Detekcija svetlobe

1) Fotopomnoževalke (klasične)
2) Večanodne fotopomnoževalke in mikrokanalne plošče
3) Fotodiode
4) Plinski detektorji svetlobe

1) Fotopomnoževalka

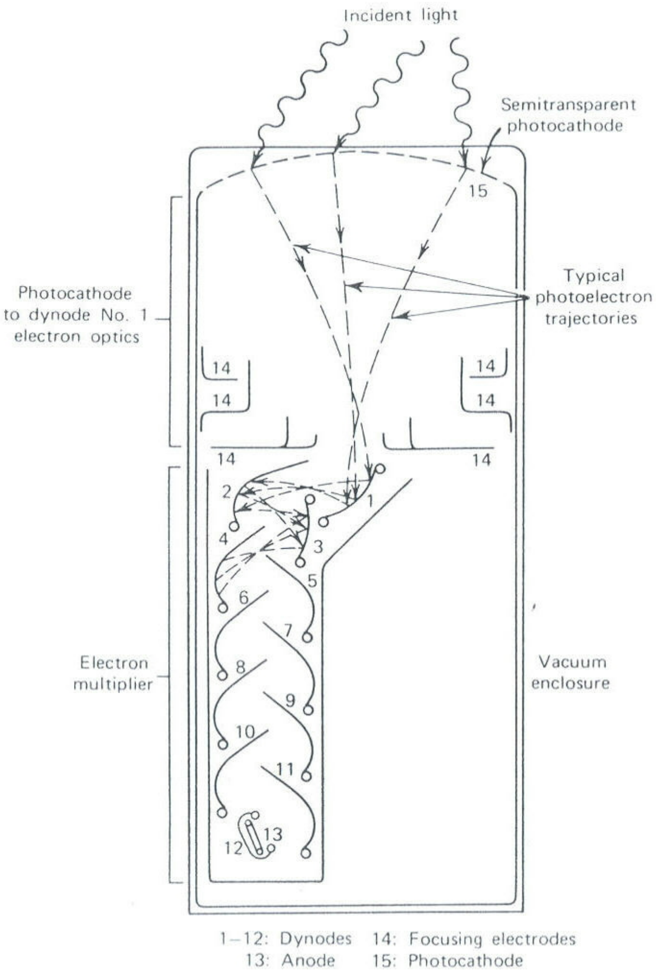
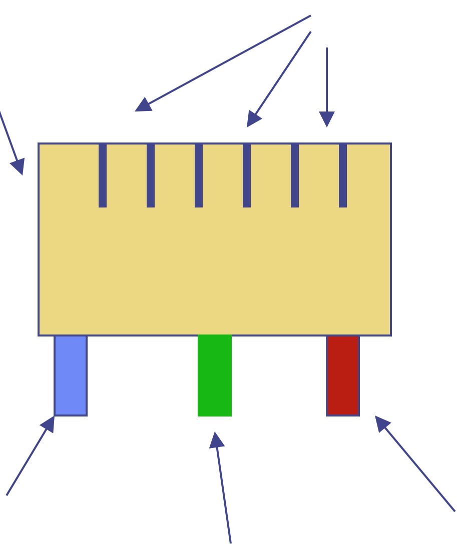


Figure 9-1 Basic elements of a PM tube. (From Ref. 1.)

+



BAZA

(uporovna veriga etc)

kontakti za fotokatodo in dinode

anodni signal

zadnja dinoda

visoka napetost

1) meritev sunkov
2) meritev toka

Fotokatode

- Fotoefekt : $E_e = h\nu - \Phi$

maksimalna energija elektrona

energija fotona

izstopno delo (energija praga)

- kvantni izkoristek (Quantum Efficiency)

$$\eta(\lambda) = \frac{\text{število fotoelektronov iz katode}}{\text{število vpadnih fotonov}}$$

ali sevalna občutljivost katode $E(\lambda) = \dfrac{I_k}{P(\lambda)}$

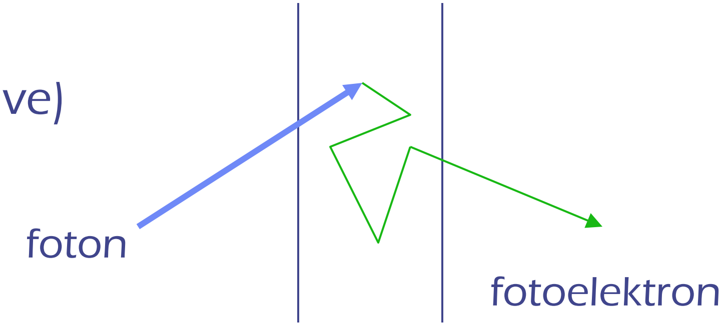
I_k ← tok fotoelektronov iz katode (A)

$P(\lambda)$ ← vpadna sevalna moč (W)

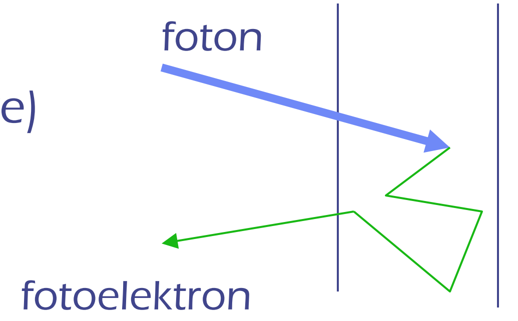
$$\eta(\lambda) = \frac{I_k/e_o}{P(\lambda)/h\nu} = \frac{hc}{\lambda e_0} E(\lambda)$$

fotokatode

prozorne (transmissive)



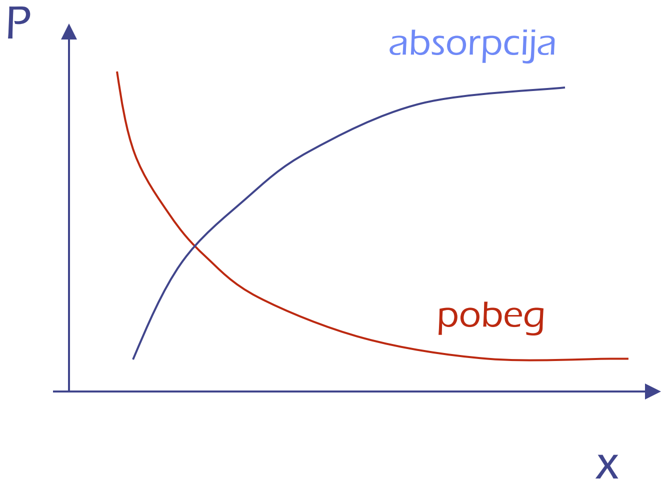
odbojne (reflective)



<u>Kvantni izkoristek je produkt</u> :

- verjetnosti za transmisijo skozi vstopno okno
- verjetnosti za absorpcijo in fotoefekt
- verjetnosti za izstop fotoelektrona iz katode

⇒ obstaja optimalna debelina fotokatode



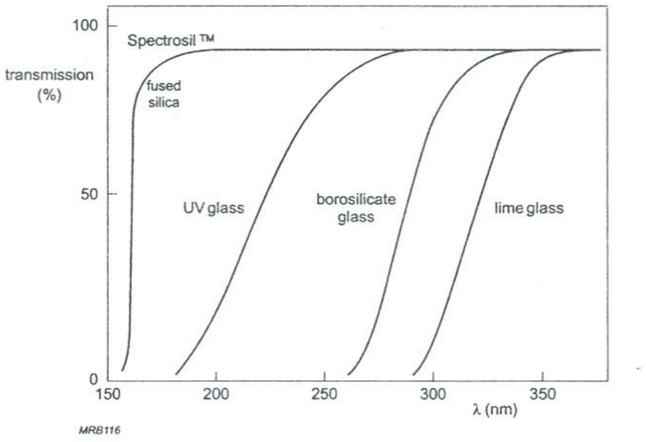


Fig.1.5 Transmission (%) as a function of wavelength λ for various glasses used in photomultiplier input windows (thickness 3 mm)

