Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 13

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What is this lecture about?

- Scintillators
  - Basic principles
  - Important materials in current use
  - Light detection
  - Low energy applications (spectroscopy, medicine)
  - High energy applications (calorimeters, Time-of-flight)

Key points from previous lecture

- Scintillators are materials that produce light when ionising radiation interacts with them.
- Inorganic scintillators are primarily crystalline (there are glasses too).
- Organic scintillators are mainly plastic based.
- Noble gasses in liquid form are an important class of scintillator (UV emission) combined with a much slower ionisation signal (see self-triggered TPC).
- Some scintillators are very fast (BaF_2 and most plastics) but some important materials (e.g. NaI(Tl)) have relatively long decay times.
- Inorganic scintillators can have high mean Z and high (> 7 gcm^{-3}) densities – important for electromagnetic calorimeters in colliding beam experiments.

Photonics in Particle Physics

- “The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon” (from Photonics Spectra magazine)
- In our context it is
  - The detection of light generated by some process related to the measurement of some property of particles (e.g. Energy or velocity).
  - The transmission and reception of analogue & digital information connected with the electrical signals from particle detectors.

What systems are used in HEP?

- Calorimeters (which measure energy and position)
  - Scintillation light
  - Cherenkov light
- Time-of-flight
  - Fast scintillators used to determine the speed of a particle
- Readout of electronics in large *hermetic* detectors.
- Fibre backbone for Local and Wide Area Networks (I will not cover this aspect)

The human eye (historic!)

- Detection of α particles (He nuclei)
  - Historic experiments of Geiger & Marsden (1909) using ZnS(Ag) scintillator screens
  - Visual detection of scintillation light
  - Rate limited to about 60 s^{-1}
  - Each detected flash contained around 300 photons entering the observer's eye
- Last important visual experiment was the disintegration of Li neuclei by protons (Cockcroft & Walton (1932)
  - Used a human coincidence counter technique

Solid state photodetectors

- These use the *internal photoelectric effect*
- A photon with energy larger than the bandgap of the material generates an electron-hole pair (eh-pair) *with some probability < 100%*
- The eh-pair is separated by an internal field (e.g. a junction inside a diode)

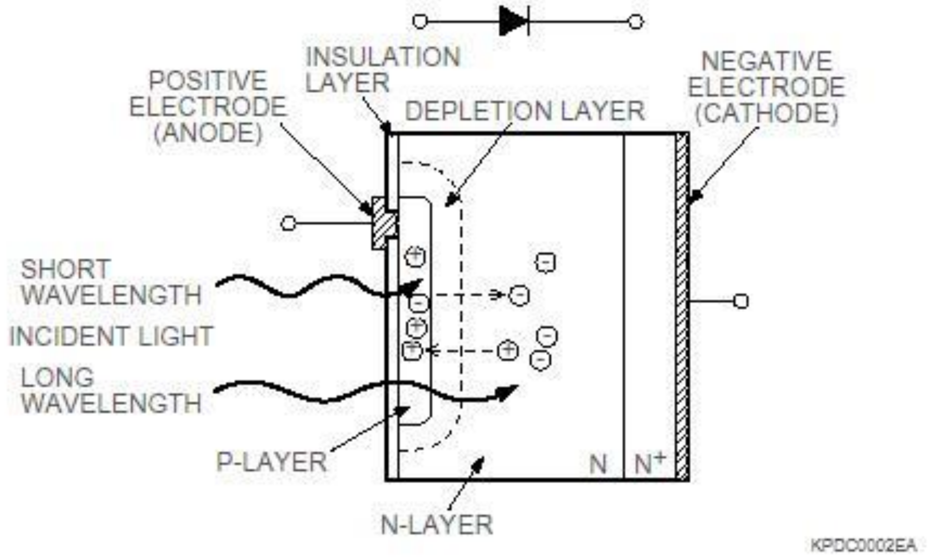
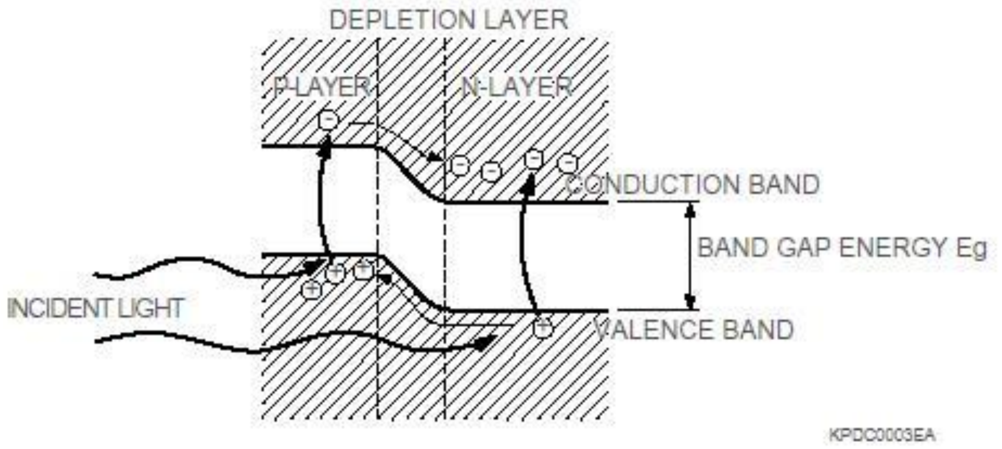


