06 - Photomultiplier tubes and photodiodes

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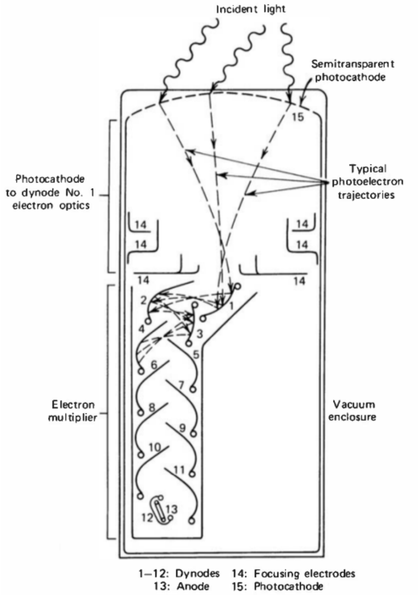
Version 2

The Photomultiplier (PM) tube

- Detection of very weak scintillation light
- Provide electrical signal
- Can be also done with silicon photodiodes, but PM are most widely used
- Characterized by spectral sensitivity

Structure of PM tube



Photoemission process

- Conversion of incident light to photelectron in sequence of processes
- (1) photon absorbed, it’s energy transfered to electron in material
- (2) Migration of electron to the surface of material
- (3) Escape of electron from the surface of photocathode
- Must overcome potential barrier (work function) of the material

Spontaneous electron emission

- Thermionic noise by the surface barrier
- Thermal kinetic energy of conduction electrons may be sufficient to overcome the barrier
- Average of thermal energy is 0.025 eV, but the tail of the distribution reaches higher energies

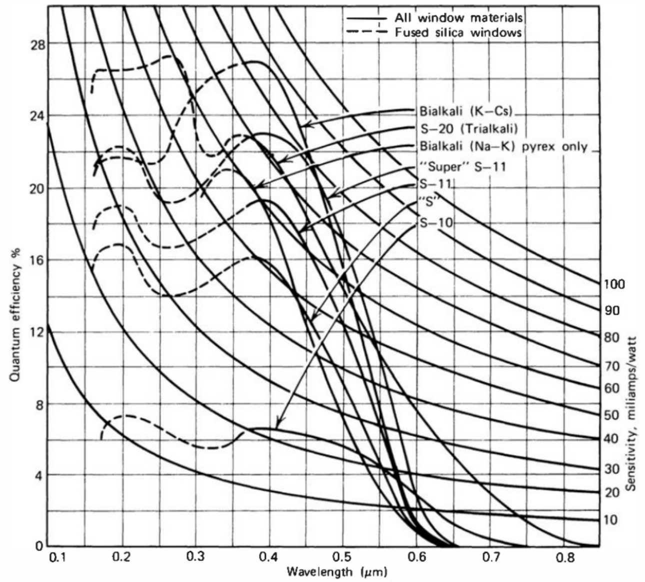
Fabrication of photocathodes

- Opaque - thickness > maximal escape depth
- Semitransparent - deposited on transparent backing
- Important uniformity of thickness

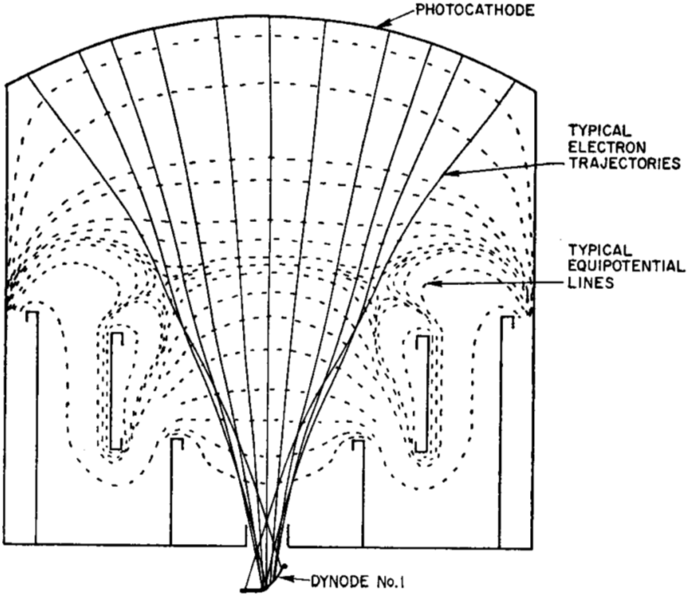
Quantum efficiency and spectral response

