Photo detectors

25/Nov/2022

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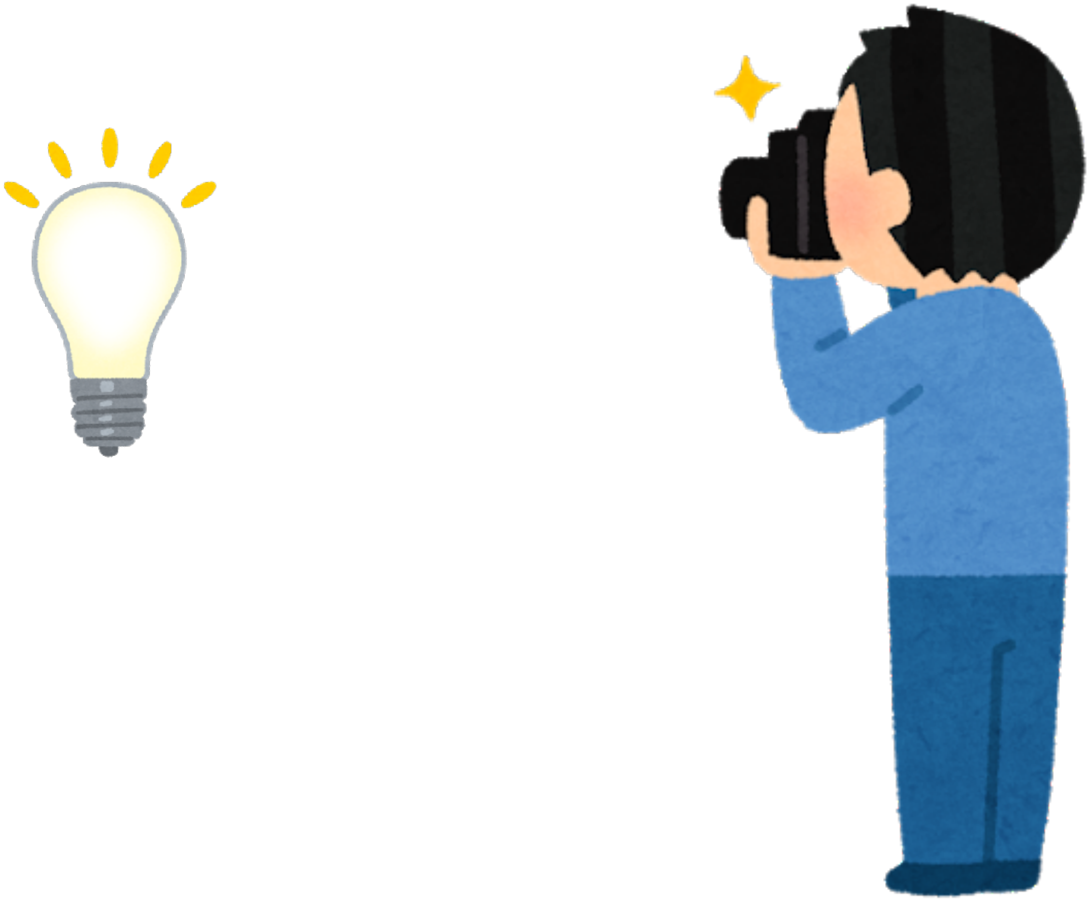
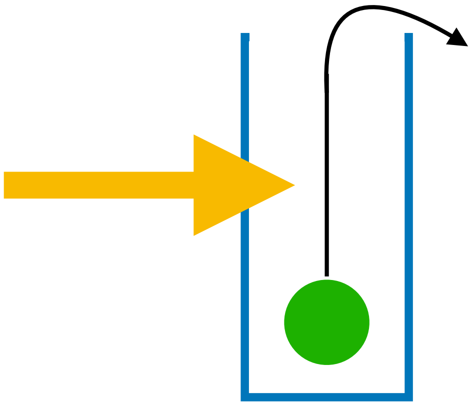
Light detection





How can we detect light

We need ENERGY to excite the micro system

How can we detect weak light
Do we need accumulate the energy enough to excite?

No.
Energy is quantize as photon.
Count the photon.

Quantized Energy flow

Energy flow is quantized.

Intensity is the number of photon

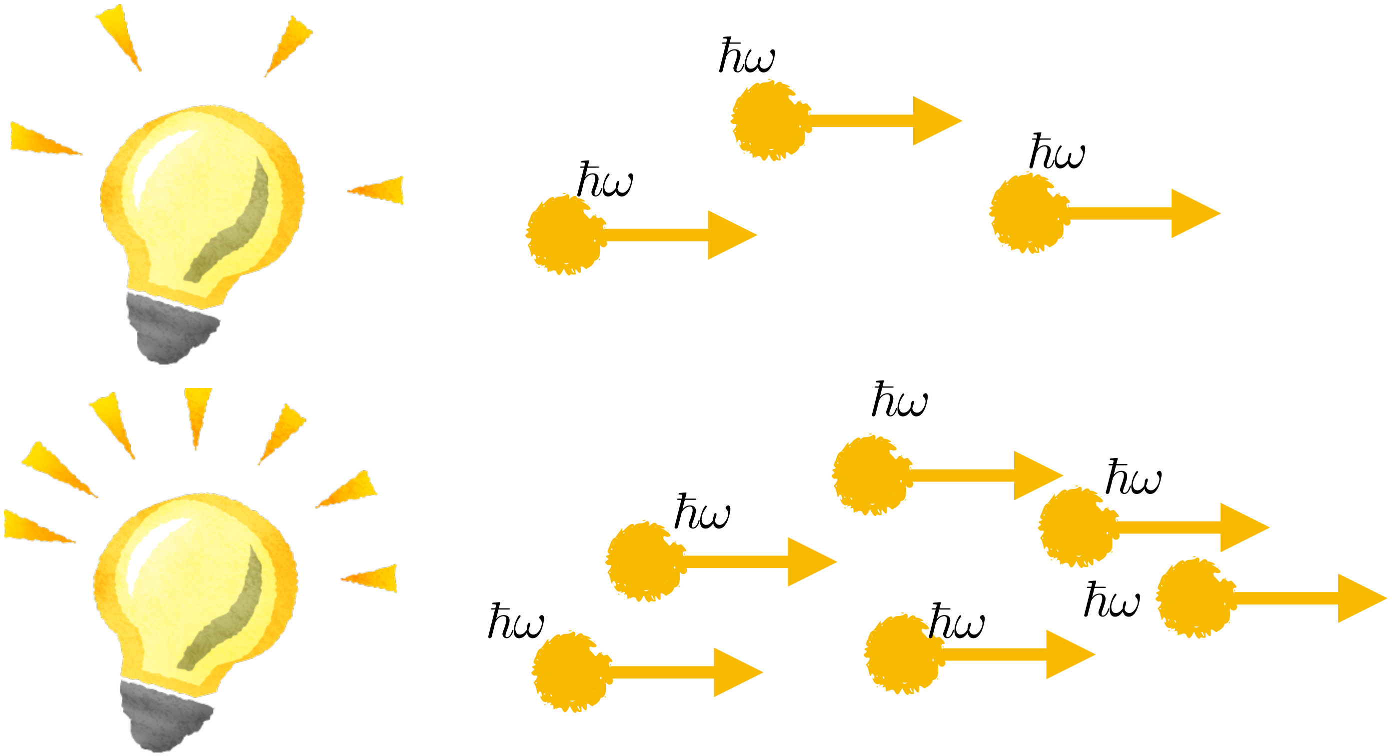


Photo from the Nobel Foundation archive.

