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SiPM Basic Survival Guide

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ICFA

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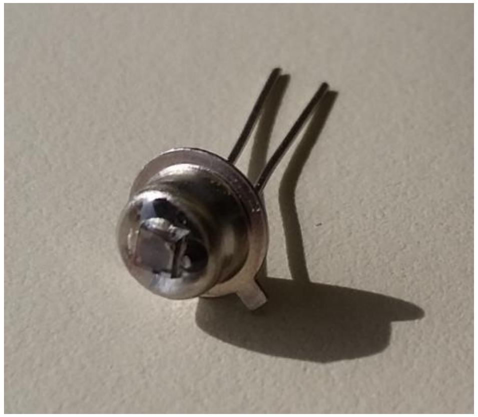
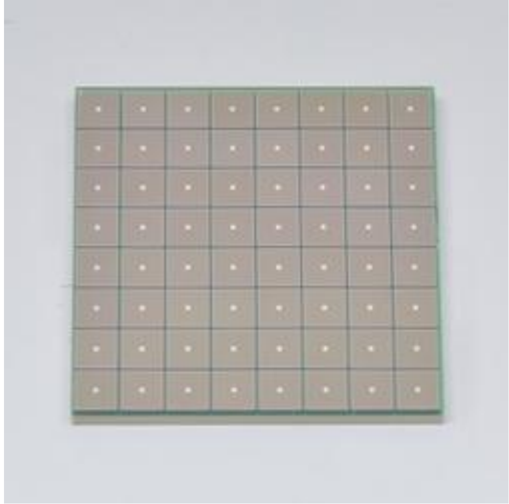
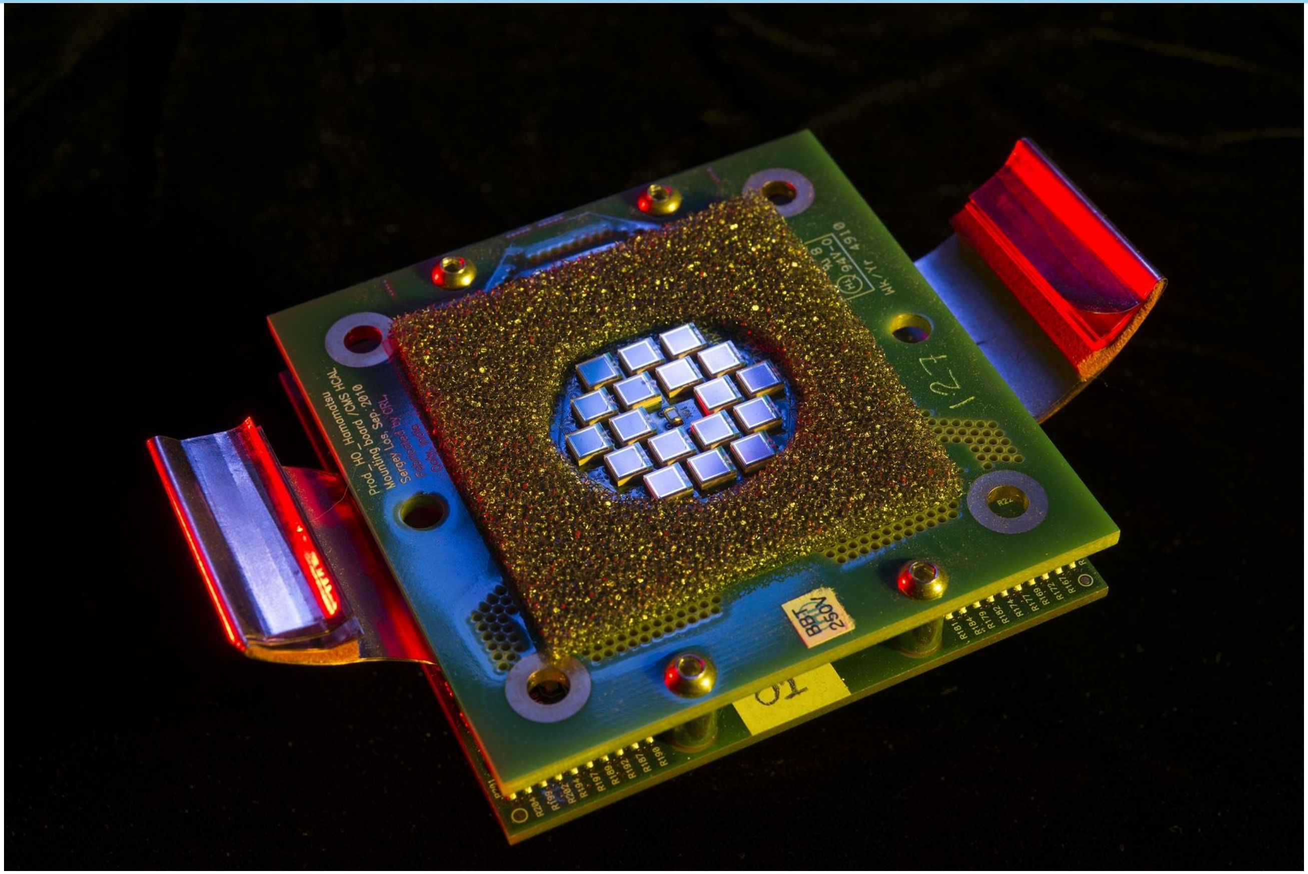
What is a Silicon Photo-Multiplier?