Figure 1-2 Photodiode P-N junction state



Absorption of Light

- In ideal (non scattering) materials the absorption of light is governed by the ***Beer-Lambert* law.** This relates transmittance, *T,* to absorbance, *A,* and *optical depth* τ, by the fundamental relationship

$$\boxed{T = e^{-\tau} = 10^{-A}}$$

If the *attenuation coefficient* μ is given and the physical depth *l*, then

$$\boxed{T = e^{-\mu l}}$$

For some actual values for real semiconductors see this site:
http://www.ioffe.ru/SVA/NSM/Semicond/

Silicon photodiodes

- Silicon is the primary material since in general we are detecting fast scintillation or Cherenkov light (near UV to visible)
- Silicon diode technology is well advanced and the quantum efficiency (QE) is high (around 80% peak)
- Silicon devices are tolerant to quite high radiation levels, although there are problems with hadrons.
- Silicon photodiodes are linear over many orders of magnitude.
- An important manufacturer is Hamamatsu, you can see their current range of photodiodes here: https://www.hamamatsu.com/resources/pdf/ssd/si_pd_kspd0001e.pdf

Ideal behaviour

Photocurrent is proportional to the optical (signal) power

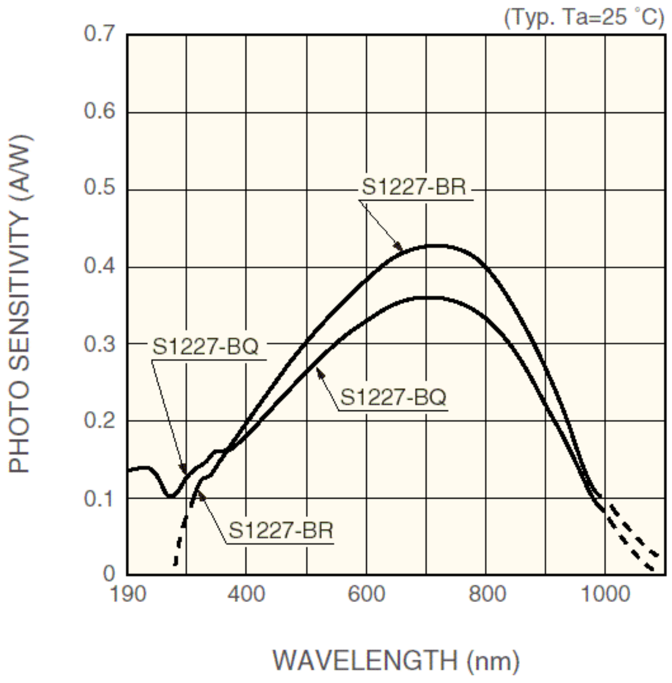
How large is the responsivity R (in A/W) and how does it vary with wavelength for an ideal photodetector?