Max Planck

The Nobel Prize in Physics 1918

Prize motivation: "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"

photoelectric effect

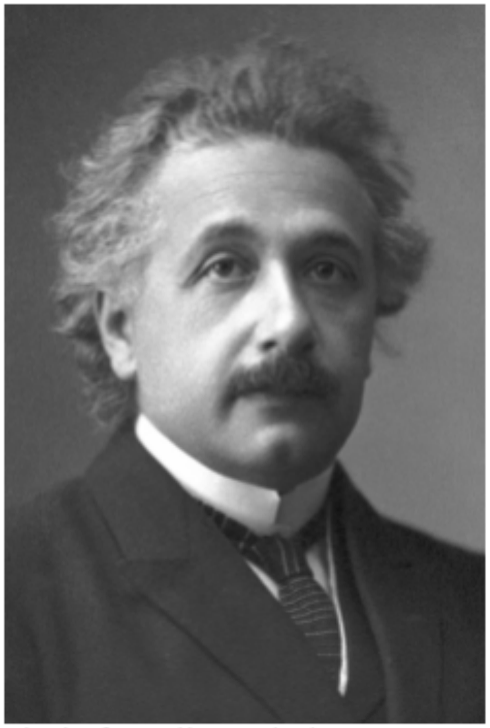
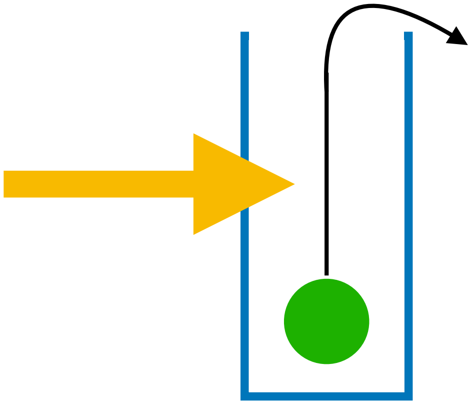


Photo from the Nobel Foundation archive.

Albert Einstein

The Nobel Prize in Physics 1921

Prize motivation: "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

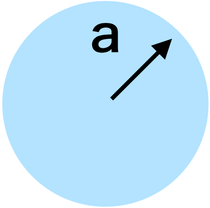


binding energy

The Feynman Lectures on Physics, Volume I

Chapter 38.The Relation of Wave and Particle Viewpoints **38–4The size of an atom**

The uncertainty principle $\Delta x \Delta p \geq \frac{1}{2}\hbar$



The Kinetic Energy $\frac{p^2}{2m}$ is of the order $\frac{\hbar^2}{2ma^2}$

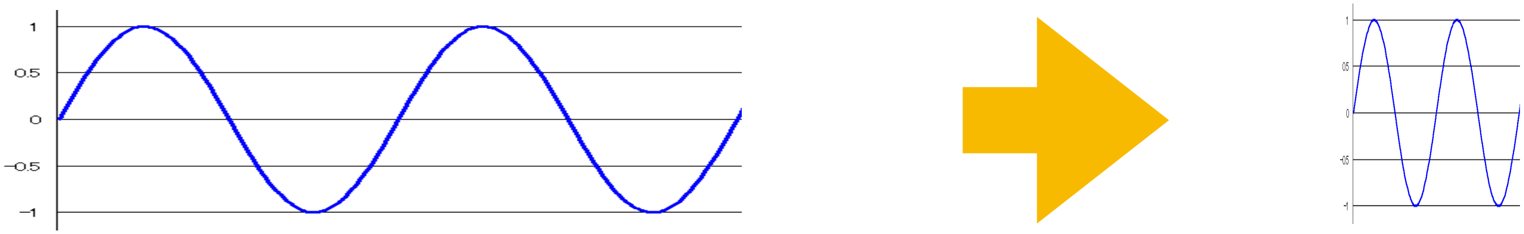
The Potential Energy is $-\frac{1}{4\pi\epsilon_0}\frac{e^2}{a}$

The Total Energy is $\frac{\hbar^2}{2ma^2} - \frac{1}{4\pi\epsilon_0}\frac{e^2}{a}$ **it is minimum at** $a = \frac{4\pi\epsilon_0\hbar^2}{me^2}$

Fine structure constant $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137}$

The Total Energy is $-\frac{1}{2}mc^2\alpha^2$ = -13.6 eV

$\hbar c$ = 197 eV nm $\hbar c$ = 197 MeV fm



$$\text{Energy} = \frac{2\pi\hbar c}{\text{Wave length}}$$

2 eV = 600 nm (Visible light)
1 keV = 1.2 nm (∼size of atom)
20MeV = 60 fm (∼size of atomic nuclei)

chemical energy

Battery voltage is related to the chemical interactions.

Alkaline manganese battery (1.5V)

$MnO_2 + H_2O + Zn$
$\rightarrow Mn(OH)_2 + ZnO$

Ni-Cd battery (1.2V)

$2NiOOH + Cd + 2H_2O$
$\rightleftarrows 2Ni(OH)_2 + Cd(OH)_2$

Thermal Energy

Energy of gas molecular is proportional to the temperature.