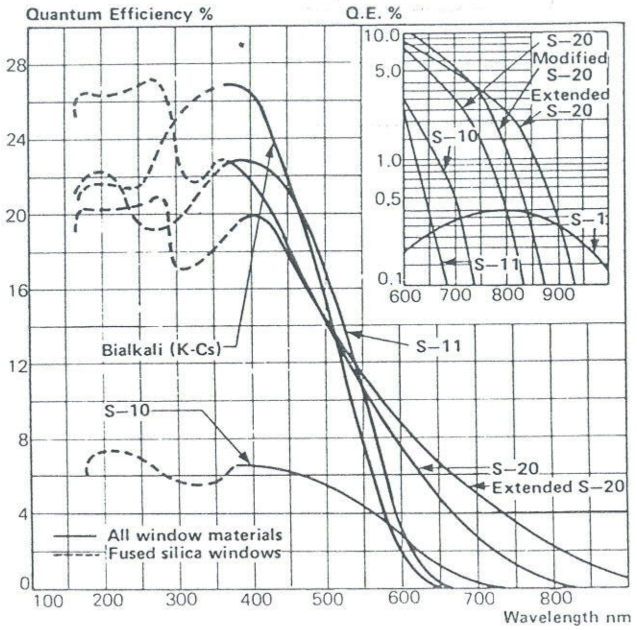
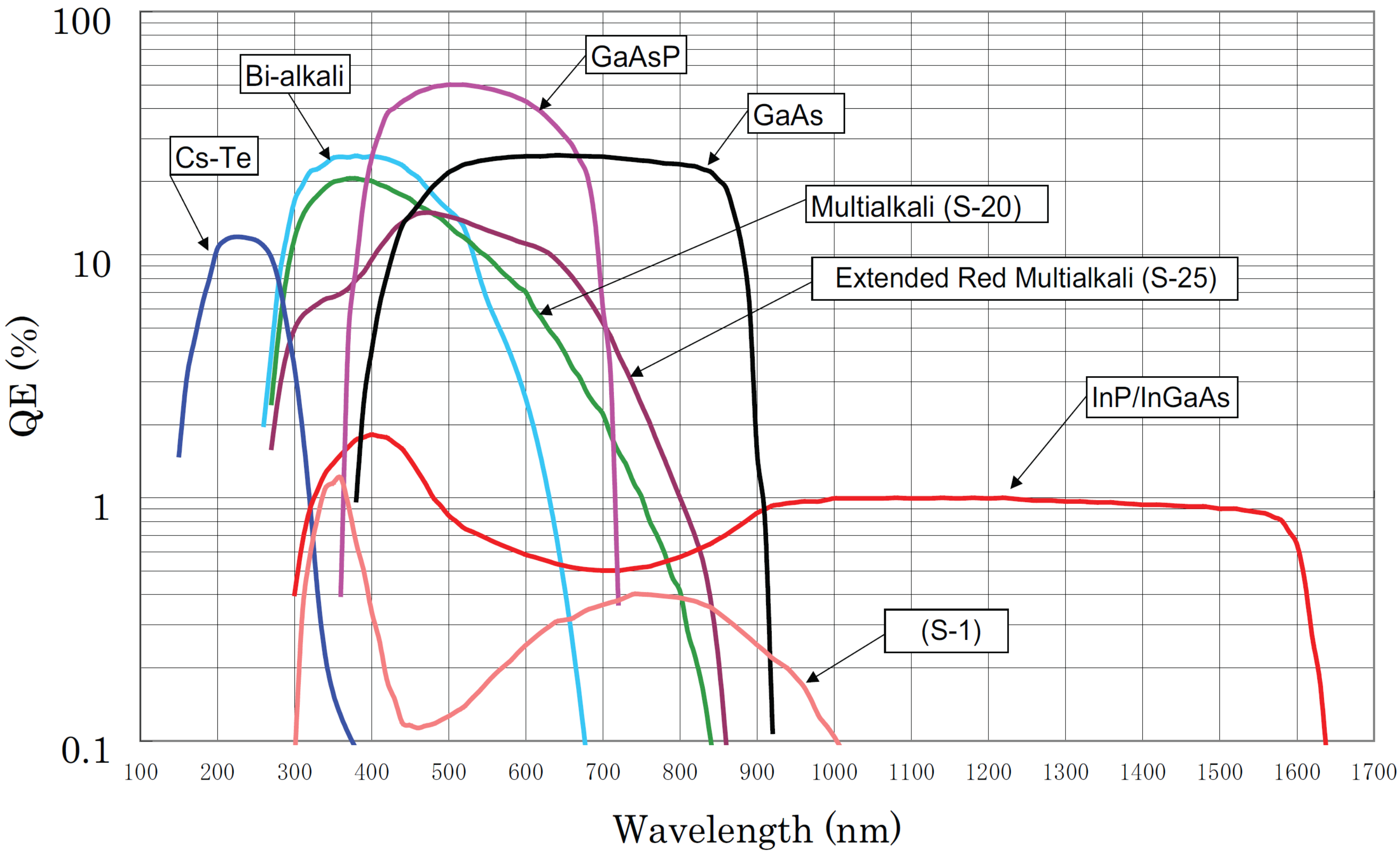


Fig. 8.2. Quantum efficiency of various photocathode materials (from *EMI Catalog* [8.2])

Table 8.1. Photocathode characteristics (from RTC catalog [8.3])

Cathode type	Composition	λ at peak response [nm]	Quantum efficiency at peak
S1 (C)	Ag – O – Cs	800	0.36
S4	SbCs	400	16
S11 (A)	SbCs	440	17
Super A	SbCs	440	22
S13 (U)	SbCs	440	17
S20 (T)	SbNa – KCs	420	20
S20R	SbNa – KCs	550	8
TU	SbNa – KCs	420	20
Bialkali	SbRb – Cs	420	26
Bialkali D	Sb – K – Cs	400	26
Bialkali DU	Sb – K – Cs	400	26
SB	Cs – Te	235	10

Quantum efficiency



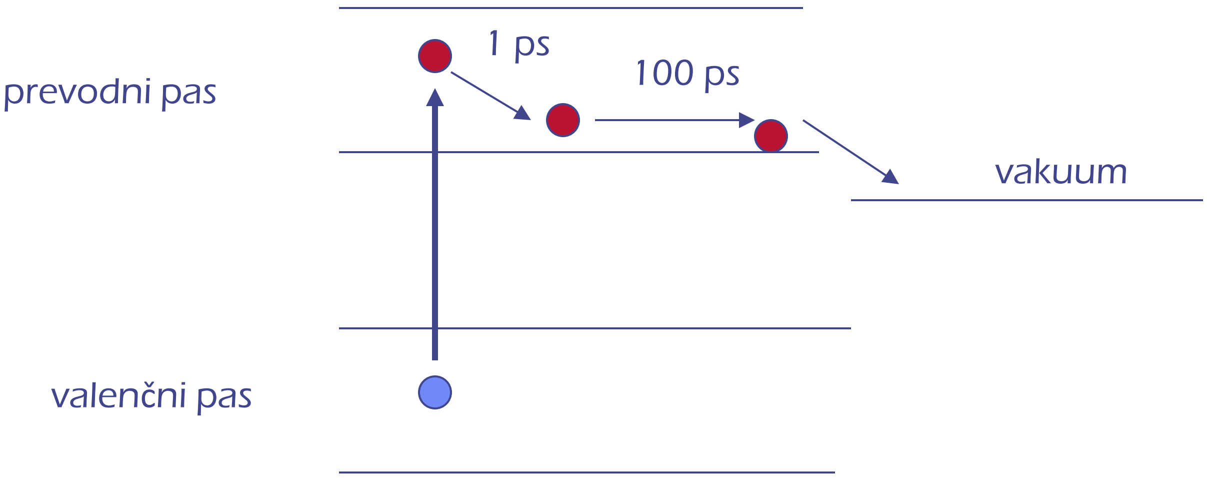
večinoma so fotokatode polprevodniki

antimon (Sb) + alkalne kovine (K, Cs, Rb, Na …)

- zaradi zasedenosti stanj v polprevodniku izgublja fotoelektron manj energije pri trkih z ostalimi elektroni in zato lažje pride do površine (vezani elektroni imajo veliko maso, zato je manj izgube energije), η = 10 – 30 %.

- v kovinah so velike izgube zaradi trkov s prostimi elektroni ($\eta \approx 0.1$ %) .

- galijev fosfid (GaP), dopiran z Zn+Cs, ima negativno "elektronsko afiniteto" (negative electron afinity) za elektron v prevodnem pasu, $\eta \approx 80$ %.



