Light sources and detectors for optical spectroscopy

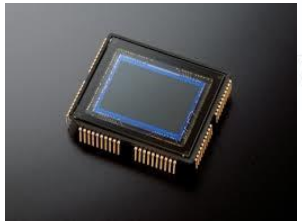
PART II

Salvatore Amoruso

Atomic, Molecular Physics and Laser Spectrocopy

Photodetectors

- ✓ Photodetector parameters
- ✓ Photomultiplier tubes (PMT)
- ✓ Semicondictor photodetectors
- ✓ Powermeters, joulemeters
- ✓ Measure of pulse duration



Photodetector parameters

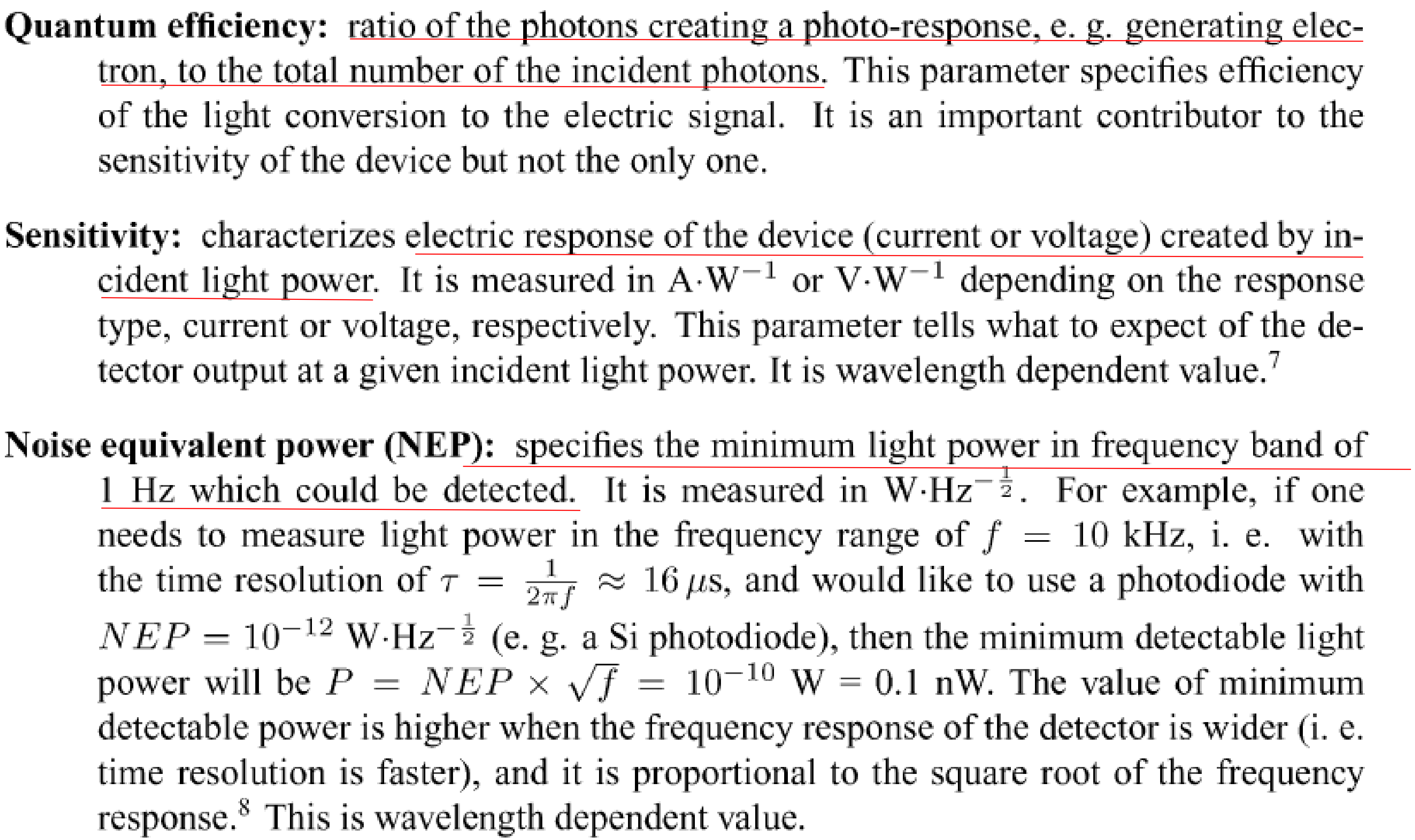
Photodetectors convert light into an eletrical signal

Photodetectors characteristics important for optical spectroscopy

- Sensitivity
- Efficiency
- Spectral range
- Time resolution

- Photosensitive area
- Dynamic range
- Dimensions
- Power consumption and electronics

Photodetector parameters

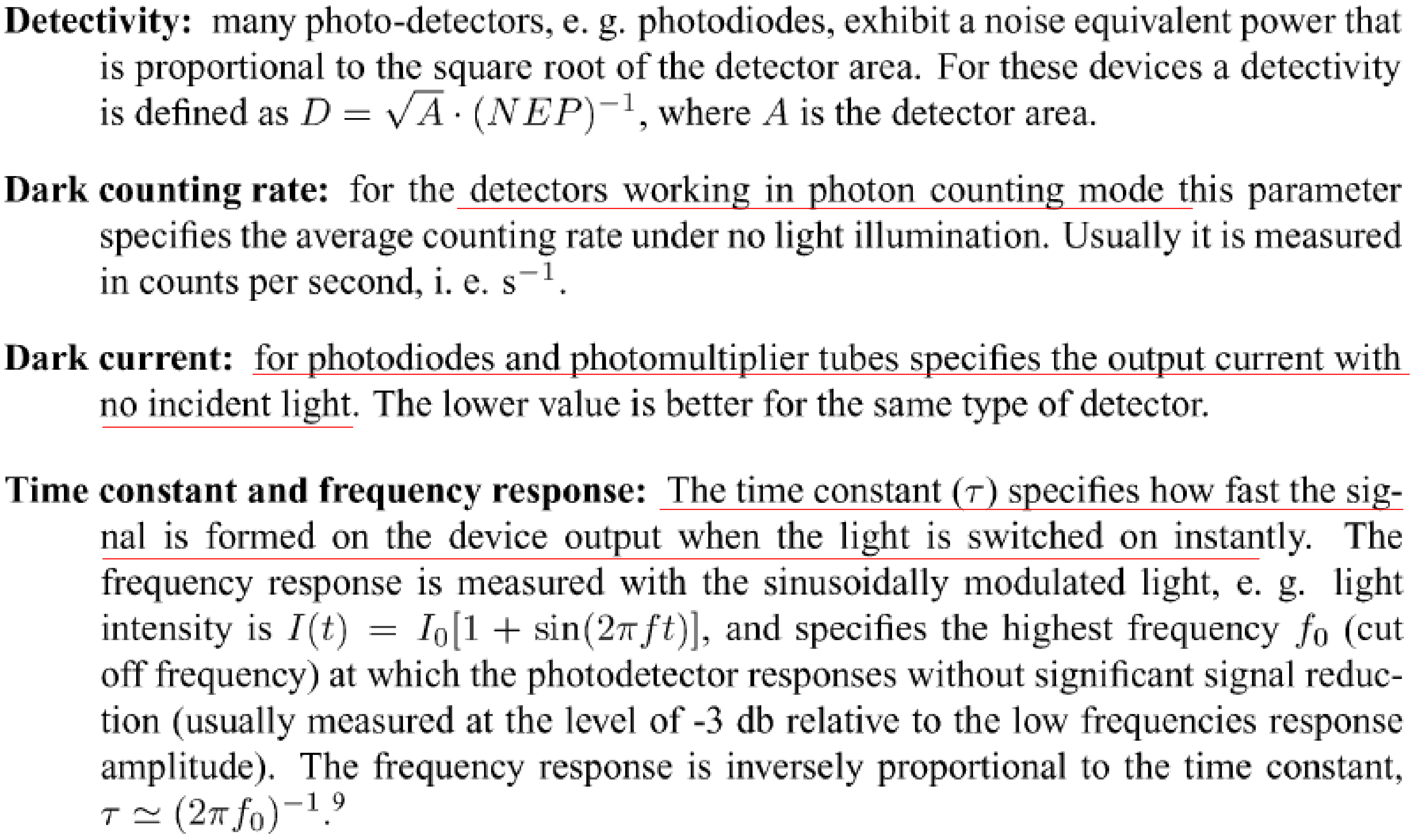


Quantum efficiency: ratio of the photons creating a photo-response, e. g. generating electron, to the total number of the incident photons. This parameter specifies efficiency of the light conversion to the electric signal. It is an important contributor to the sensitivity of the device but not the only one.