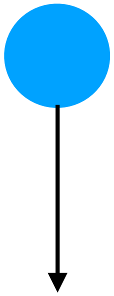
$$\boxed{E = kT}$$

k is Boltzmann constant `8.6171E-5 eV/K`

at room temperature, it is about 26 meV = 0.03 eV

It is much lower than the ionization energy

Gravitation



Free fall of 1 kg from 1m high

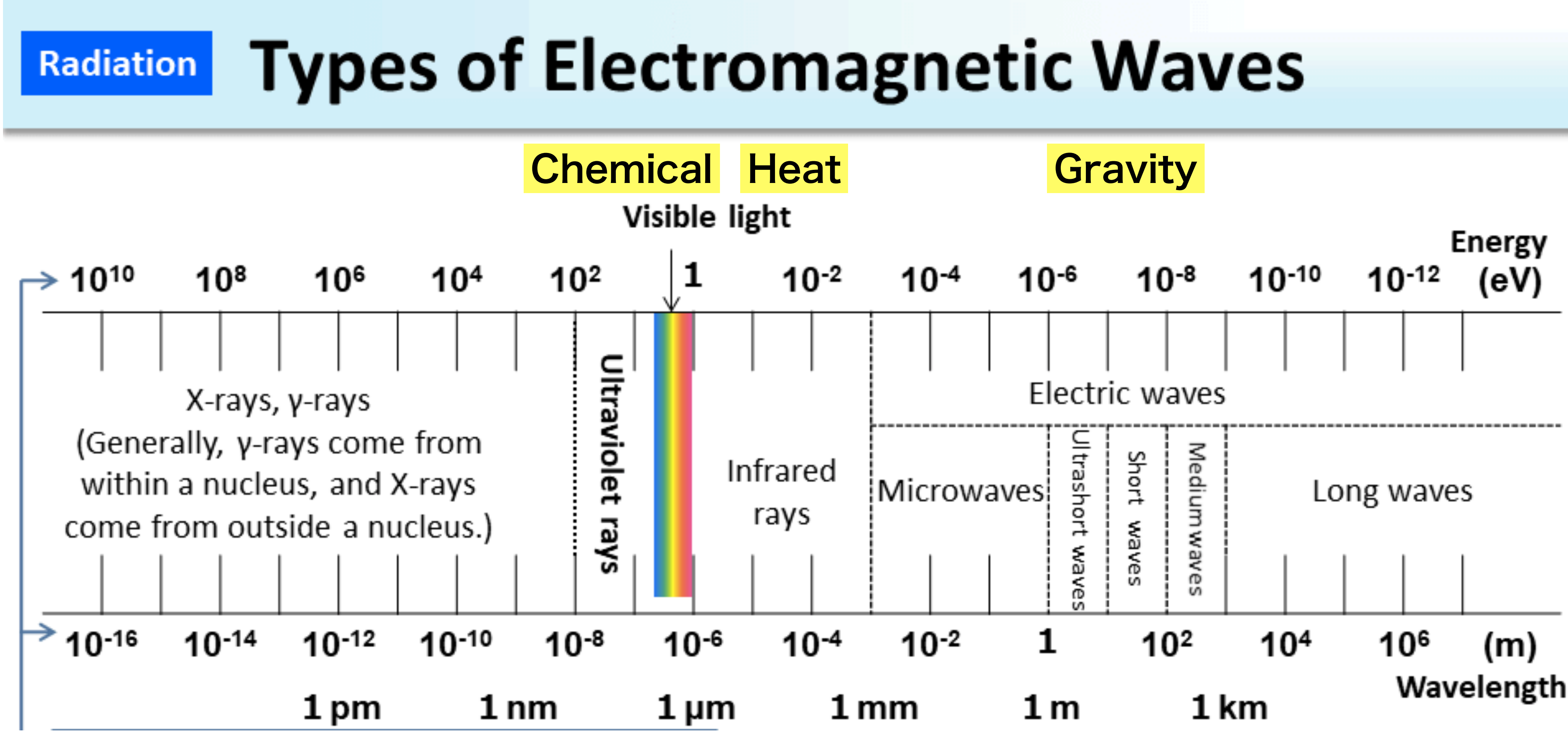
mgh = ~10 J = 6 x 10^{19} eV

It is large energy but each nucleon may get …

6 x 10^{19} eV / (1000 x 6 x 10^{23}) = 1 x 10^{-7} eV = 100 neV

Compare to other Energy, it is several order smaller.

Energy Scaleionizing radiation

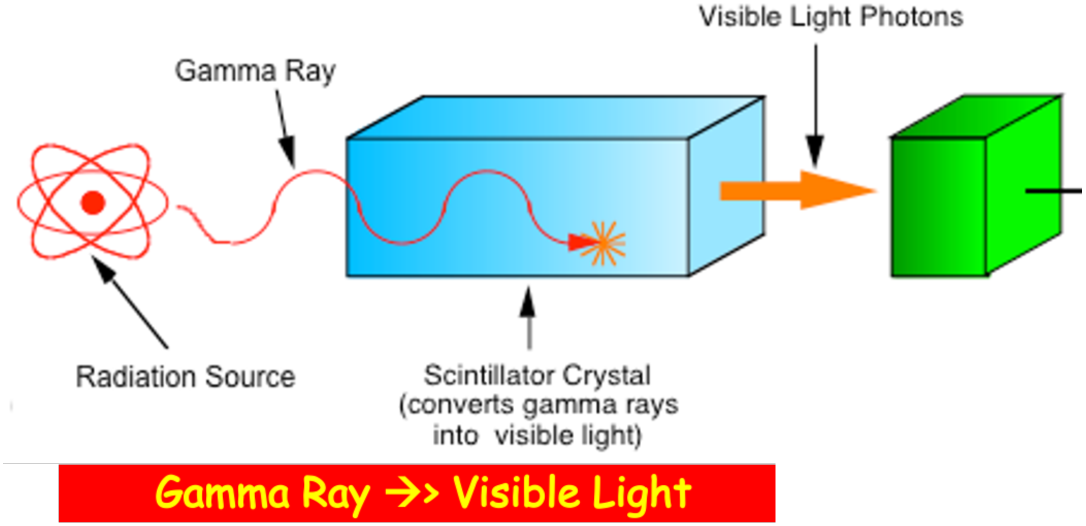


ionizing radiation

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Photon Counting

How many photon from scintillator?



LYSO scintillating crystal causes 16,000 photon for 511keV gamma rays.
We see ~one direction out of 6 (L-R,U-D,F-B) direction.
So ~2,670 photon will come out.
LYSO is 2mm x 2mm but Sensor is 1mm x 1mm. It is 1/4
Consequently, only 670 photon will hits the sensor.

The number of photon

How many photon are we seeing?

Visible light is ~2eV $\quad 1\mathrm{eV} = 1.6\times10^{-19}\mathrm{J}$

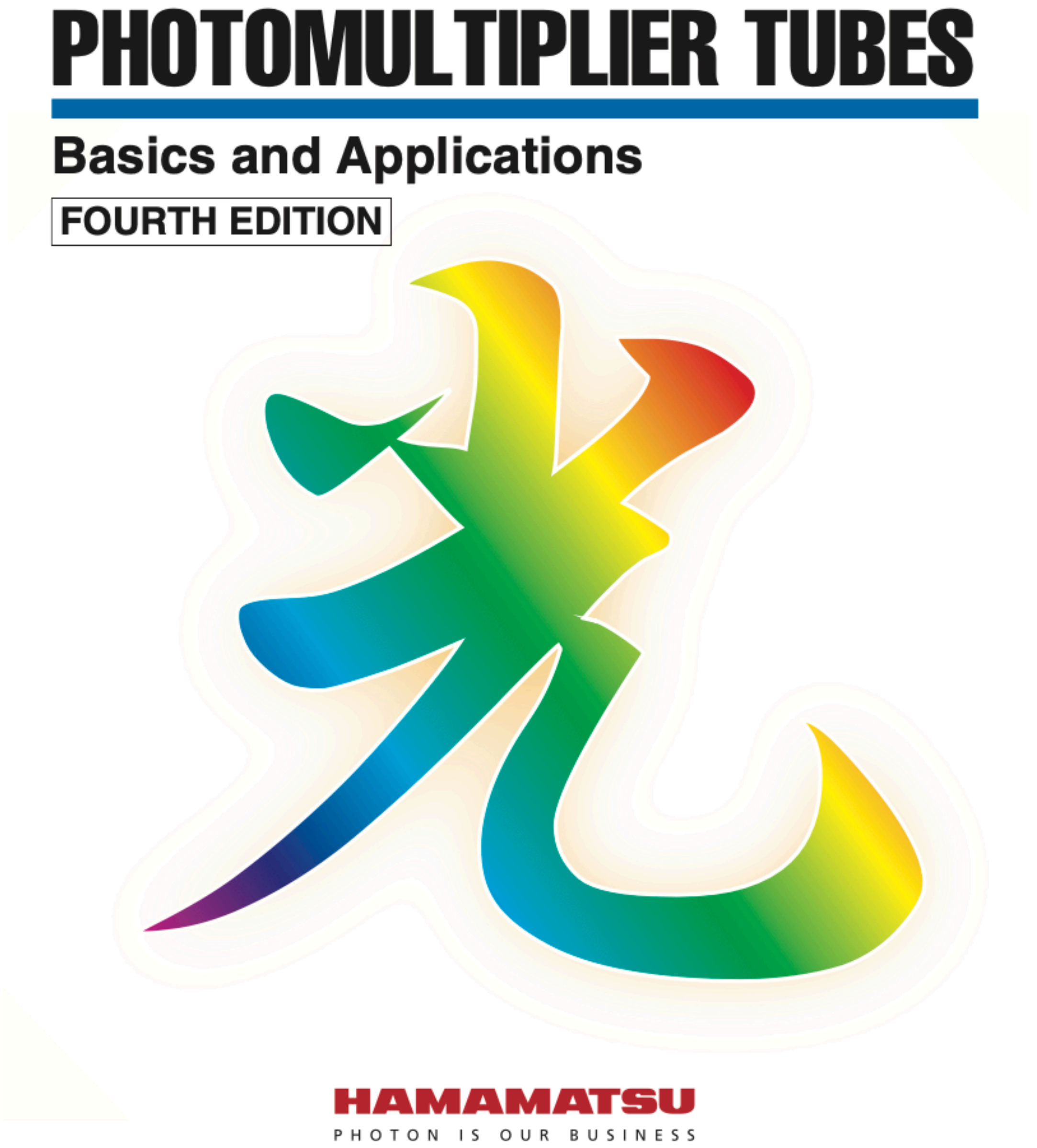
$$1\mathrm{W} = 1\,\mathrm{J/s} = \frac{1}{1.6\times10^{-19}}\mathrm{eV/s} = \frac{10^{19}}{1.6}\times\frac{1}{2\mathrm{eV}/e}\mathrm{eV/s} = 3\times10^{18}\,e/s$$