- SiPM is a solid state multi-pixel Geiger mode photo-detector
- The main reason why they are called Silicon Photo-multipliers is that they have a similar gain and are replacing vacuum Photo tubes in many applications
- Since their first practical introduction about 15 years ago
  - Available now in arrays up to 24x24 mm^2
  - Photo detection efficiency around 50%
  - Price of about $10 for a 3x3$mm^2$ device
  - Pixel size between 10 and 100 um





Do SiPMs Exist in Everyday Life?



- They do! Here is a photograph of the first SiPM upgrade for CMS HCAL detector at LHC
- Eighteen 3x3mm^2 SiPMs replace a vacuum photo-cathod based HPD (hybrid photo-detector)
- Circa 2007-2011

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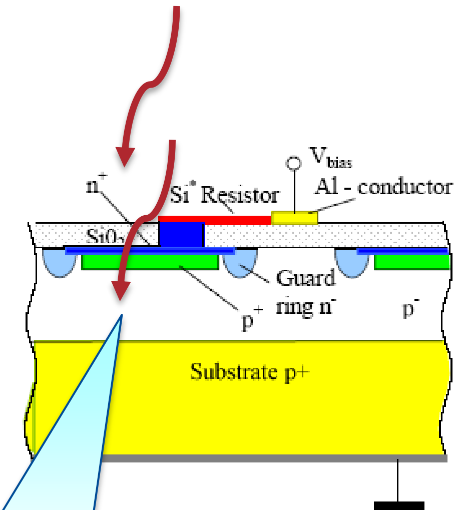
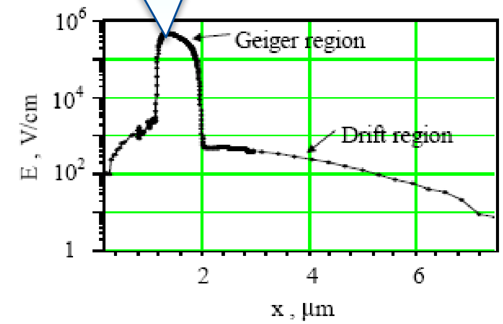
How Does it Work?

- **Photo-effect in semiconductor**
- **Avalanche gain in a high field region**
- **Self-quenching due to field drop**
- **Pulses from all pixels are being added together to generate a signal proportional to the incident light intensity**
- **Number of pixels determine the output signal dynamic range**



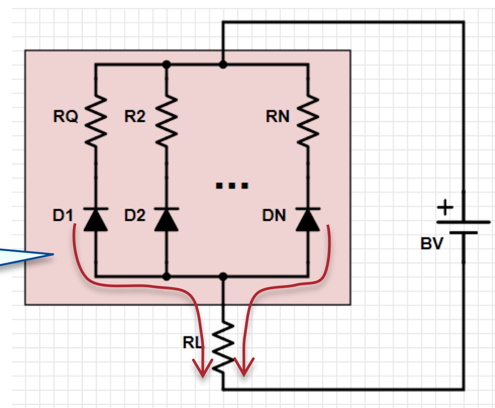
1. Conversion area, electrons drift back to the gain region