Sensitivity: characterizes electric response of the device (current or voltage) created by incident light power. It is measured in $\mathrm{A{\cdot}W^{-1}}$ or $\mathrm{V{\cdot}W^{-1}}$ depending on the response type, current or voltage, respectively. This parameter tells what to expect of the detector output at a given incident light power. It is wavelength dependent value.[7]

Noise equivalent power (NEP): specifies the minimum light power in frequency band of 1 Hz which could be detected. It is measured in $\mathrm{W{\cdot}Hz^{-\frac{1}{2}}}$. For example, if one needs to measure light power in the frequency range of $f = 10$ kHz, i. e. with the time resolution of $\tau = \frac{1}{2\pi f} \approx 16\,\mu$s, and would like to use a photodiode with $NEP = 10^{-12}\ \mathrm{W{\cdot}Hz^{-\frac{1}{2}}}$ (e. g. a Si photodiode), then the minimum detectable light power will be $P = NEP \times \sqrt{f} = 10^{-10}$ W = 0.1 nW. The value of minimum detectable power is higher when the frequency response of the detector is wider (i. e. time resolution is faster), and it is proportional to the square root of the frequency response.[8] This is wavelength dependent value.

Photodetector parameters



Detectivity: many photo-detectors, e. g. photodiodes, exhibit a noise equivalent power that is proportional to the square root of the detector area. For these devices a detectivity is defined as $D = \sqrt{A} \cdot (NEP)^{-1}$, where A is the detector area.

Dark counting rate: for the detectors working in photon counting mode this parameter specifies the average counting rate under no light illumination. Usually it is measured in counts per second, i. e. s^{-1}.

Dark current: for photodiodes and photomultiplier tubes specifies the output current with no incident light. The lower value is better for the same type of detector.

Time constant and frequency response: The time constant (τ) specifies how fast the signal is formed on the device output when the light is switched on instantly. The frequency response is measured with the sinusoidally modulated light, e. g. light intensity is $I(t) = I_0[1 + \sin(2\pi f t)]$, and specifies the highest frequency f_0 (cut off frequency) at which the photodetector responses without significant signal reduction (usually measured at the level of -3 db relative to the low frequencies response amplitude). The frequency response is inversely proportional to the time constant, $\tau \simeq (2\pi f_0)^{-1}$.[9]

Photomultiplier tubes (PMT)

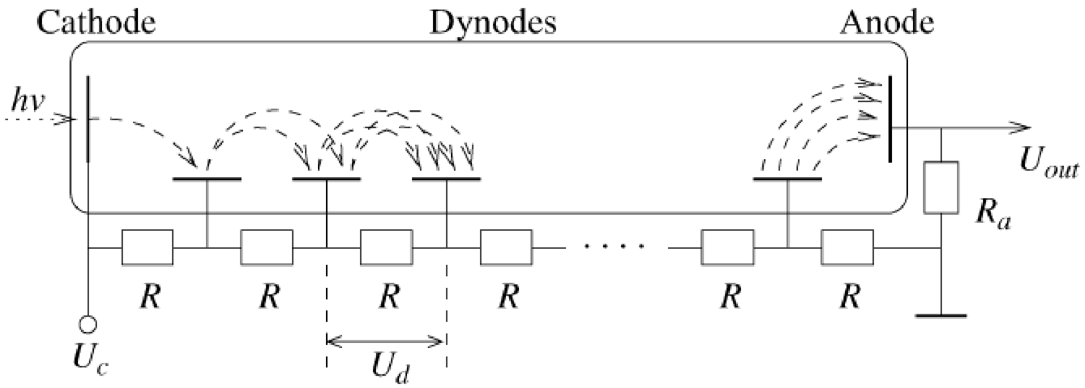
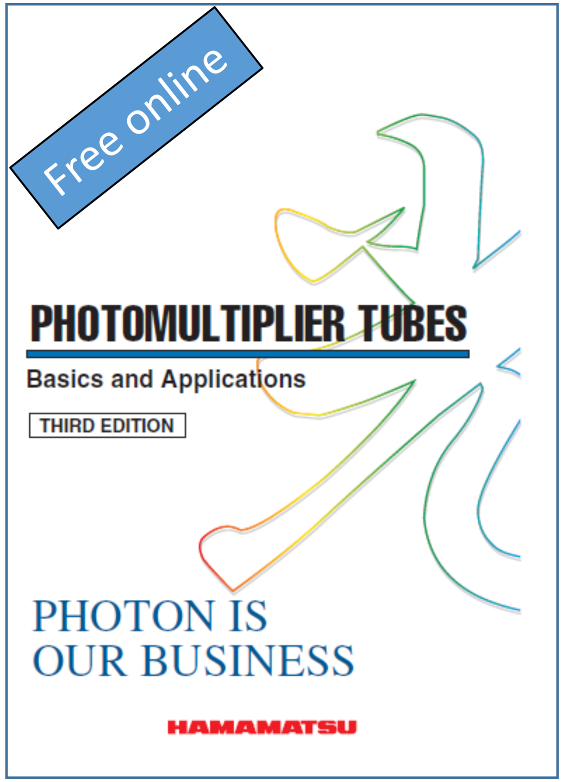


Figure 4.4: Schematic diagram of a photomultiplier.


Free online

PHOTOMULTIPLIER TUBES
Basics and Applications
THIRD EDITION

PHOTON IS
OUR BUSINESS

HAMAMATSU

Typical characteristics

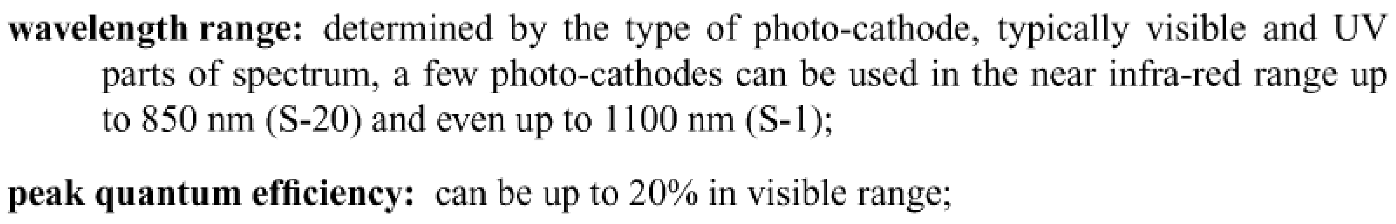
N. of dynodes	9-12	
U_d (×3-4 e^-)		100-150 V
U_c (Power supply)		800-2000 V
Current multiplication		10^6 - 10^7