0.1s flush ~ 3x10^{17} photon

R

Int eye $\quad \dfrac{\pi r^2}{4\pi R^2} = \left(\dfrac{r}{2R}\right)^2$ of probability

600 photon = 1 W flush 0.1s is seen in 22 km distance



PHOTOMULTIPLIER TUBES

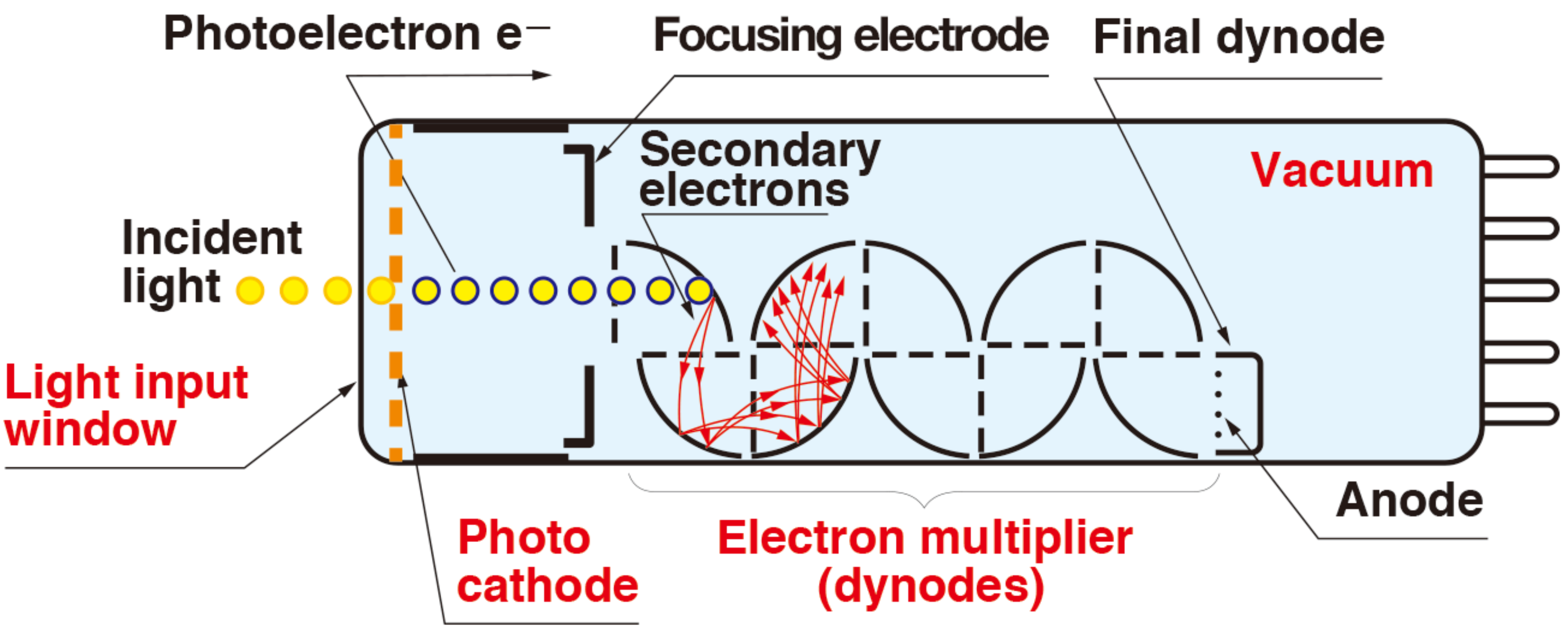
Basics and Applications

FOURTH EDITION

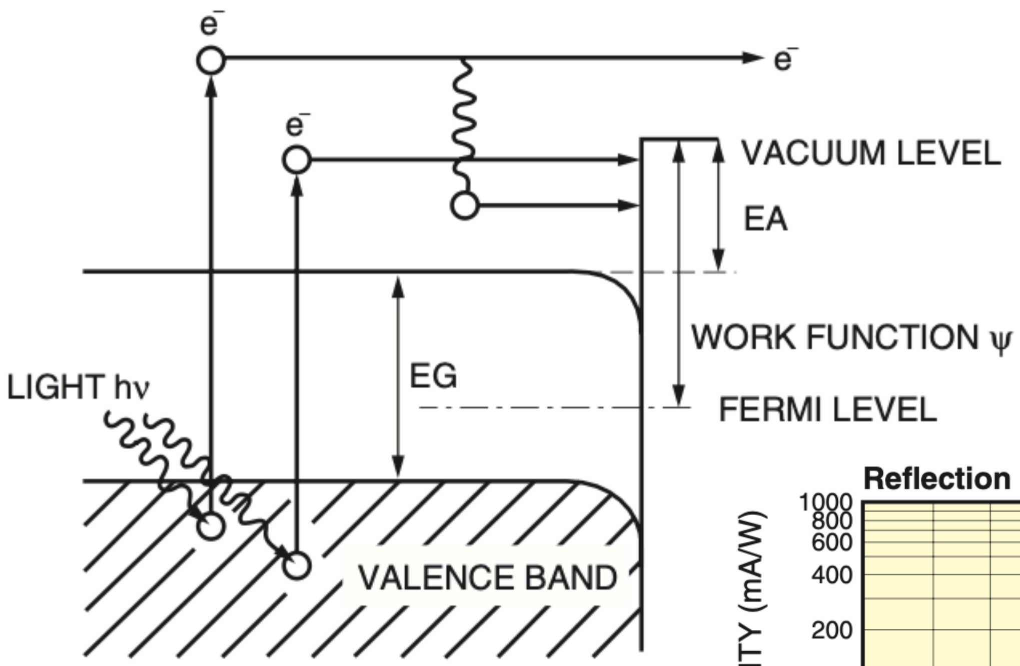
HAMAMATSU

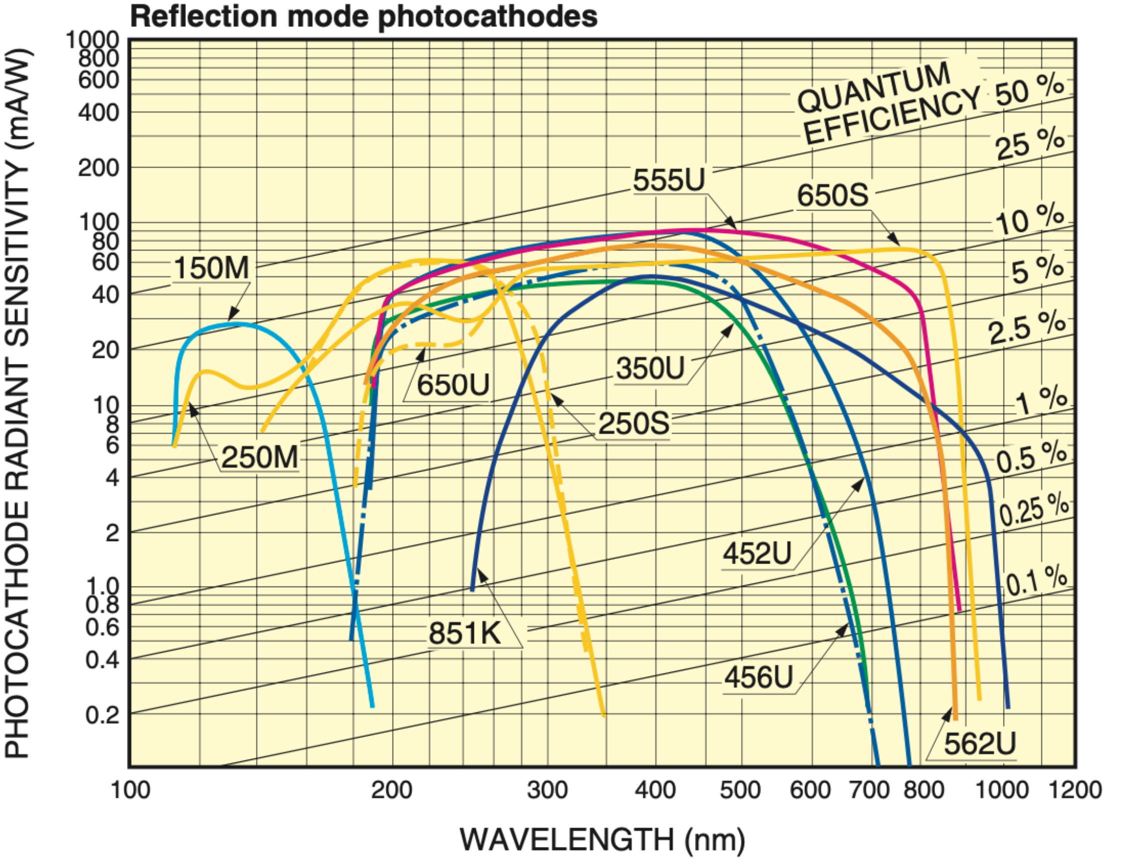
PHOTON IS OUR BUSINESS

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/PMT_handbook_v4E.pdf


Photoelectron e⁻
Focusing electrode
Final dynode
Secondary electrons
Vacuum
Incident light
Light input window
Photo cathode
Electron multiplier (dynodes)
Anode

(1) ALKALI PHOTOCATHODE





THBV4_0402

Figure 4-2 (a): Typical spectral response characteristics of reflection type photocathodes

2.4 Electron multiplier (dynode)

As stated above, the potential distribution and electrode structure of a photomultiplier tube is designed to provide optimum performance. Photoelectrons emitted from the photocathode are multiplied by the first stage through the last stage (up to 19 stages) in the electron multiplier, with current amplification ranging from 10 to as much as 10^8 times, and are finally sent to the anode.

Major secondary emissive materials[17)-21)] generally used are alkali antimonide (Sb), beryllium oxide (BeO), and magnesium oxide (MgO). These materials are coated onto a substrate electrode made of nickel, stainless steel, or copper-beryllium alloy. Figure 2-6 shows a model of the secondary emission multiplication of an electron multiplier.