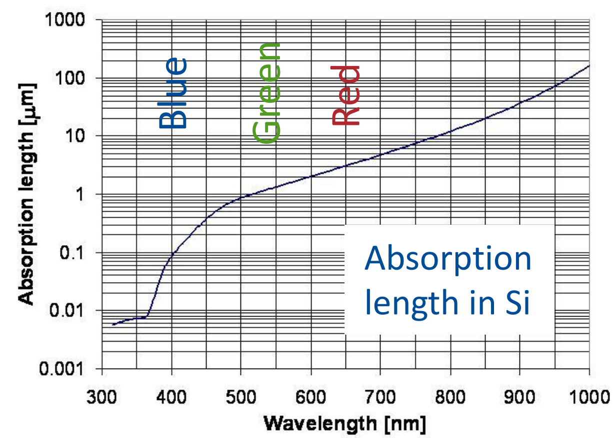
2. Avalanche causes voltage drop and quenches itself



Diagrams from B. Dolgoshein et. al., “An advanced study of silicon photomultiplier”, ICFA-2001

3. Output signal is a sum of individual pulses from all micropixels



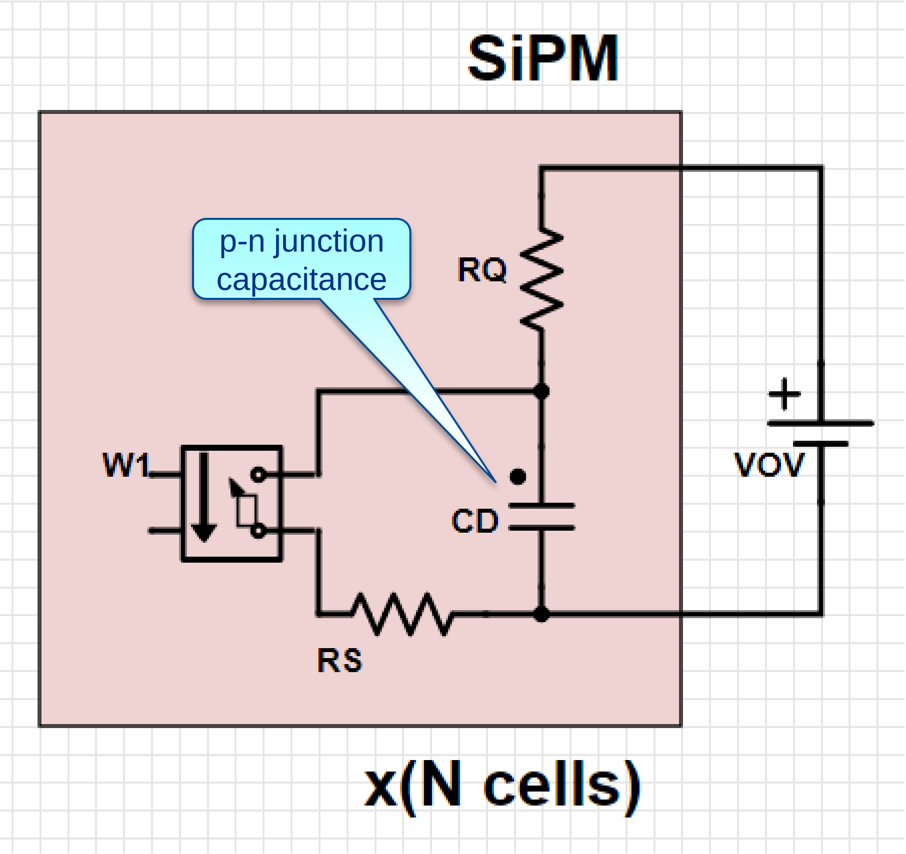


SiPM Simplified Electric Diagram

- Main parameters of a SiPM:
- Vbr – breakdown voltage, more or less when gain starts being seen, usually is a linear approximation of a gain curve (good linear fit at +0.5V and above)
- PDE – photon detection efficiency (≈50%)
- N – Pixel number
- Cd – Capacitance of an individual pixel
  - Cd ≈ Ctot / N
- Rq – Quenching resistor
  - Provides cell recovery
  - Limits recovery current
- Rs - Avalanche resistance of a pixel
  - Not a fixed value