Photomultiplier Tubes

HAMAMATSU

PMT Characteristics

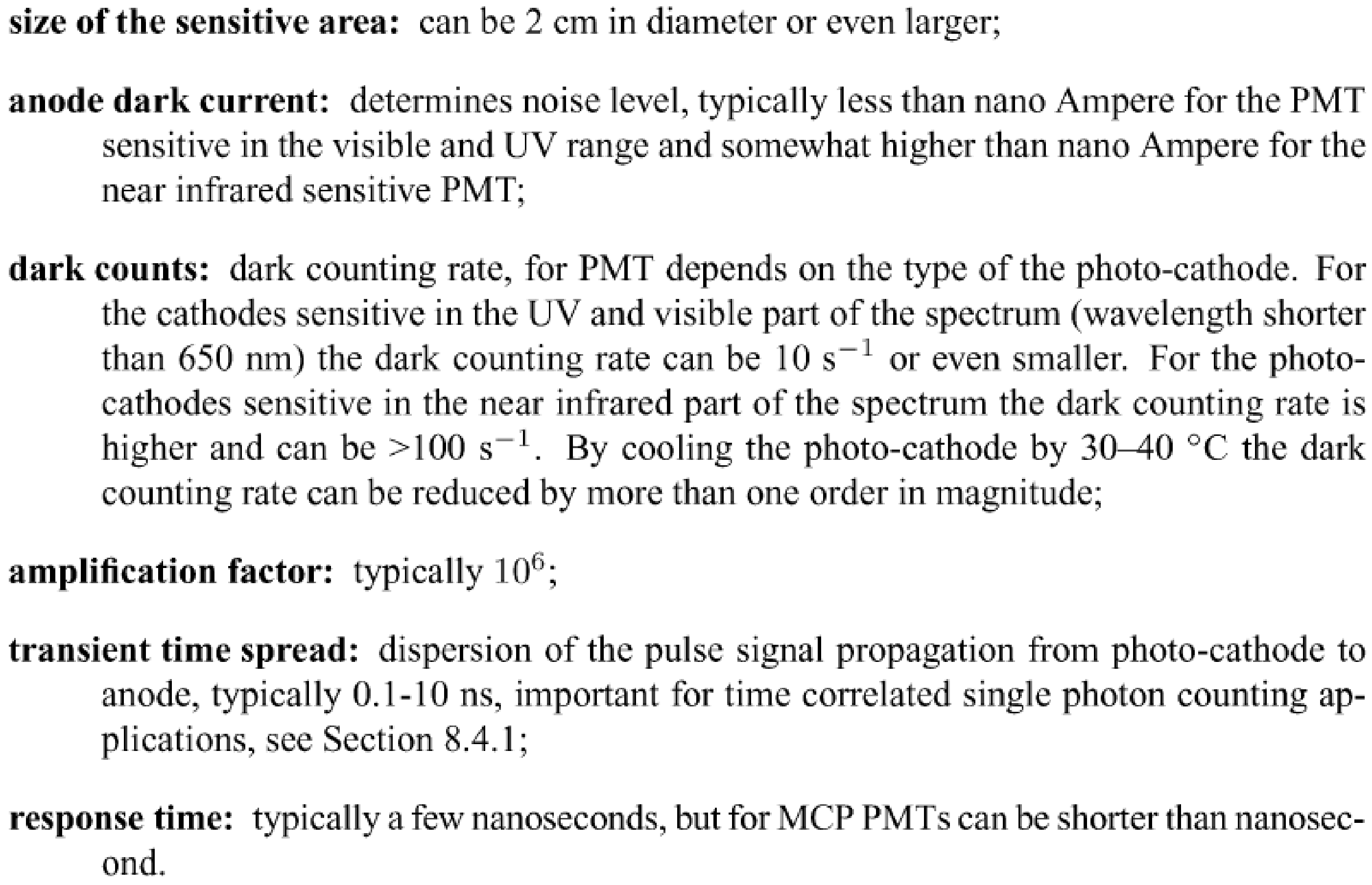
cathode



wavelength range: determined by the type of photo-cathode, typically visible and UV parts of spectrum, a few photo-cathodes can be used in the near infra-red range up to 850 nm (S-20) and even up to 1100 nm (S-1);

peak quantum efficiency: can be up to 20% in visible range;

anode



size of the sensitive area: can be 2 cm in diameter or even larger;

anode dark current: determines noise level, typically less than nano Ampere for the PMT sensitive in the visible and UV range and somewhat higher than nano Ampere for the near infrared sensitive PMT;

dark counts: dark counting rate, for PMT depends on the type of the photo-cathode. For the cathodes sensitive in the UV and visible part of the spectrum (wavelength shorter than 650 nm) the dark counting rate can be 10 s^{-1} or even smaller. For the photo-cathodes sensitive in the near infrared part of the spectrum the dark counting rate is higher and can be >100 s^{-1}. By cooling the photo-cathode by 30–40 °C the dark counting rate can be reduced by more than one order in magnitude;

amplification factor: typically 10^6;

transient time spread: dispersion of the pulse signal propagation from photo-cathode to anode, typically 0.1-10 ns, important for time correlated single photon counting applications, see Section 8.4.1;

response time: typically a few nanoseconds, but for MCP PMTs can be shorter than nanosecond.

Photocathode response

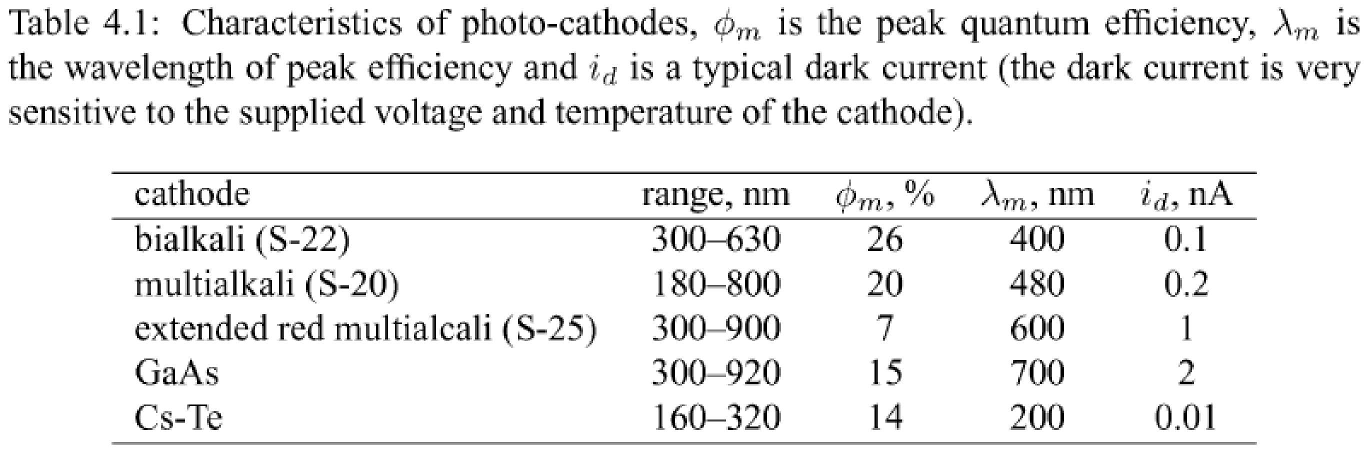
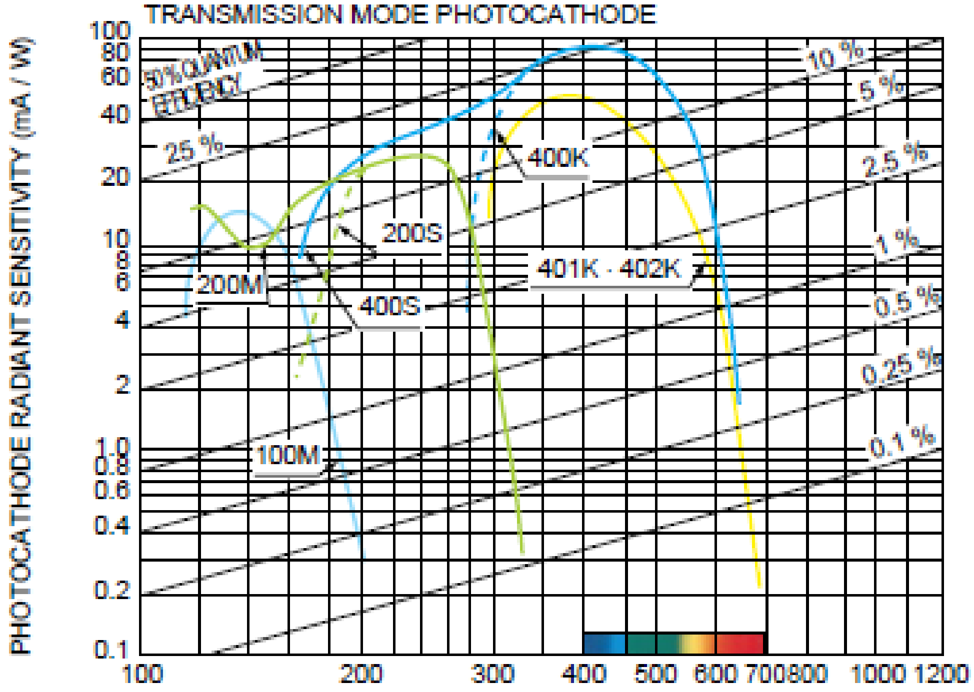