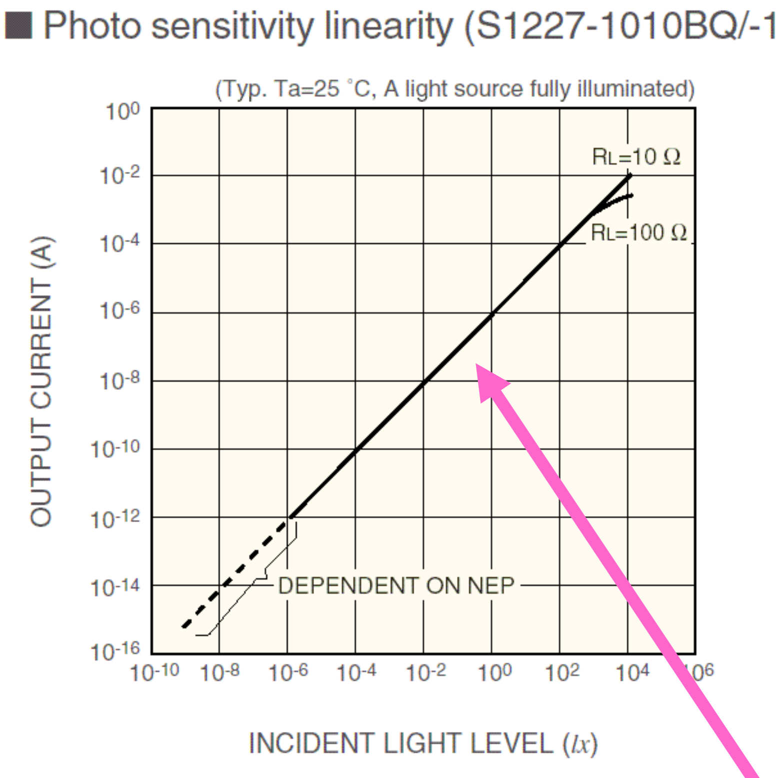
In an ideal photodiode with no gain (i.e. pn or pin structure or a Schottky device) one gets one e/h pair per absorbed photon. This has the largest value when the photon energy is the *smallest* allowed, i.e. just above the band gap. Numerically, for wavelengths in nm and band-gaps in eV

$$R = \frac{q}{E_{ph}}$$

$$R = \frac{1}{E_g[eV]} \approx \frac{\lambda[nm]}{1240}$$

A commercial large area (10×10 mm^2)PIN diode




■ Photo sensitivity linearity (S1227-1010BQ/-1010BR)