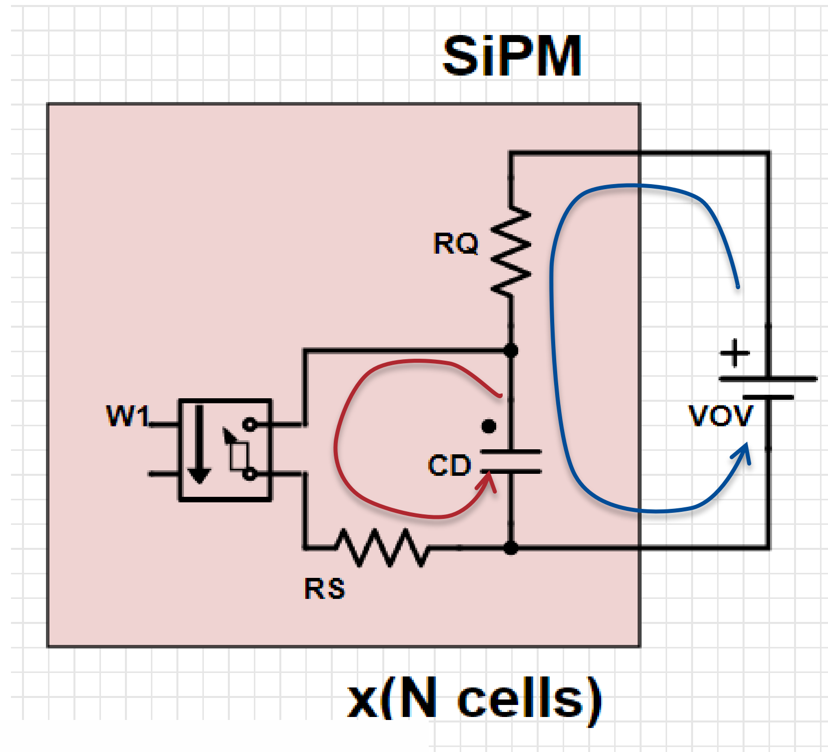
- Switch on the diagram turns ON when an electron gets to the gain region and causes a hot carrier discharge; OFF when current drops below a threshold value (since Rs<<Rq, that happens when V=Vbr)
- Vov – over-voltage = BV – Vbr

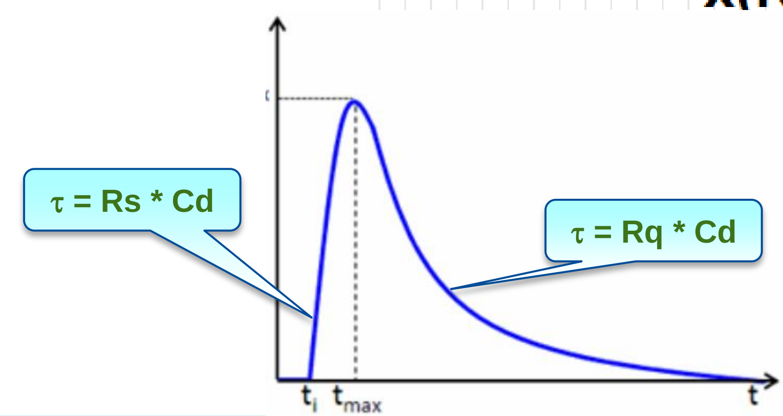
- What is SiPM gain? G = (Cd x Vov)/Qe
  - Typically 10^6 or 160 fC/pe (Qe=1.6E-19 C)