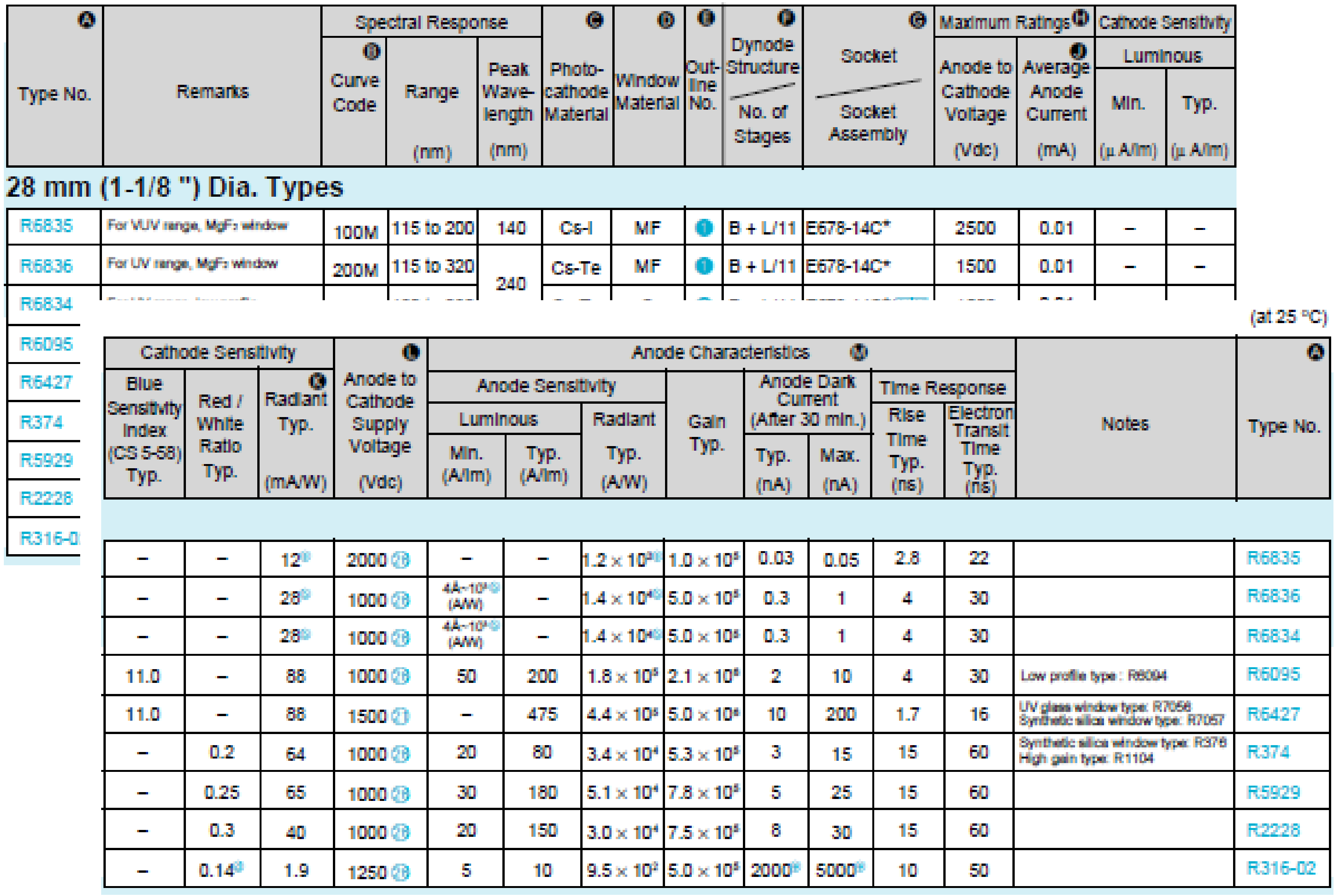
Table 4.1: Characteristics of photo-cathodes, ϕ_m is the peak quantum efficiency, λ_m is the wavelength of peak efficiency and i_d is a typical dark current (the dark current is very sensitive to the supplied voltage and temperature of the cathode).

cathode	range, nm	ϕ_m, %	λ_m, nm	i_d, nA
bialkali (S-22)	300–630	26	400	0.1
multialkali (S-20)	180–800	20	480	0.2
extended red multialcali (S-25)	300–900	7	600	1
GaAs	300–920	15	700	2
Cs-Te	160–320	14	200	0.01