Note 8 to 10 decades of linear response

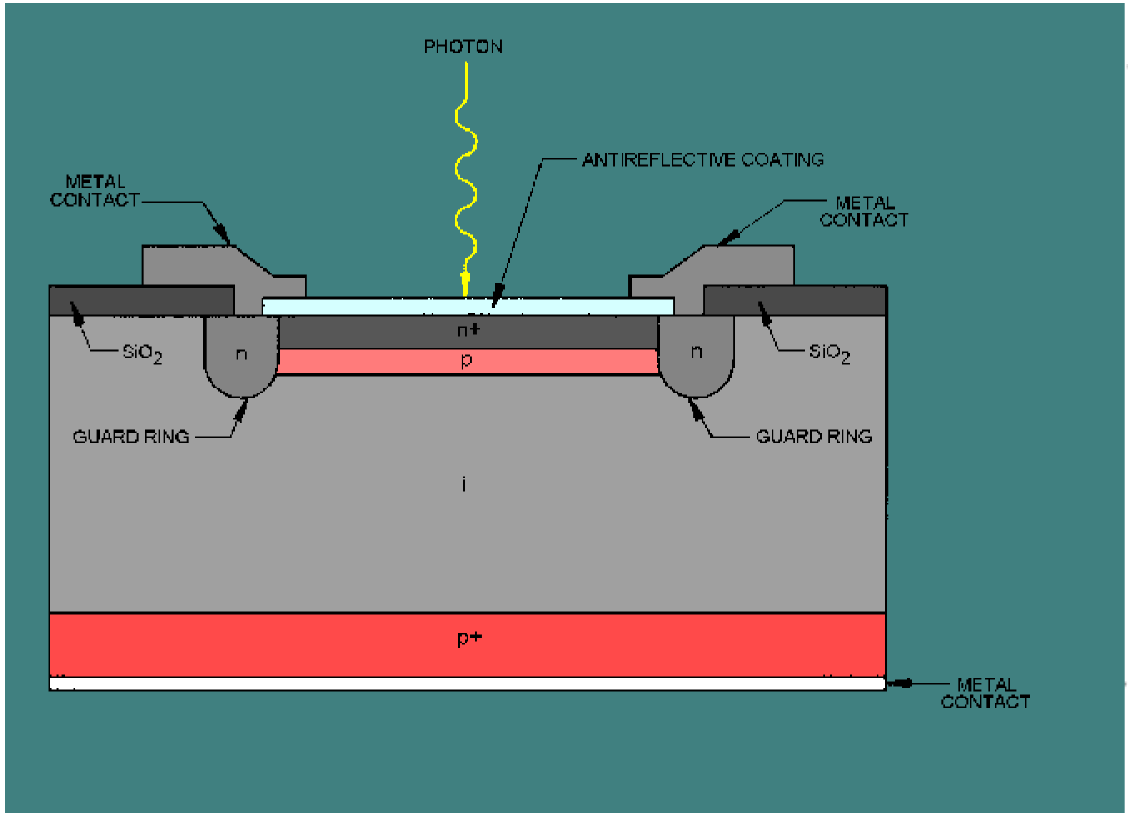
Data from Hamamatsu Photonics