SiPM Signal Rise and Fall Times

- When a carrier starts an avalanche in a single pixel, plasma in the gain region shorts the pixel with an equivalent resistance Rs and voltage across the pixel drops approximately as:
  - V = Vov * exp(-t / Rs*Cd)
  - Rise time constant τ = Rs * Cd (<100ps)
- From the moment when avalanche quenches, pixel capacitance is being recharged via Rq:
  - V=Vov[1-exp(-t / Rq*Cd)], τ = Rq * Cd (≈10ns)
- Self-discharge of a pixel can not be seen from outside, what we see is a current developed across Rq as the voltage drops across the pixel (and increases across Rq)
  - Iq(max) = Vov / Rq

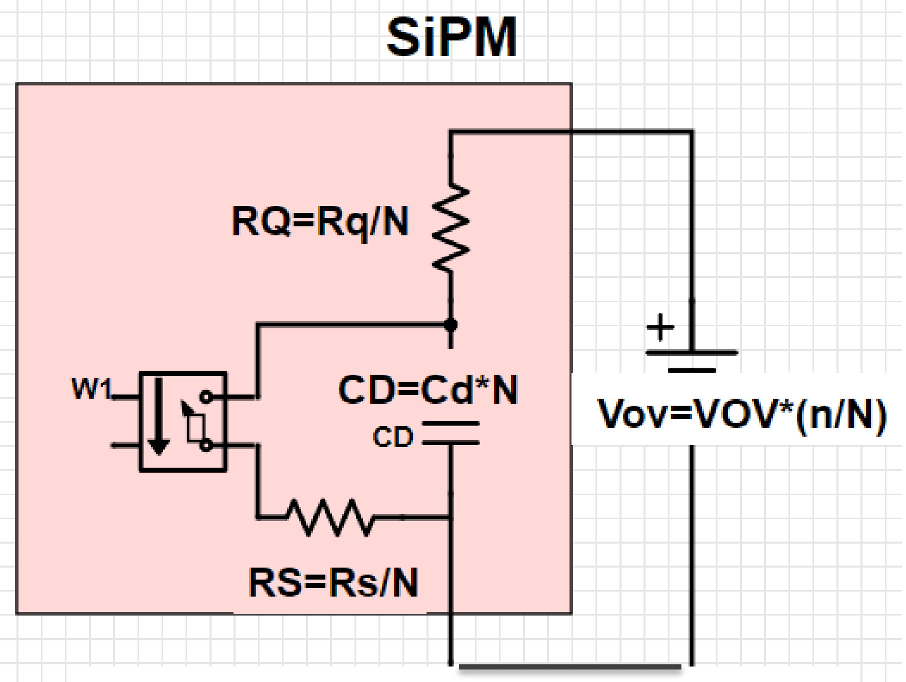




Multi-Pixel Signal

- Multiple pixels firing at the same time
  - Each pixel is loaded with N identical circuits (including itself), from a signal point of view that is a frequency-compensated divider and the output pulse shape does not change, just scales with the number of the pixels fired
  - I(n) = I(1) * n

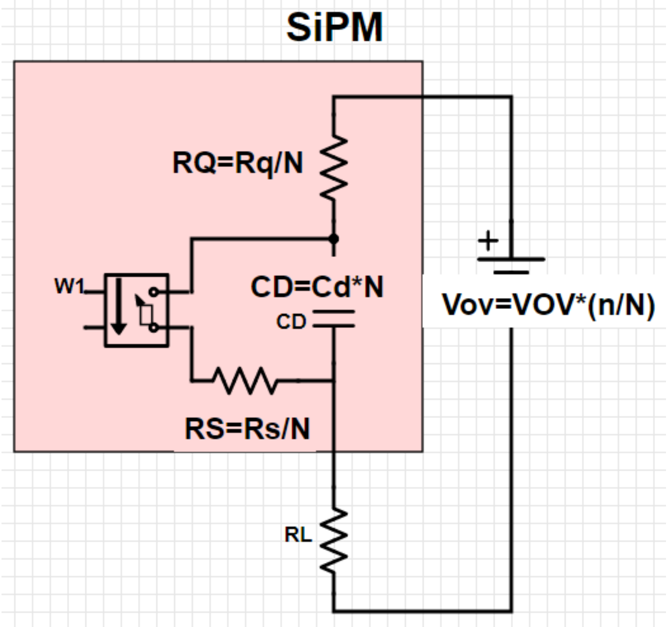
- To analyze output pulse shape it is convenient to use a diagram with all pixels combined in a single cell
  - For simulation the number of pixel fired can be represented by a fraction of actual overvoltage
  - Number of the pixels fired does not mean there were n/PDE incident photons (even on average), since there is a combinatorial probability for the same cell to be hit with multiple photo-electrons (pe)
  - Number of the incident photons can be calculated (with a certain accuracy)
  - Thus dynamic range of a SiPM measurement can go well beyond the pixel number N



