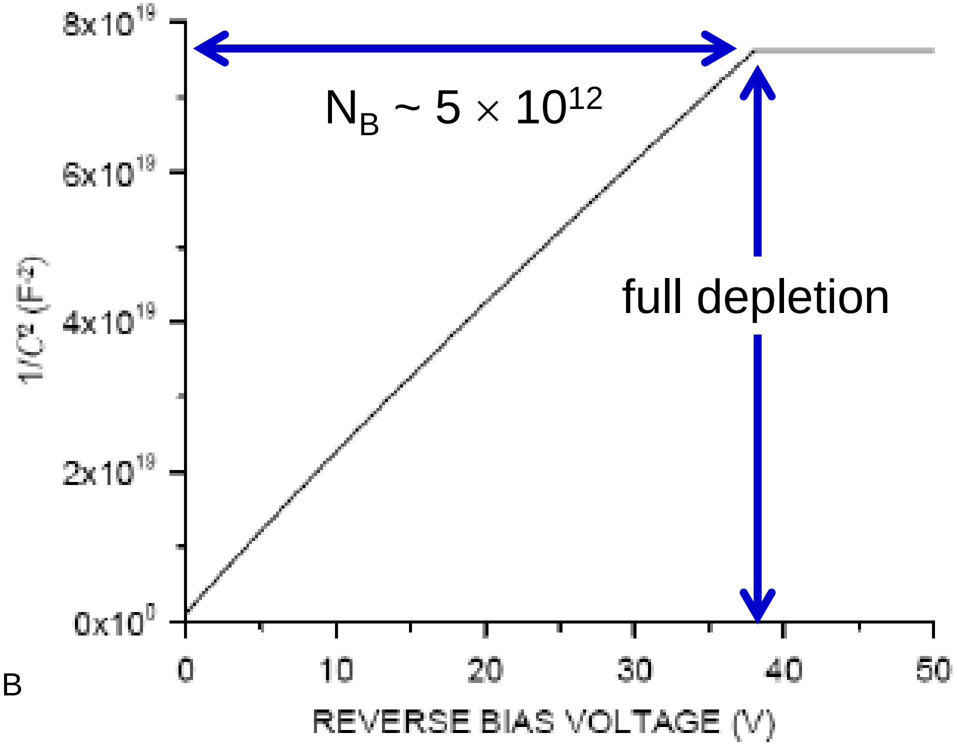
$$\frac{C}{A} = \frac{\varepsilon_{Si}}{W} \approx 1\left[\mathrm{pF/cm}\right]\frac{1}{W}$$

which favors highly segmented diodes.

The ratio C / A vs V_{bias} allows us to

1) determine the full depletion voltage

2) measure the doping concentration N_B



$N_B \sim 5 \times 10^{12}$

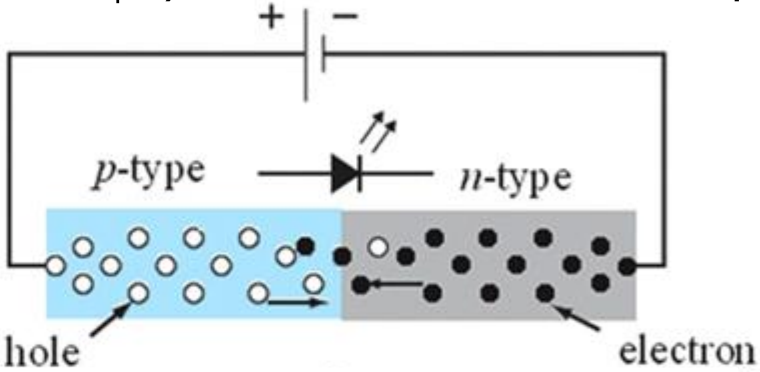
full depletion

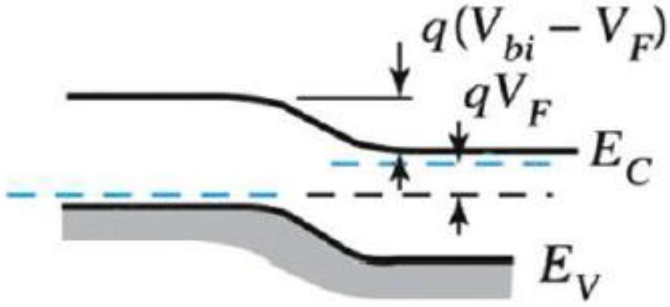
Light Emitting Diode

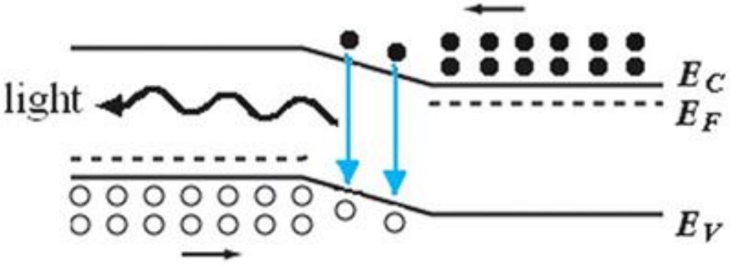
Light emitting diodes are narrow band light sources based mainly on the *pn* junctions that can emit spontaneous radiation in ultraviolet, visible, or infrared regions.

Multitude of applications, including detector calibration.

Under forward bias, **e^-** are injected from the *n*-side and **h^+** from the *p*-side.
V_{bi} is lowered by an amount equal to the applied potential V.
The injected carriers can traverse the junction, where they become excess minority carriers. In the vicinity of the junction the excess of carriers is more than the equilibrium value ($pn = n_i^2$!) and recombination takes place.



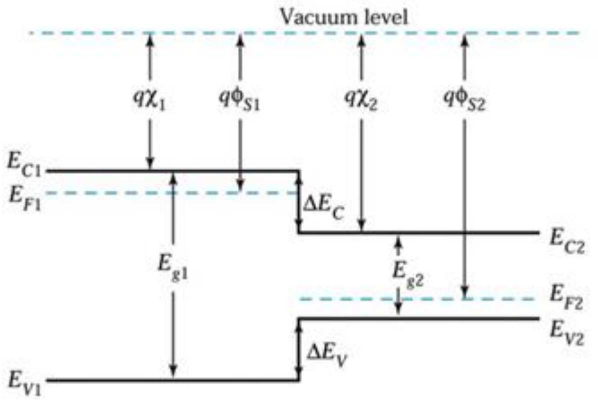


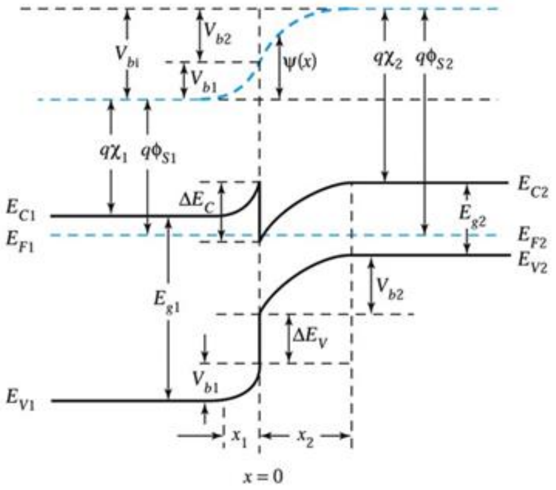


forward biased
the depletion region decreases
if $V_{bias} > |V_{bi}|$, $|V_{bi} = 0 \rightarrow W = 0$
if $V_{bias} > |V_{bi}|$ the diode conducts

Heterojunction

A different way of forming a junction is to combine two dissimilar semiconductors, typically AlGaAs compounds with different concentrations of the elements





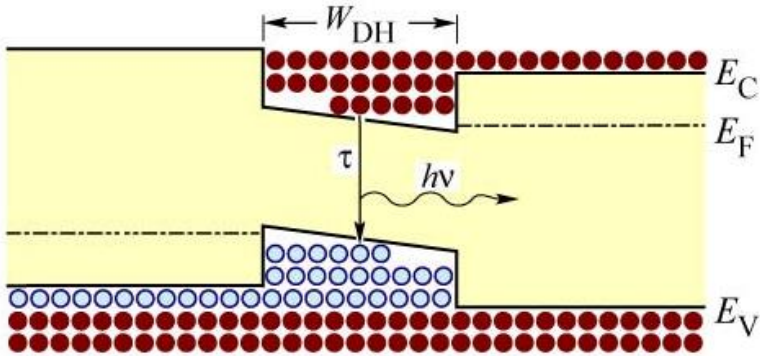
H. Kroemer
Z. I. Alferov

2000

With a double heterojunction design the LED efficiency can be much improved.
The central layer consists of the same material and usually it is not doped.
The junction is bound by layers with higher energy gaps.
Carriers confined to the well region (the radiative recombination lifetime shortened because of a higher **e^-** – **h^+** concentration).

The thickness of the central layer can be decreased down to 10 nm → quantum well: confines carriers to two dimensions

→ even higher carrier densities
→ more efficient.



Some LED Characteristics

Emitted photon energy

$$h\nu = E_g + kT \;\rightarrow\; E_g$$

Spectral width

$$\Delta\lambda = 1/hc\; \lambda^2\, \Delta E$$

(it depends on λ^2 and T :
$\Delta\lambda$ = 20 nm (green ~ 550 nm) and $\Delta\lambda$ = 120 nm (infrared ~ 1300 nm))

Frequency response

$$P(\omega) = \frac{P(0)}{\sqrt{1+(\omega\tau)^2}}$$

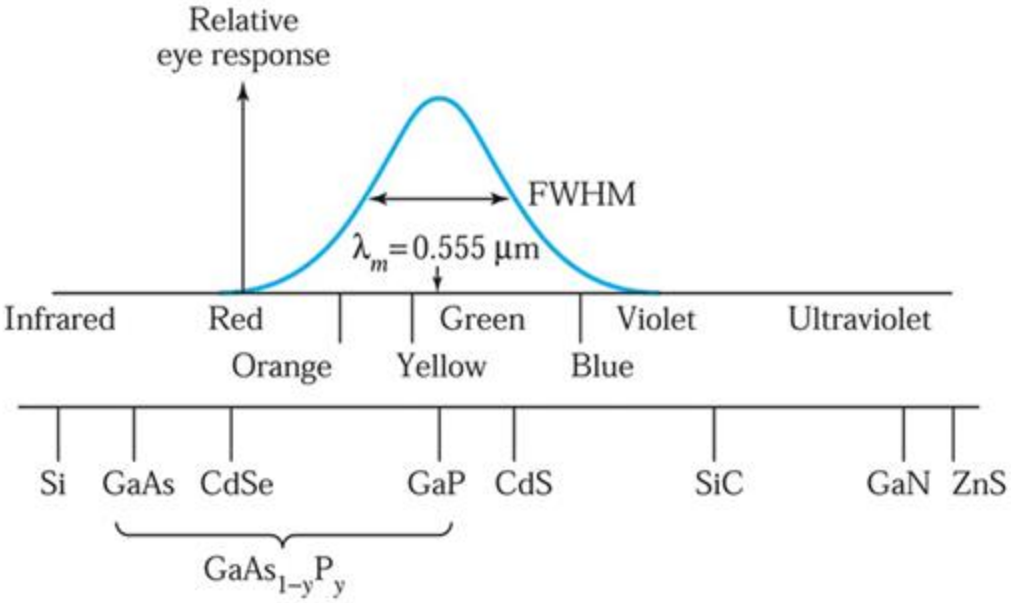
with τ the overall carrier lifetime
→ modulation bandwidth $\Delta f = 1 / 2\pi\tau$, Δf ~ 300 MHz for GaAs

Internal Quantum Efficiency

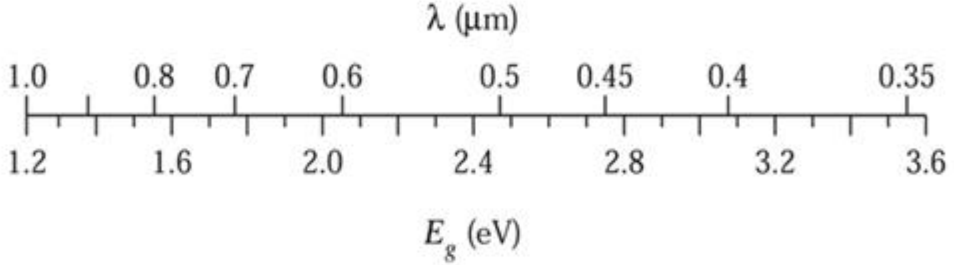
$$QE_{in} = \frac{\#\text{photons emitted internally}}{\#\text{carrier passing the junction}}$$

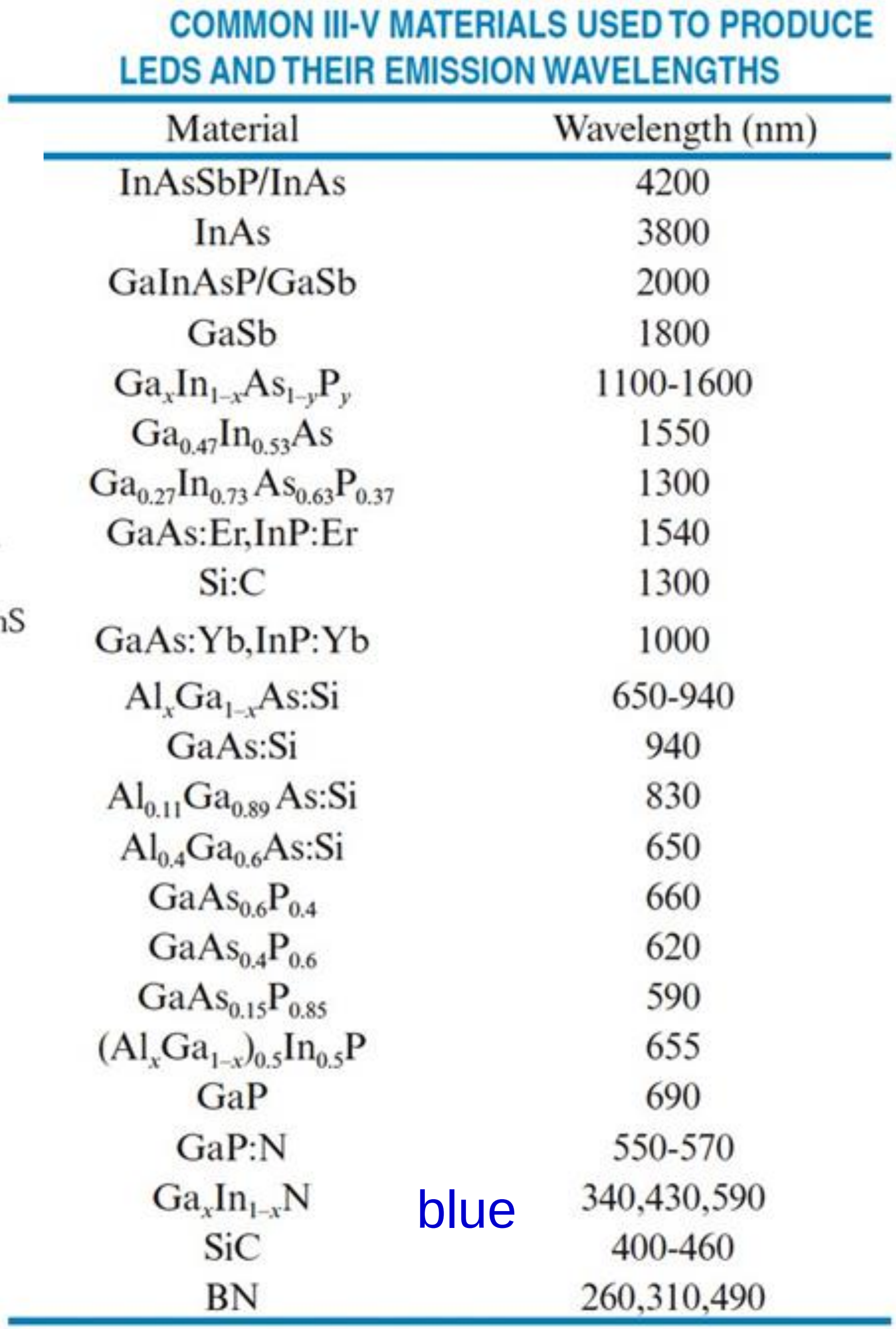
(note that the definition is reversed w.r.t. to e.g. the Q.E. of a photocathode)

LED “Materials”



semiconductors of interest for visible LEDs





COMMON III-V MATERIALS USED TO PRODUCE LEDS AND THEIR EMISSION WAVELENGTHS

Material	Wavelength (nm)
InAsSbP/InAs	4200
InAs	3800
GaInAsP/GaSb	2000
GaSb	1800
$Ga_xIn_{1-x}As_{1-y}P_y$	1100-1600
$Ga_{0.47}In_{0.53}As$	1550
$Ga_{0.27}In_{0.73}As_{0.63}P_{0.37}$	1300
GaAs:Er,InP:Er	1540
Si:C	1300
GaAs:Yb,InP:Yb	1000
$Al_xGa_{1-x}As$:Si	650-940
GaAs:Si	940
$Al_{0.11}Ga_{0.89}As$:Si	830
$Al_{0.4}Ga_{0.6}As$:Si	650
$GaAs_{0.6}P_{0.4}$	660
$GaAs_{0.4}P_{0.6}$	620
$GaAs_{0.15}P_{0.85}$	590
$(Al_xGa_{1-x})_{0.5}In_{0.5}P$	655
GaP	690
GaP:N	550-570
$Ga_xIn_{1-x}N$	340,430,590
SiC	400-460
BN	260,310,490

blue

Unfortunately this table does not show the carrier lifetimes and mobilities.