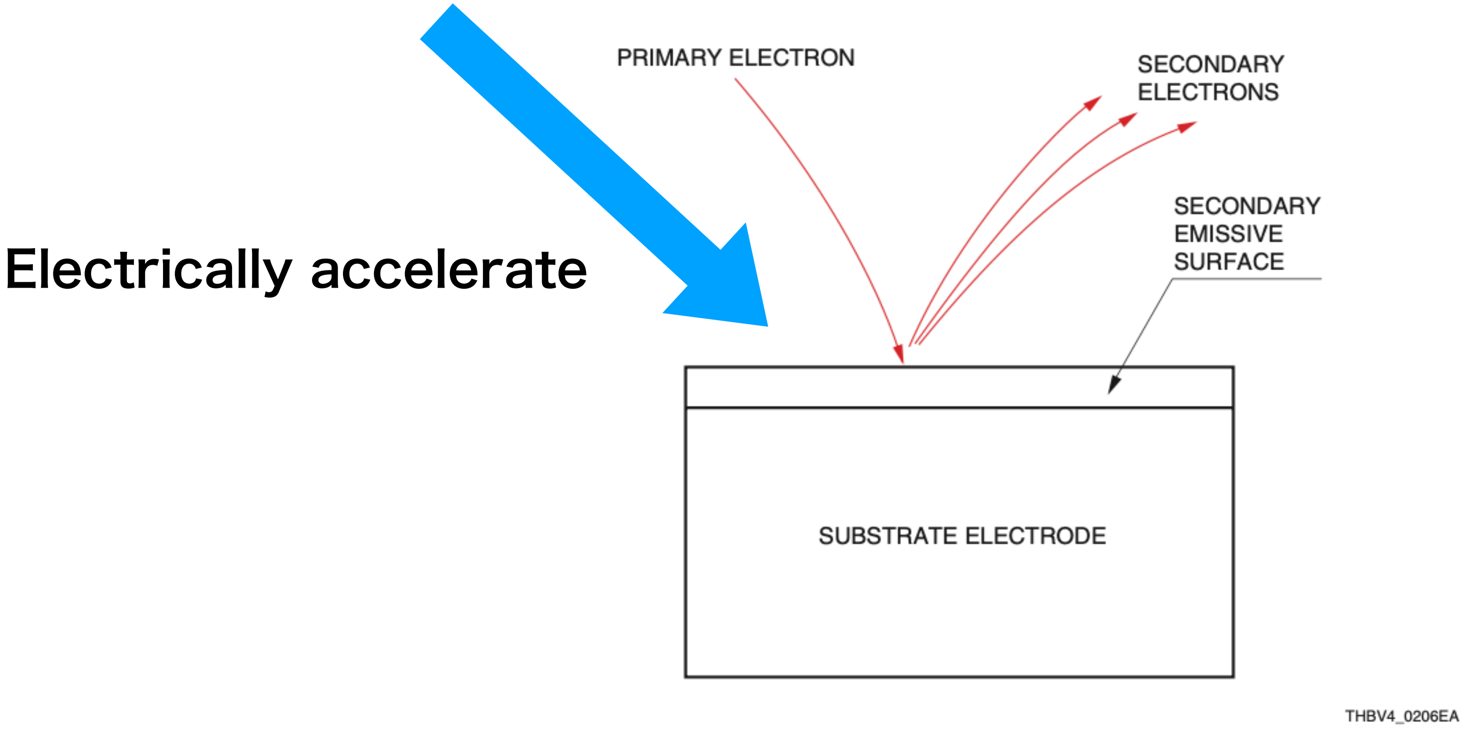


Figure 2-6: Secondary emission model of electron multiplier

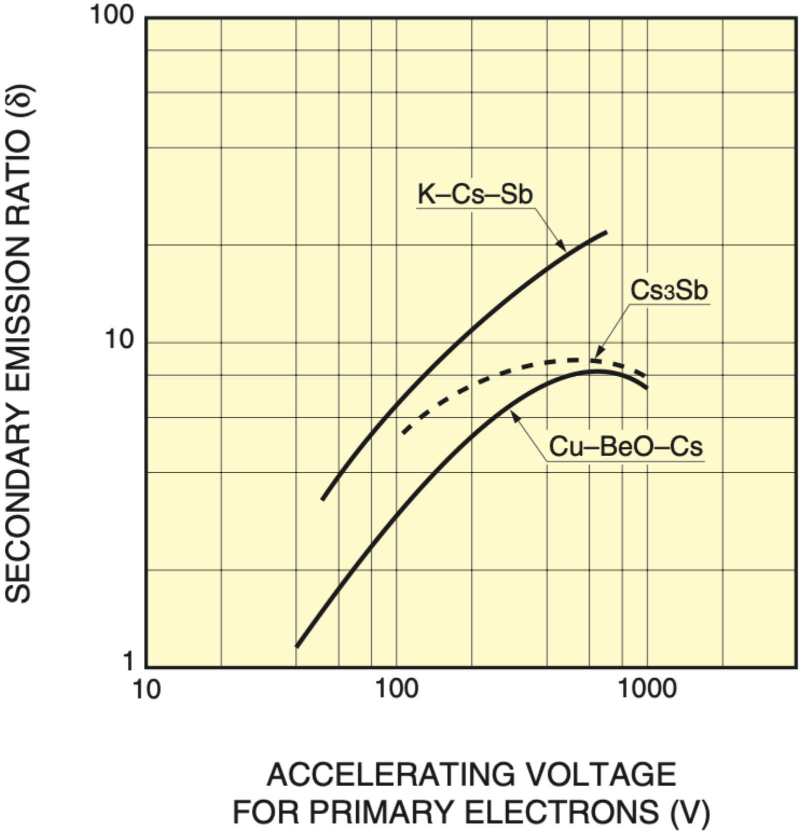


Figure 2-7: Secondary emission ratio

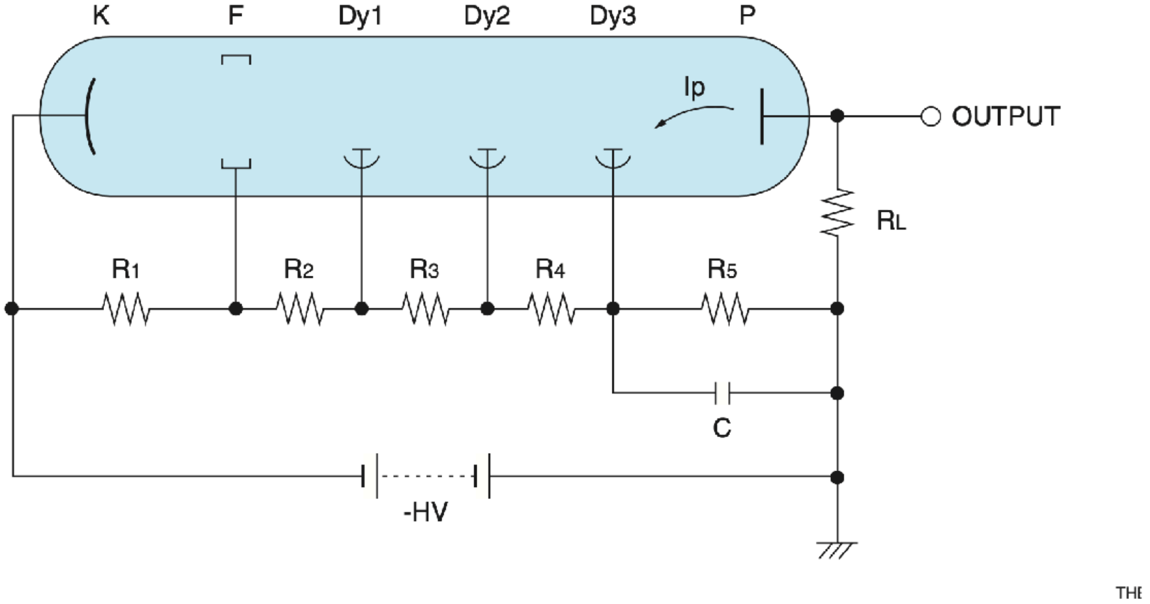


Figure 3-3: Basic photomultiplier tube operation using a voltage-divider circuit

- The number of photoelectron ~ 1000
- Multiplication ~ 10^5 -> 10^8 electron
- Can we measure?

Electron Counting

How many electron do we need?