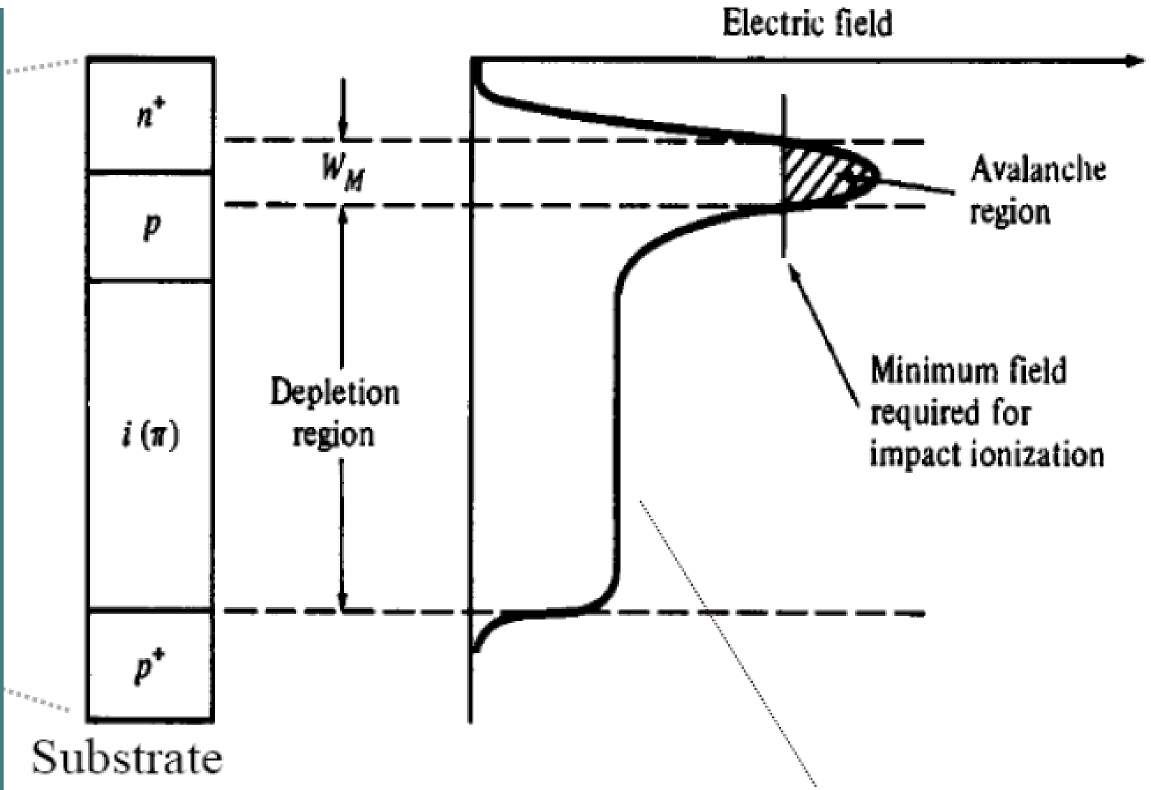
Avalanche Photodiode (APD) – a diode with gain