Maximum SiPM output current (when all pixels have fired)

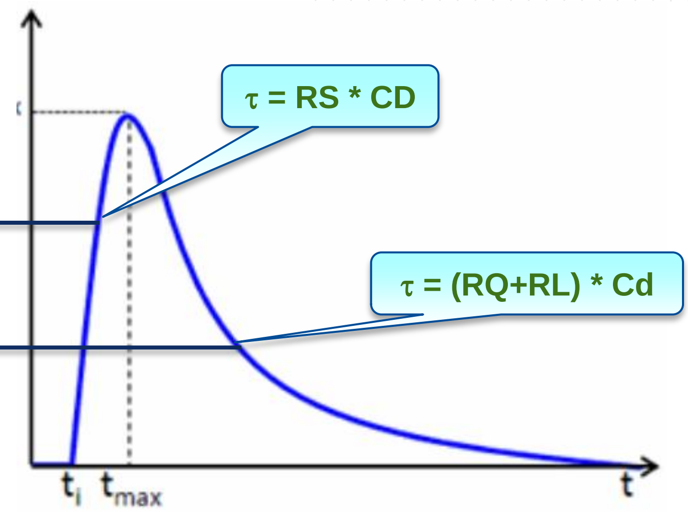
I(max) = Vov / RQ   RQ = Rq / N

Pulse Shape with non-Zero Load



- For this simplified equivalent diagram of a SiPM:
  - Rise time of the signal does not depend on the input impedance of the load (amplifier)
  - Fall time does increase since now both the RQ and RL are in the recharging circuit

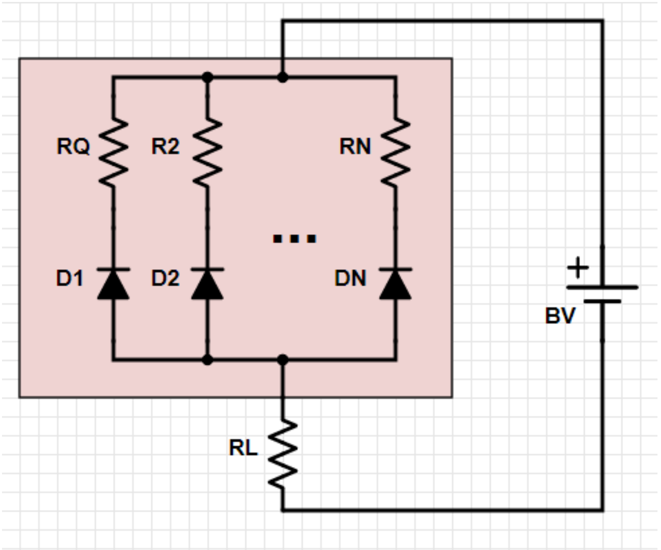
  - I = (Vov/RQ) * [1-exp(-t/RS*CD)]
  - I = (Vov/RQ) * exp(-t/(RQ+RL)*Cd)