Examples of LEDs

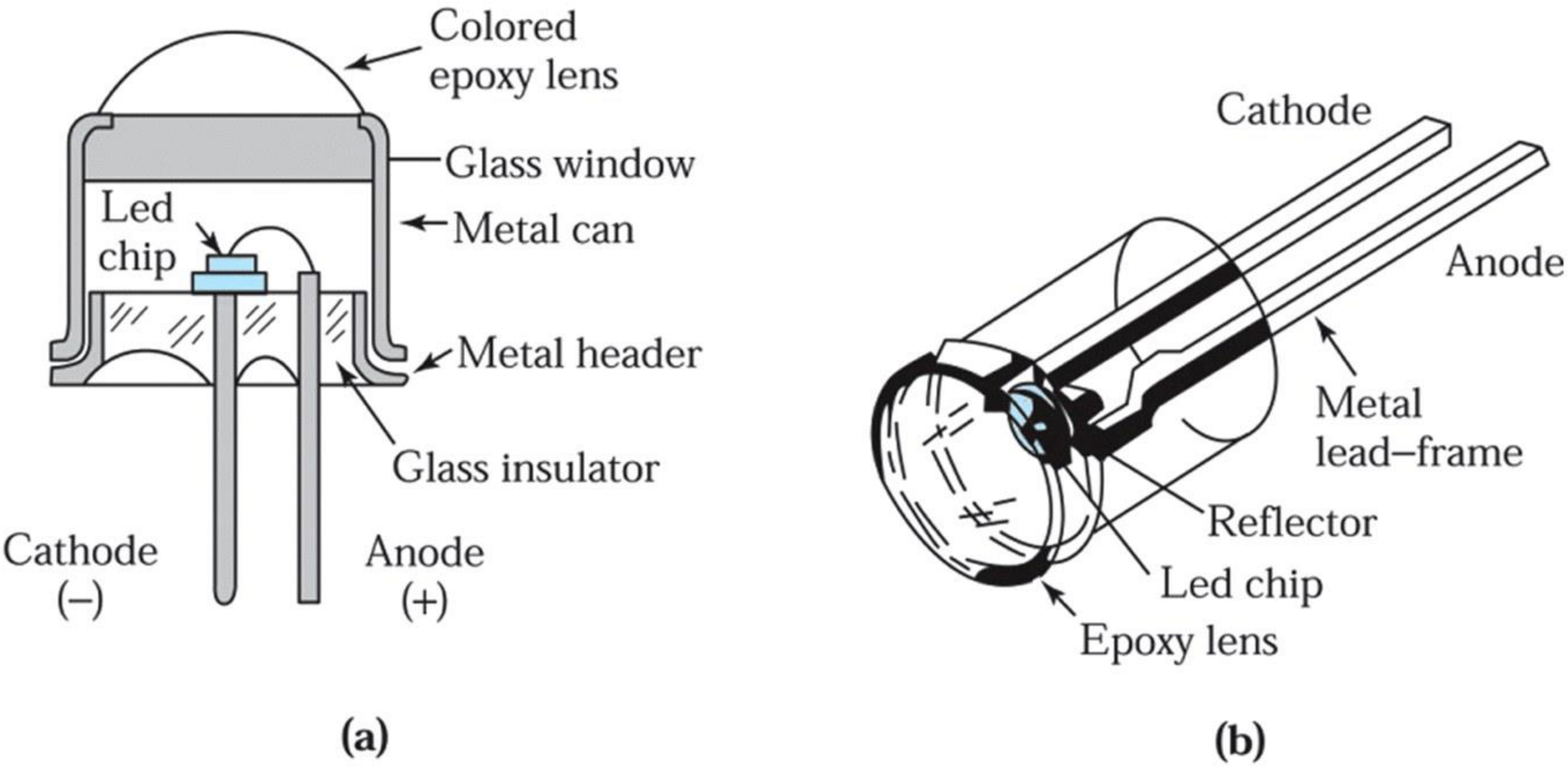
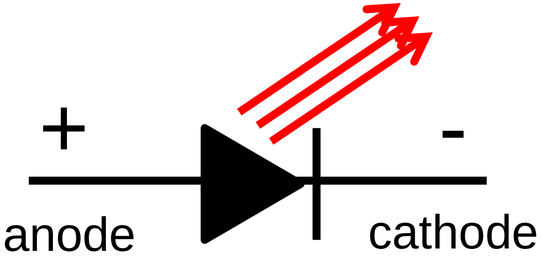
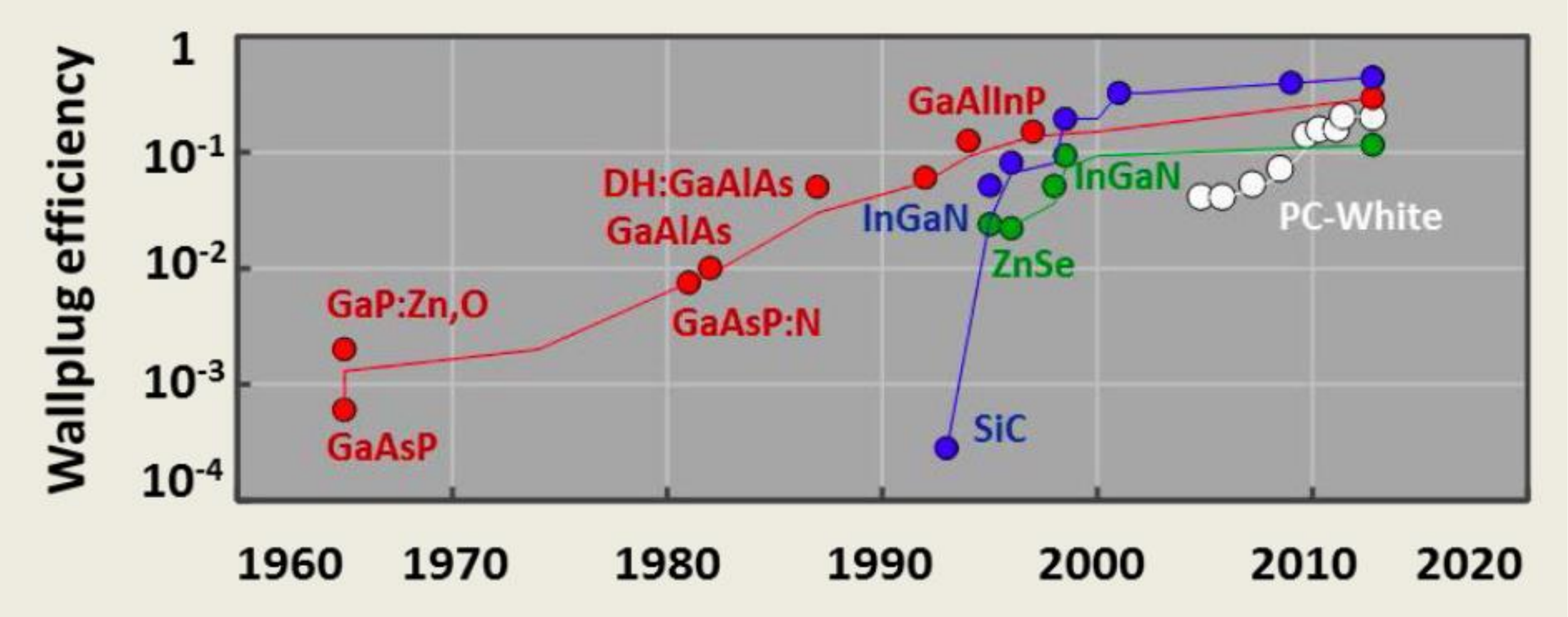


Figure 9.12



LED Efficiency Evolution



Historical evolution of commercial LEDs.
PC-White = phosphor converted white light
DH = double heterostructure.
The wallplug efficiency is the ratio between emitted light power and supplied electrical power.

White Light LEDs

2014

2014 Nobel Prize in Physics to

I. Akasaki, H. Amano and S. Nakamura

"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources".

LEDs have much higher efficiency than incandescent lamps and can last 10 × longer. Since lighting represents 20-30% of our electrical energy consumption, and since these new white light sources require ten times less energy than ordinary light bulbs, the use of efficient blue LEDs leads to significant energy savings, of great benefit to mankind.

The development of efficient blue LEDs ($E_g = 3.4$ eV) in the 80's required

1. the production of GaN-based alloys with different compositions and
2. their integration into multilayer structures such as heterojunctions and quantum wells.

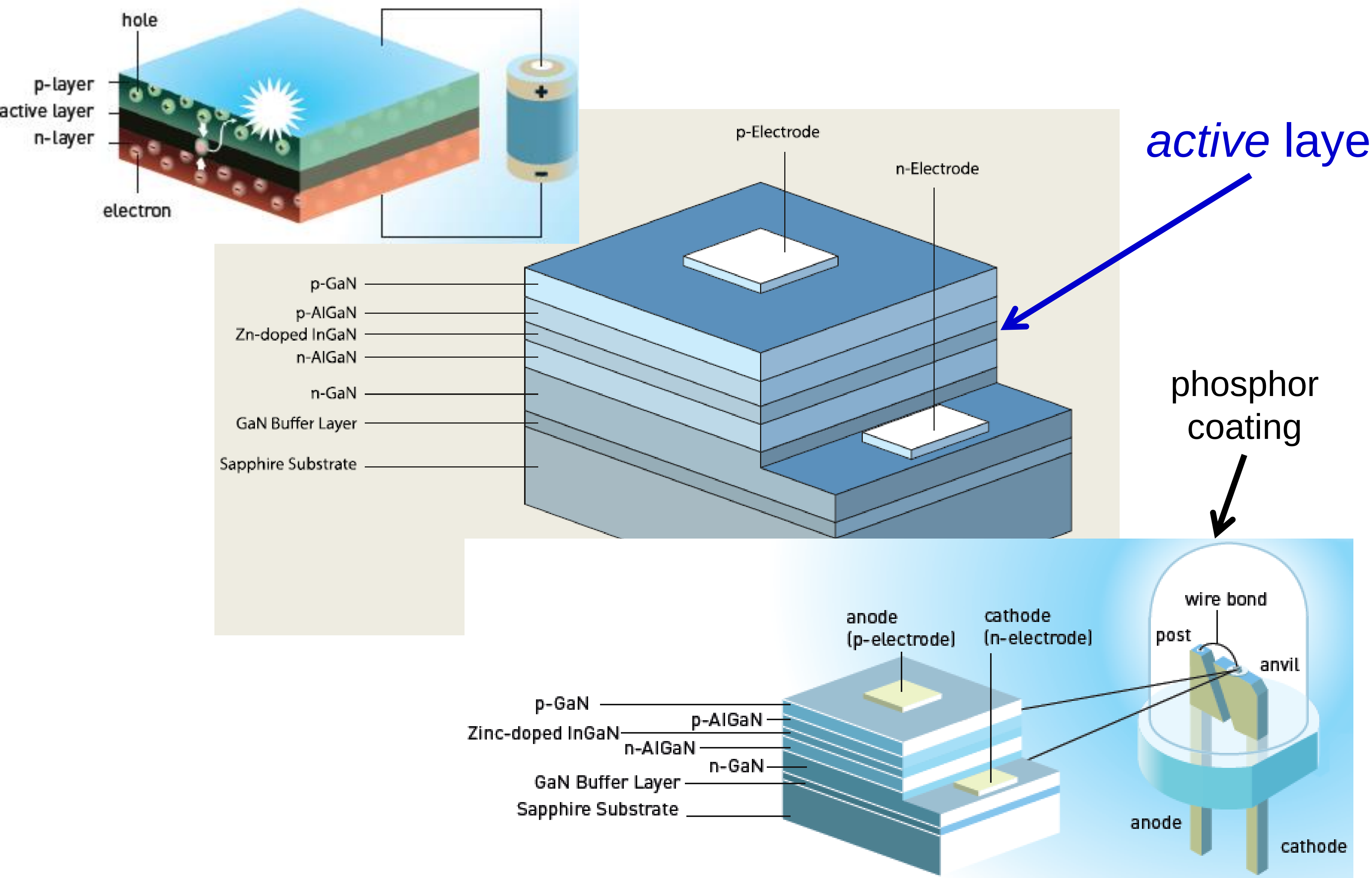
The invention of efficient blue LEDs has led to white light sources for illumination.

There are two approaches to achieving white light:

1. combine LEDs of different colors red, green, and blue (costly)
2. use a single LED covered with a color converter
   blue LED with a yellow phosphor: the blue light from the LED is mixed with the yellow light from the phosphor to produce white light.

Structure of a Blue LED

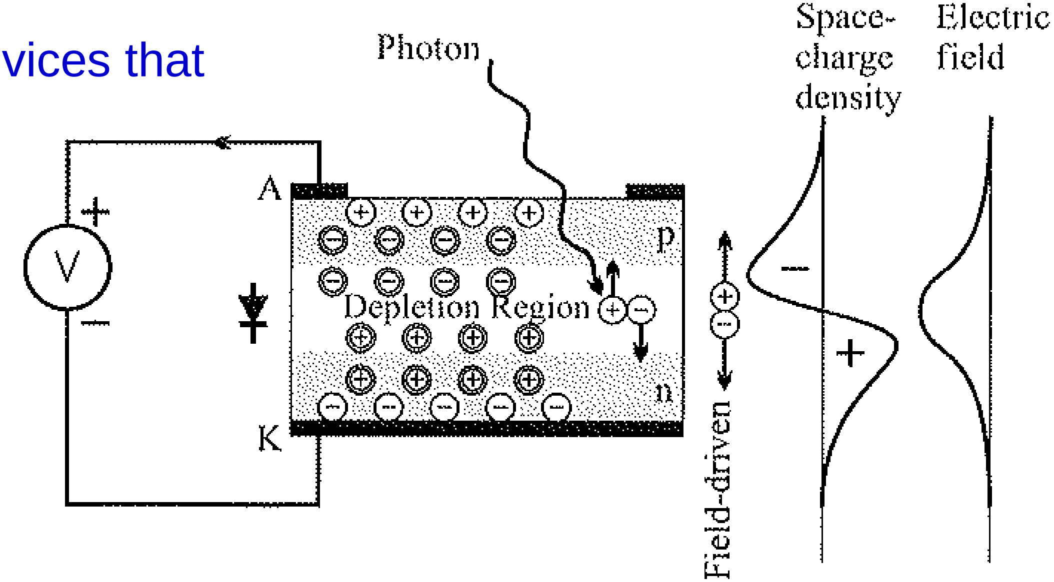
Structure of a blue LED with a double heterojunction InGaN / AlGaN



active layer

phosphor coating

Principle of Photo–Diode Operation



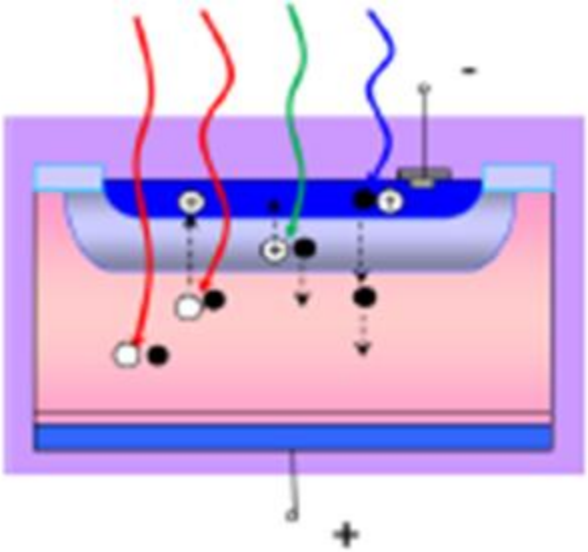
Photodetectors are semiconductor devices that (electrically) detect optical signals.

At its operating wavelength

- high sensitivity
- high response speed
- minimum noise
- small size
- low voltage
- high reliability

pn junction operated in reverse bias

The E-filed is non-uniform and maximal at the junction.

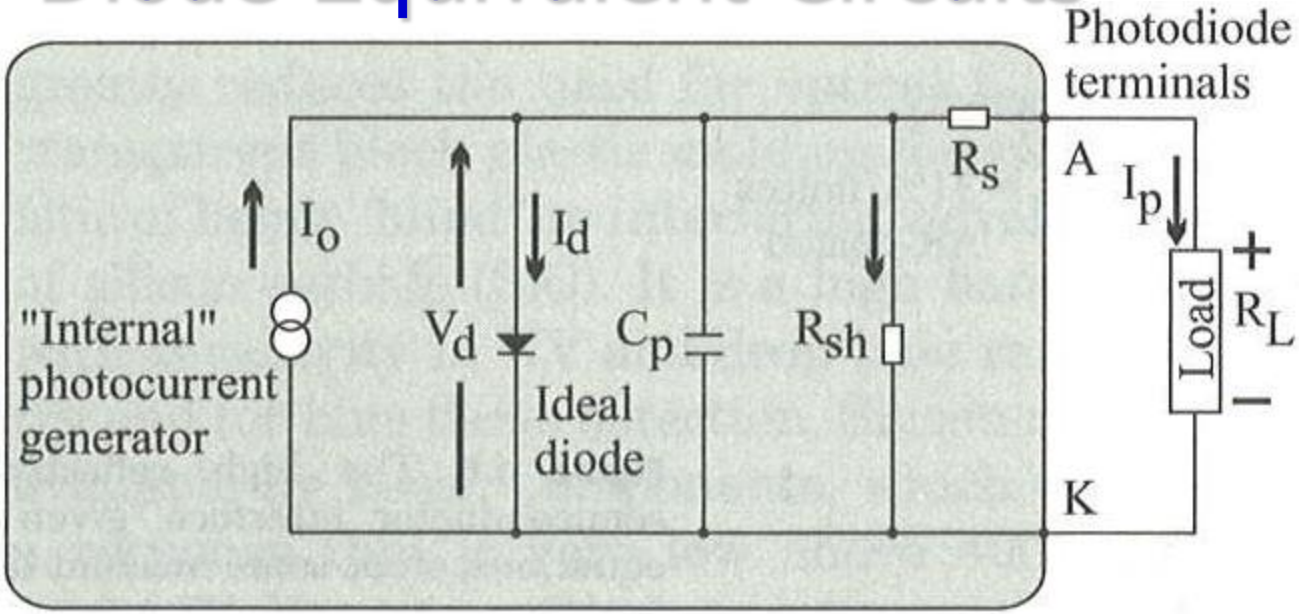


A photon of hν = $E_\gamma > E_g$ is absorbed in the depletion region of the Si-PD:

1. the hole will drift toward the *p*-side and recombine with electrons on the negative electrode
2. the electron will drift toward the *n*-side.

If there are many photons, a small current will be detected.

Photo-Diode Equivalent Circuits



A photodiode can be modeled as a current source proportional to the incident light intensity in parallel with an ideal diode, a parallel resistance and a parallel capacitance (depletion and diffusion capacitance) and a resistor in series.

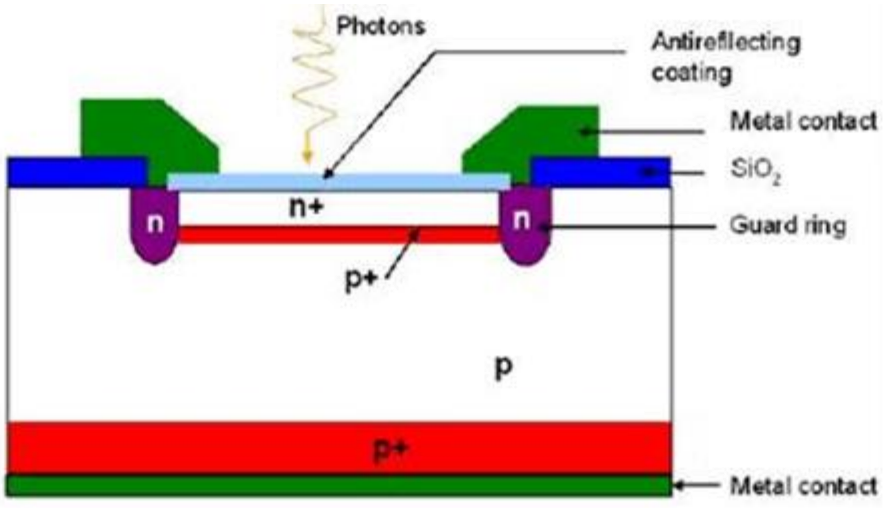
Noise is quoted as “equivalent noise charge” ENC (i.e. the noise at the input of the the amplifier in elementary charges).