Sistem zbiranja fotoelektronov

- večinoma uporabljajo električno polje med fotokatodo in prvo dinodo (ponekod tudi magnetno polje)

Zahteve:

- velik izkoristek zbiranja fotoelektronov (različne poti, izstopne energije in različne smeri).

- izkoristek naj bo čimmanj odvisen od mesta nastanka QE(r)

- čas potovanja od fotokatode do prve dinode naj bo čimmanj odvisen od mesta nastanka, ker to prispeva k časovni ločljivosti ($\Delta t \approx 0.3$ ns)

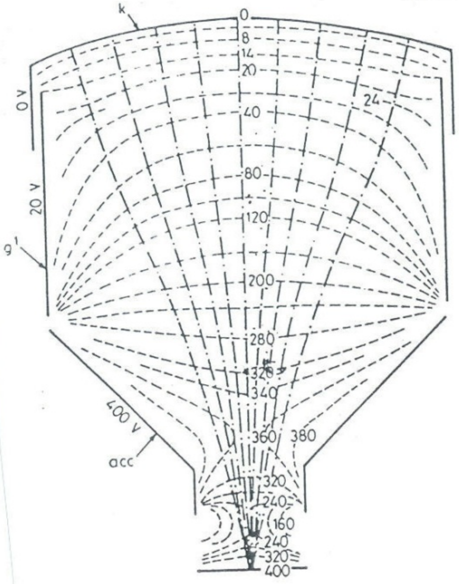


Fig. 8.15. Equipotential lines in the ele
tron-optical input system of a fast phot
multiplier (from *Hull* [8.9])

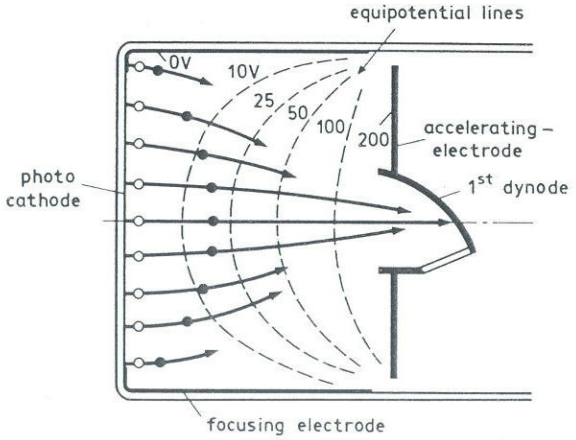


Fig. 8.14. Transit time difference (from *Schonkeren* [8.1])

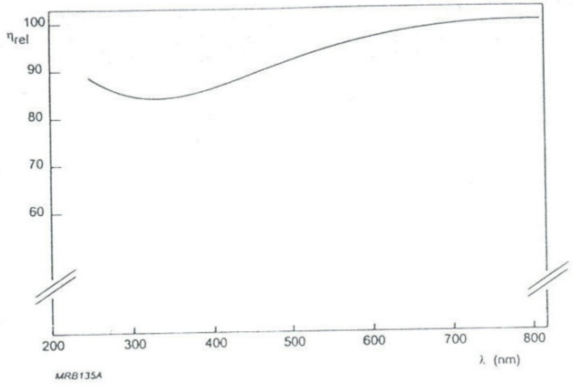
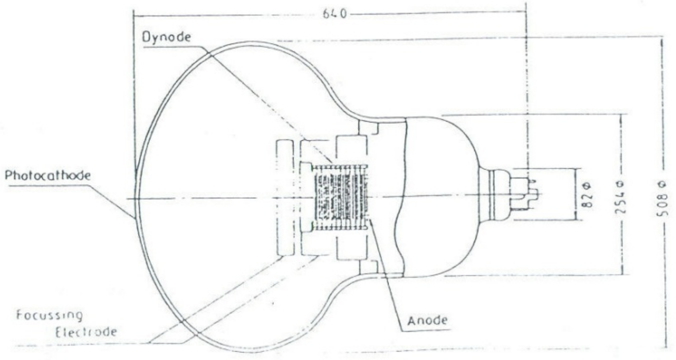


Fig.2.2 Example of relative input system collection efficiency as a function of wavelength

Fig. 4.2. Section through photomultiplier tube R 1449 with a spherical photocathode of 508 mm diameter [KU 83].



Pomnoževalni sistem (dinode)

- sekunadarna emisija na dinodah, $\delta \approx 3\text{-}5$
- dinode iz polprevodnikov in izolatorjev (isti razlog kot za fotokatode)
- polprevodnik na prevodni podlagi, ker potrebujemo E za pospeševanje
- lahko tudi zlitina (Ag-Mg, Cu-Be, Cs-Sb).

  Alkalna kovina na površini oksidira in tvori izolatorsko plast.

Zahteve:

- _veliko pomnoževanje, faktor sekundarne emisije δ
- stabilnost pri velikih tokovih
- nizka termična emisija (šum)

- 10-14 dinod → G = 10^7-10^8
- GaP dinode → 5 dinod → isti G

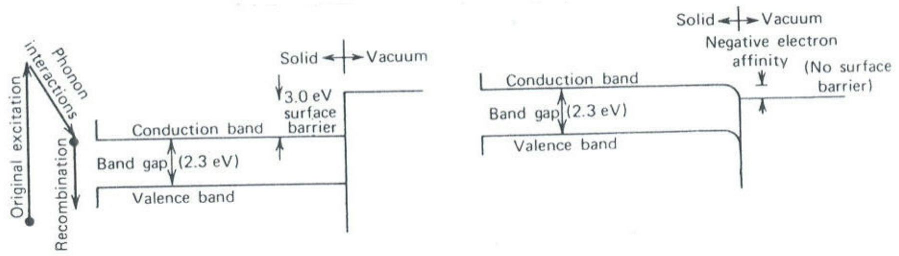


Figure 9-4 Band structure near the surface for conventional semiconductors (left) and NEA materials (right). (Adapted from Krall et al.[7])

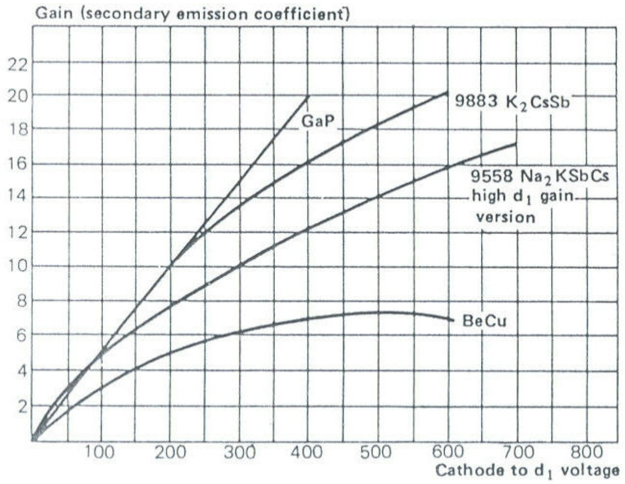


Fig. 8.9. Secondary emission factor for several dynode materials (from *EMI Catalog* [8.2])

konfiguracija dinod

Linear focused

circular

“venetian blind”

“box grid”