- Measures sensitivity of photocathode
- QE = (number of photoelectrons emitted) / (number of incident photons)
- Depends on photon wavelength

Quantum efficiency and spectral response



Focusing the electrons from photocathode towards the first dynode



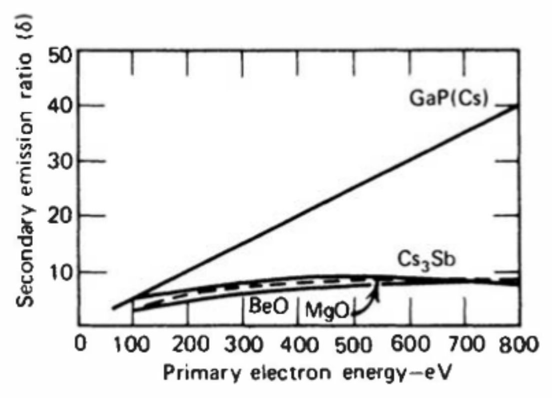
RCA Photomultiplier Manual. Technical Series PT-61, 1970

Electron multiplication

- Secondary electron emission
- Electron from photocathode accelerated towards the dynode
- Deposited energy cause re-emission of more secondary electrons
- Excited electrons within dynode, only some escape the surface
- Yield of secondary electrons is function of incident energy

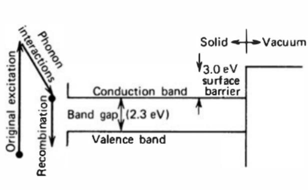
Secondary electron emission

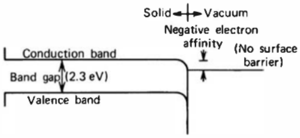
- At one dynode δ = (number of secondary electrons emitted) / (primary incident electrons)
- Depends on incident electron energy

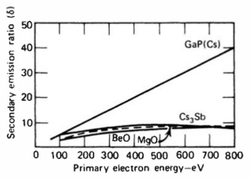


Negative electron affinity

- Used to increase of secondary emission yield
- Achieved by ionized acceptors by electrons from thin electropositive surface layer
- Band structure bent at the surface, electron at the bottom of conduction band may escape without further energy loss
- Secondary emission yield shows monotonic increase with incident electron energy







Multiple stage multiplication

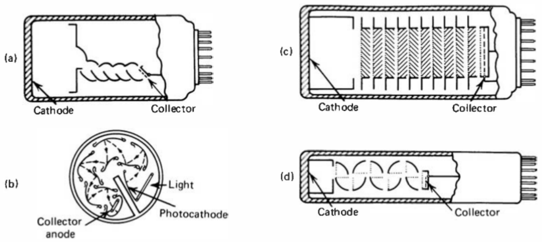
- Needed to achieve gain about 10^6
- Second dynode attact secondary electrons emitted at low energy by first dynode
- Can be repeated many times

$$\text{gain} = \alpha\delta^N \tag{1}$$

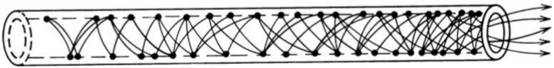
- Overall gain is function of voltage
- Statistical broadening of response by fluctuations in multiplication
- Variance dominated by multiplication factor at first dynode