Noise contributions come from
  leakage current I → shot noise
  detector capacitance C (pF)
  detector parallel resistance R_p (Ω)
  detector serial resistance R_s (Ω)

Response Speed

The response speed is limited by :

1) diffusion of carriers
2) drift time in the depletion region
3) capacitance of the depletion region



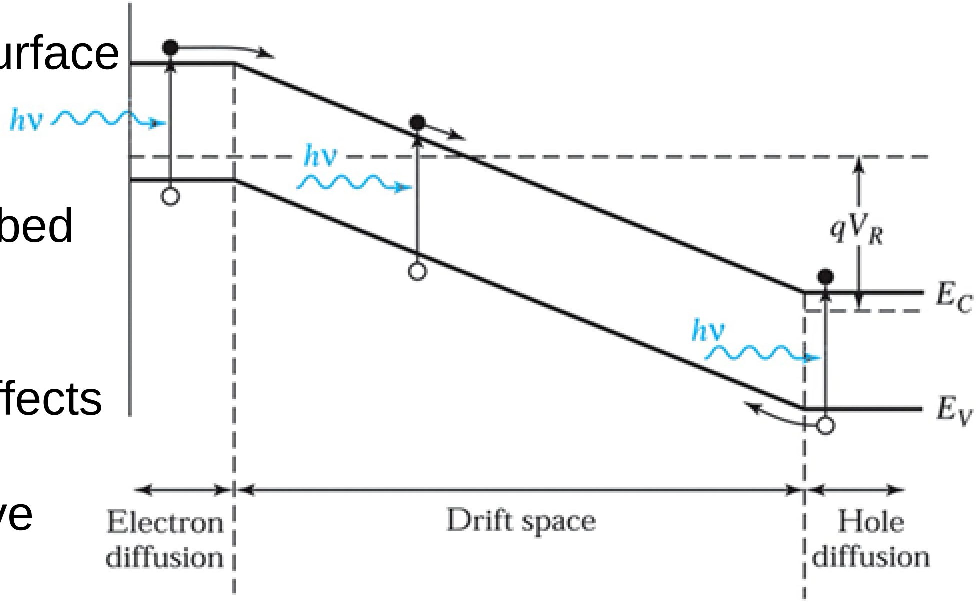
Carriers generated outside the depletion region must diffuse to the junction leading in considerable time delay

→ junction formed very close to the surface

The largest amount of light will be absorbed when the depletion region is wide.
The depletion layer

1) should not be too wide or transit effects will limit the frequency response.
2) should not be too thin, or excessive capacitance will result in large RC

Good compromise → 25 μm thickness



Anti-Reflecting Coating

Light is reflected at the
photo-detector surface.

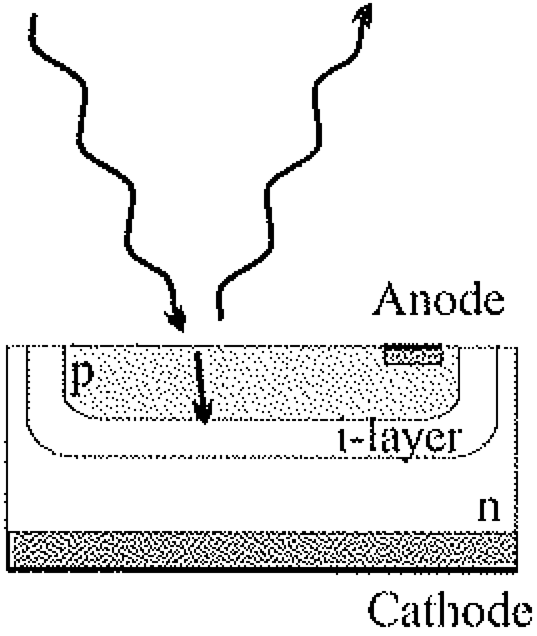
Refractive index of Si n = 3.5

Normal reflectivity

$$R = \left(\frac{n-1}{n+1} \right)^2 = 31\%$$

This means that 31% of incident
light is reflected
unless the detector is appropriately
coated (anti-reflecting coating).

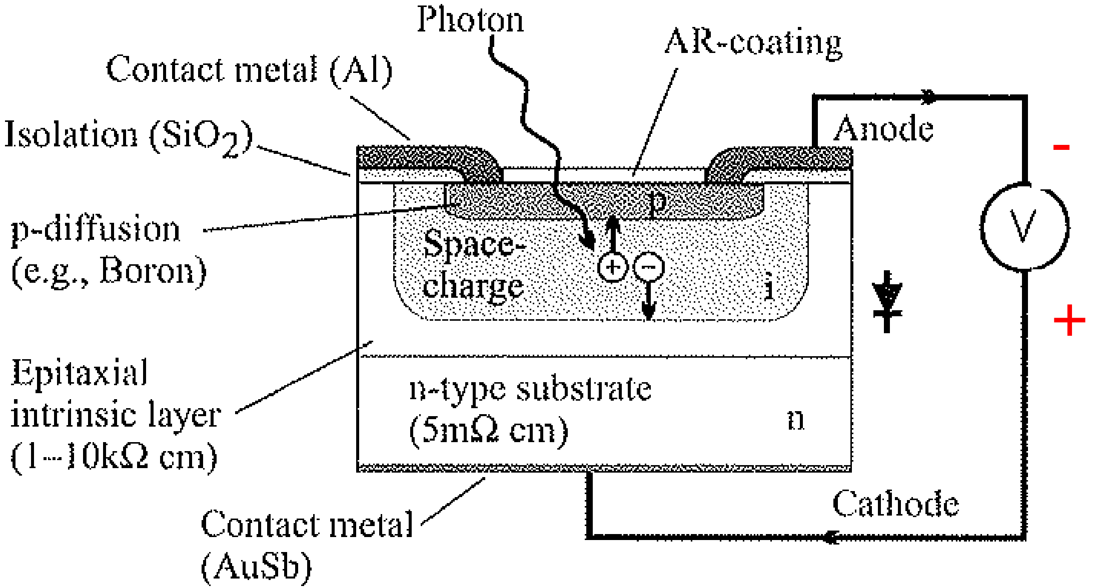
Si_3N_4 with n = 1.9 is a good choice.



p-i-n Photodiode

The *pn* junction photodiode has two major drawbacks :

1. the junction capacitance is not sufficiently small (small depletion layer)
2. the depletion layer is not sufficiently wide to make the penetrating depth greater than the depletion layer at long wavelengths



The solution is to add an *intrinsic* semiconductor layer between the *p*-side and the *n*-side

→ *p-i-n* photodiode

The intrinsic *i*-layer is completely depleted with a thickness up to few 100 μm.

The *p-i-n* photodiode is the simplest, most reliable and cheapest photo-sensor, in which an intrinsic piece of semiconductor is sandwiched between two heavily (oppositely) doped regions.

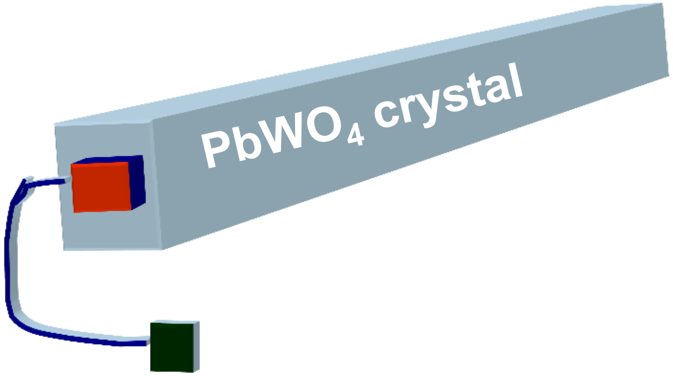
The two charge sheets (on the n^+ and p^+) sides produce a field which, even without an external field supplied, will tend to separate charges produced in the depleted region. The separated charges will be swept to either terminal and can be detected as a current provided that they did not recombine.

p-i-n Photodiode

The *p-i-n* photodiode is a very successful device

- high quantum efficiency, up to 80%
- very small volume
- insensitive to magnetic field

The *p-i-n* photodiode, however, has no internal amplification (multiplication) of the signal



It is used in many big calorimeters in high energy physics.
A MIP traversing a *p-i-n* photodiode creates ~ 30,000 e-h pairs (for a diode thickness of 300 μ, typically 100 pairs / μ).
Light generated by a 7 GeV photon in a $PbWO_4$ and detected with a *p-i-n* photodiode generates the same number of e-h pairs.

Metal Semiconductor Photodiode

metal film ~ 10 nm

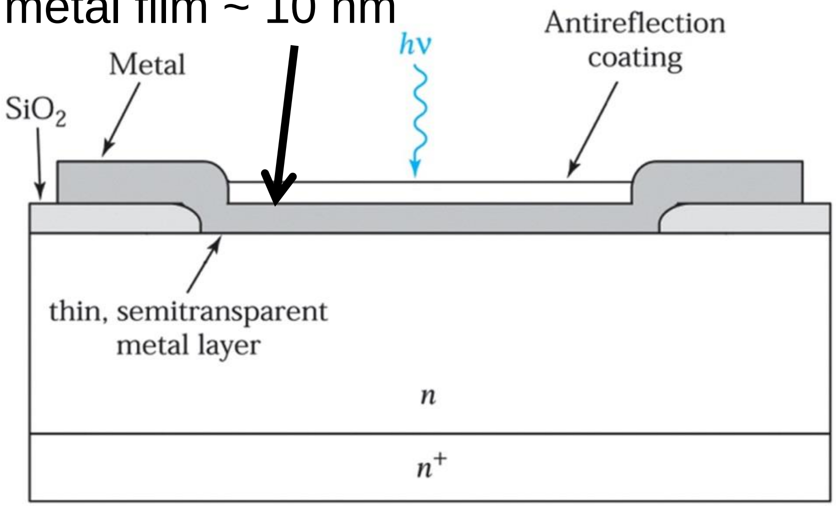


Figure 10.5
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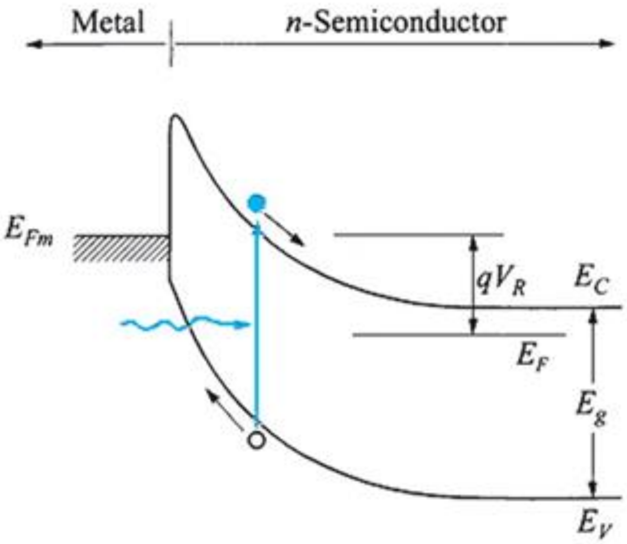
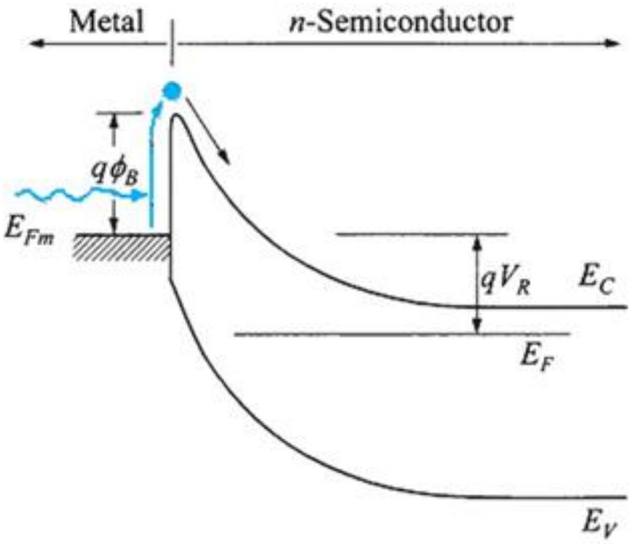
Two operation modes:

1. $E_\gamma > E_g$
behaves as the *p-i-n* photodiode

2. $E_\gamma < E_g$
internal photoemission from the metal film: the photo-excited electrons in the metal can surmount the barrier and be collected by the semiconductor
→ Schottky-barrier height measurement

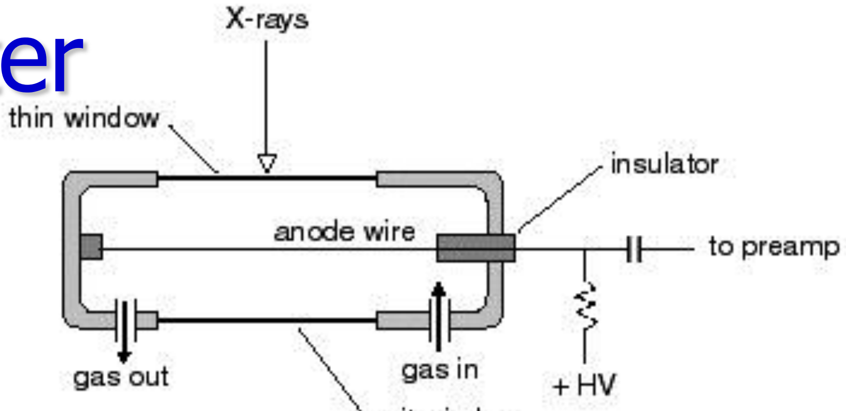


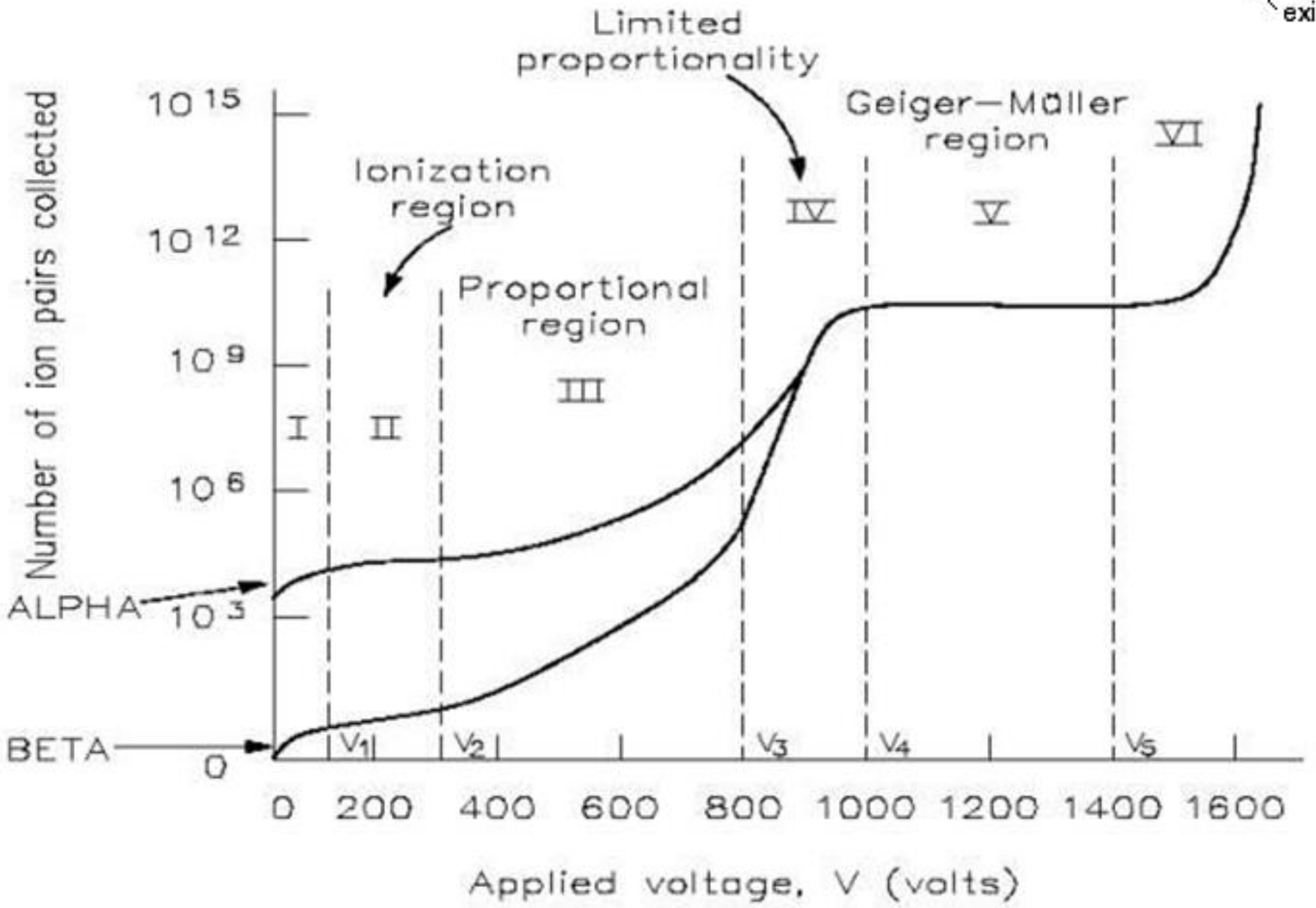
band to band excitation $E_\gamma > E_g$



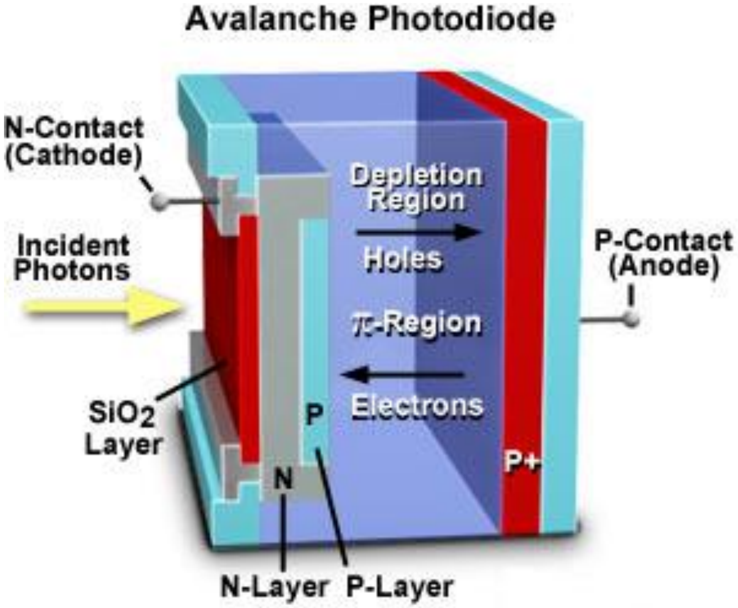
internal photoemission from metal $E_\gamma < E_g$