PMT Quantum efficiency and photocatode sensitivity: a typical chart



PMT Characteristics



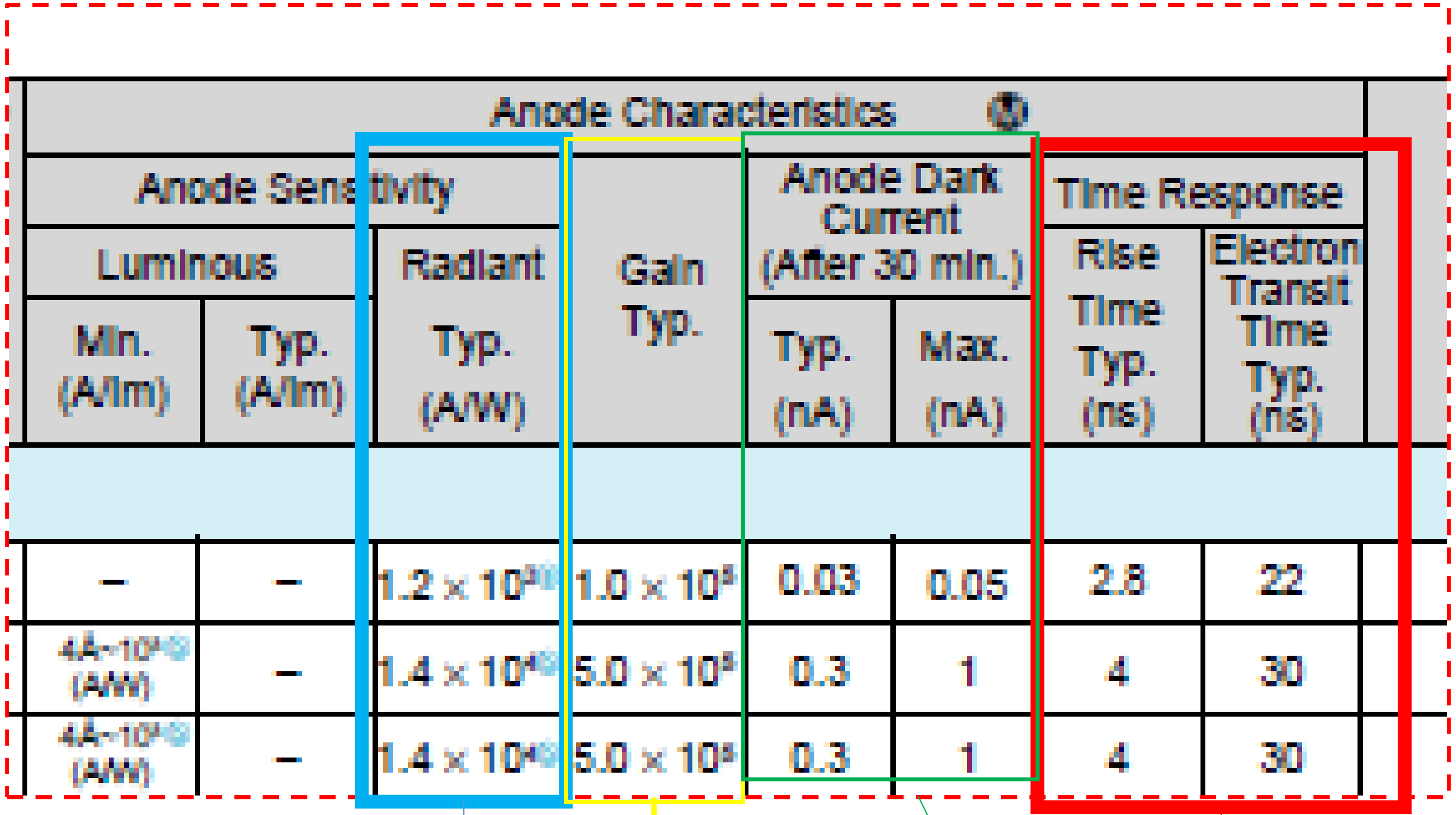
Head-On Type Photomultiplier Tubes

Type No. Ⓐ	Remarks	Spectral Response: Curve Code Ⓑ	Spectral Response: Range (nm)	Spectral Response: Peak Wave-length (nm)	Photo-cathode Material Ⓒ	Window Material Ⓓ	Out-line No. Ⓔ	Dynode Structure / No. of Stages Ⓕ	Socket / Socket Assembly Ⓖ	Maximum Ratings Ⓗ: Anode to Cathode Voltage (Vdc)	Maximum Ratings: Average Anode Current (mA) Ⓘ	Cathode Sensitivity: Luminous Min. (µ A/lm)	Cathode Sensitivity: Luminous Typ. (µ A/lm)
28 mm (1-1/8 ") Dia. Types													
R6835	For VUV range, MgF₂ window	100M	115 to 200	140	Cs-I	MF	①	B + L/11	E678-14C*	2500	0.01	–	–
R6836	For UV range, MgF₂ window	200M	115 to 320	240	Cs-Te	MF	①	B + L/11	E678-14C*	1500	0.01	–	–
R6834													
R6095													
R6427													
R374													
R5929													
R2228													
R316-0													

(at 25 °C)

Cathode Sensitivity: Blue Sensitivity Index (CS 5-58) Typ.	Cathode Sensitivity: Red / White Ratio Typ.	Cathode Sensitivity: Radiant Typ. (mA/W) Ⓚ	Anode to Cathode Supply Voltage (Vdc) Ⓛ	Anode Characteristics Ⓜ: Anode Sensitivity Luminous Min. (A/lm)	Anode Sensitivity Luminous Typ. (A/lm)	Anode Sensitivity Radiant Typ. (A/W)	Gain Typ.	Anode Dark Current (After 30 min.) Typ. (nA)	Anode Dark Current (After 30 min.) Max. (nA)	Time Response: Rise Time Typ. (ns)	Time Response: Electron Transit Time Typ. (ns)	Notes	Type No. Ⓐ
–	–	12	2000 ㉘	–	–	1.2×10^4	1.0×10^6	0.03	0.05	2.8	22		R6835
–	–	28	1000 ㉘	4Å~10^4 (A/W)	–	1.4×10^4	5.0×10^5	0.3	1	4	30		R6836
–	–	28	1000 ㉘	4Å~10^4 (A/W)	–	1.4×10^4	5.0×10^5	0.3	1	4	30		R6834
11.0	–	88	1000 ㉘	50	200	1.8×10^5	2.1×10^6	2	10	4	30	Low profile type : R6094	R6095
11.0	–	88	1500 ㉗	–	475	4.4×10^5	5.0×10^6	10	200	1.7	16	UV glass window type: R7056 Synthetic silica window type: R7057	R6427
–	0.2	64	1000 ㉘	20	80	3.4×10^4	5.3×10^5	3	15	15	60	Synthetic silica window type: R376 High gain type: R1104	R374
–	0.25	65	1000 ㉘	30	180	5.1×10^4	7.8×10^5	5	25	15	60		R5929
–	0.3	40	1000 ㉘	20	150	3.0×10^4	7.5×10^5	8	30	15	60		R2228
–	0.14	1.9	1250 ㉘	5	10	9.5×10^2	5.0×10^5	2000	5000	10	50		R316-02

PMT Characteristics



Anode Characteristics							
Anode Sensitivity			Gain Typ.	Anode Dark Current (After 30 min.)		Time Response	
Luminous		Radiant					
Min. (A/lm)	Typ. (A/lm)	Typ. (A/W)		Typ. (nA)	Max. (nA)	Rise Time Typ. (ns)	Electron Transit Time Typ. (ns)
–	–	1.2 × 10^3	1.0 × 10^5	0.03	0.05	2.8	22
4A~10^4 (A/W)	–	1.4 × 10^4	5.0 × 10^5	0.3	1	4	30
4A~10^4 (A/W)	–	1.4 × 10^4	5.0 × 10^5	0.3	1	4	30

Radiant Sensitivity
~ 10^3-10^4 A/W

Gain
~ 10^5-10^6 A/W

Dark current
≤ 1nA

Response time
- ✓ Rise time (~ 2-4ns)
- ✓ Transient time spread [ETT] (~ 20-30ns)

MCP-PMT: reduction of the ETT to improve temporal resolution

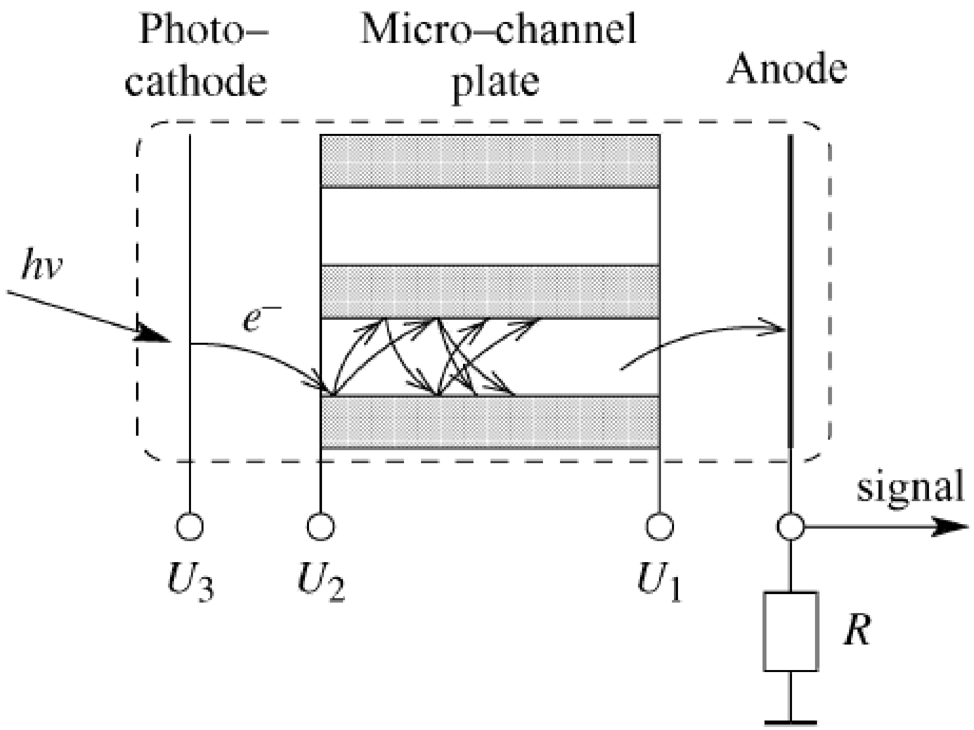
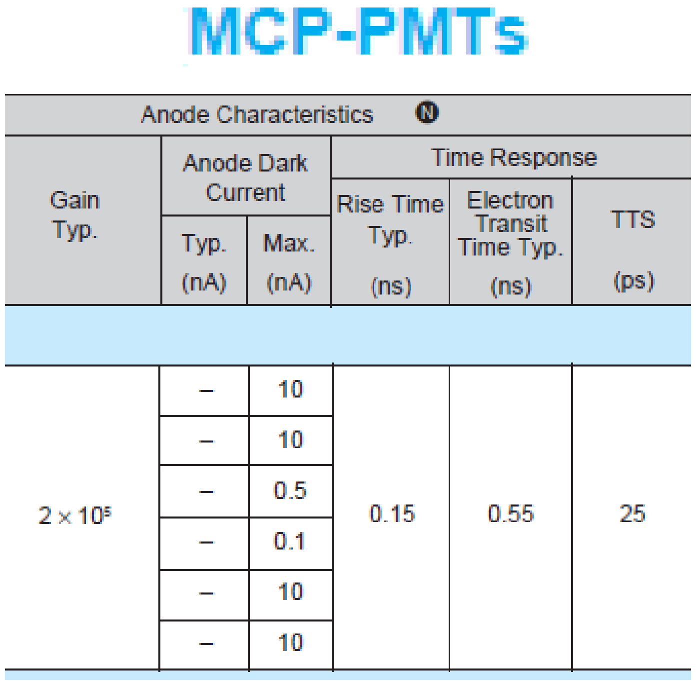