Ammeter can measure about 1 μA. How many electron?

$$1\mu\text{A} = \frac{10^{-6}}{1.6\times 10^{-19}}\,\text{e/s} = 6\times 10^{12}\,\text{e/s}$$

We can see→ 0.1s

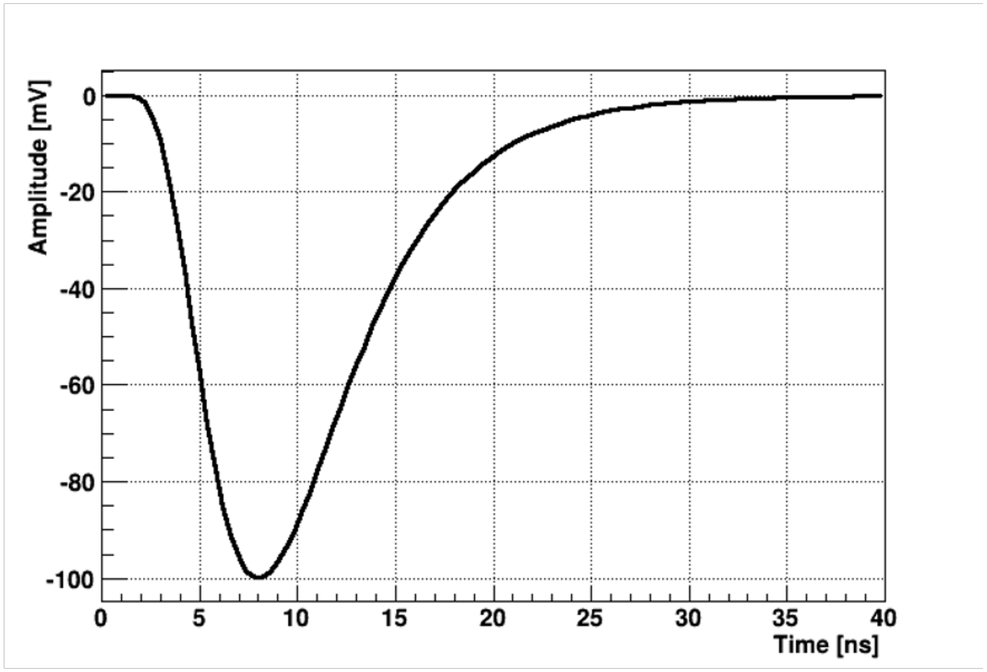
6×10^{11} electron is needed to “See”

10^{8} is not enough to “See”

10^8 electron pass in 10ns.
Current = Charge/ Time
$1.6\text{x}10^{-19}$ x 10^8 / (10 x 10^{-9}) = 1.6 mA

Cannot see in Ammeter but can be detected by electronics.