Proportional Gas Counter





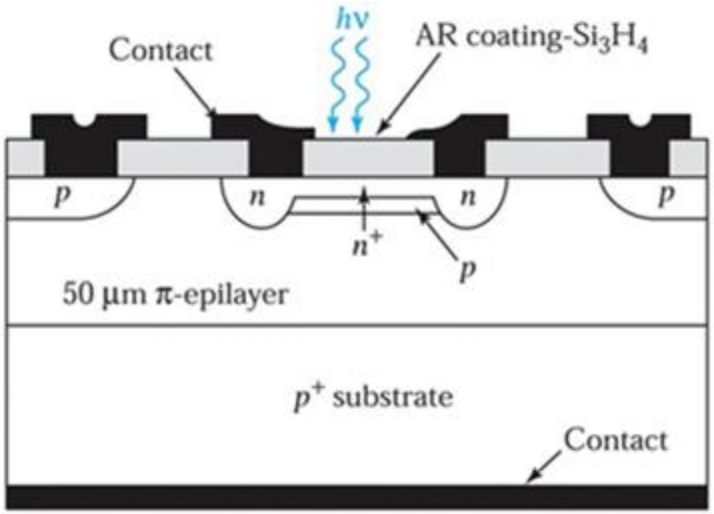
Avalanche Photodiode

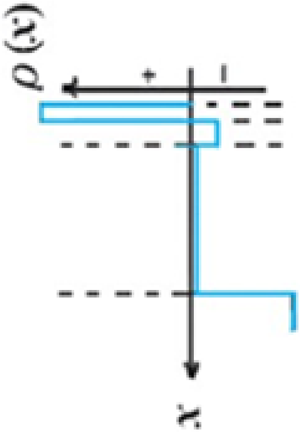


An avalanche photodiode (APD) is a diode operated under sufficiently high reverse bias (100 – 200 V) to enable avalanche multiplication.
The multiplication results in

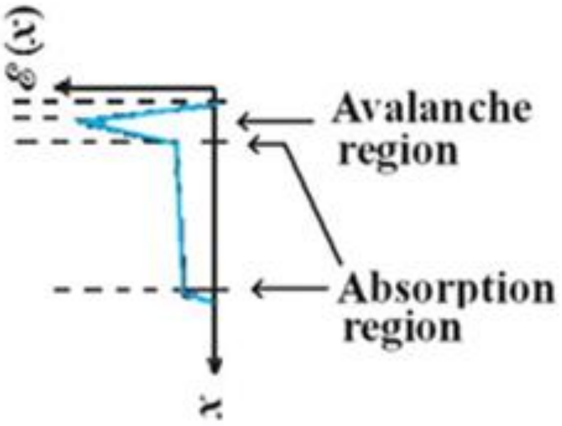
1. internal current gain 100 – 1000 ×
2. can respond to light modulated frequencies
3. limited avalanche multiplication (limited gain !)

Structure of an APD having a n^+-p-π-p^+ doping profile (π is lightly doped p region). There are three p-type layers p-π-p^+ with different concentrations next to the n^+ layer. The maximum E-field is at the n^+-p junction, almost constant in the π-layer due to the small net space charge density.



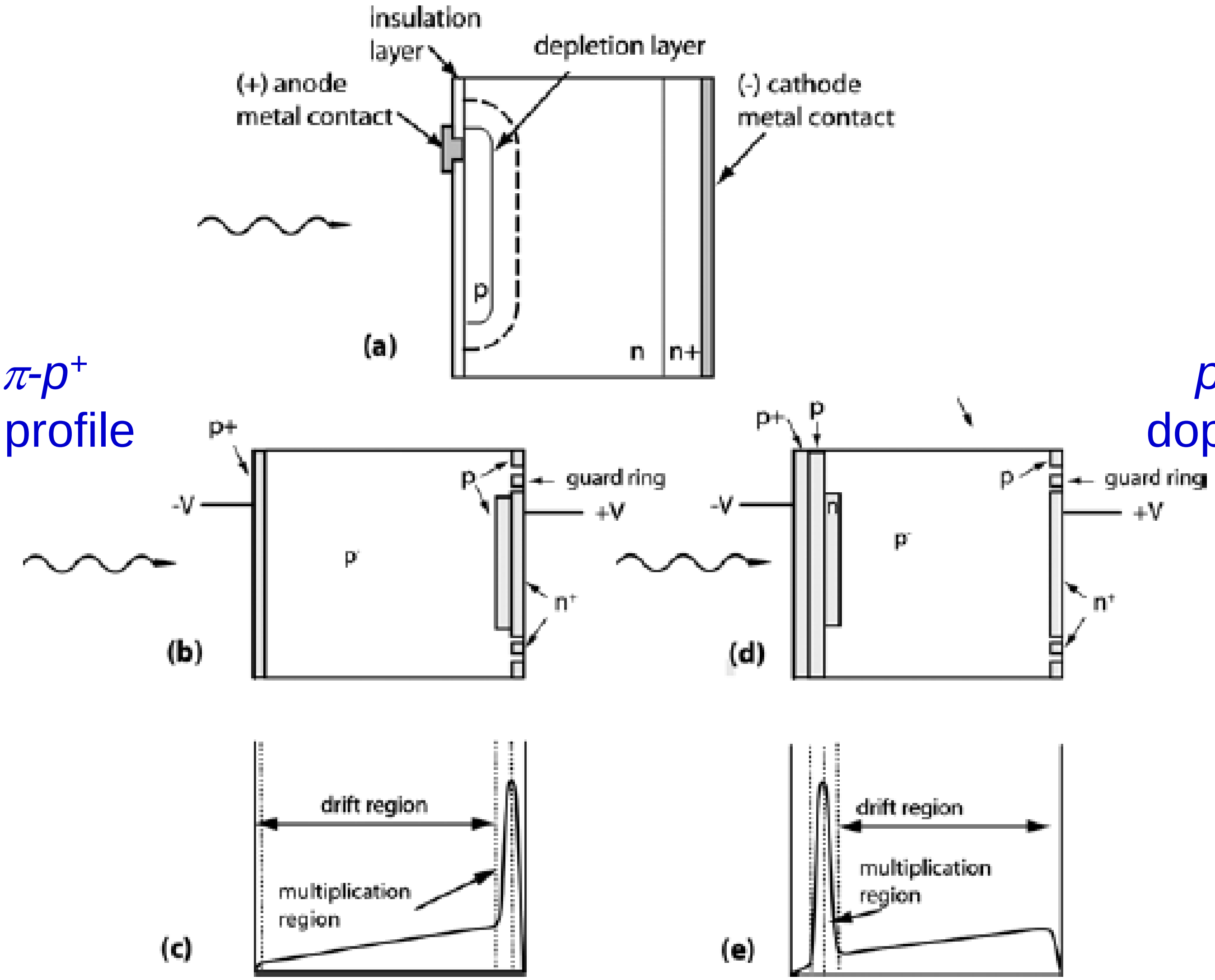


space charge



E-filed distribution

Different Doping Profiles



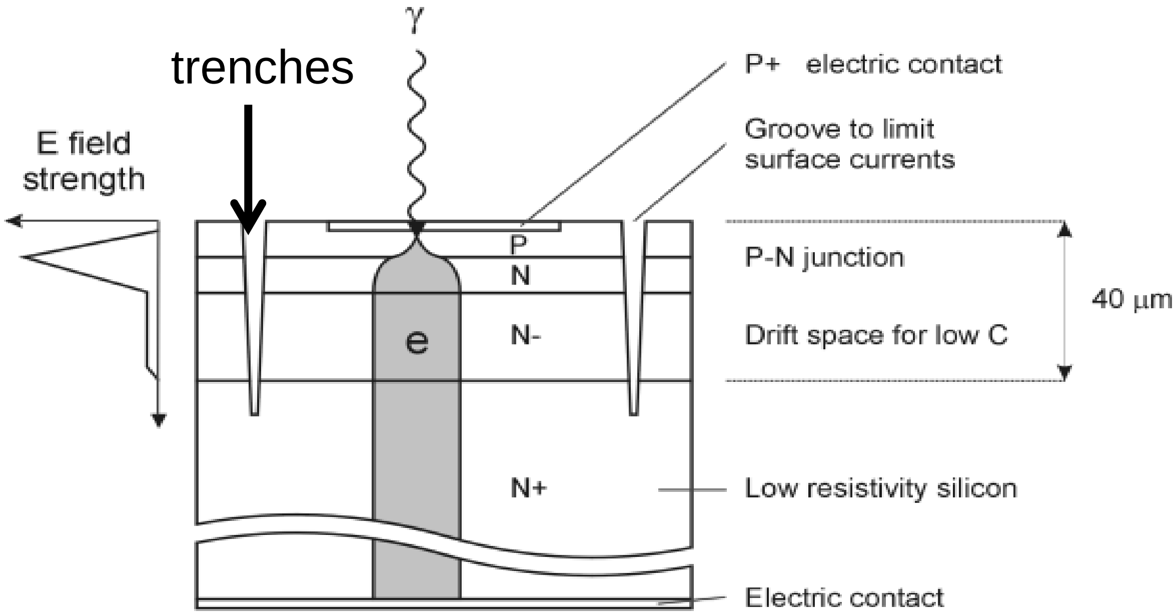
n^{+}-p-π-p^{+}
doping profile

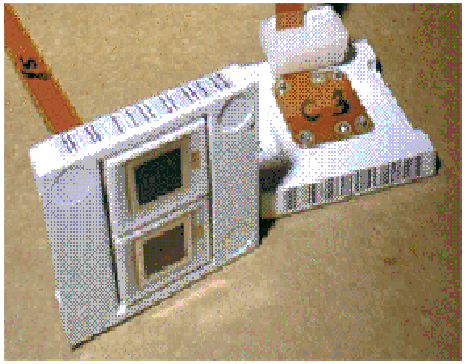
p^{+}-n-ν-n^{+}
doping profile

electron multiplication

hole multiplication

Basic APD Structure



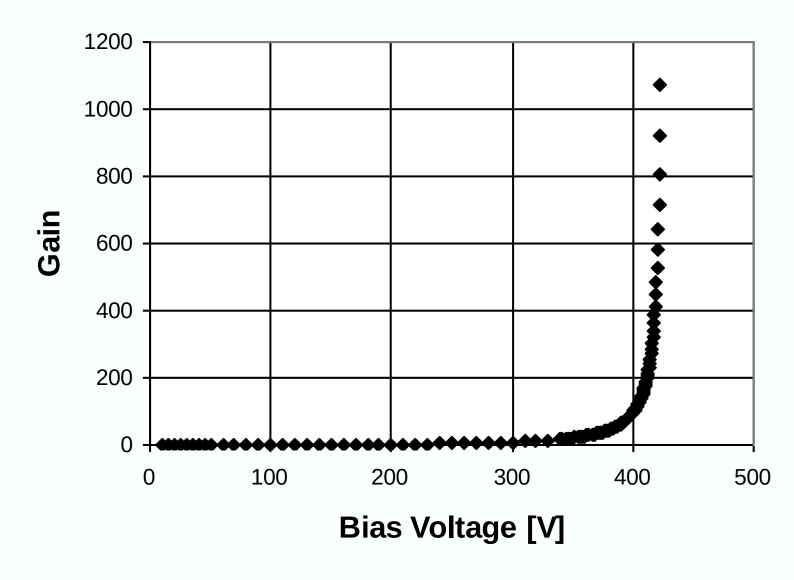


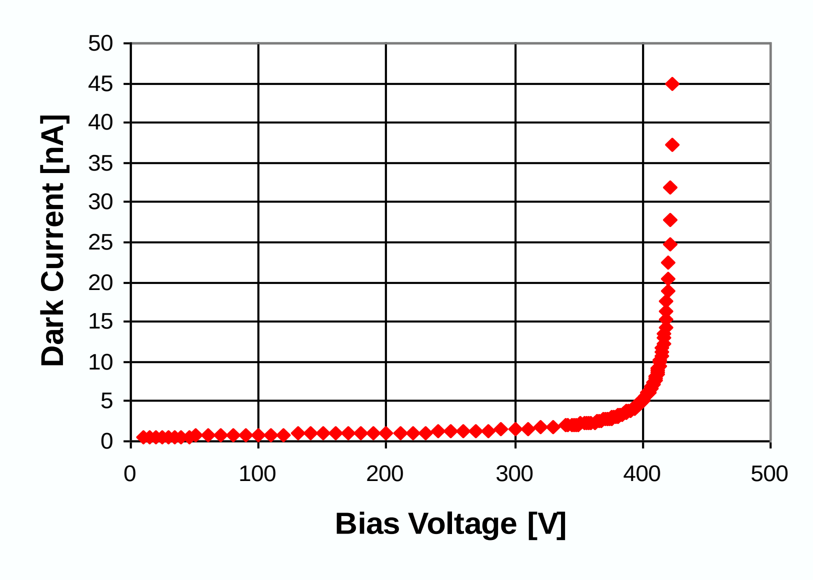
Photons create e-h pairs in the thin p-layer on top of the device and the electrons induce avalanche amplification in the high field at the p-n junction.
Holes created behind the junction contribute little because of their much smaller ionization coefficient.

Electrons produced by ionizing particles traversing the bulk are not amplified.
The effective thickness for the collection and amplification of electrons which have been created by a MIP is therefore about 6 μm.

The ENC is 50 times smaller than in a *p-i-n* diode.

Gain and Dark Current





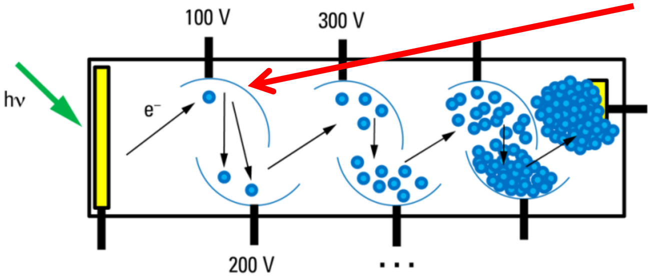
Near the breakdown voltage, where we get noticeable amplification, the gain is a steep function of the bias voltage. The breakdown voltage depends on the temperature due to energy loss of the electrons in interactions with phonons. Consequently the gain depends on the temperature and the dependence increases with the gain.

Avalanche noise from random nature of avalanche multiplication (every e-h pair does not experience same amplification). At high gain the fluctuations of the gain become large and the excess noise factor ENF increases.

Signal Fluctuations

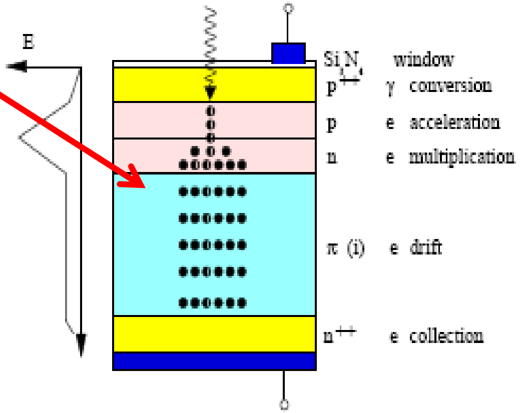
photo-detectors with internal gain

PMT



statistical fluctuation of the avalanche multiplication widen the response of a photo-detector to a given photon signal beyond simple photoelectron statistics

APD



characterized by the excess noise factor ENF

$$ENF = \frac{\sigma_{out}^2}{\sigma_{in}^2}$$

general definition (gain = 1)

$$ENF = 1 + \frac{\sigma_M^2}{M^2}$$

M = gain

$$\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_{pe}}}$$

quality of energy measurement

Approximate values for photo-detectors

detector	ENF
PMT	1 – 1.5
MCM-PMT	1
APD	2 @ gain 50
HPD	1 – 1.5
Si-PM	1 – 1.5

impacts the photon counting capability for low light measurements

deteriorates the stochastic term in the energy resolution of a calorimeter

Energy Resolution and ENF

Energy ≡ # collected secondary carriers

$$E = M \times PDE \times N_\gamma$$

M – Mean Multiplication coefficient, a stochastic variable with variance σ_M^2, for SiPM it has a major fluctuation due to after-pulsing and cross-talk.

Energy resolution including readout noise

$$\frac{1}{SNR} = \frac{\sigma}{E} = \sqrt{\frac{ENF}{PDE \times N_\gamma} + \left[\frac{ENC}{M \times PDE \times N_\gamma}\right]^2}$$

ENF – Excess Noise Factor due to the multiplication process

ENC – Equivalent Noise Charge due to the electronics noise

Excess Noise Factor for single ph.el. (also noted F or F^2)

$$ENF_{1pe} = 1 + \frac{\sigma_M^2}{M^2}$$

Energy Resolution and ENF

Operational definition for n ph.el.

$$ENF_{Npe} = \frac{\sigma^2_{n_{out}}}{\sigma^2_{n_{in}}}$$

if n_{in} is Poissonian

$$ENF_{Npe} = M^2 \cdot ENF_{1pe}$$

Hybrid Photo Detectors (HPD's)

Combination of vacuum photon detectors and semiconductor technology

Photo-emission from cathode

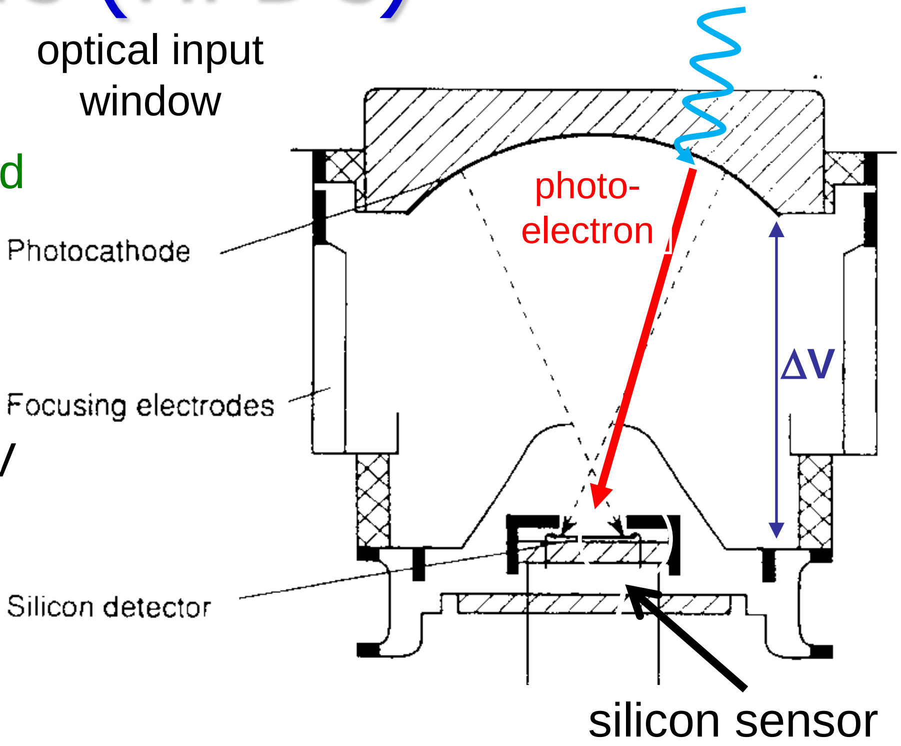
Photo-electron acceleration to ΔV ~ 10-20 kV

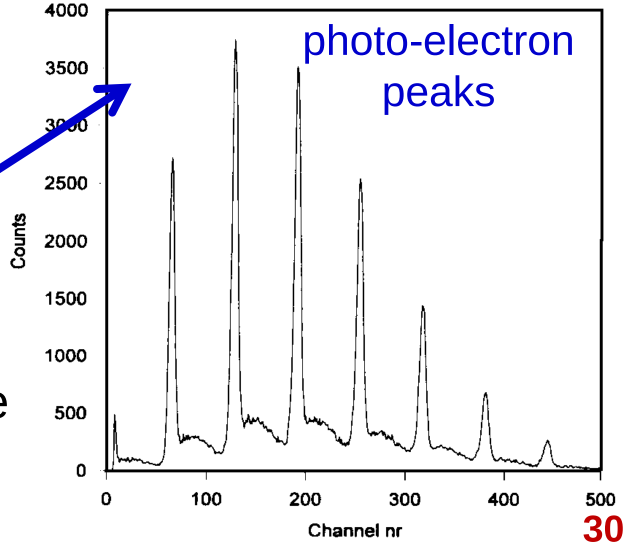
Gain achieved in one step by energy dissipation of keV photo electrons in semiconductor detector.
This results in low gain fluctuations.