- A junction photodetector *with internal gain*
- Uses *impact ionisation* that occurs at very high internal electric fields.
- The avalanche process is an *additional* source of noise (excess noise factor *F*)
- Use the **majority carrier** to minimise *the excess noise*
    - Use an n^+-p-π-p^+ structure for silicon

    - Interesting paper: *IEEE TRANSACTIONS ON ELECTRON DEVICES*, **46** (1999) 1632

Silicon “Reach-through” APD



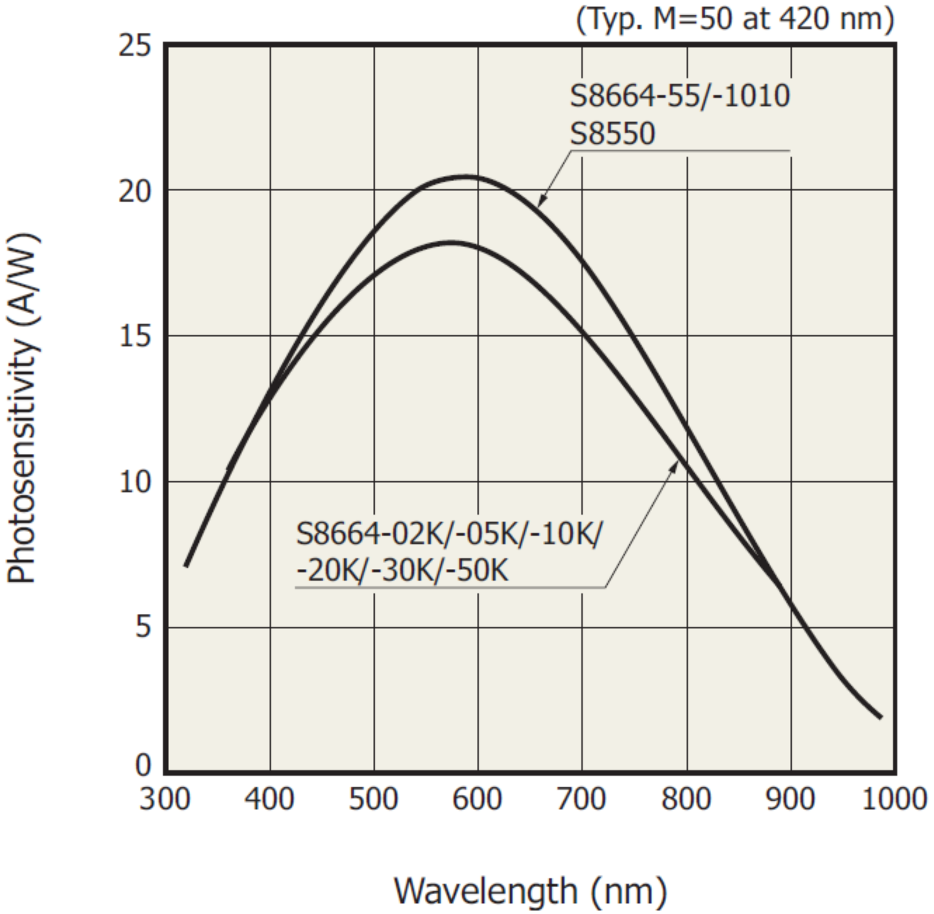


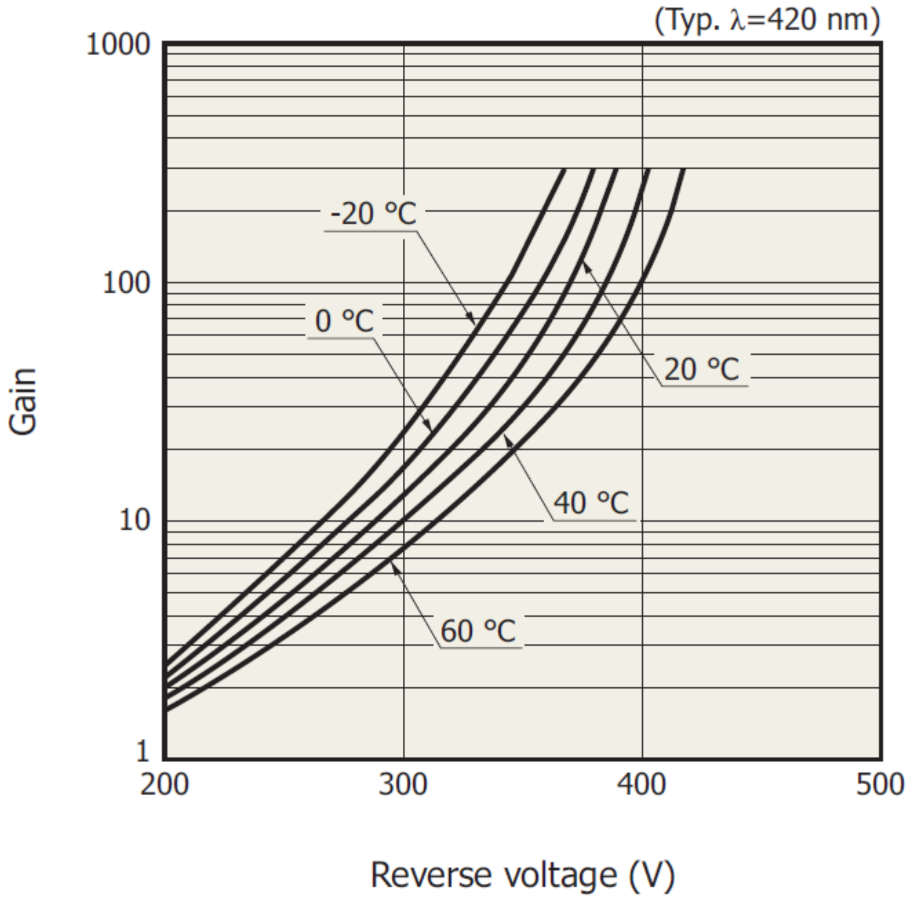
$$\frac{dE}{dx} = \frac{\rho(x)}{\epsilon}$$

Silicon RAPD structure, electrons are the carriers multiplied here.