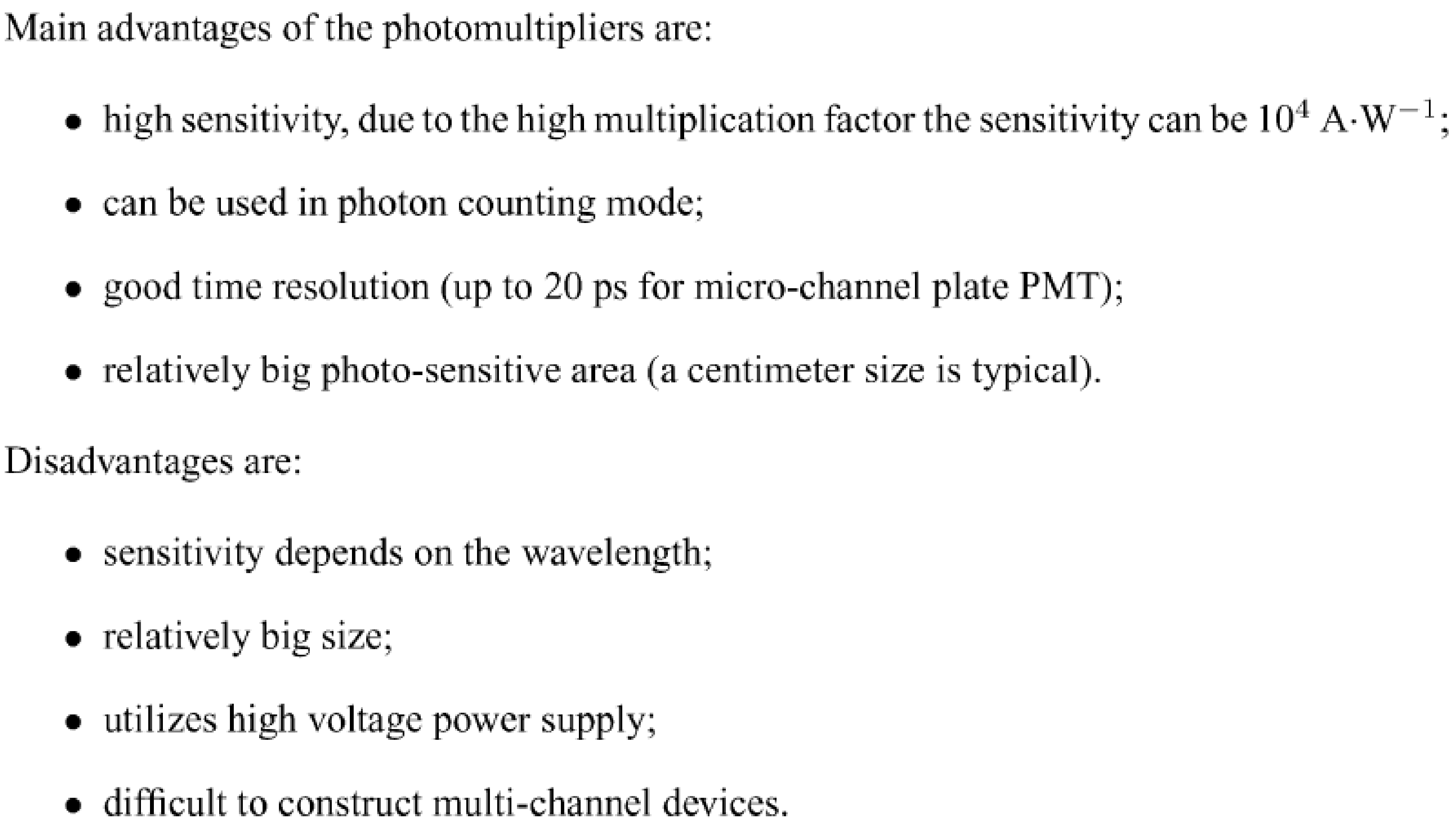
Figure 4.5: Micro-channel plate photomultiplier tube.



MCP-PMTs

Anode Characteristics					
Gain Typ.	Anode Dark Current		Time Response		
	Typ. (nA)	Max. (nA)	Rise Time Typ. (ns)	Electron Transit Time Typ. (ns)	TTS (ps)
2×10^5	–	10	0.15	0.55	25
	–	10			
	–	0.5			
	–	0.1			
	–	10			
	–	10			

PMT Characteristics



Main advantages of the photomultipliers are:

- high sensitivity, due to the high multiplication factor the sensitivity can be 10^4 A·W^{-1};
- can be used in photon counting mode;
- good time resolution (up to 20 ps for micro-channel plate PMT);
- relatively big photo-sensitive area (a centimeter size is typical).

Disadvantages are:

- sensitivity depends on the wavelength;
- relatively big size;
- utilizes high voltage power supply;
- difficult to construct multi-channel devices.