Output direct electronic signal

Suited for single photon detection with high resolution

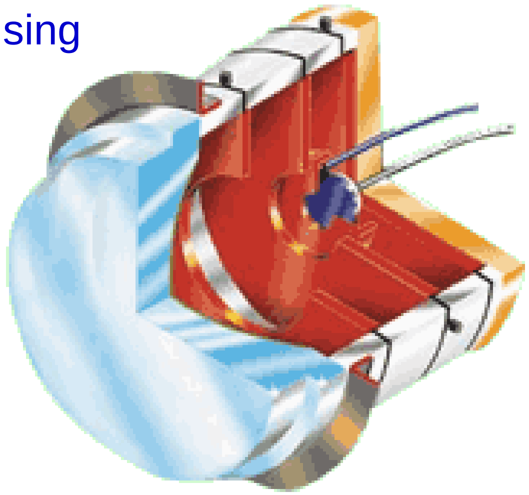
Segmented (multipixel) silicon sensor
→ can reconstruct impact point of photon on photocathode



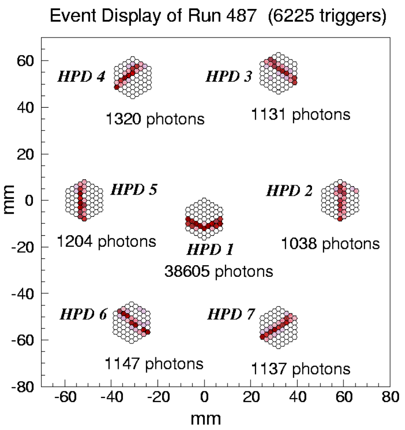


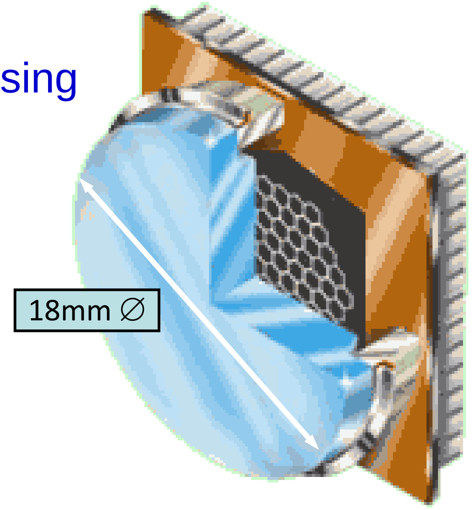
Various Types of Commercial HPD's

single-diode
cross-focusing

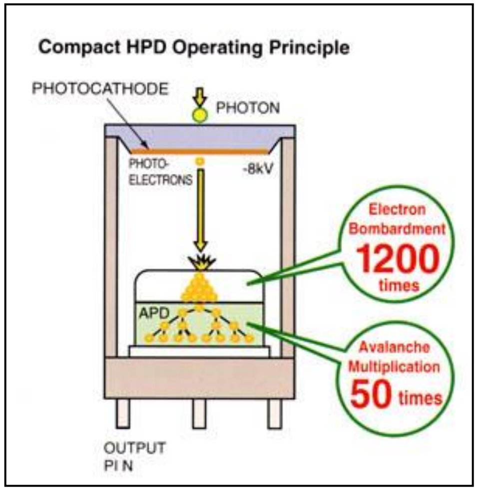


multi-pixel
proximity-focusing

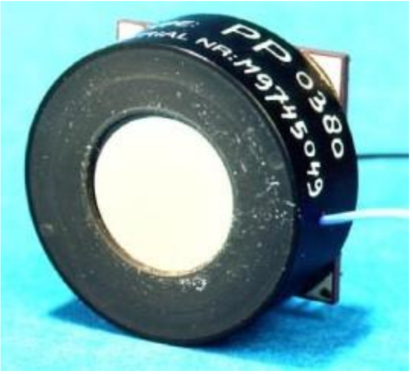




single avalanche diode HPD



multi-pixel HPD



From PMT’s to GM-APD’s

PMT‘s have been developed during almost 100 years. The first photoelectric tube was produced by Elster and Geiter 1913.
RCA made PMT‘s a commercial product in 1936.
Single photons can be detected with PMT‘s.
The high price, the bulky shape and the sensitivity to magnetic fields of PMT‘s forced the search for alternatives.

***p-i-n* photodiodes** are very successful devices and are used in most big experiments in high energy physics but due to the noise of the amplifier the minimal detectable light pulses need to have several 100 photons.

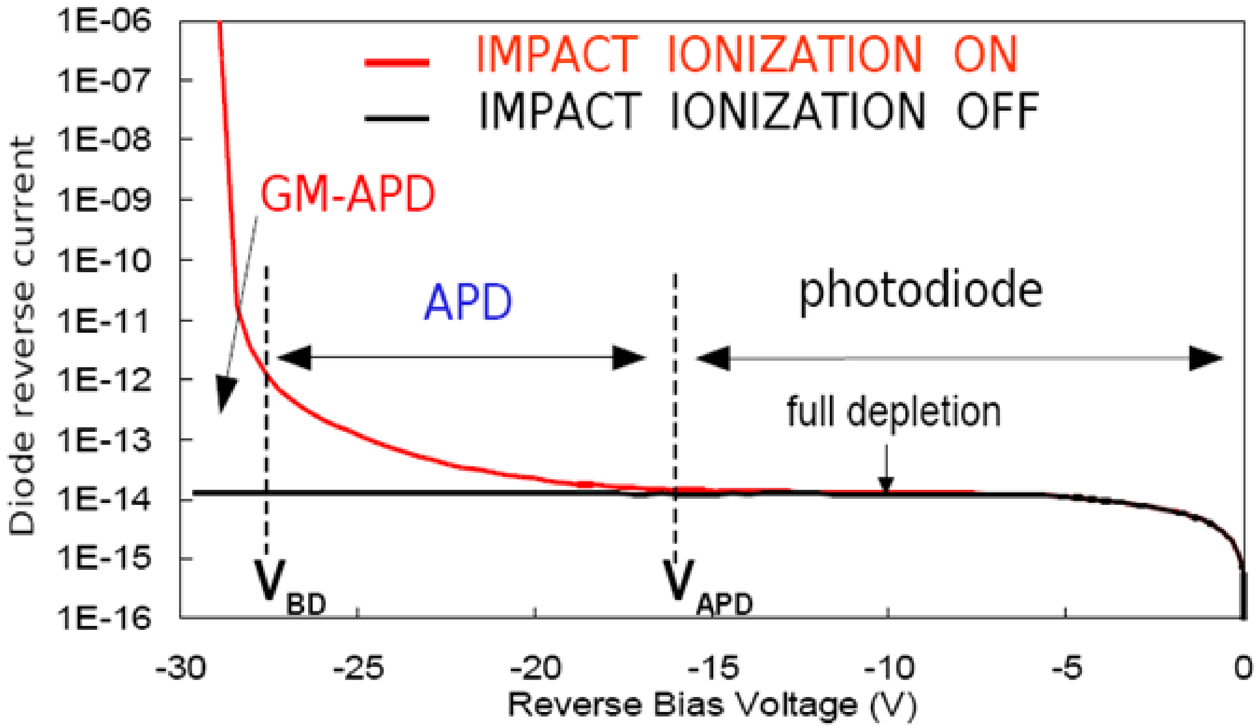
Avalanche photodiodes have internal gain which improves the signal to noise ratio but still some 20 photons are needed for a detectable signal.
The excess noise, the fluctuations of the avalanche multiplication limits the useful range of gains.

HPDs combination of vacuum photon detectors and semiconductor technology. Capable of single photon counting but require very high accelerating voltages (~ 10 kV).

GM-APD‘s can detect single photons.
They have been developed and widely used since ~2000.

From Photo-Diodes to GM-APD’s

Different working regimes for reverse biased diode



GM-APD

$V_{bias} > V_{BD}$ (V_{bias}-V_{BD} ~ few volts)

$G \Rightarrow \infty$

Geiger-mode operation

can operate at single photon level

APD

$V_{APD} < V_{bias} < V_{BD}$

G = M (50 - 500)

linear-mode operation

Photodiode

$0 < V_{bias} < V_{APD}$ (few volts)

G = 1

operates at high light level

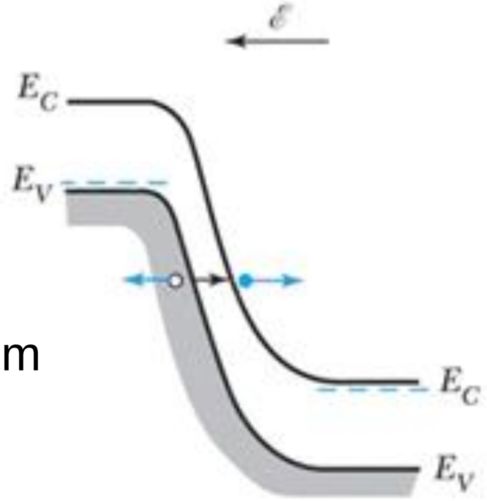
(few hundreds of photons)

Breakdown

When a sufficiently large reverse voltage is applied to a *pn* junction, the junction breaks down and conducts a very large current.
To avoid damage (like overheating) one must limit the current.

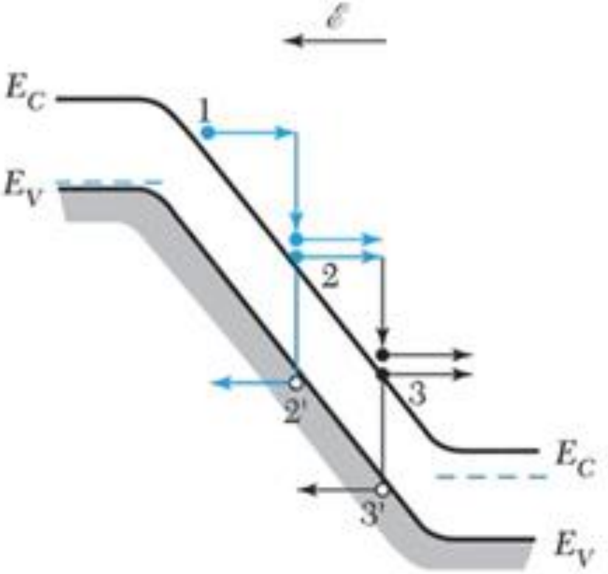
There are two important breakdown mechanisms

tunneling



$E > 10^6$ V / cm

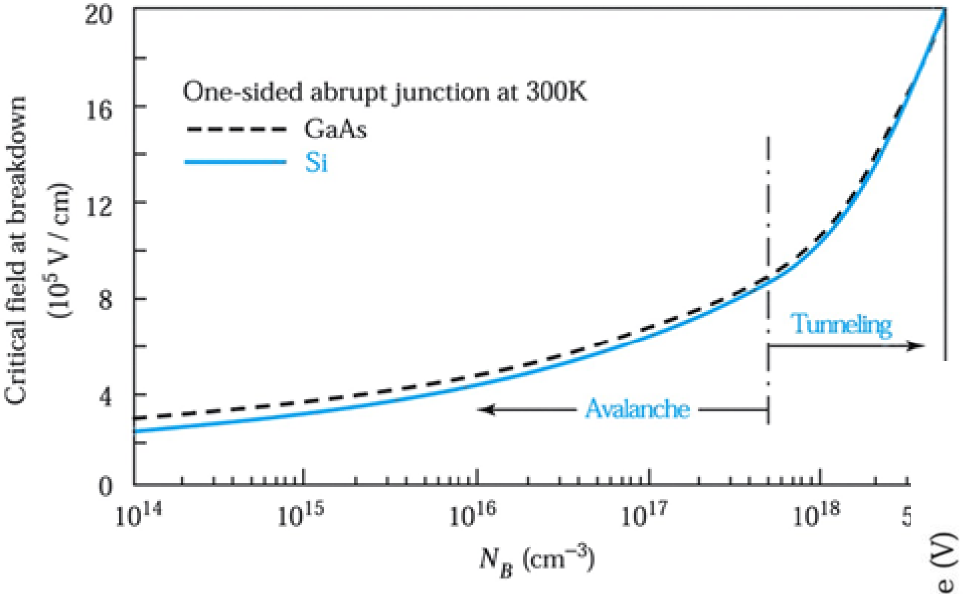
avalanche multiplication



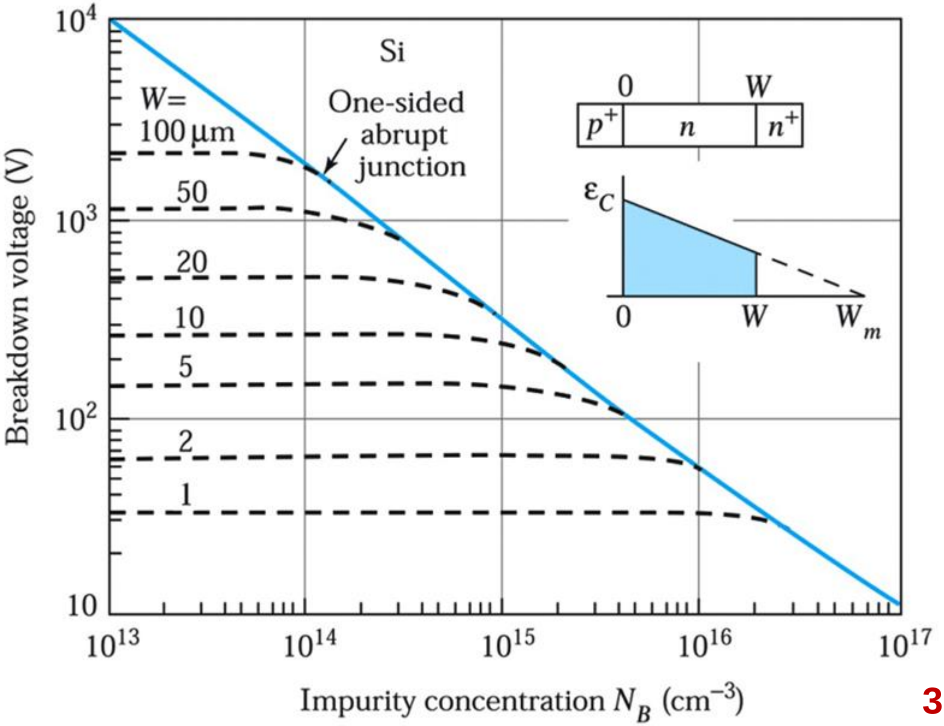
Avalanche multiplication occurs when a free electron gains enough kinetic energy that can break lattice bonds on collisions with an atom creating an electron-hole pair.
And the newly created electron-hole in turn continue the process …

Breakdown

critical field at breakdown vs background doping N_B
(N_B impurity concentration in the lightly doped region)



breakdown voltage
p^+-π-n^+ or p^+-ν-n^+



What is a Si-PM?

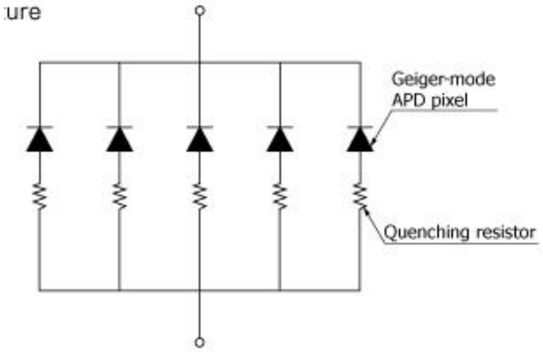
The Si-PM is a type of photon-counting device using multiple APD (avalanche photodiode) pixels operating in Geiger mode.

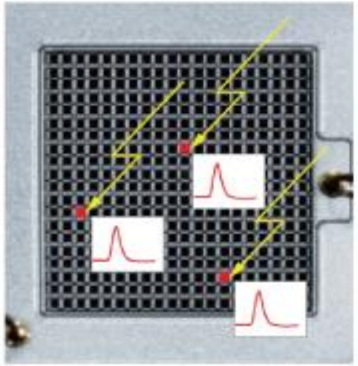
The Si-PM features a high multiplication ratio (gain), high photon detection efficiency, fast response, excellent time resolution, and wide spectral response range.

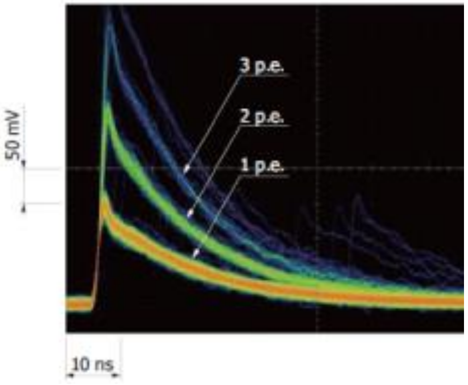
It is immune to magnetic fields, highly resistant to mechanical shocks, and will not suffer from “burn-in” by incident light saturation.

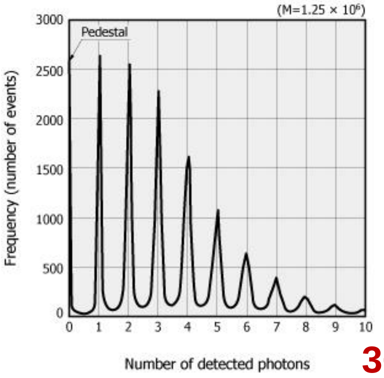
It has a wide range of applications and fields including medical diagnosis, academic research, and measurements.