Electronics can measure voltage.
Current to Voltage
1.6mA x 50Ω = 80mV

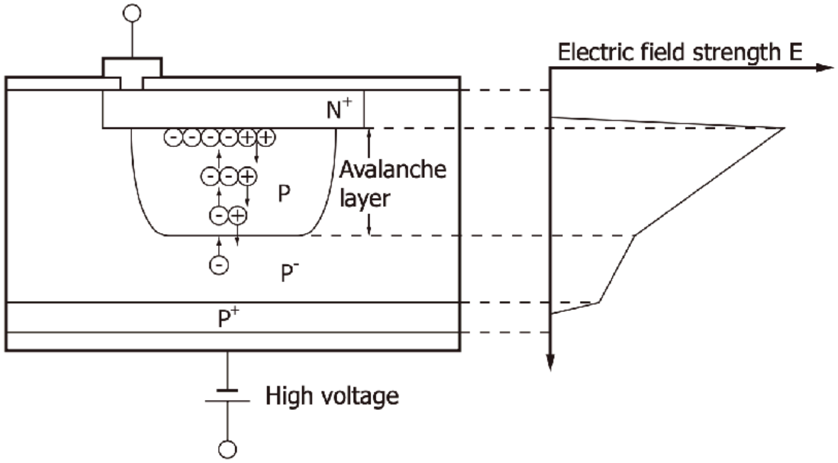


MPPC (SiPM)

Multi-Pixel Photon Counter (MPPC), also known as silicon photomultiplier (SiPM)

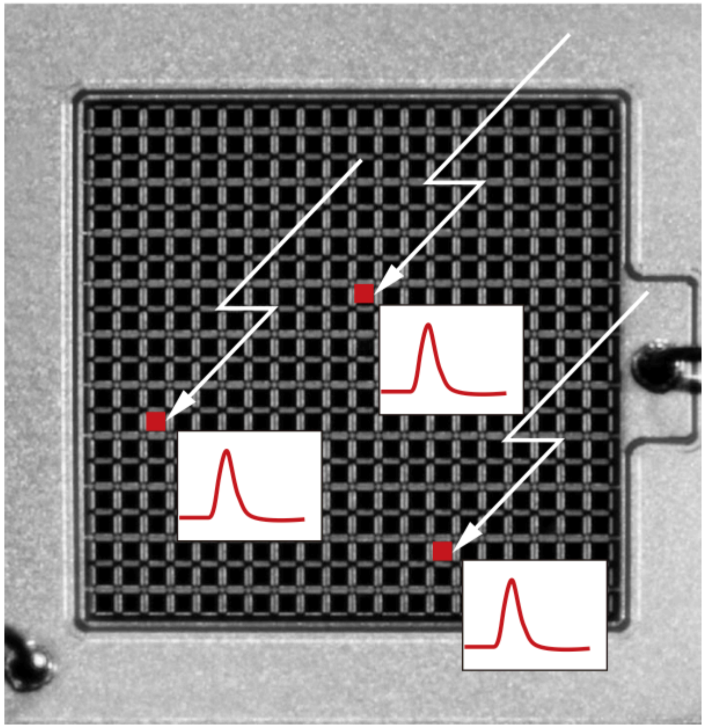
https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/si-apd_kapd9007e.pdf
https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/mppc_kapd9008e.pdf

[Figure 1-1] Schematic diagram of avalanche multiplication (near infrared type)



KAPDC0006EC

[Figure 1-2] Image of MPPC's photon counting

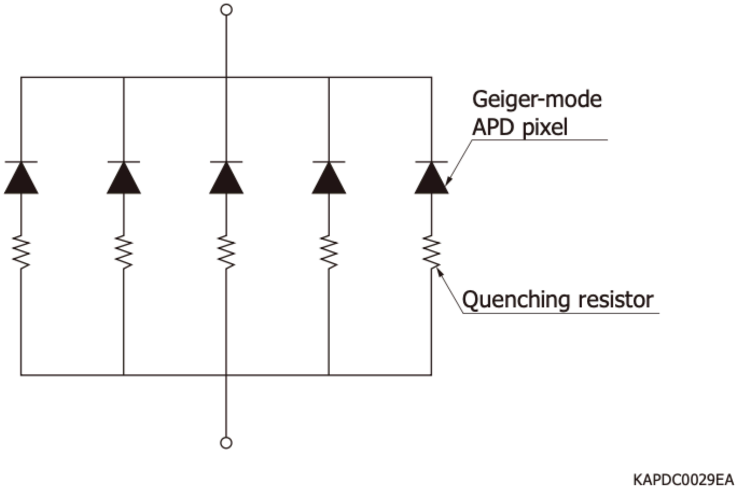


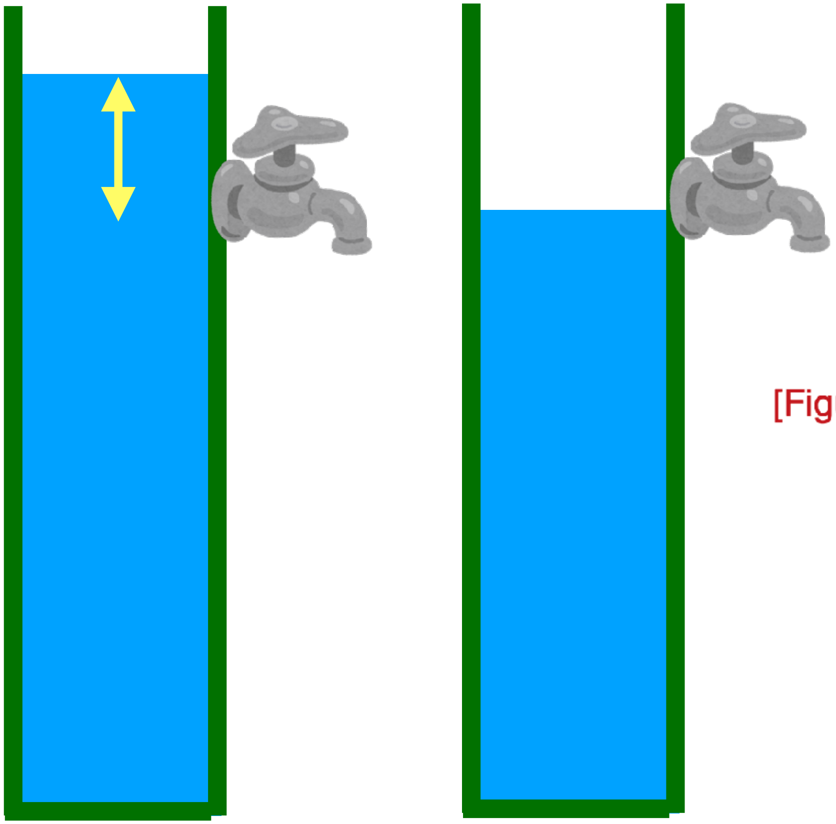
KAPDC0049EA

https://goalp.com/qa-139

Figure 1-1 shows a structure of an MPPC. The basic element (one pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor, and a large number of these pixels are electrically connected and arranged in two dimensions.