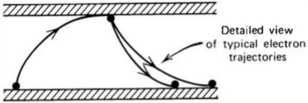
Structural differences of PM tubes

- Several configurations of photocathode and multiplier section

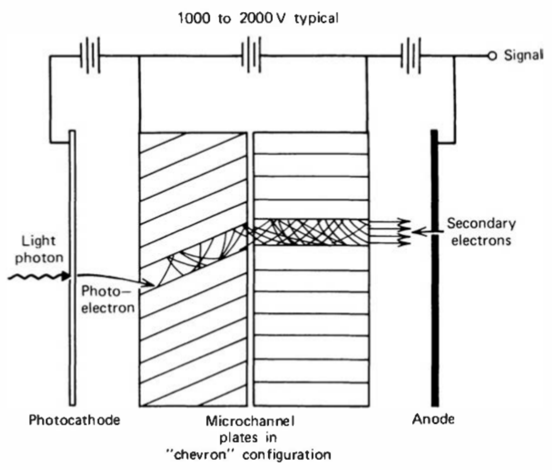


- Continuous channel electron multiplier (channeltron)



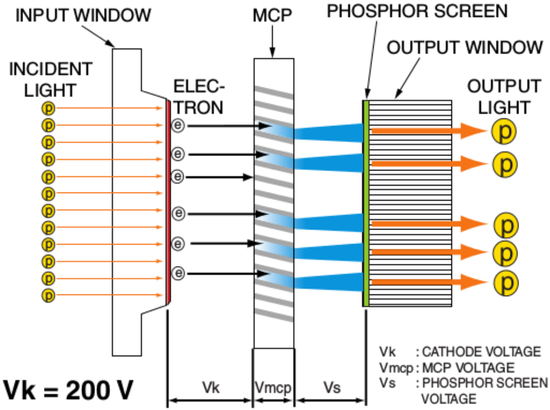


Microchannel plate



- Many individual tubes with small diameter
- Short electron transit time

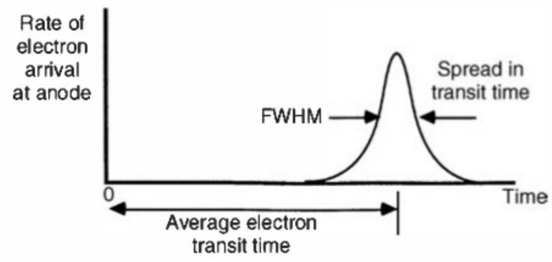
Microchannel plate (MCP) in image intensifier



Hamamatsu, Image intensifiers, TII 0004E02, SEPT. 2009 IP

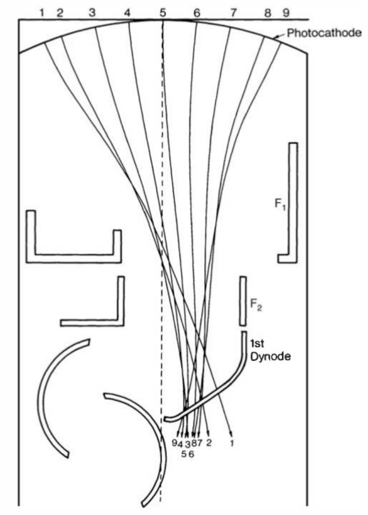
Pulse timing properties

- Time characteristics of PM given by electron trajectories
- Electron transit time is average time difference between arrival of photon at photocathode and collection of the pulse of electrons at anode
- Width of pulse given by spread in transit time



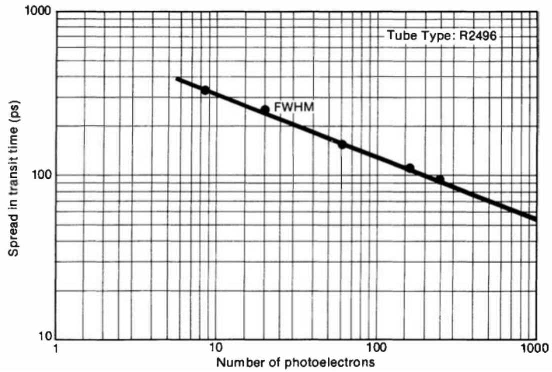
Pulse timing properties

- Difference in electron paths dominant in spread of transit time



Spread of transit time

- Measured spread as a function of average number of photoelectrons per pulse



Maximum ratings

- Maximal voltage and current ratings
- Voltage between anode and cathode + photocathode and first dynode, between dynodes and last dynode and anode
- Current limits for photocathode and anode, of no concern in scintillator pulse counting