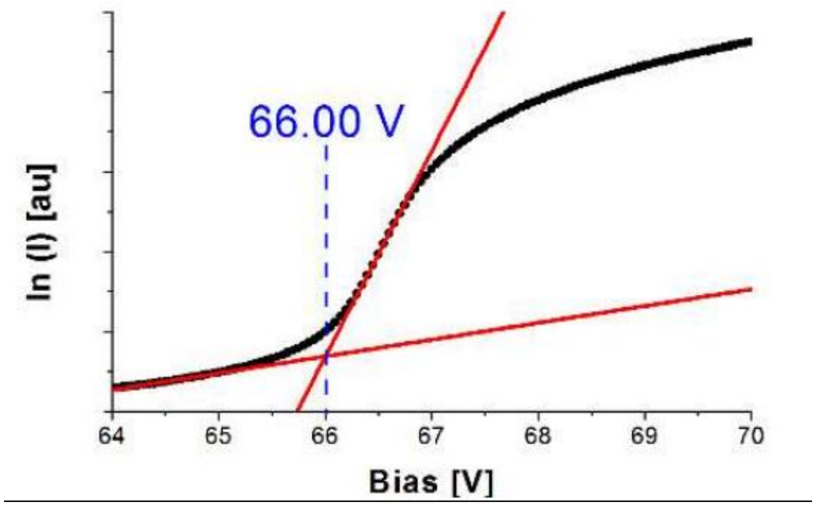


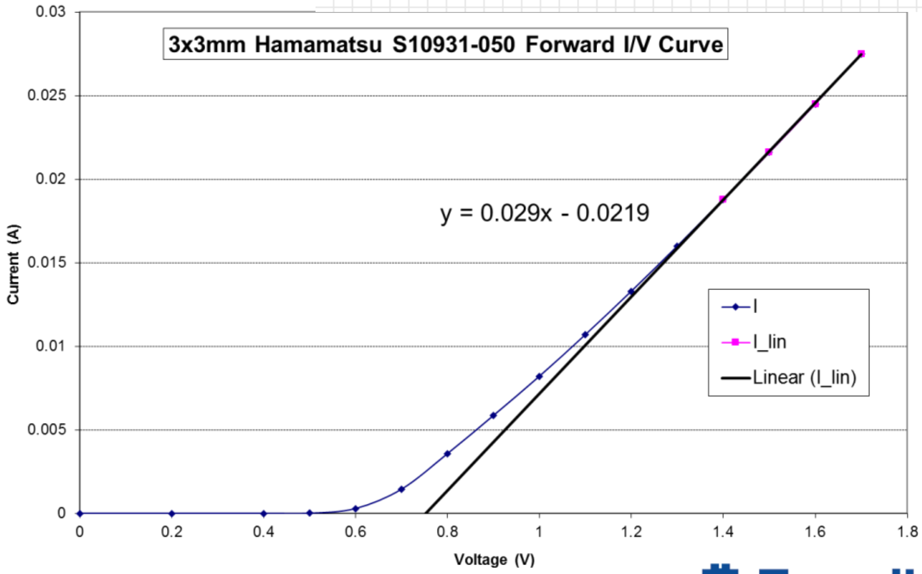
Extracting Some SiPM Parameters

- Capacitance CD of the whole SiPM can be directly measured and is often known from manufacturer's data (30-60pf/mm^2)