It is used for low light detection, single photon to a few 1k photons possible.









Geiger Mode Avalanche Photodiode (G-APD)

Use APDs operating in limited Geiger mode

Advantage: single photon counting
very high intrinsic gain (~10^6)

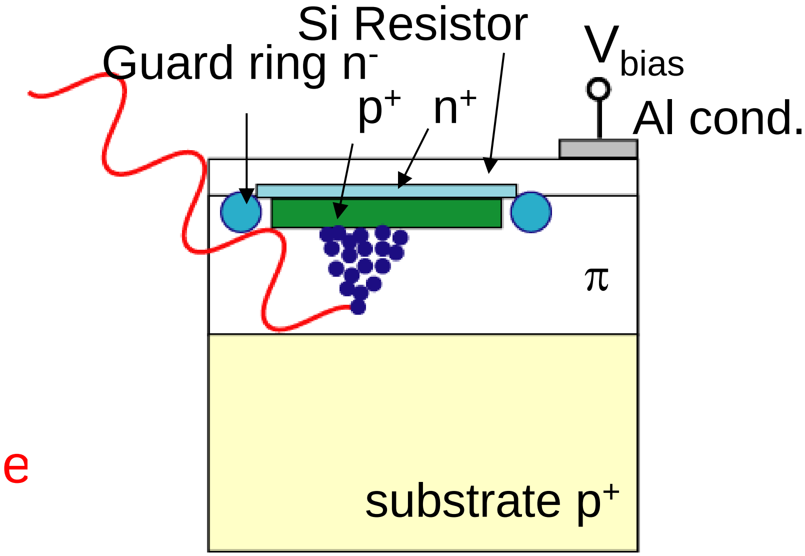
disadvantage: no dynamic range at all, however …

dark counts limits the area to < 200 µm Ø

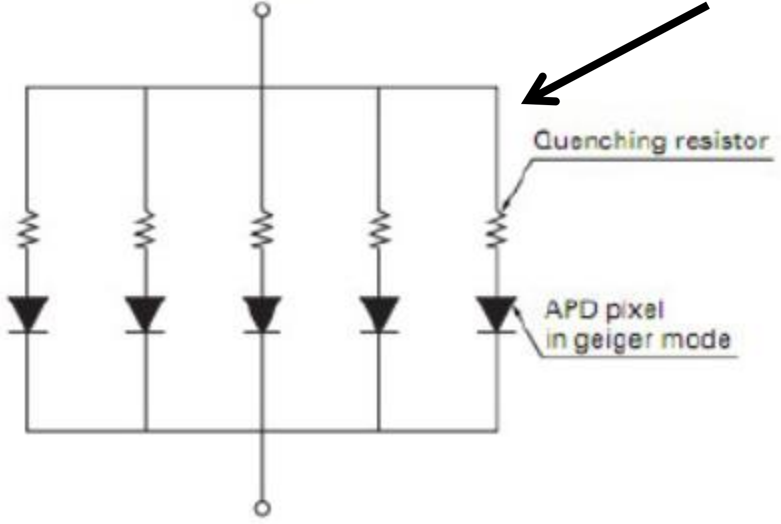
combine many small APD pixels onto the same substrate with a common anode

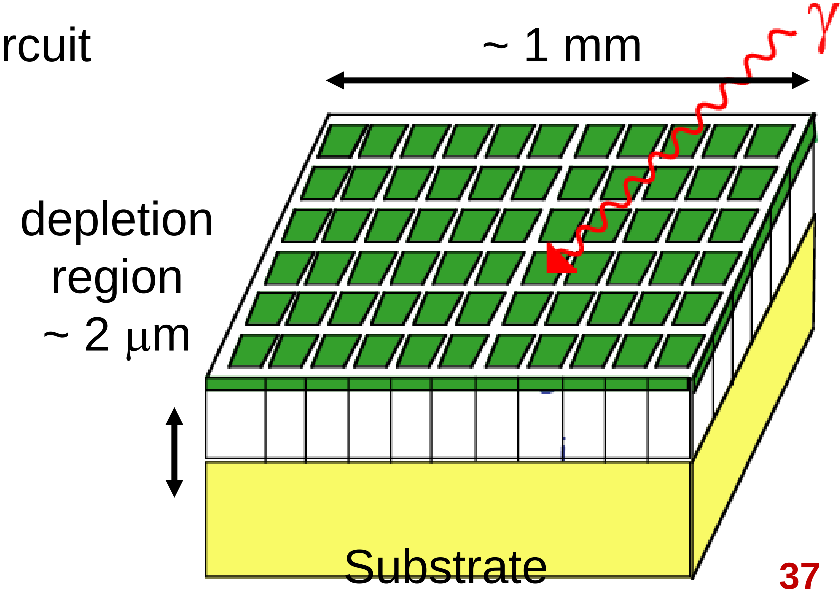
→ gain dynamic range

→ single photon resolution

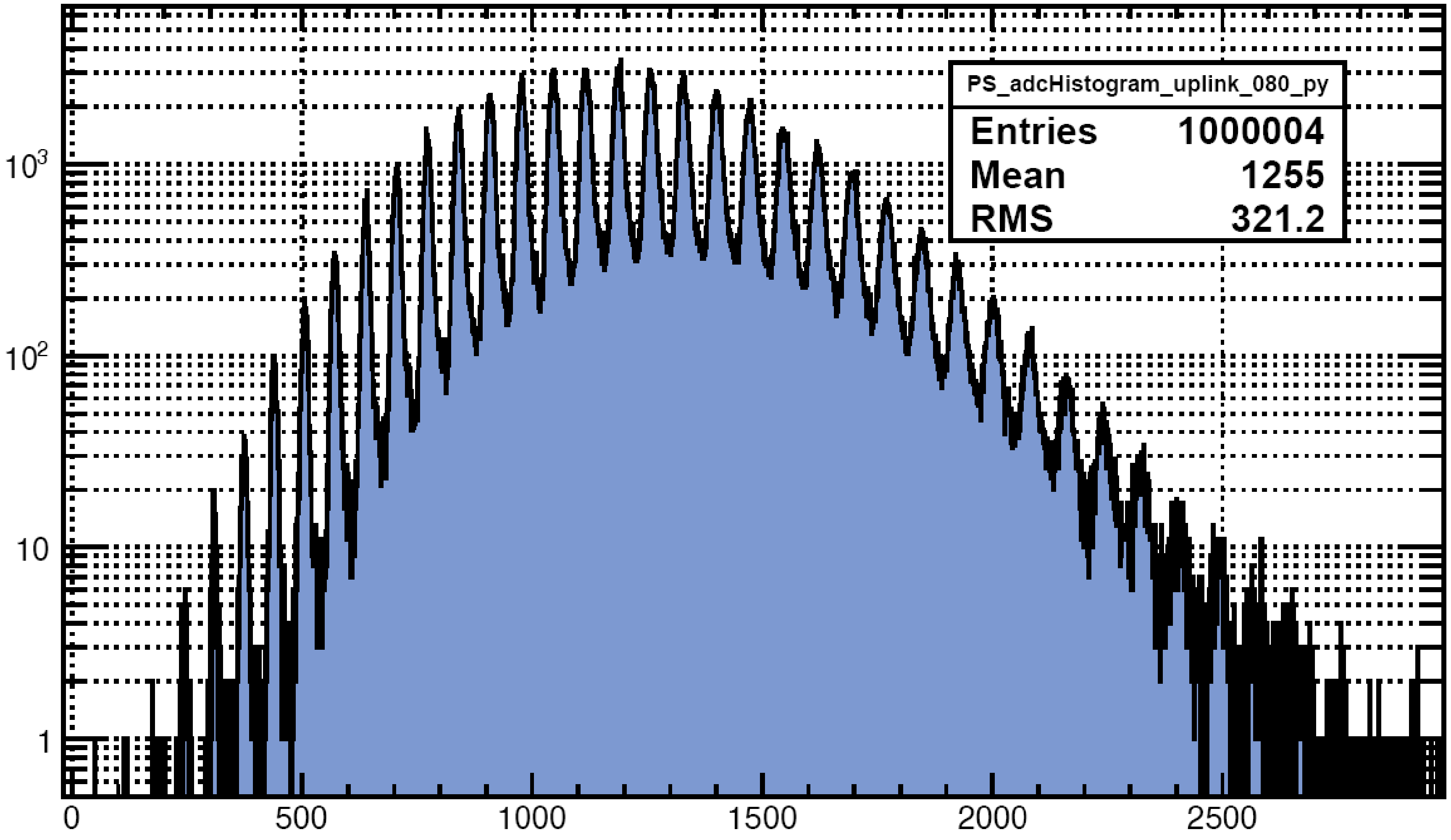


equivalent circuit



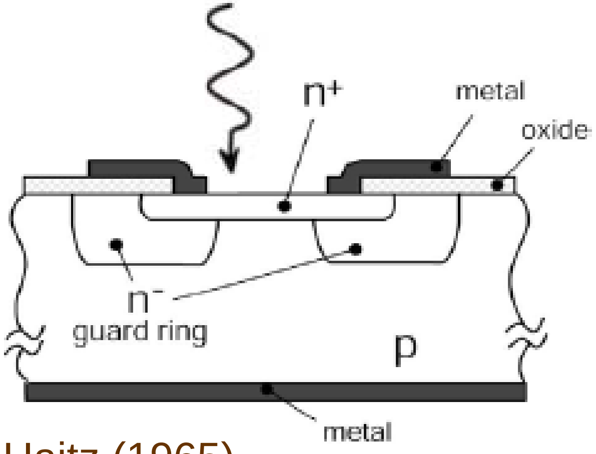


Single Photon Counting

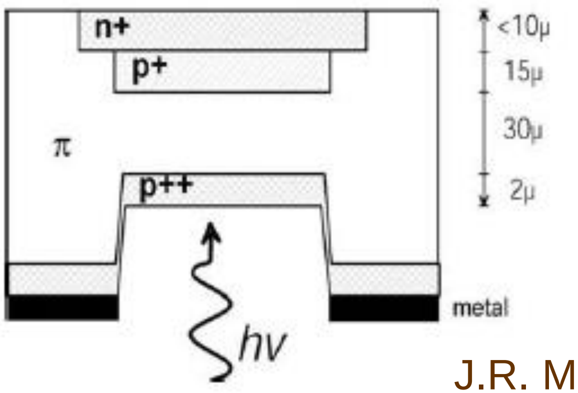


Geiger Mode Avalanche Photodiode (G-APD)

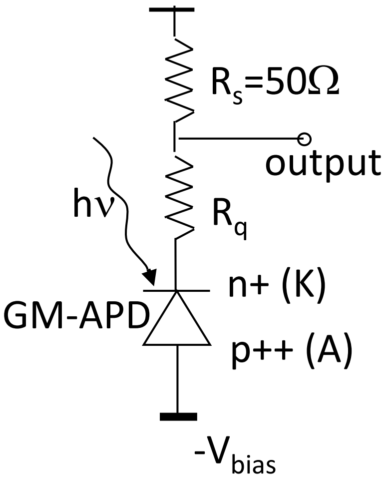
First single photon detectors operated in Geiger-mode



R.H. Haitz (1965)



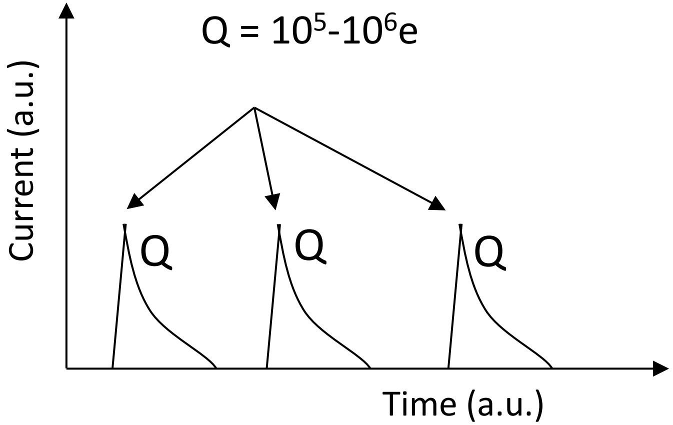
J.R. McIntire (1966)



passive quenching circuit

Standard output signal

$Q = 10^5\text{-}10^6 e$



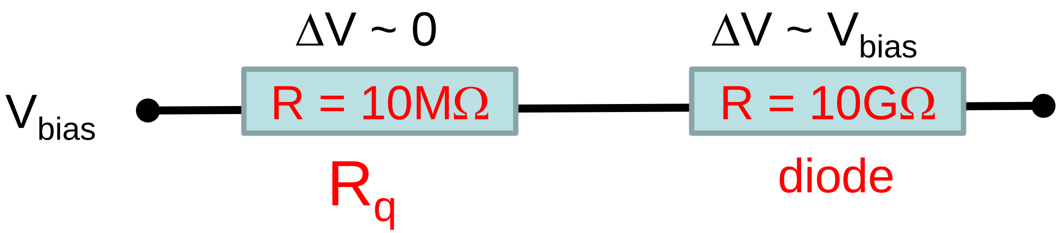
Binary device

if one or more simultaneous photons fire the GM-APD,
the output is anytime a standard signal: $Q \sim C(V_{bias} - V_{BD})$
GM-APD does not give information on the light intensity

Quenching

How to stop the avalanche?

Switch of the bias!

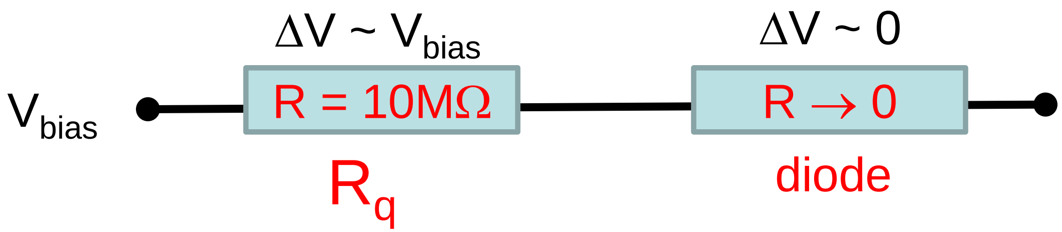


$\Delta V \sim 0$ $\Delta V \sim V_{bias}$

V_{bias} R = 10MΩ R = 10GΩ

R_q diode

during the avalanche, the diode becomes conductive: R → 0



$\Delta V \sim V_{bias}$ $\Delta V \sim 0$

V_{bias} R = 10MΩ R → 0

R_q diode

and the (bias) voltage drops to zero across the quench resistor R_q,
so that there is no bias on the diode.

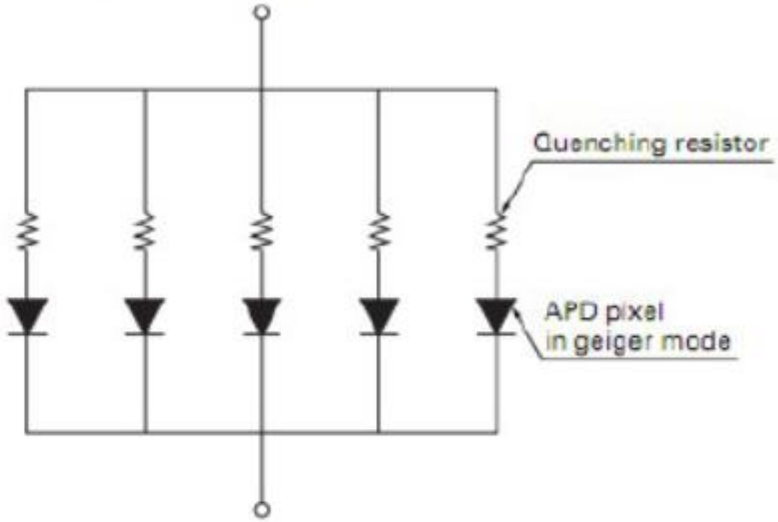
The avalanche stops,
and the device starts recovering and getting ready for the next “event”.

MPPC

Multi Pixel Photon Counter (Hamamatsu nomenclature)

combine many small APD pixels onto the same substrate with a common anode

- → gain dynamic range
- → single photon resolution



output signal proportional to the number of “excited cells”

typical parameters

sensitive area

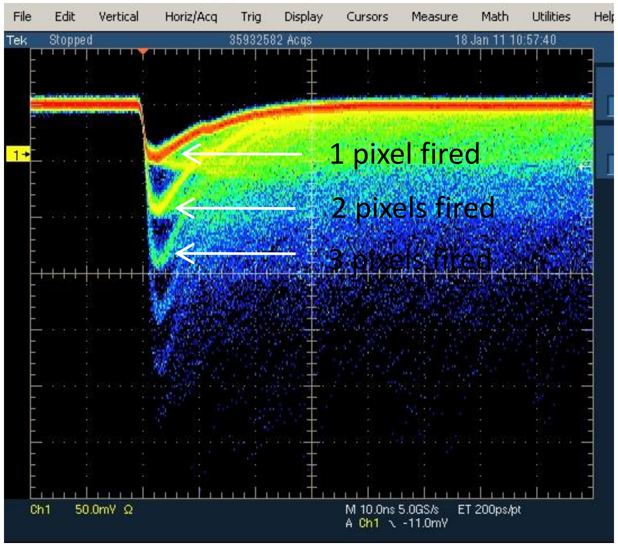
1 x 1 mm2 to 6 x 6 mm2

pixel (cell) size

10 μm to 100 μm

on a 1 mm^2 device have 400 50 μm x 50 μm cells as long # γ < 10% # cells excellent linearity

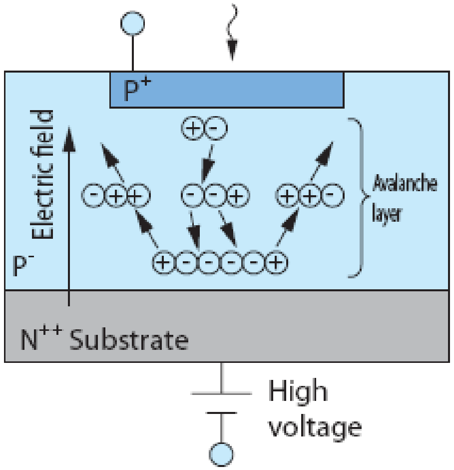
large pixels, large filling factor, higher PDE



MPPC – GM-APDs

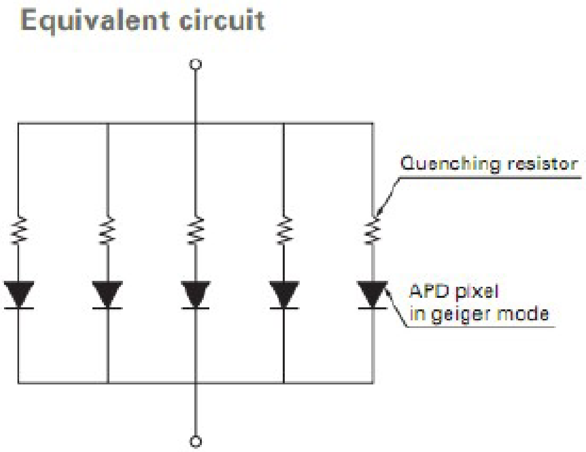
Multi-pixel Avalanche PhotoDiodes operated in Geiger mode

(Single pixel G-APDs developed long time ago (~ 1963), however not able to operate in multi-photon mode, sensitive area limited by dark current, etc.)