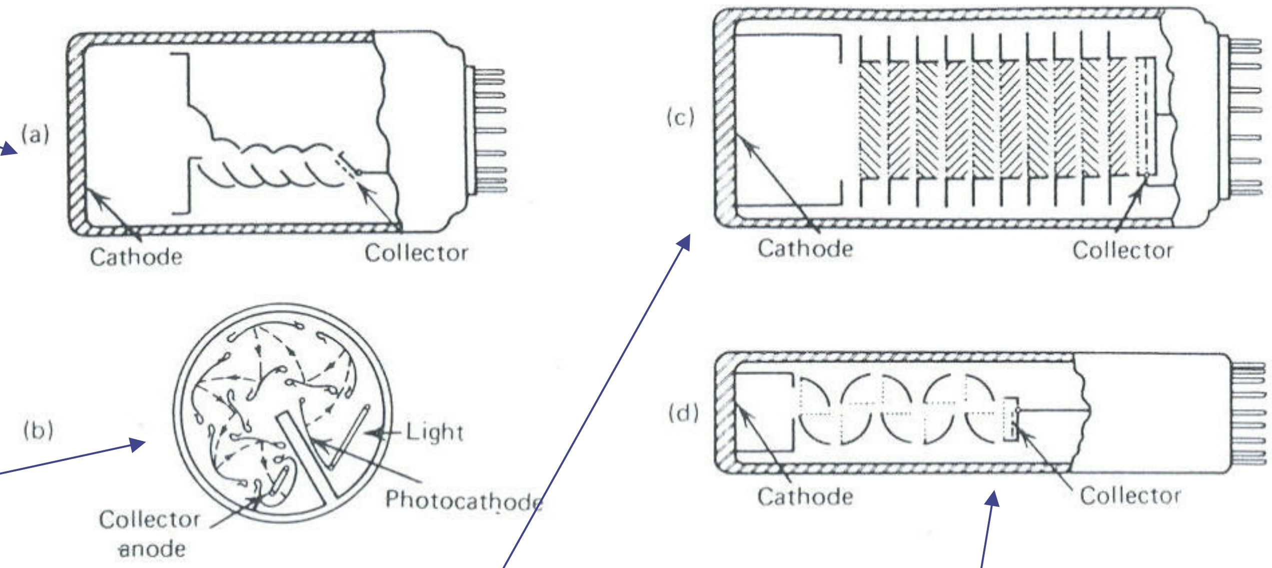


Figure 9-7 Configurations of some common types of PM tubes. (a) Focused linear structure. (b) Circular grid. (c) Venetian blind. (d) Box-and-grid. (Courtesy of EMI GENCOM Inc., Plainview, NY.)

Delilniki napetosti

- napetost na dinodah vzdržujemo z uporovno verigo skozi katero teče tok I_R
- med fotokatodo in elektrodo za fokusiranje je potenciometer za optimizacijo zbiranja
- anodni tok I_a vpliva na spremembo dinodne napetosti in s tem ojačenja G:

$$\Delta G/G \approx I_a/I_R \quad \Longrightarrow \quad I_a \approx I_R/100 \text{ za } \Delta G/G \approx 1\%$$

- zadnje dinode opremimo s kondenzatorji, v katerih je shranjen naboj za tokovni sunek ali z Zener diodami, ki vzdržujejo napetost.
- napetost na fotokatodi
  - -anoda ozemljena
  - - puščanje toka skozi steklo na ozemljene dele (baza,scintilator) (elektroluminesc.)
  - - ni potreben sklopitveni kondenzator
  - - uporabno za hitre pulze, timing
- variacije VN se preko kondenzatorja prenašajo na izhod v primeru, da je anoda na visoki napetosti in katoda ozemljena

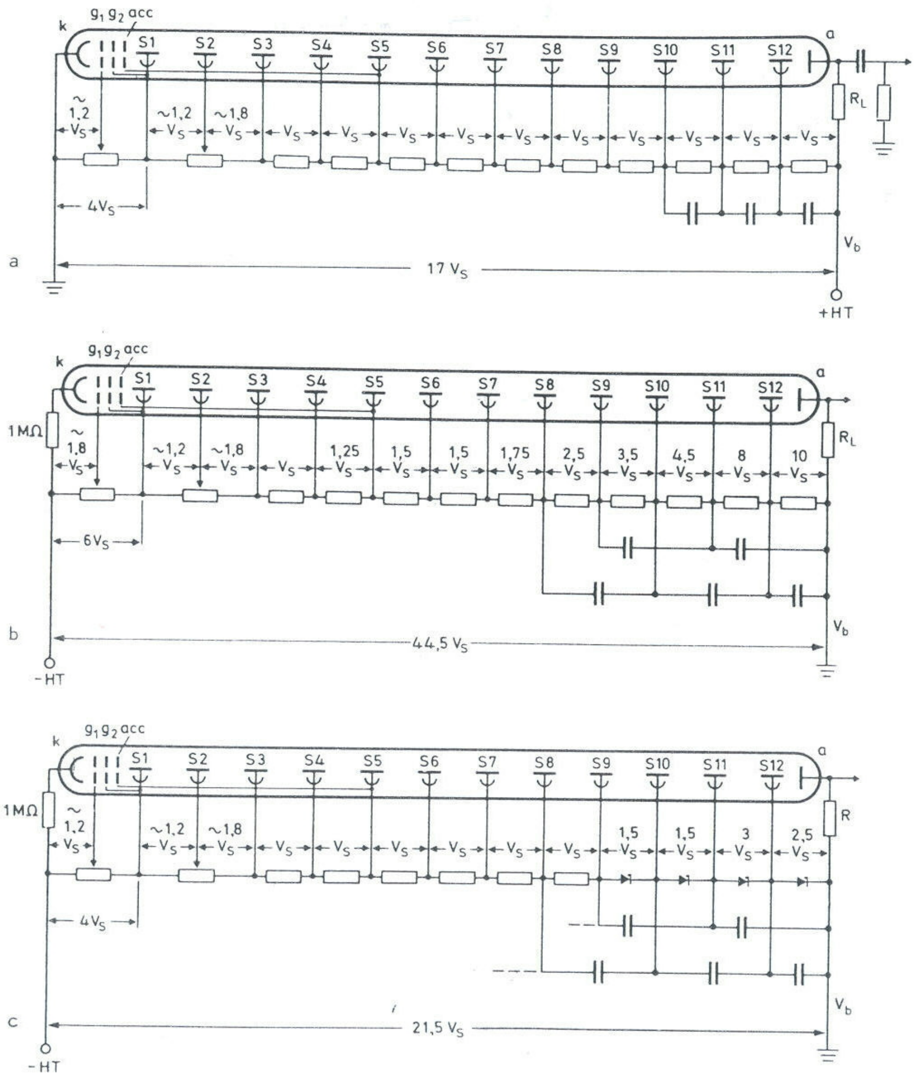


Fig. 8.10 a – c. Examples of PM voltage divider networks (after examples from *Philips Catalog* [8.7]: (**a**) divider network using positive high voltage; note the AC coupling capacitor at the anode, (**b**) a network using negative high voltage and decoupling capacitors for maintaining the voltages between the last few dynodes, (**c**) example of the use of zener diodes to maintain voltages on the last few dynodes

Visoka napetost

G...pomnoževalni faktor FP
δ...faktor sekundarne emisije
n...število dinod
U_d..napetost med dinodama
U...celotna napetost na FP

Približno velja:

$G = \delta^n$ $\delta = k\, U_d$ in $U = n\, U_d$

Odtod sledi:

$G \approx k^n\, U^n / n^n$ in $dG/G \approx n\, dU/U$

Pri $n=10$ in $dU/U \approx 0.1\ \%$

dobimo $dG/G \approx 1\ \%$,

torej potrebujemo
stabilizirano napetost.

Porazdelitev višin signalov enega fotoelektrona

Variacija pomnoževanja:

- statistična narava sekundarne emisije
- variacija sekundarne emisije po površini dinode
- različne energije fotoelektrona
- različni koti izstopa iz fotokatode

Meritev:

a) šibka osvetlitev in
b) integracija izhodnega signala (meritev naboja)

Porazdelitev Polya približno opiše spekter enega fotoelektrona.

$$P(q) = \frac{1+\Theta}{q_{av}\,\Gamma(1+\Theta)} \left[\frac{(1+\Theta)q}{q_{av}} \right]^{\Theta} \exp - \left[(1+\Theta)q/q_{av} \right]$$

$\Theta = 0.113\, q_{av} - 0.095$, q_{av} (fC)

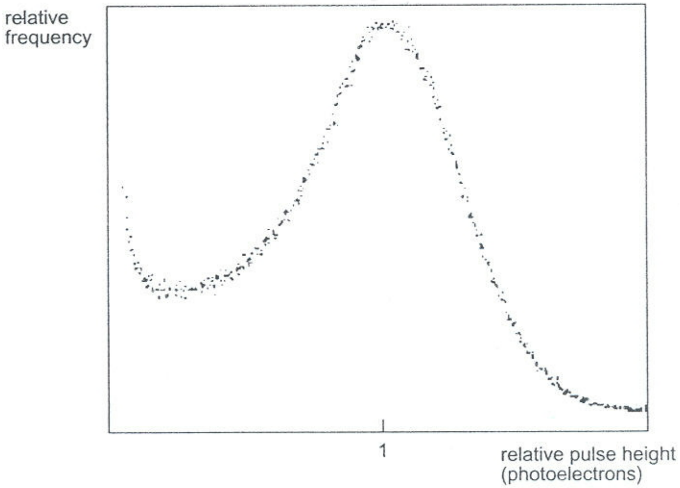


Fig.2.4 Typical single-electron spectrum. Resolution 67% FWHM.
Peak-to-valley ratio 2.8:1