Figure from http://www.tpub.com/neets/tm/111-4.htm

A commercial large area (5×5 mm^2)APD





Data from Hamamatsu Photonics

Silicon photomultiplier

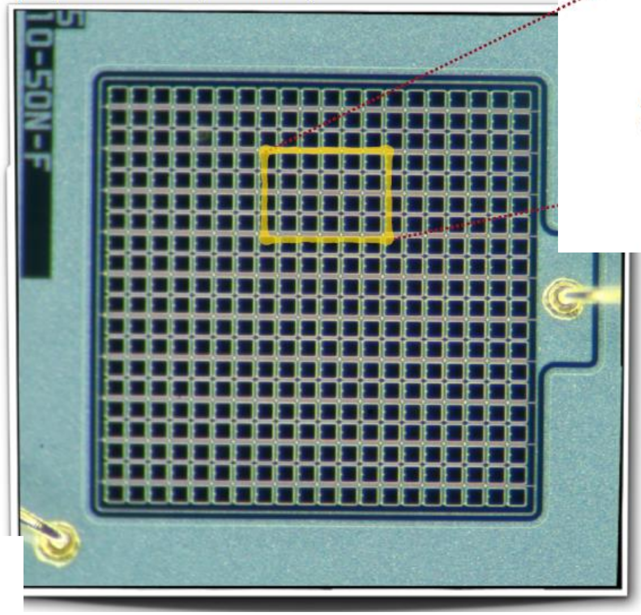
Take an APD, increase the reverse bias to get a very high gain (Geiger mode) .
PROBLEM! The first photon detected will generate a huge avalanche in the high field region which could be destructive.
SOLUTION: limit current with external quench resistor.

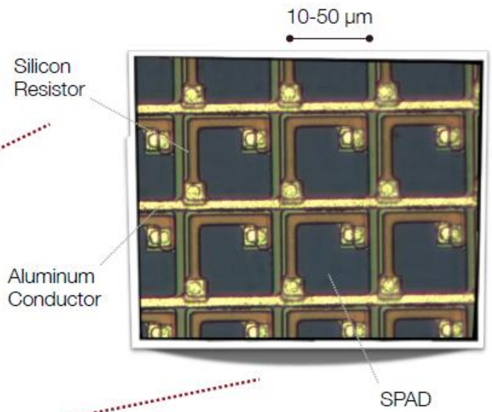
Clever idea: couple together lots of tiny APD (cells) in parallel to make a moderate area device (several square millimetres), then can get an quantised output (up to ~ the number of cells) which allows photon counting.

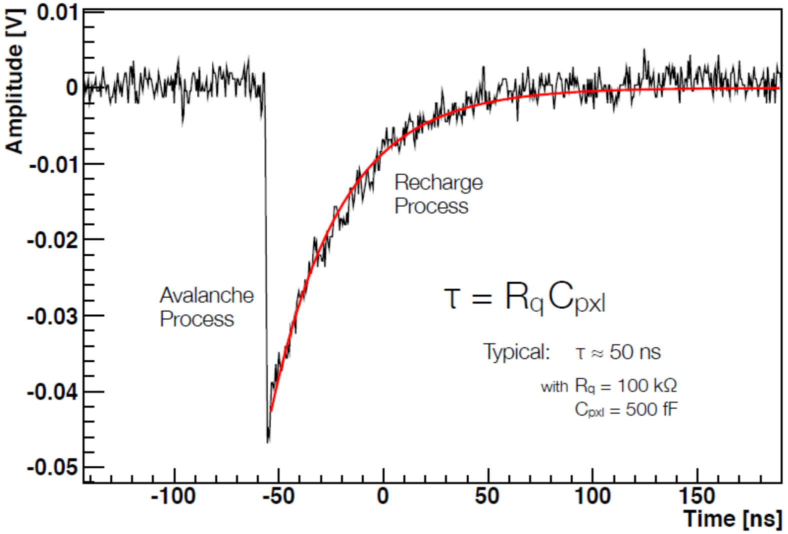
Geiger mode also produces a fast signal so get good timing information (Time-of-Flight applications fro example).