PMT allows **PHOTON COUNTING** measurements

Photon counting allows detecting very-low light level signals

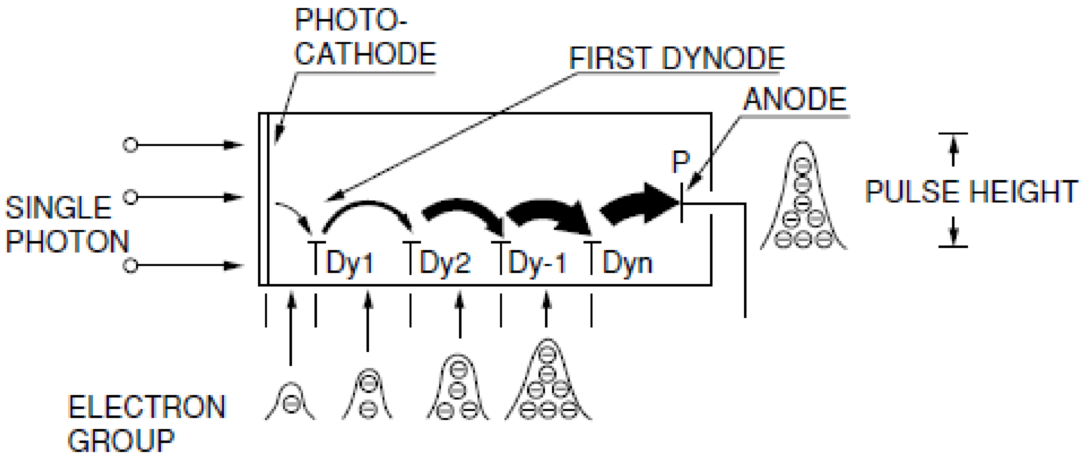


Figure 6-1: Photomultiplier tube operation in photon counting mode

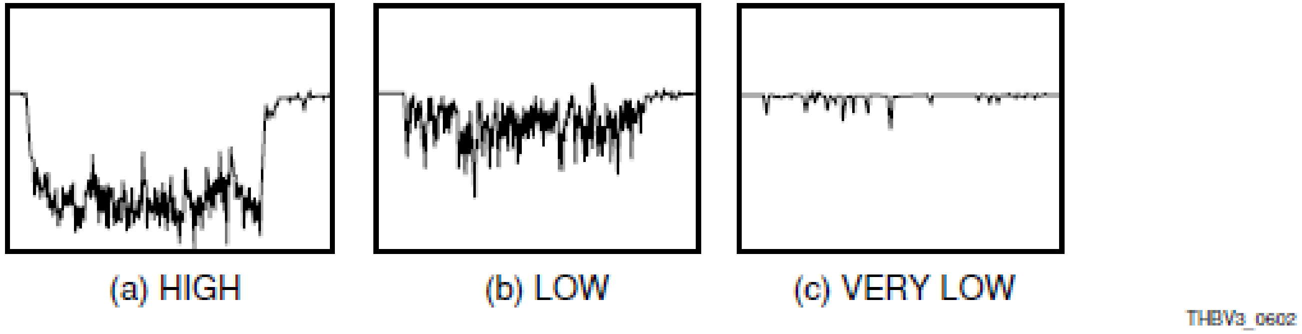
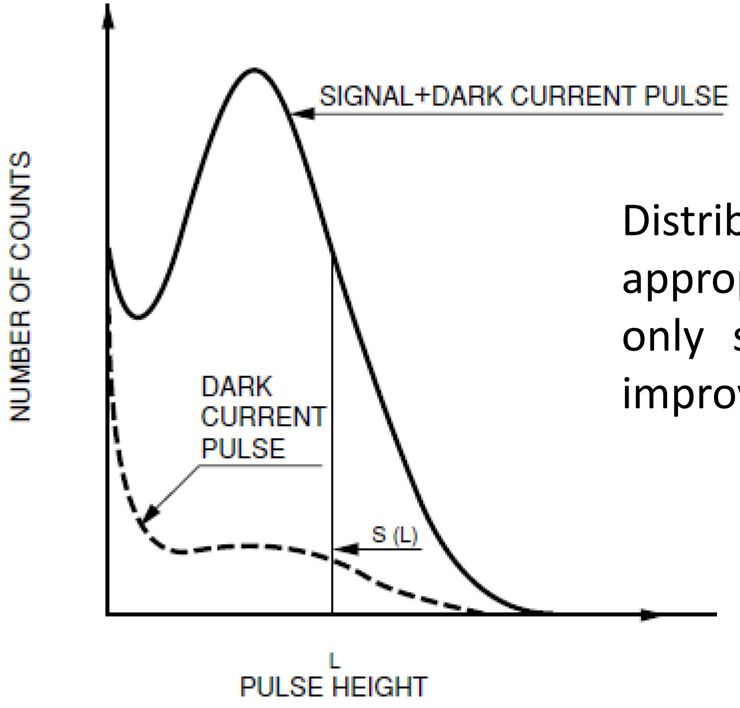

(a) HIGH (b) LOW (c) VERY LOW

Figure 6-2: Photomultiplier tube output waveforms observed at different light levels

PMT Characteristics



(a) DIFFERENTIAL SPECTRUM

Distribution of the pulse heigth. By appropriate discrimination one can count only signal above a threshold level and improve the S/N ratio

Example of a typical circuit for photton counting

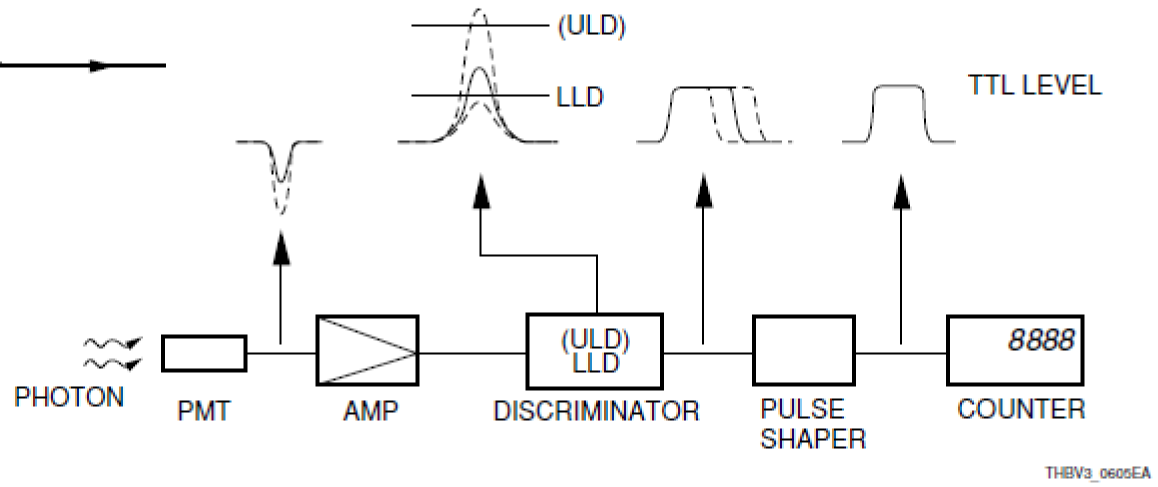


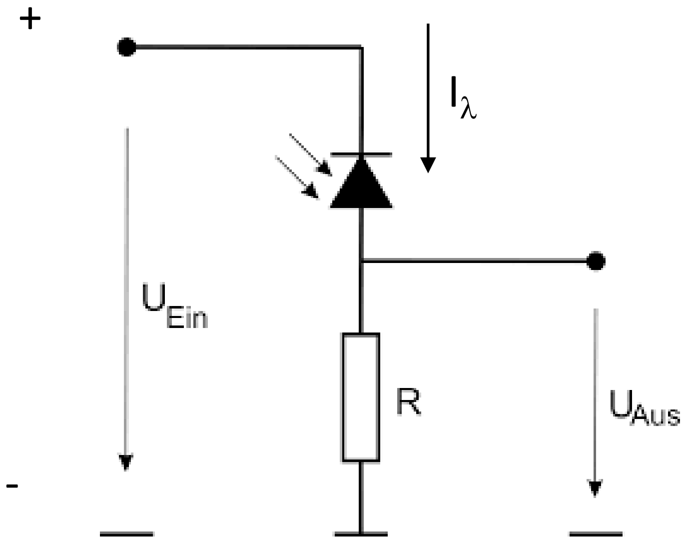
Figure 6-5: Circuit configuration for photon counting

We will come back to Photon Counting when discussing Time Correlated Single Phtoton Counting Spectroscopy