γ absorption / ionization

avalanche multiplication



Geiger avalanched quenched by individual pixel resistors

high gain ~O(PMT) and high efficiency ~O(1-2 x PMT), 100 – 20,000 pixels / mm^2

each pixel works as a binary device, for low N_γ the device behaves as an analog detector

The GAPD produces a standard signal when any of the cells goes to breakdown.

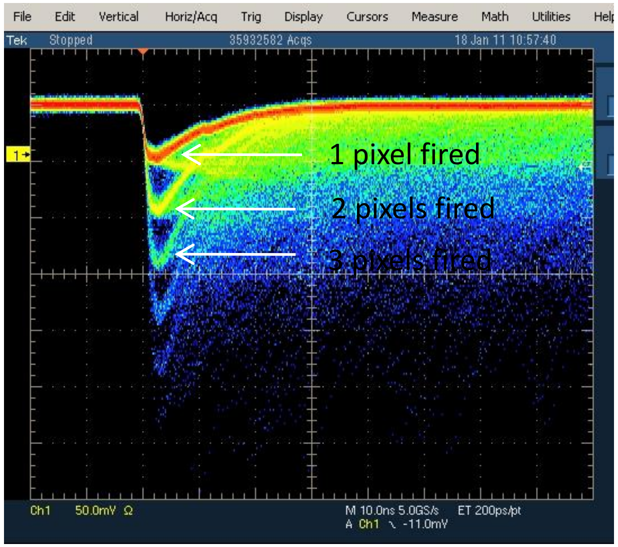
The amplitude A_i is proportional to the capacitance of the cell times the overvoltage

$$A_i \sim C \cdot (V - V_b)$$

When many cells fire at the same time the output is the sum of the standard pulses

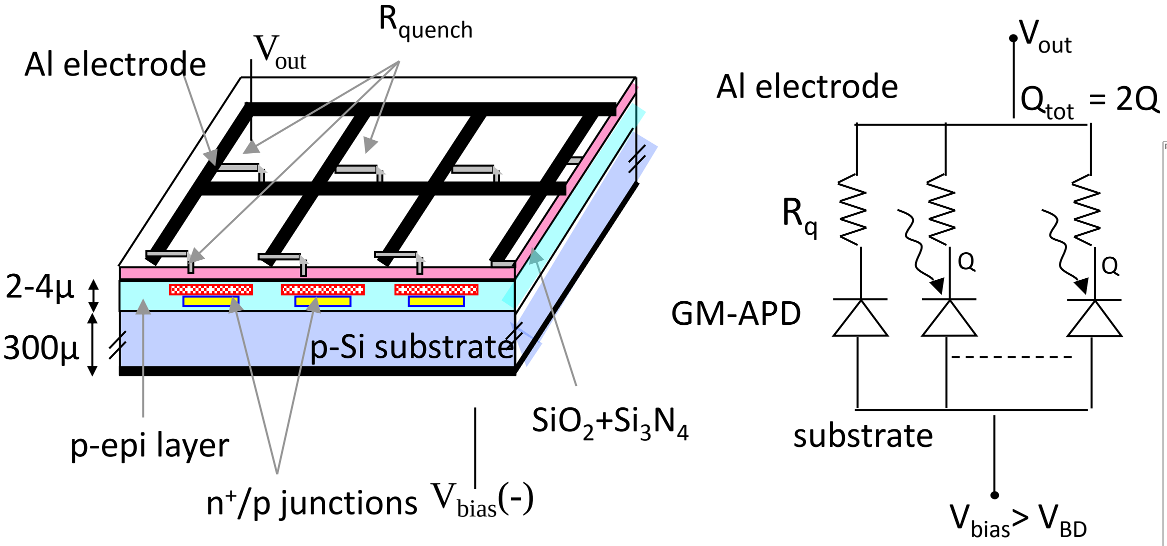
$$A = \Sigma A_i$$

Silicon Photo-Multiplier (Si-PM)



matrix of n pixels connected in parallel
(e.g. few 100 - 1000 / mm^2)
on a common Si substrate

each pixels = GM-APD in series with R_{quench}



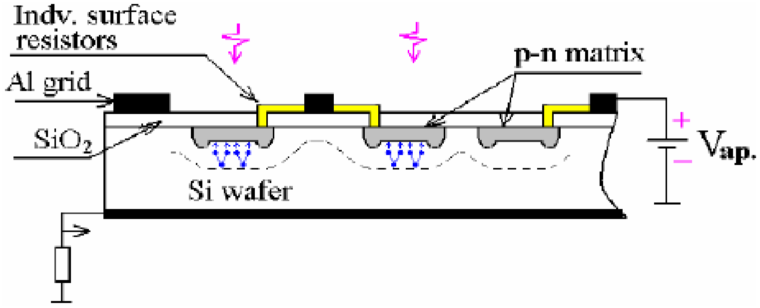
key developers :
V. Golovin, Z. Sadygov

Quasi-analog device

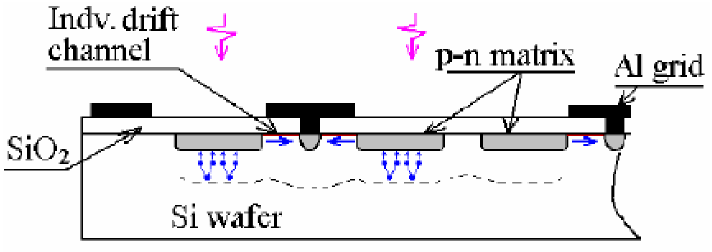
If simultaneously photons fires different pixels, the output is the sum of the standard signals:

$Q \sim \Sigma Q_i$

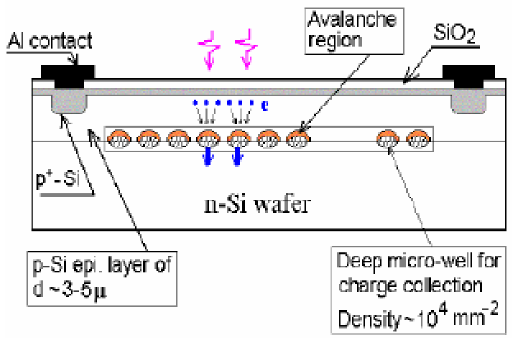
Types of G-APDs



- CPTA/Photonique (Moscow/Geneva)
- MEPhI/Pulsar (Moscow, Russia)
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL (Cork, Ireland)
- RMD (Boston, USA)
- MPI Semiconductor Lab. (Munich, Germany)
- FBK-irst (Trento, Italy)
- STMicroelectronics (Catania, Italy)
- ……



- Z. Sadygov (JINR, Dubna, Russia)
  (1989 !)



- Zecotek (Singapore) (Z.Sadygov)

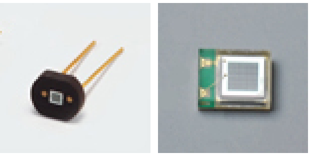
Every producer has its own name for this type of device:
MRS APD, MAPD, Si-PM, MPPC, SSPM, SPM, DADP, PPD …

Commercial Si-PMs

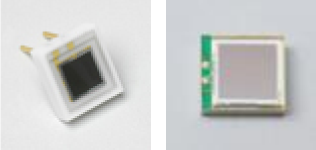
Hamamatsu HPK (http://jp.hamamatsu.com/)

$25x25\mu m^2$, $50x50\mu m^2$, $75x75\mu m^2$ pixel size

$1.3x1.3mm^2$

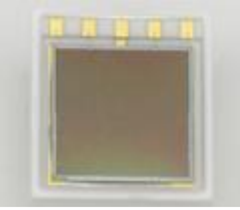


$3x3mm^2$



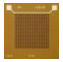
Si-PM Arrays

$1x4mm^2$
1x4 channels

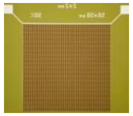


$6x6\ mm^2$
2x2 channels

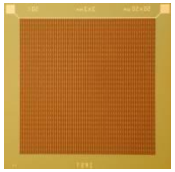
FBK-IRST



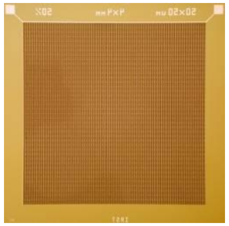
$1x1mm^2$



$2x2mm^2$

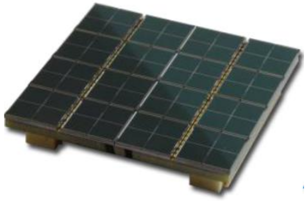


$3x3mm^2$



$4x4mm^2$

$4x4mm^2$
2x2 channels



$3x3\ cm^2$
8x8 channels

SensL (http://sensl.com/)

$3.16x3.16mm^2$
4x4 channels

$3.16x3.16mm^2$
4x4 channels

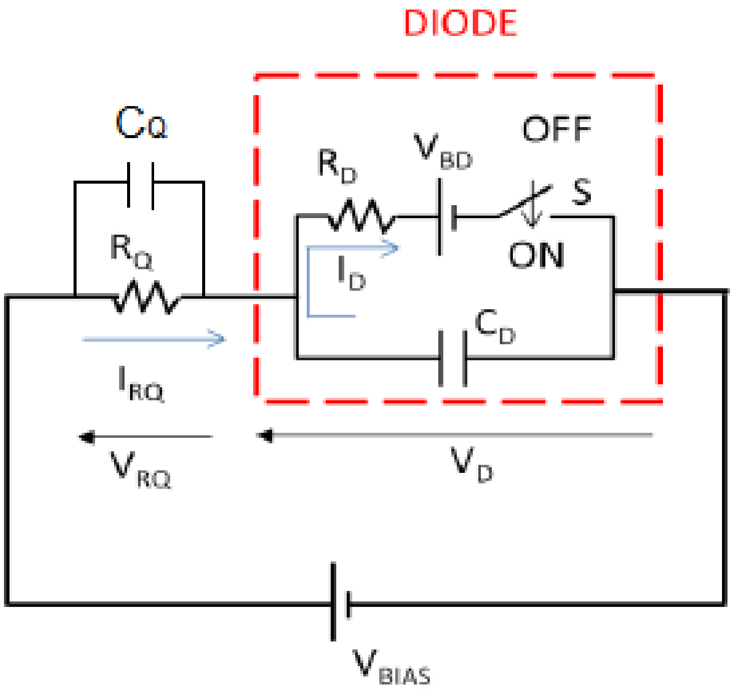
$6\ x\ 6\ cm^2$
16x16 channels

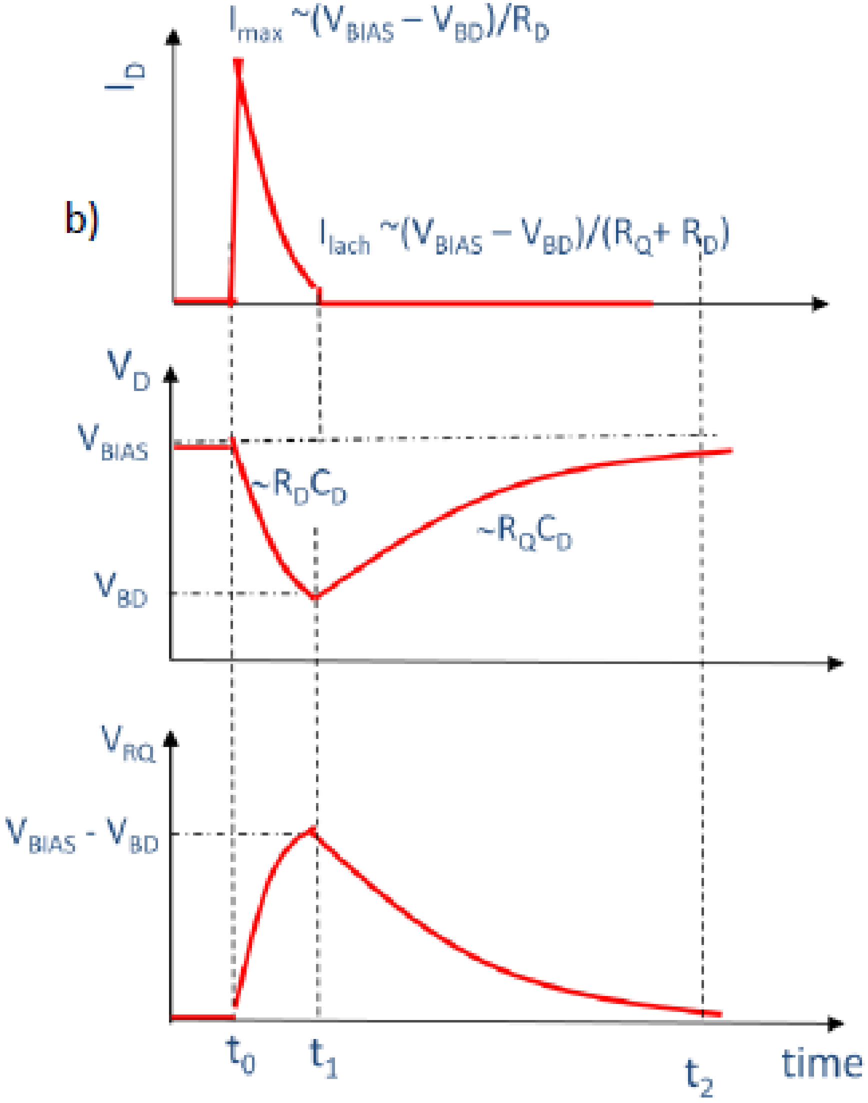
Si-PM Equivalent Circuit

Single cell

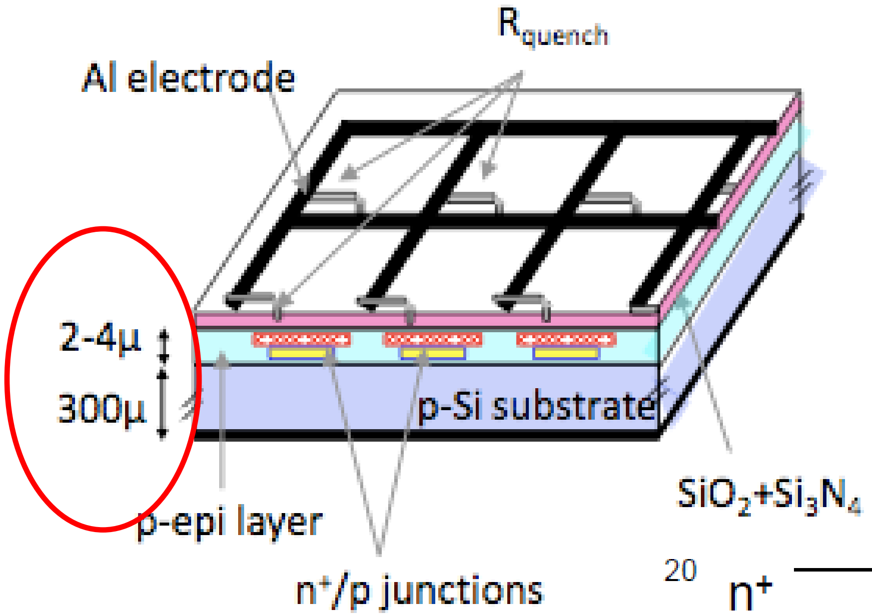
The time characteristics of the signal are determined by

- detector capacitance C_D
- quench resistance R_Q
- detector resistance R_D
- quench capacitance C_Q



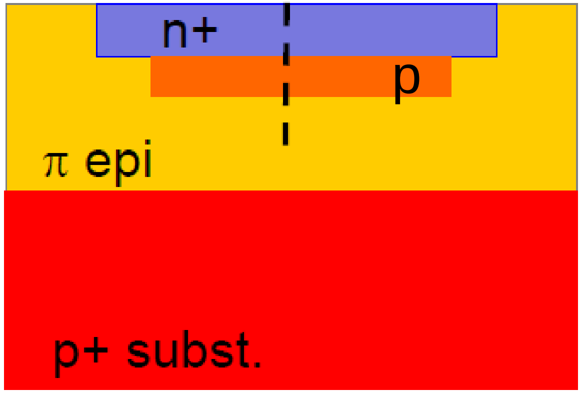


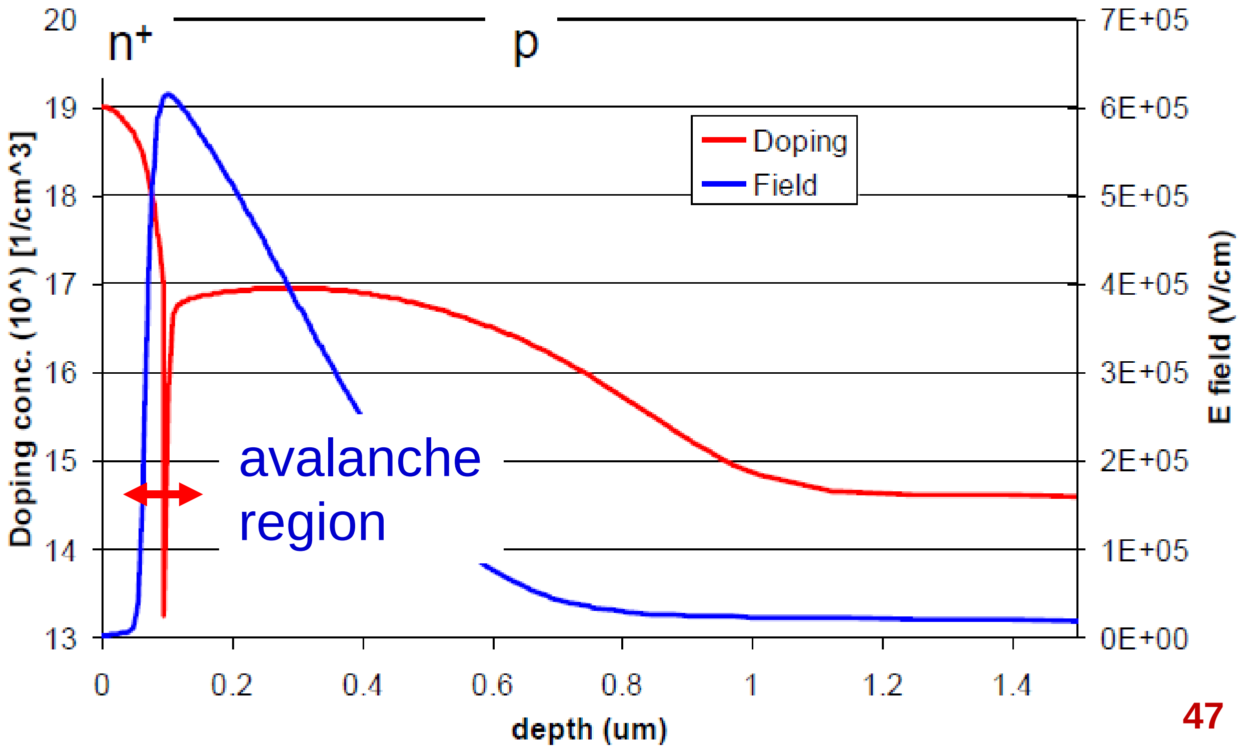
Basic Si-PM Structure (FBK)