Photomultiplier tube specifications

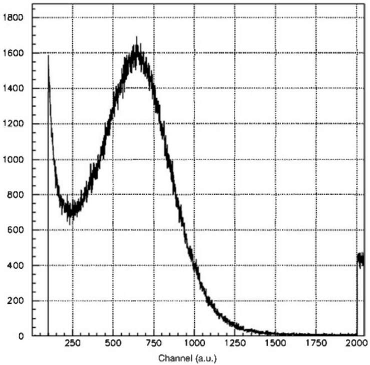
- Overall luminous sensitivity
- Cathode luminous sensitivity
- Overall radiant sensitivity
- Cathode radiant sensitivity
- Dark current
- Anode pulse rise time
- Anode pulse width

Linearity

- Electron multiplication factor independent of number of original photoelectrons
- Output pulse amplitude linearly proportional to intensity of scintillation light
- Nonlinearity can be caused by space charge between last dynode and anode
- Demands on PM by high light yield at fast decay time of new scintillators

Noise and spurious pulses

- Spontaneous termionic emission of electrons from photocathode
- Dark spectrum of pulses from single electron:



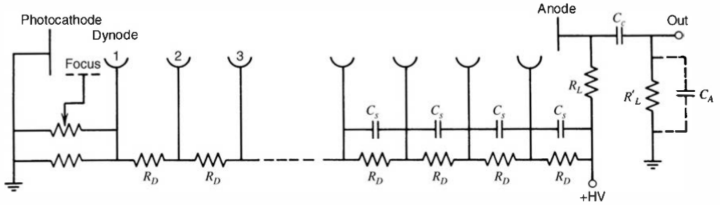
- Afterpulses from ionized residual gas drifting to photocathode

Non-ideality of PM

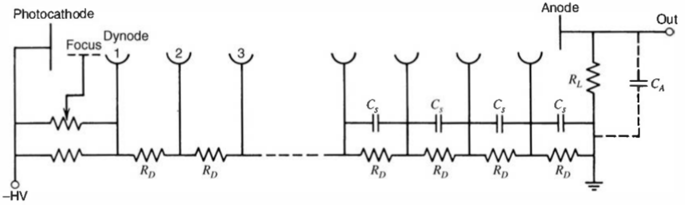
- Photocathode nonuniformities
- Change of gain during measurement
- Space charge and thermal effects

High voltage supply and voltage divider

- Positive polarity (a), negative polarity (b)
- Current through divider larger than internal current of PM



(a)



(b)

Photomultiplier summary

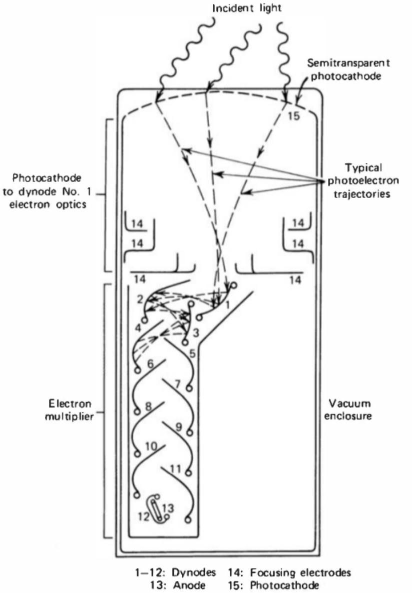
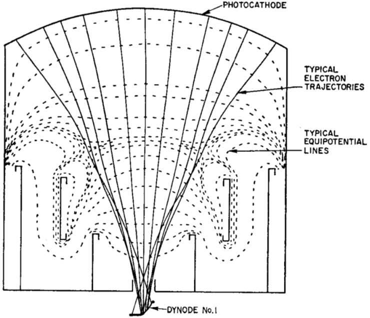