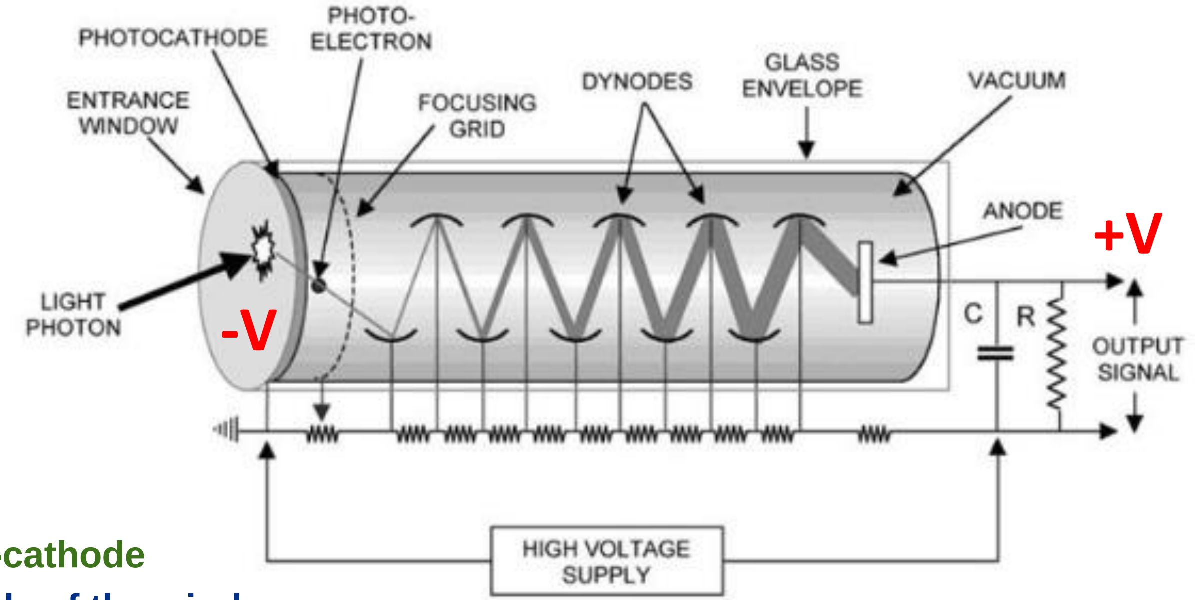
- Forward and reverse I/V curves
  - Reverse I/V curve shines light on the breakdown voltage
  - Forward I/V curve allows to measure RQ, since after a volt or so p-n junction voltage saturates and the further current increase is determined by the RQ (dI=dV/RQ)







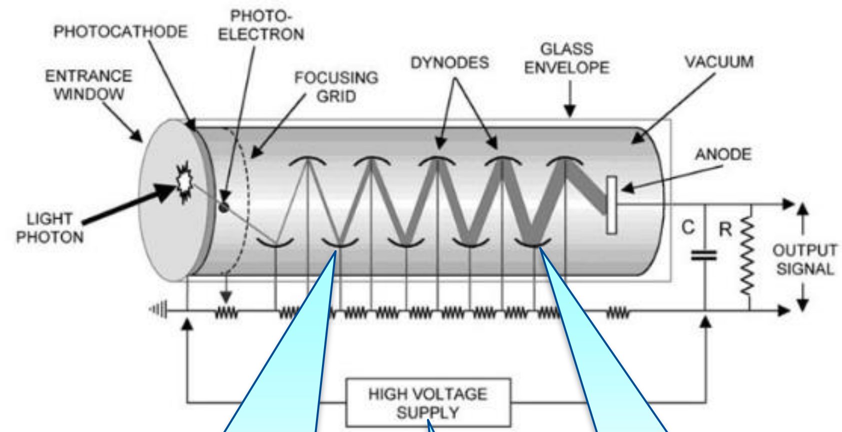
Vacuum Photo-Multiplier



- **Optically transparent window**
  - **Guides light to the photo-cathode**
- **Photo-cathode on the inner side of the window**
  - **Incident photons release electrons**
  - **Quantum efficiencies as high as 50%**
- **A set of N dynodes with increasing applied voltages**
  - **Multiply the number of incident electrons (secondary emission)**
- **Anode electrode**
  - **Collects output electrons and channels to the registration electronics**

Vacuum Photo-Multiplier

- **Overall gain G = P(Gi) = (1/P(Ki)) * V^N typ. 1E6-1E7**
  - **Number of dynodes can be derived from its I/V curve**
- **Each dynode gain due to secondary emission Gi = Vi/Ki (subject to saturation)**
- **Single pe resolution is determined by the gain of the first dynode $1/\mathrm{sqrt}(G_1)$ so higher voltage and better materials are typically used fore the first dynode**
  - Amplitude resolution for a single pe at G_1=4 is 50%
- **Electrons moving through the dynode system are not nearly relativistic (100eV electron has velocity of 6000 km/s)**
  - Signal transient time (in tens of ns)
- **Output signal width is small, typically a few ns, despite a long transient time, thanks to electron paths equalization**
  - Small output capacitance, a few pf, so 50 ohm readout dos not add to signal deterioration



What's an average secondary emission for a 10-stage tube at a 1E6 gain? =4

Number of dynodes 8-12, less for the modern tubes

Operating voltage 50-200 V per stage