Si-PM structure

electric field “inside” the Si-PM

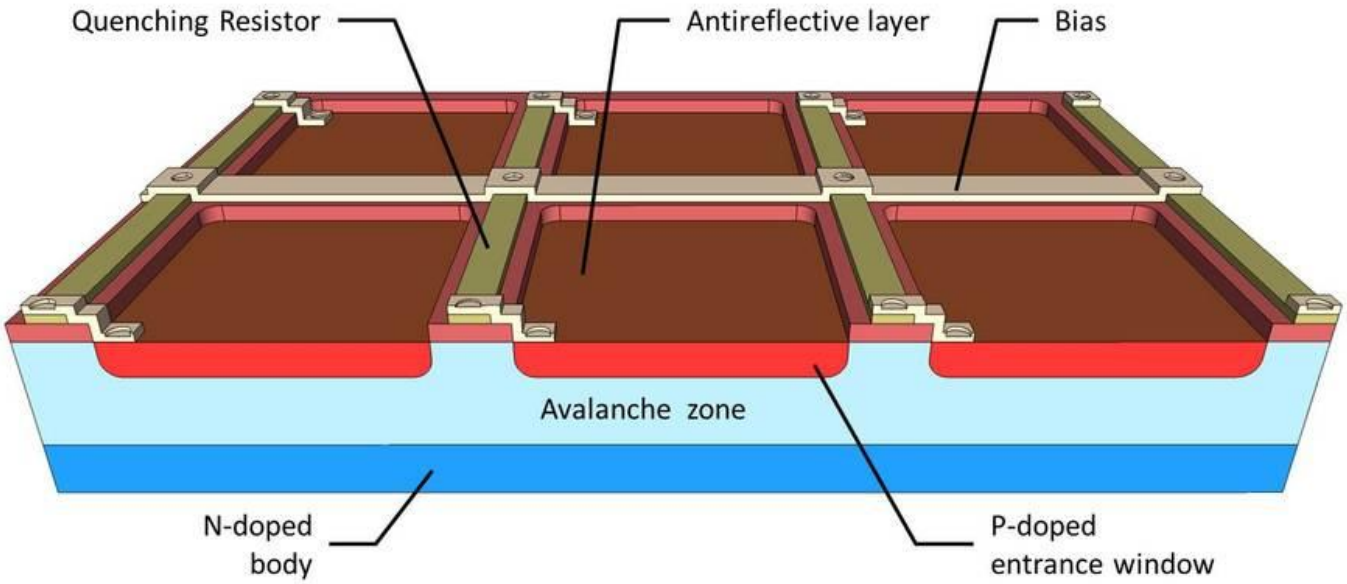




Basic Si-PM Structure (KETEK)

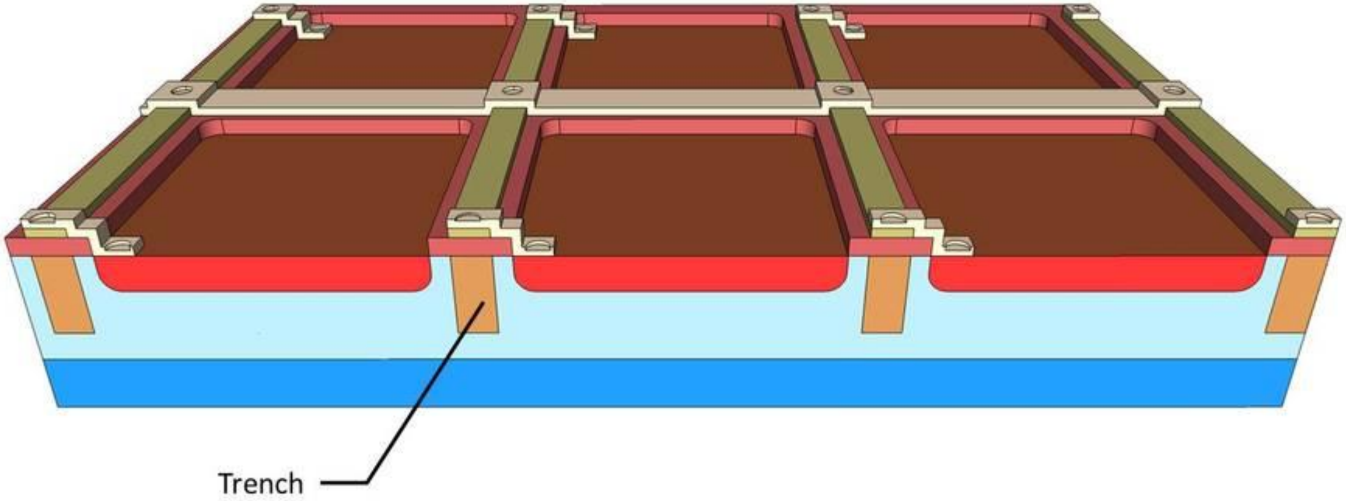
P-on-N

standard design



P-on-N

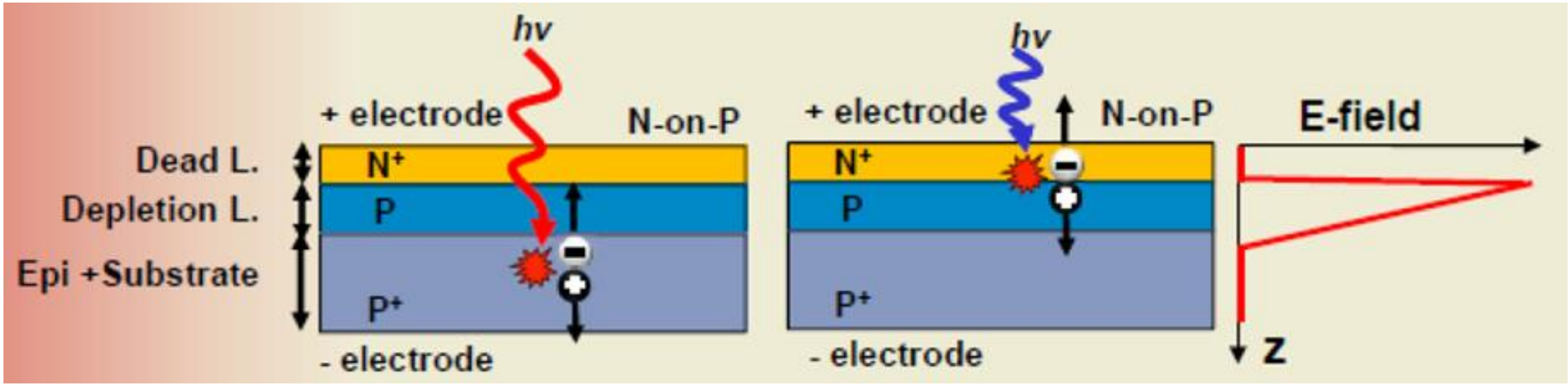
design with trenches (to reduce x-talk)



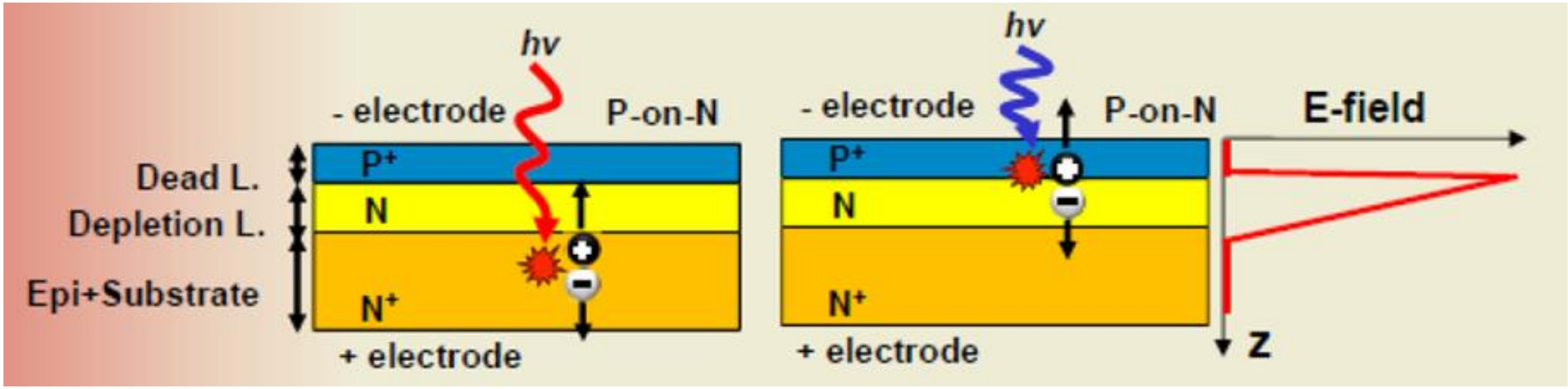
n-on-p Devices vs *p-on-n* Devices

longer wavelength → deeper penetration depth

electrons, higher mobility → higher ionization probability



n-on-p higher QE at longer wavelengths



p-on-n higher QE at shorter wavelengths

Si-PM Parameters

You will measure most of these

- I-V curve
  - V breakdown
  - V built in
- Pulse shape
  - rise time
  - decay time
- Recovery time
- Quench resistance
- Capacitance
- Photo Detection Efficiency
- Dark count rate
- Gain
- Cross talk between pixels
- After pulsing
- Saturation
- Temperature dependence

Photo Detection Efficiency

Photo-Detection Efficiency (P.D.E.) :

combined probability to produce a photoelectron and to detect it

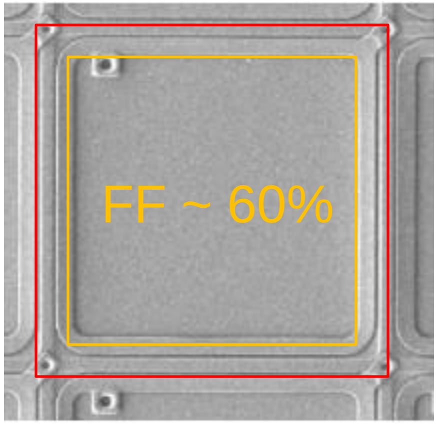
$$PDE(\lambda, \Delta V, T, \ldots) = \varepsilon_{geom} \cdot QE(\lambda) \cdot P_{trig}(\lambda, \Delta V)$$

DV = $V_{bias} - V_{BD}$

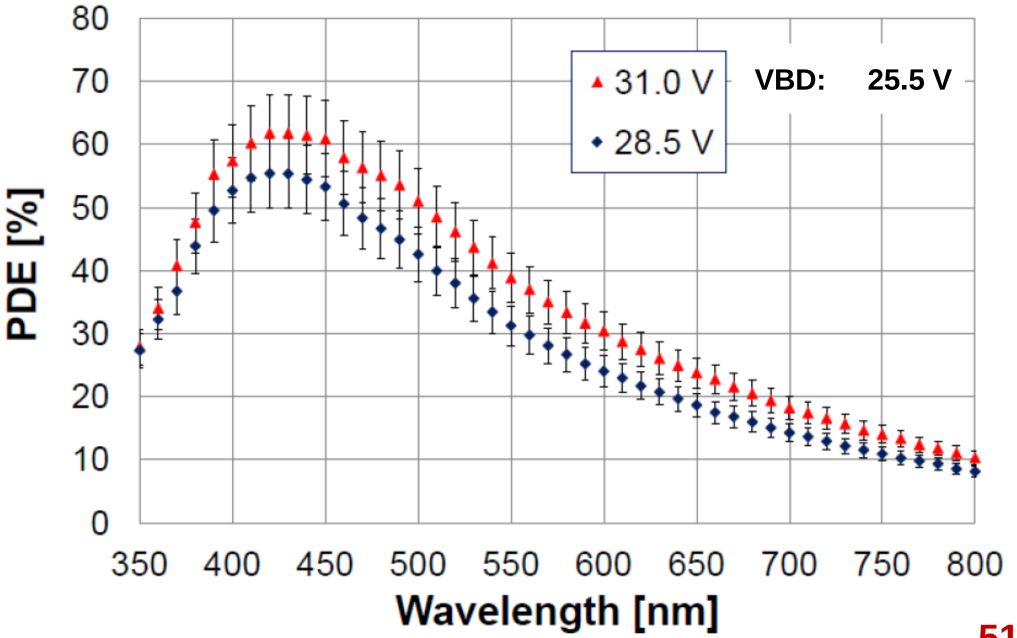
ε_{geom}: fill factor = sensitive area / total area

P_{trig}: avalanche triggering probability, higher the ΔV, higher the P_{trig} (> 95%)

QE: quantum efficiency



50 μm cell



Si-PM Characteristics

Advantages

☺ high gain (10^5 - 10^6)
☺ work with low voltage (< 100V)
☺ low power consumption (< $50\mu W / mm^2$)
☺ fast (timing resolution ~ 100 ps RMS for single photons)
☺ insensitive to magnetic field (tested up to 10 T)
☺ high photon detection efficiency (30 - 50% blue-green)
☺ excess noise factor close to 1
☺ compact and rugged
☺ tolerate accidental illumination
☺ cheap: produced n standard CMOS process

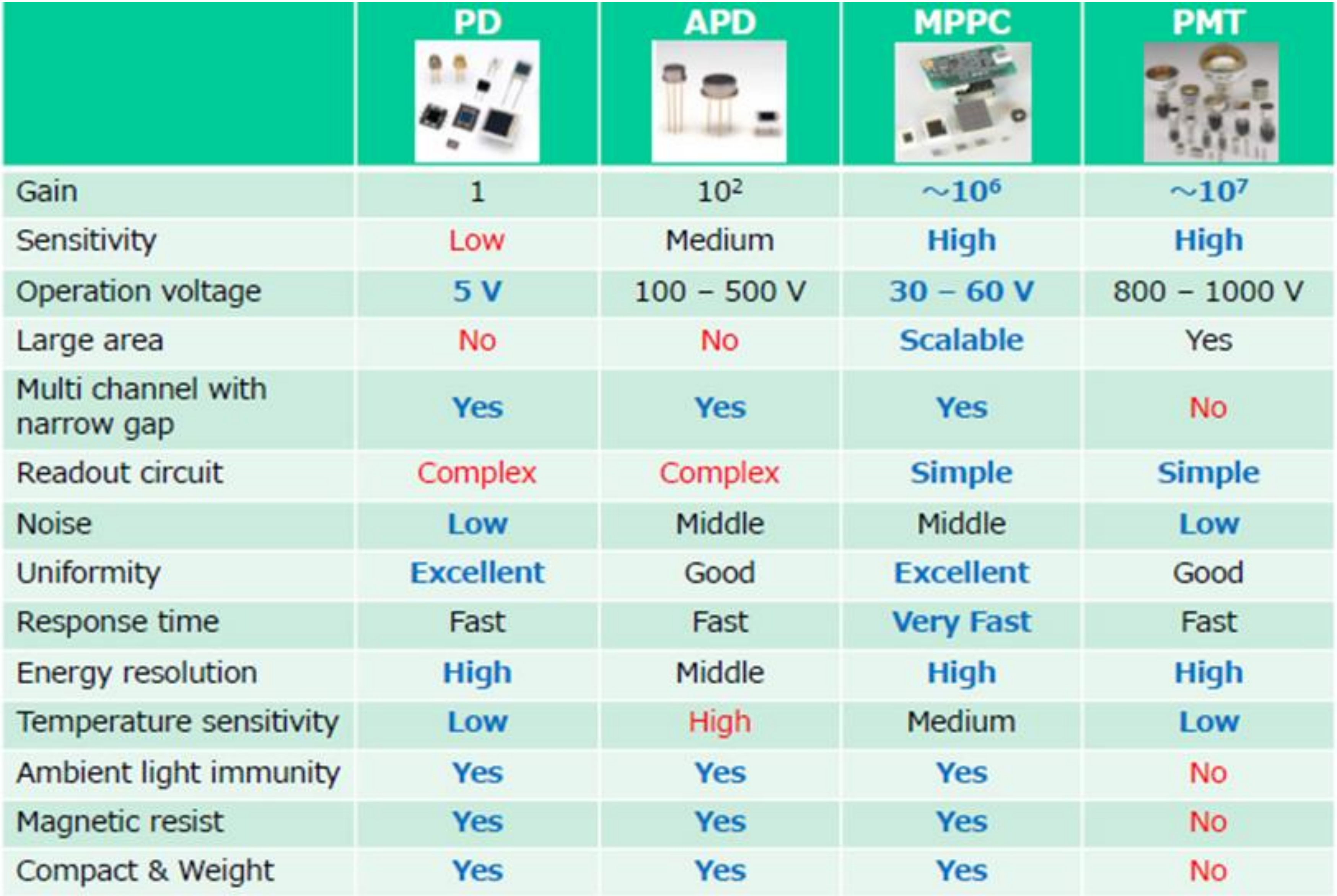
Possible drawbacks

☹ high dark count rate (DCR) at room temperature
  10 kHz – 100 kHz / mm^2
  thermal carriers, cross-talk, after-pulses
☹ temperature dependence (but relatively small)
  V_{BD}, G, R_q, DCR
☹ nonlinear response against input light (saturation)

PMT vs Si-PM

	PMT	MPPC
Gain	10^4~10^7	10^4~10^7
Photon Detection Eff.	0.1 ~ 0.2	0.2~ 0.5
Response	Fast	Fast
Photon counting	Yes	Great
Bias voltage	~ 1000 V	~ 20 - 90 V
Size	Small - Big	Compact
B field	Sensitive	Insensitive
Cost	Expensive	Not expensive (area!)
Dynamic range	Good	Determined by # of pixels
Long-term Stability	Good	Good
Robustness	Decent	Good
Radiation hardness	Good	Acceptable
Noise	Quiet	Noisy (order of 10 kHz)

Si-PM Comparison



	PD	APD	MPPC	PMT
Gain	1	10^2	$\sim 10^6$	$\sim 10^7$
Sensitivity	Low	Medium	High	High
Operation voltage	5 V	100 – 500 V	30 – 60 V	800 – 1000 V
Large area	No	No	Scalable	Yes
Multi channel with narrow gap	Yes	Yes	Yes	No
Readout circuit	Complex	Complex	Simple	Simple
Noise	Low	Middle	Middle	Low
Uniformity	Excellent	Good	Excellent	Good
Response time	Fast	Fast	Very Fast	Fast
Energy resolution	High	Middle	High	High
Temperature sensitivity	Low	High	Medium	Low
Ambient light immunity	Yes	Yes	Yes	No
Magnetic resist	Yes	Yes	Yes	No
Compact & Weight	Yes	Yes	Yes	No