SiPM

[400 pixel SiPM device; Hamamatsu]





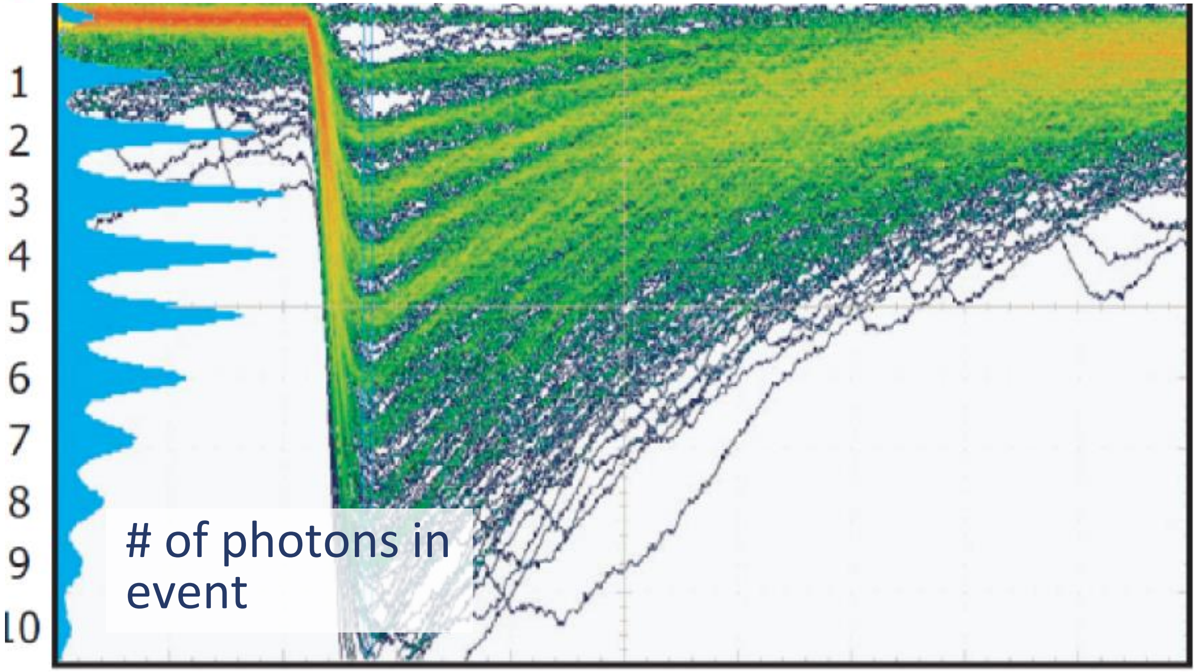


$\tau = R_q C_{pxl}$

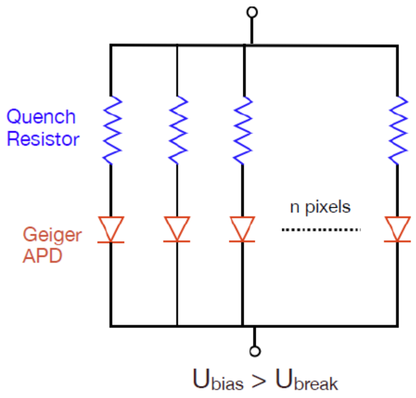
Typical: $\tau \approx 50$ ns

with $R_q = 100$ kΩ

$C_{pxl} = 500$ fF



# of photons in event



$U_{bias} > U_{break}$

SiPM summary

Pros:

High gain	[10^5 to 10^7
Compactness	[1 to 3 mm^2
Insensitive to magnetic fields	[up to few T
Low operation voltage	[30 - 70 V

Cons:

Limited dynamical range	[$N_{pxl} = O(1000)$
Cross-talk, after-pulsing	[1-10%
High dark-rate	[0.1 to few MHz
Temperature sensitivity	[20-50 mV/K