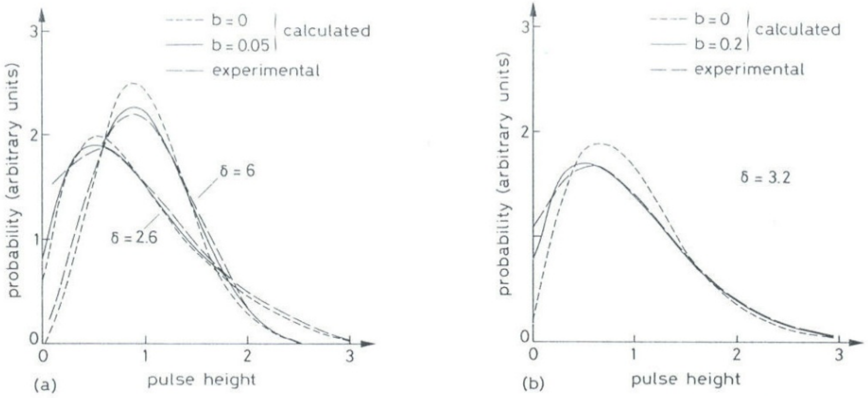


Fig. 8.8. Single-electron spectra for **(a)** linear-focused PM, **(b)** venetian blind PM (from *Schonkeren* [8.1])

- enaka porazdelitev v VŽPK

- konvolucija za več fotoelektronov

$$\sigma_N/N \approx \sigma_1/(N_{f.e.})^{1/2}$$

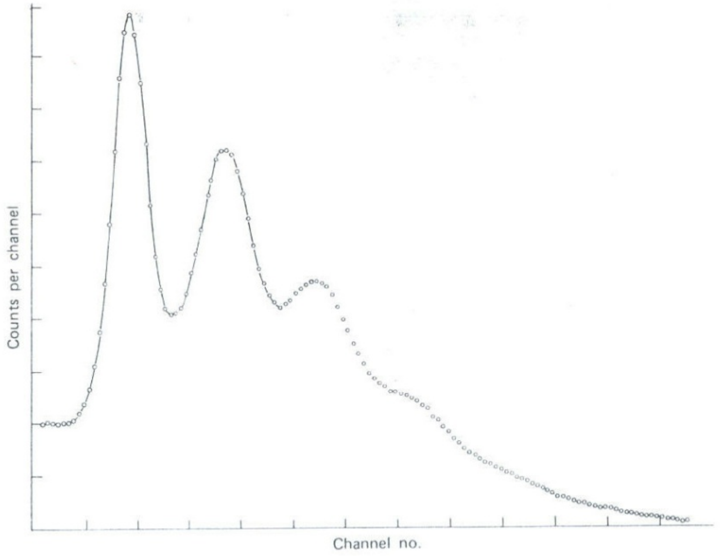


Figure 9-6 The measured pulse height spectrum for weak scintillation events obtained from a RCA 8850 photomultiplier tube. The high-gain first dynode results in distinguishable peaks in the spectrum corresponding to 1, 2, and 3 photoelectrons per pulse. (From Houtermans.[12])

Šum fotopomnoževalke

(temni tok = enolelektronski sunki)

1) termična emisija iz katode in dinod
(največji prispevek)

$I \propto T^2 \exp(-e\phi/kT)$, Richardson

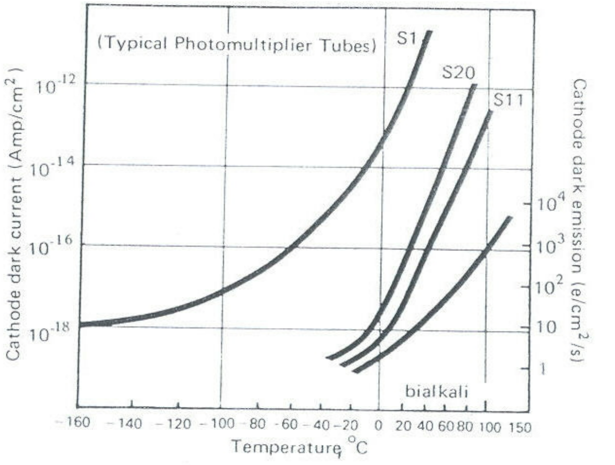


Fig. 8.19. Dark noise vs. temperature for various photocathodes (from *Wardle* [8.10])

2) tok iz kontaktov na bazi ("leakage")

3) radioaktivna kontaminacija fotopomnoževalke lahko direktno izbije elektrone iz dinod ali povzroči fluorescenco v steklu.

"afterpulsing"

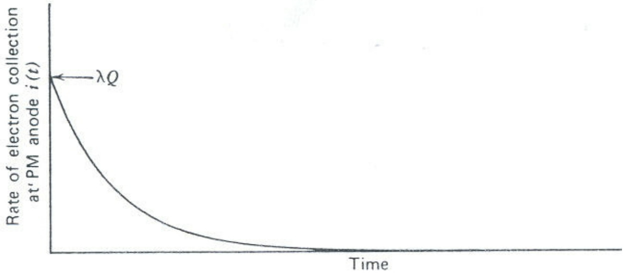
- Ionizacija residualnega plina v FP. Ioni se vrnejo na katodo, kjer izbijejo nov fotoelektron: $\Delta t \approx 100$ ns – 1 μs

- "electrode glow": zadnje dinode lahko sevajo svetlobo, ki pride do fotokatode in izbije nov fotoelektron; $\Delta t \approx 30$-60 ns.

Oblika sunkov

Fotopomnoževalka je tokovni generator

$I(t)=(GNe_0/\tau_s)\exp(-t/\tau_s)$, $GNe_0 = Q$



N…število fotoelektronov
G…pomnoževalni faktor
Q…naboj v sunku
τ_s …razpadni čas vzb. stanj v scintilatorju

R in C … upornost in kapaciteta anode vključno z izhodno upornostjo in kapaciteto kablov.

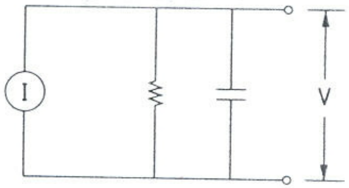


Fig. 8.12. Equivalent circuit for a photomultiplier. The PMT may be considered as an ideal current generator in parallel with a certain resistance and capacitance

Enačba:

$I = U/R + C\, dU/dt$

Rešitev:

$$U(t) = -(Q/C)\,[RC/(RC-\tau_s)]\,[\exp(-t/\tau_s) - \exp(-t/RC)]$$

Če $RC \gg \tau_s$ (voltage mode)

Napetostni signal je integral naboja.

Velik in dolg signal.

$t_r = \tau_s$, $t_d = RC$, $U_{max} = Q/C$

Če $RC \ll \tau_s$ (current mode)

Napetostni signal sledi scintilatorju.

Kratek in majhen signal.

$t_r = RC$, $t_d = \tau_s$, $U_{max} = (Q/C)(RC/\tau_s)$

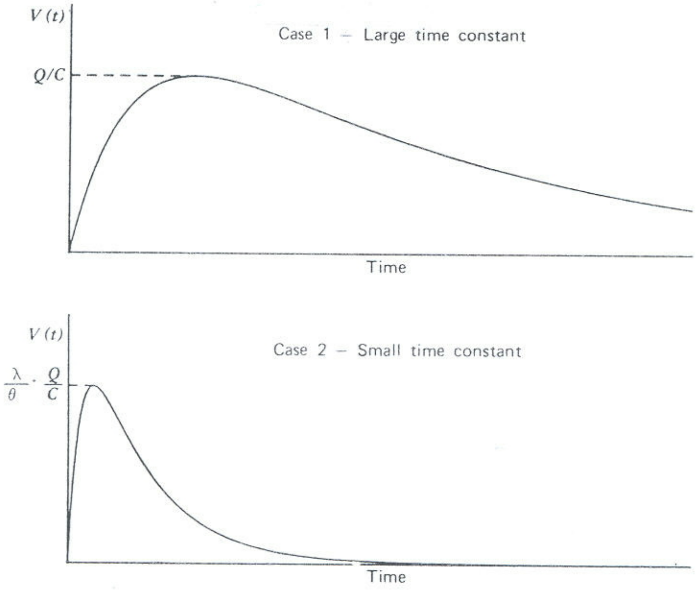


Figure 9-17 For the assumed exponential light pulse shown at the top, plots are given of the anode pulse $V(t)$ for the two extremes of large and small anode time constant. The duration of the pulse is shorter for Case 2, but the maximum amplitude is much smaller.