Figure : Typical structure



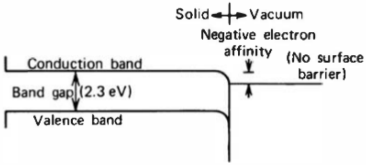


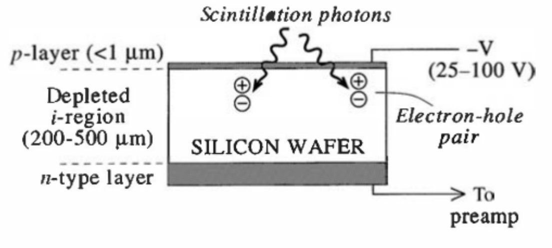
Figure : Region between photocathode and 1st dynode (up) and negative electron affinity (down)

Photodiodes

- Higher quantum efficiency, compact size
- Insensitive to magnetic field
- Conventional photodiode or avalanche photodiode

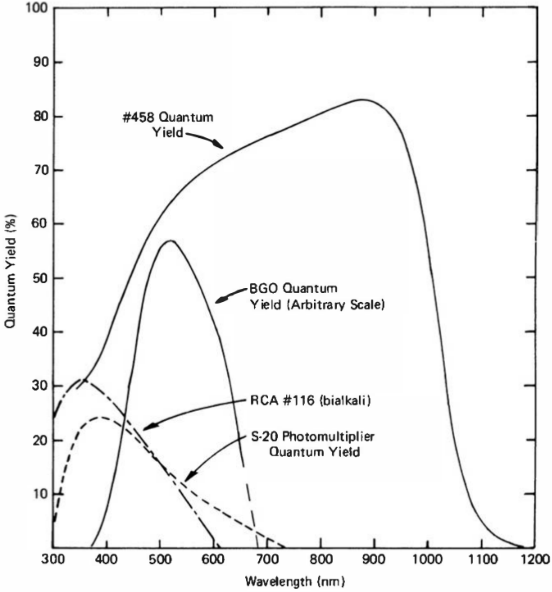
Conventional photodiodes

- High quantum efficiency over large range of incident wavelength
- No internal amplification, weak output pulses