[Figure 1-1] Structure

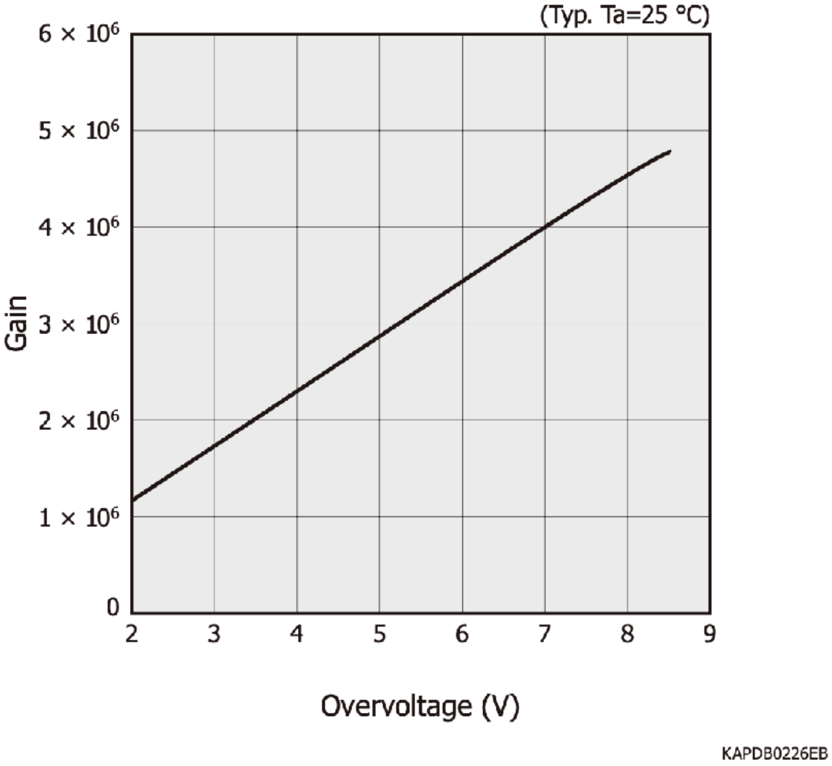




overvoltage

Too high gain (huge avalanche) destroy the device

[Figure 3-1] Gain vs. overvoltage (pixel pitch: 50 µm)



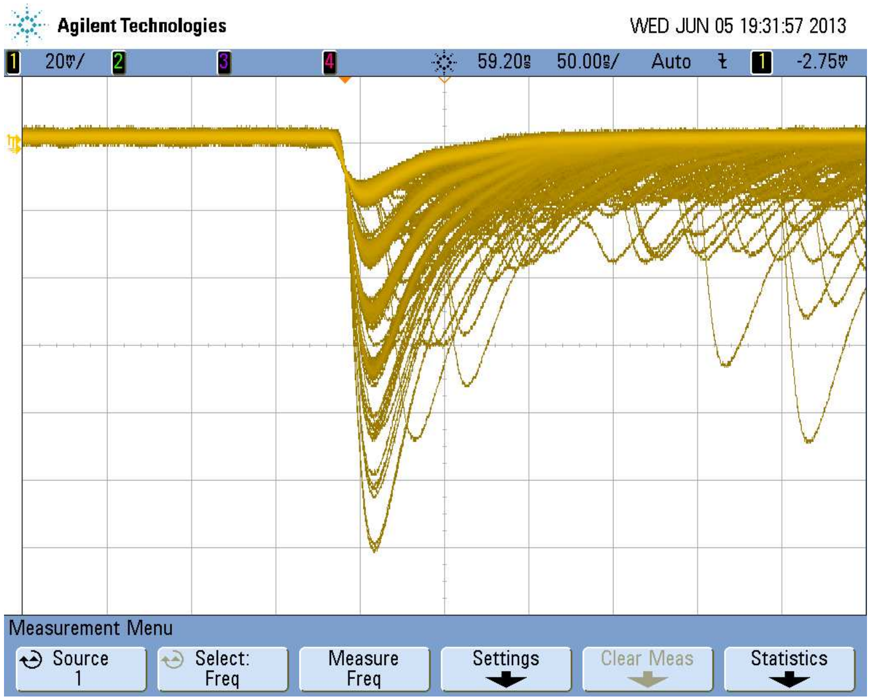


Fig. 1: Response of a SiPM Hamamatsu MPPC S10362-11-100C illuminated by a light pulse.

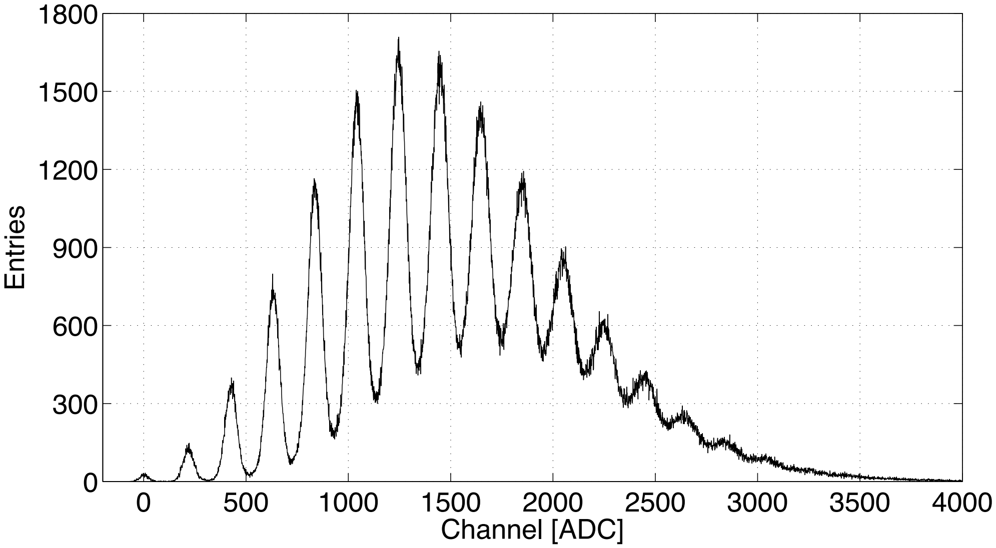


Fig. 2: Photoelectron spectrum probing a LED source measured with a Hamamatsu MPPC S10362-11-100C at a bias voltage of $70.3V$ and temperature of 25^oC.

The number of pixel is finite.
The number of photon is large, the number of pixel is not proportional.

When some pixels are already occupied, a photon has chance to hit occupied pixel. The probability of adding one more hit is the same as the probability of vacancy. Here, we discuss about a MPPC which has M pixels.

1 Occupancy

When m pixels are vacant, the probability of hitting vacant pixel is $\gamma = m/M$. When one more photon hits, the number of vacancy decreases to $m - \gamma$. Since $m = M\gamma$, the vacancy decreases to $(M-1)\gamma$.

n hit causes $M - m_n$ occupied pixels, and γ_n. Them,

$$\begin{aligned} m_{n+1} &= m_n - \gamma_n && (1) \\ M\gamma_{n+1} &= (M-1)\gamma_n && (2) \\ \gamma_{n+1} &= \frac{M-1}{M}\gamma_n && (3) \end{aligned}$$

Since $\gamma_0 = 1$,

$$\gamma_n = \left(\frac{M-1}{M}\right)^n = e^{-\alpha n} \tag{4}$$

Here

$$\alpha = -\log\left(\frac{M-1}{M}\right) \sim \frac{1}{M} \tag{5}$$

Then, the number of occupied pixels is

$$M - m_n = M - M\gamma_n = \left(1 - \left(\frac{M-1}{M}\right)^n\right) M = \left(1 - e^{-\alpha n}\right) M \tag{6}$$

SiPM in eazyPET has 400 pixel.