Časovna ločljivost

- Če za dogodek (absorpcija delca v scintilatorju) dobimo le en fotoelektron, bo časovna ločljivost določena s τ_s .

- Poleg τ_s vplivajo na časovno ločljivost še:
  1) razlike v času potovanja fotonov do fotokatode in
  2) razlike časov potovanja fotoelektronov od katode do prve dinode
     (geometrijske razlike poti in razlike začetnih hitrosti, $\Delta t \approx 0.2\text{-}0.5$ ns)

Za dobro časovno ločljivost želimo:
- hiter scintilator (majhen τ_s)
- velik pridelek
- dobro fotopomnoževalko (velik QE in hitra FP)

Zunanji vplivi

1) Osvetlitev fotopomnoževalke
   - pod napetostjo uniči FP ali v najboljšem primeru poveča temni tok
   - osvetlitev brez napetosti poveča šum, ki pa se s časom zmanjša

2) Magnetno polje (slike)
   - spremeni elektronske kaskade in zmanjša velikost signala
   - najbolj občutljiv del je zbiralni sistem of fotokatode do prve dinode
   - zaščita z μ-metalom in mehkim Fe
   - nove FP z "proximity focusing" so manj občutljive na B

3) Temperatura
   - poveča termični šum
   - QE je lahko odvisen od T (-0.5 %/^{0}C)

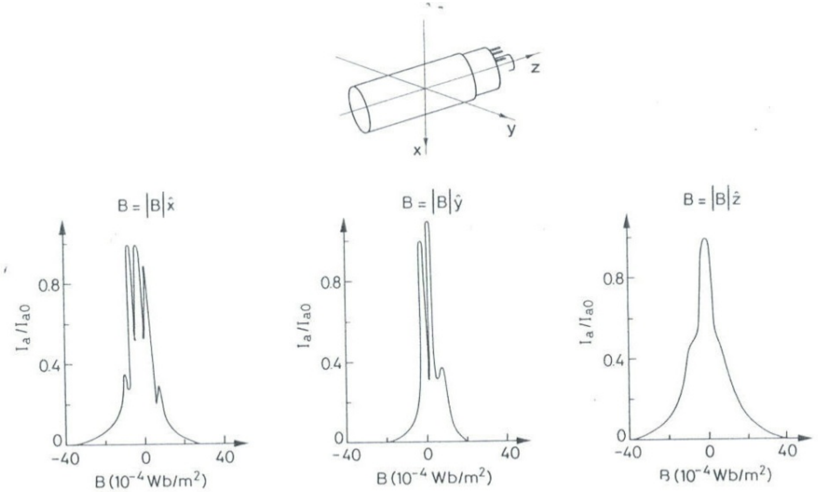


Fig. 8.17. Effect of magnetic fields on the anode current of an unscreened PM for different field orientations (from *Schonkeren* [8.1])

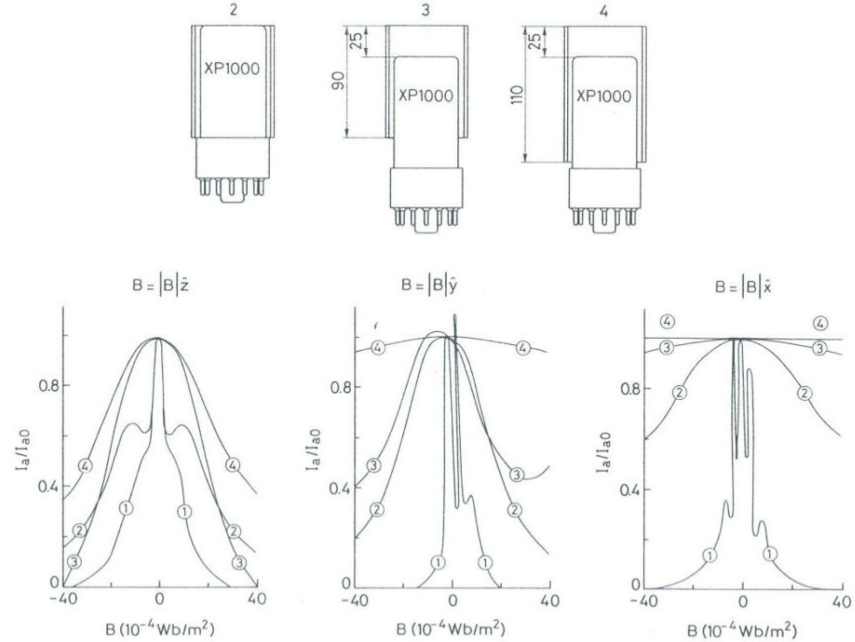


Fig. 8.18. Shielding effect of different mu-metal configurations (from *Schonkeren* [8.1])

2) Večanodne fotopomnoževalke in mikrokanalne plošče

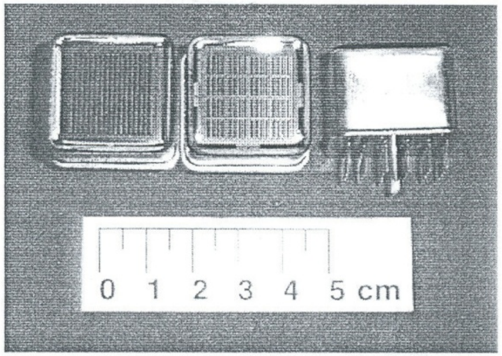
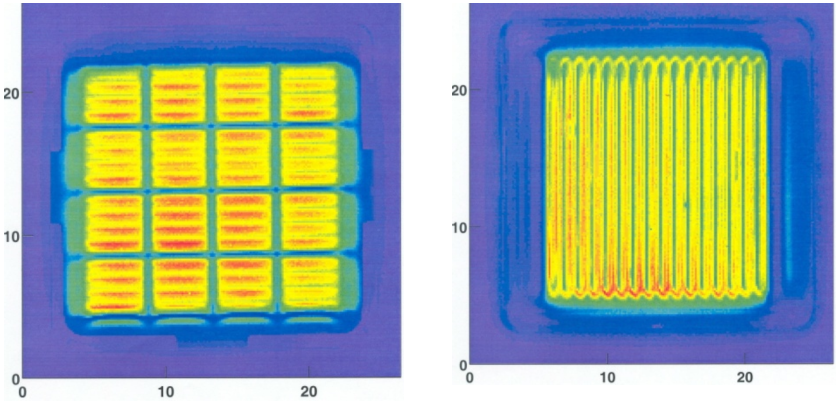
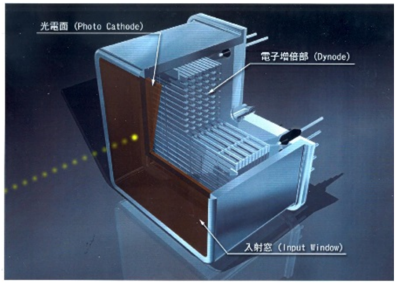


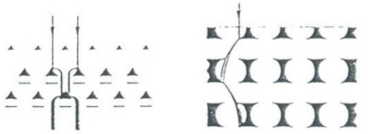
FIGURE 2. Hamamatsu multianode photomultipliers (L16, M16, M16 from left to right).



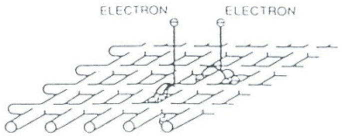


POSITION SENSITIVE PMT'S - EXAMPLES

Philips mesh
and foil types



Hamamatsu
fine mesh



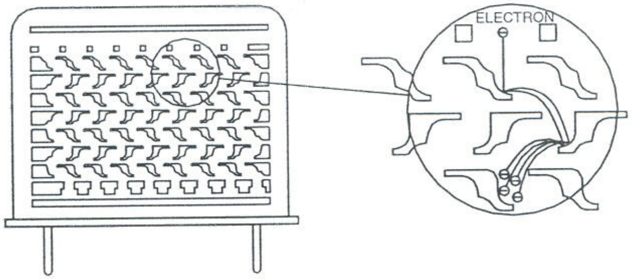


FIGURE 4. Metal channel type PMT [8].