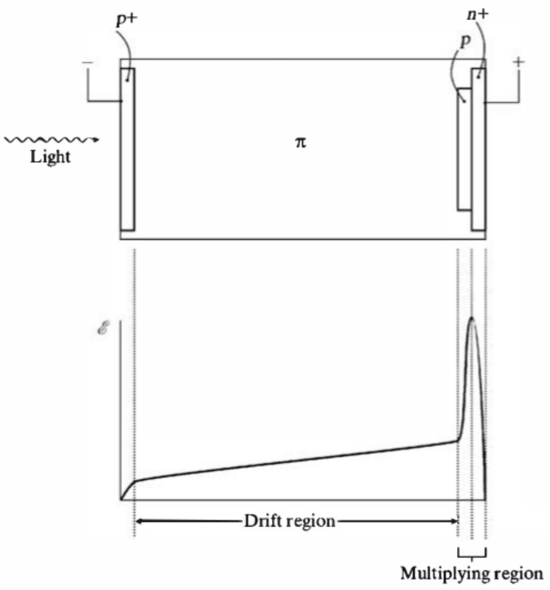
- Design as PIN detector

Spectral response of conventional photodiode



Avalanche photodiodes

- Charge multiplication in semiconductor

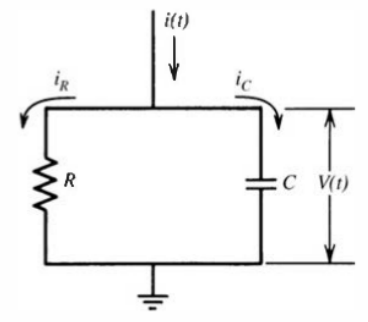


Silicon photomultiplier

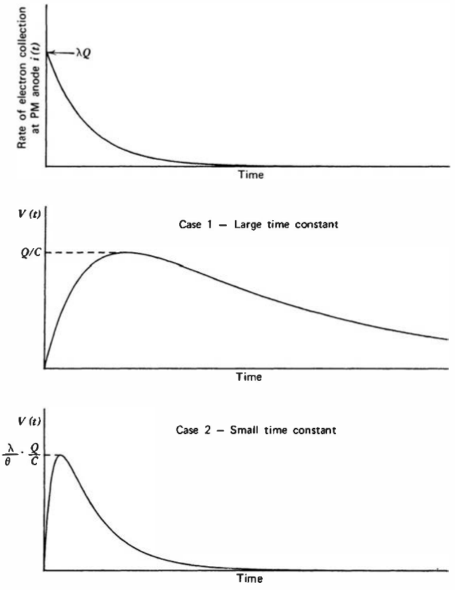
- Geiger mode of avalanche photodiode
- Single photon sensitivity
- Constructed as array of small cells
- Number of fired cells proportional to number of scintillation photons

Scintillation pulse shape analysis

- Given by time constant of anode circuit:

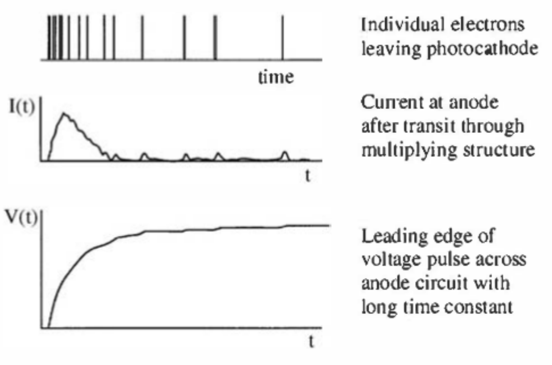


Effect of time constant



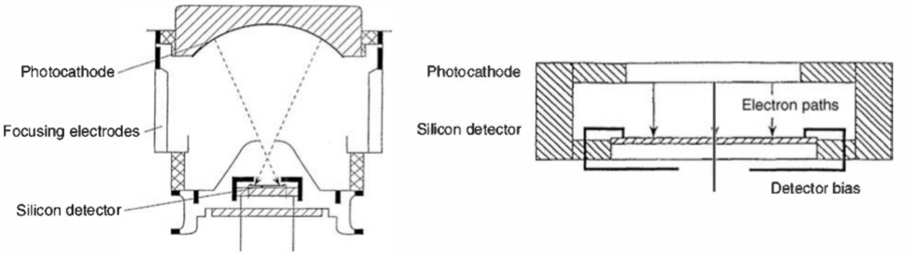
Fluctuations in pulse shape

- Short time constant sensitive to fluctuations



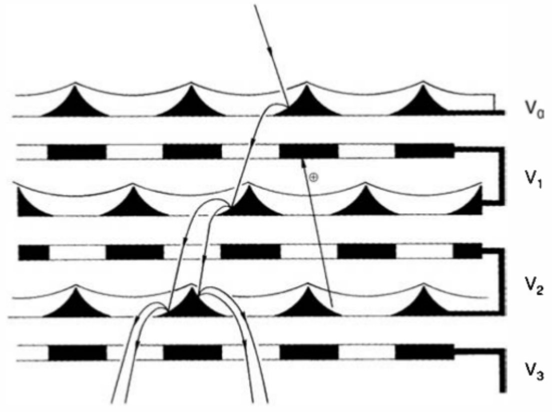
Hybrid photomultiplier tube

- Electrons emitted by photocathode detected by silicon detector

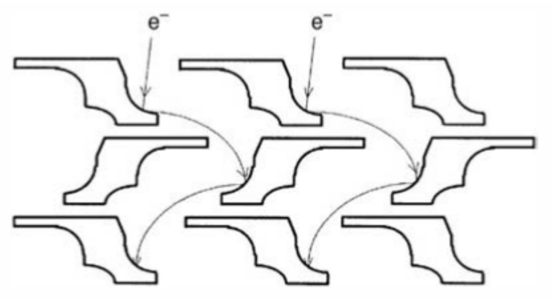


(a) (b)

Position sensing photomultiplier tubes



Metal channel dynode structure



Anode wire readout

- Reduction of readout channels by charge division