Mikrokanalne plošče

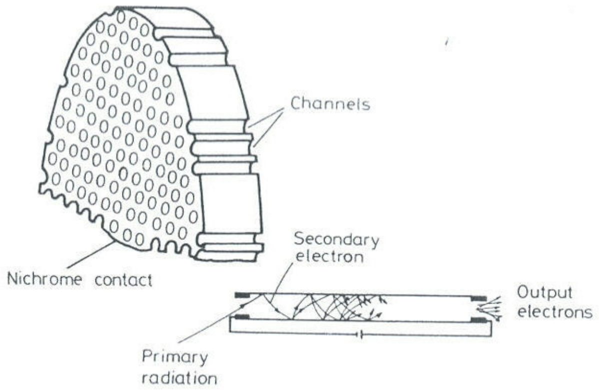


Fig. 8.6. Schematic diagram of a microchannel plate. The many channels act as continuous dynodes (from *Dhawan* [8.4]; picture © 1975 IEEE)

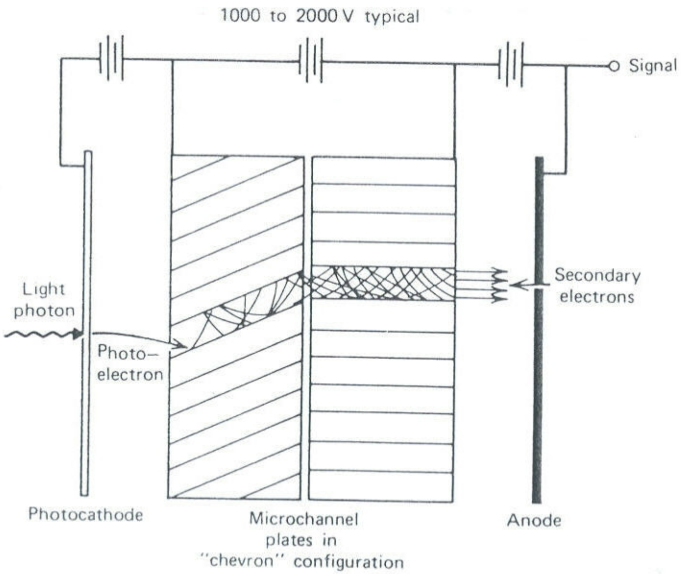


Figure 9-9 Elements of a PM tube based on microchannel plate electron multiplication.

- premer kanala 10-100 μm
- dolžina kanala $\approx$ 1mm
- površina plošče 10-50 cm^2
- ojačenje G $\approx$ 10^5-10^7 ("chevron")
- časovna ločljivost <100 ps
- pozicijska občutljivost
- kanal 25 μm: do B$\approx$0.8T
- kanal 10 μm: do B$\approx$1.5T

3) Polprevodniški senzorji

Fotodiode (PD)

- velik kvantni izkoristek (tudi v IR področju),
- ni ojačanja
- uporabno v primerih, ko je veliko svetlobe (recimo v fiziki delcev za kalorimetrijo)

Plazovne fotodiode (avalanche photodiodes, APD)

- veliko E povzroči pomnoževanje v plazu, $G \approx 10^2$-10^3.
- razmerje šum/signal je več redov velikosti slabše kot pri FP,
- šum ≈ 0.4 nA/mm^2
- uporaba v fiziki delcev za kalorimetrijo

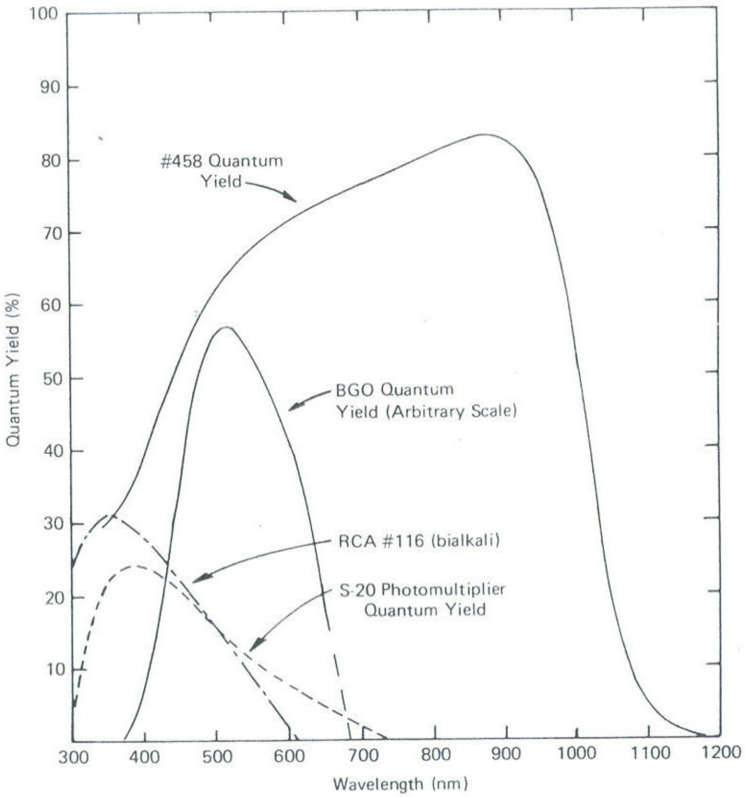
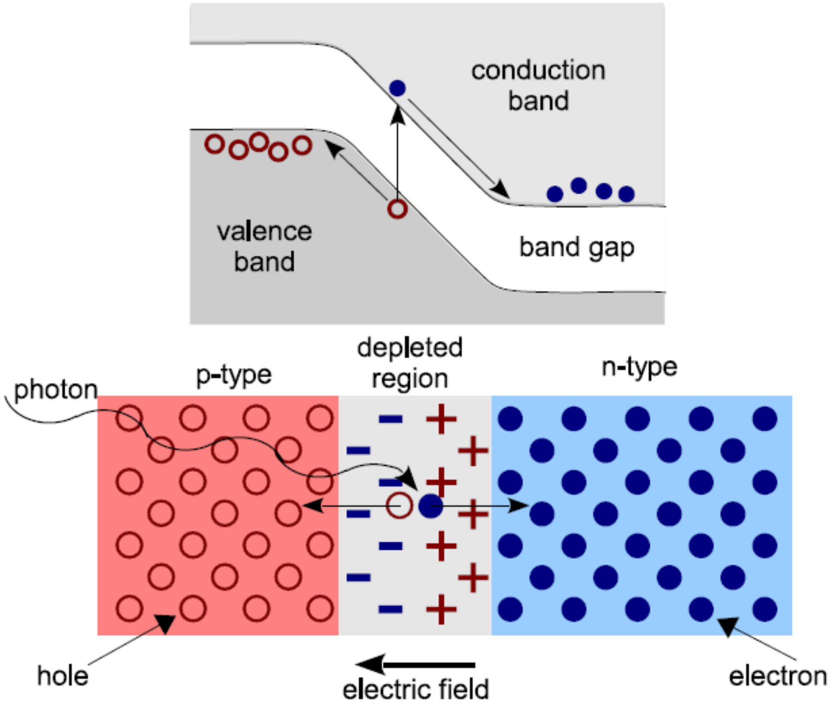
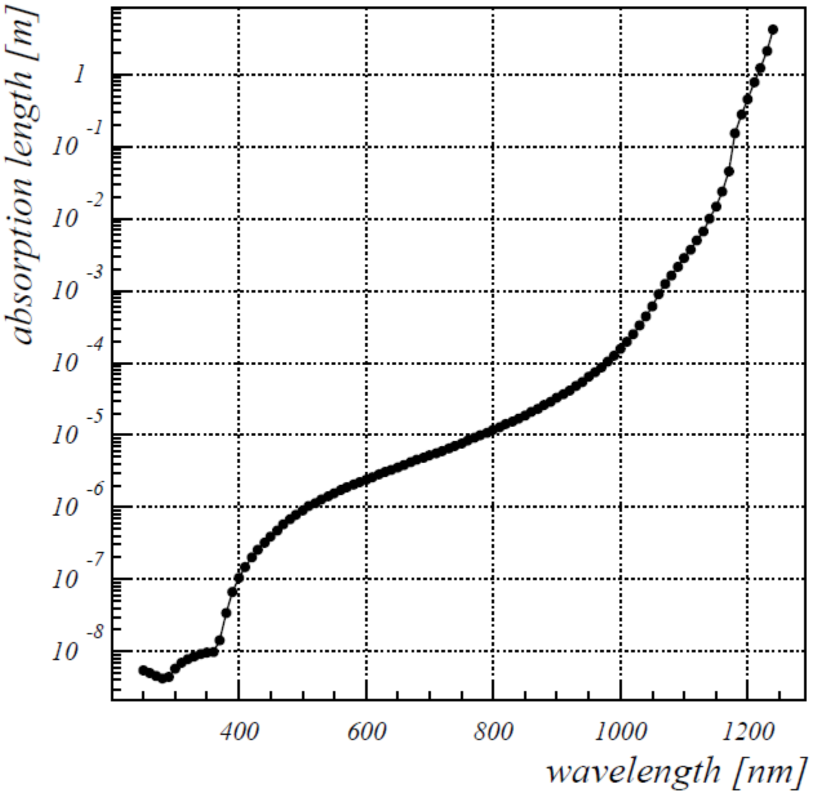


Figure 9-14 A comparison of the quantum efficiency of a silicon photodiode (labeled #458) with representative bialkali and S-20 photocathode quantum efficiencies. The emission spectrum from a BGO scintillator is shown for reference. (From Groom.[53])

Semiconductor light sensor: photodiode





Semiconductor light sensor: CCD

Semiconductor light sensor: G-APD

G-APD: Geiger mode avalanche photo-diode, also known as SiPM – Silicon Photomultiplier

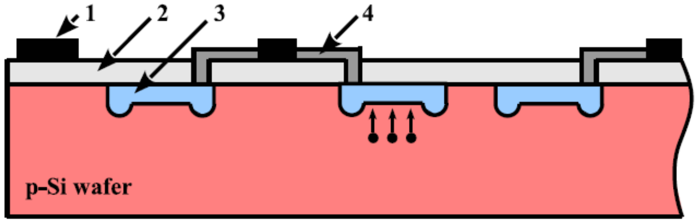


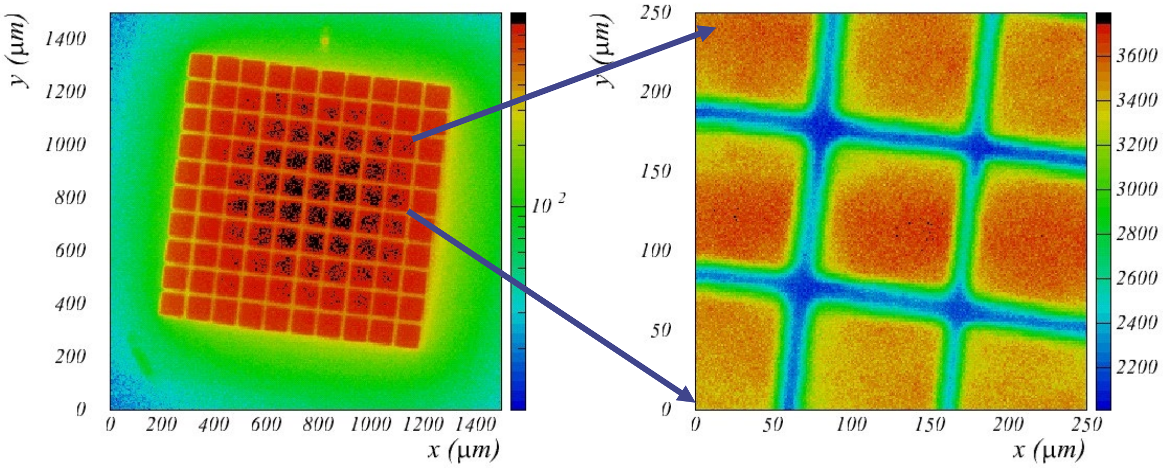
Figure 9: Schematic drawing of a cross-section of a SiPM: metal electrode (1), silicon oxide layer (2), p-n junctions/micro-cell (3) and individual quenching resistor (4) (23).

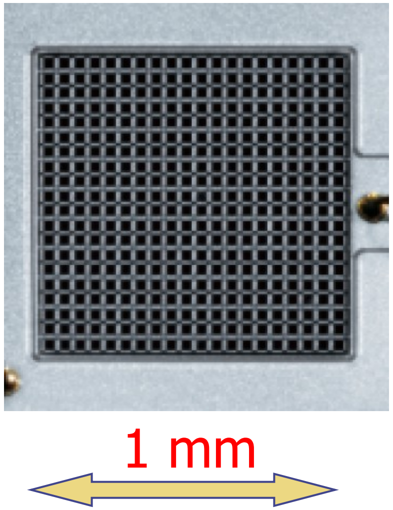
SiPM is an array of APDs operating in Geiger mode. Characteristics:

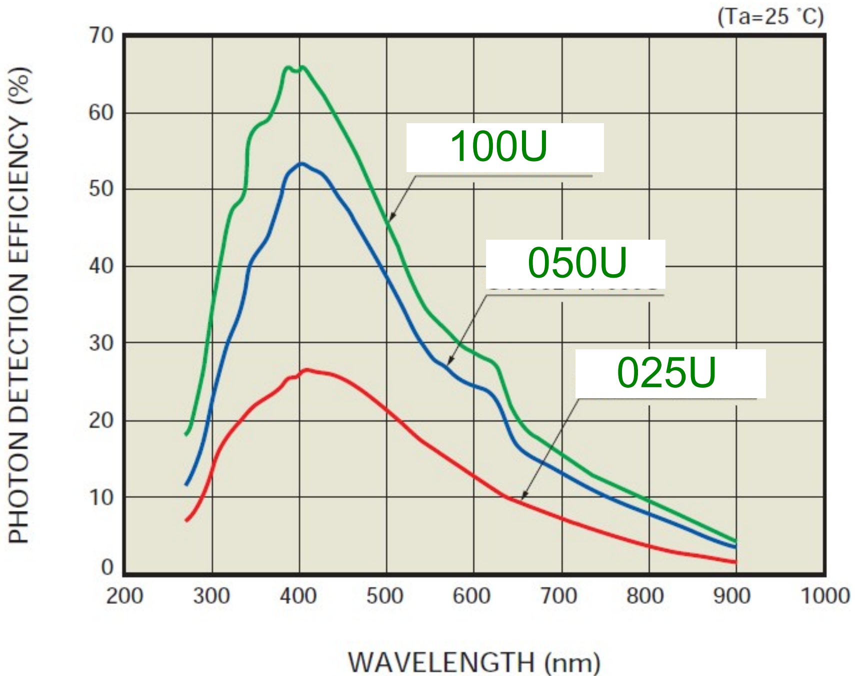
- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

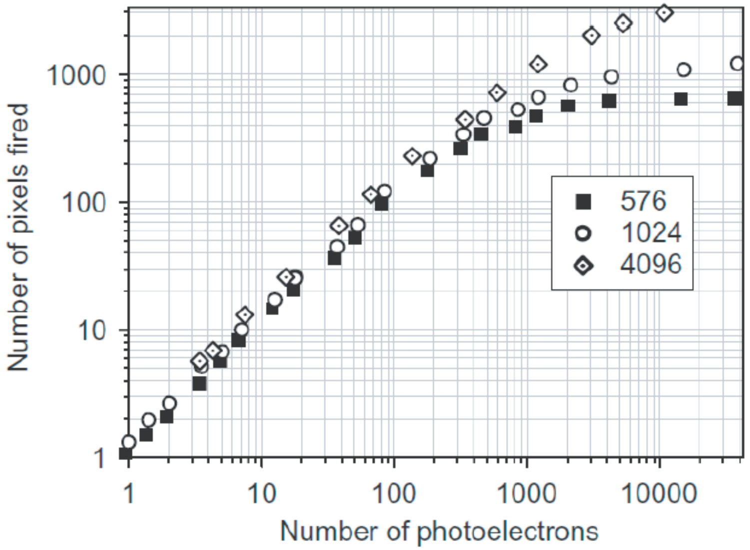
  PDE = QE x ε_{geiger} x ε_{geo} (up to 5x PMT!)
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)

SiPMs as photon detectors









Hybrid photo-detector HPD