Semiconductor Photodetectors

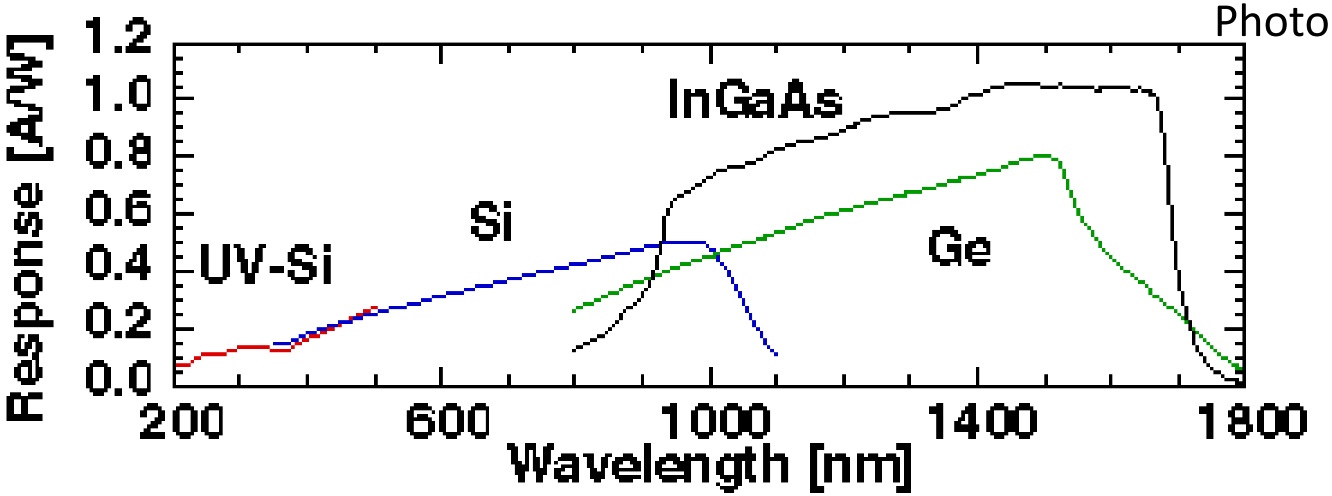
Photodiodes, Avalanche Photodiodes, Photodiode Array, CCD

❑ Photodiode (*p*-*n* or p-i-n junction)

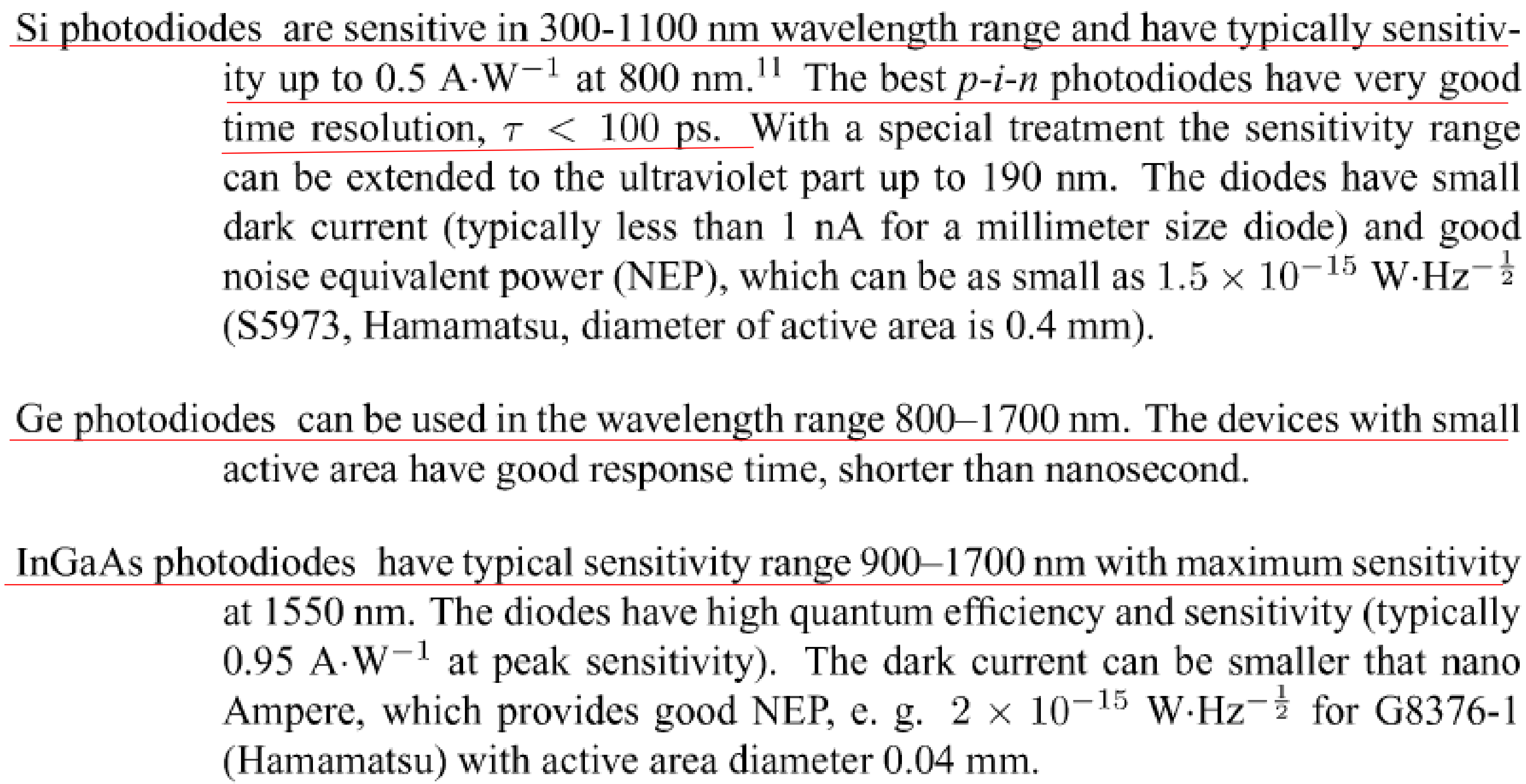


Photoconductive mode

Absolute Spectral Response



Semiconductor Photodetectors



Si photodiodes are sensitive in 300-1100 nm wavelength range and have typically sensitivity up to 0.5 $\mathrm{A \cdot W^{-1}}$ at 800 nm.[11] The best *p-i-n* photodiodes have very good time resolution, $\tau < 100$ ps. With a special treatment the sensitivity range can be extended to the ultraviolet part up to 190 nm. The diodes have small dark current (typically less than 1 nA for a millimeter size diode) and good noise equivalent power (NEP), which can be as small as 1.5×10^{-15} $\mathrm{W \cdot Hz^{-\frac{1}{2}}}$ (S5973, Hamamatsu, diameter of active area is 0.4 mm).

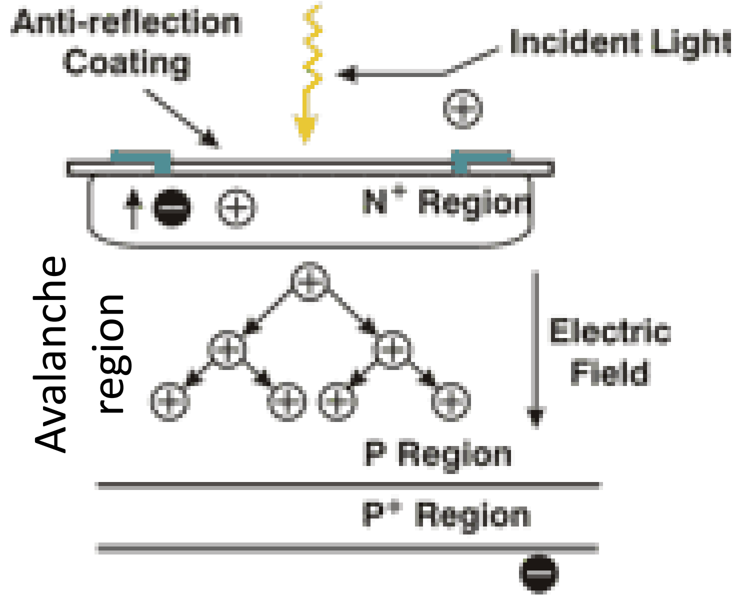
Ge photodiodes can be used in the wavelength range 800–1700 nm. The devices with small active area have good response time, shorter than nanosecond.

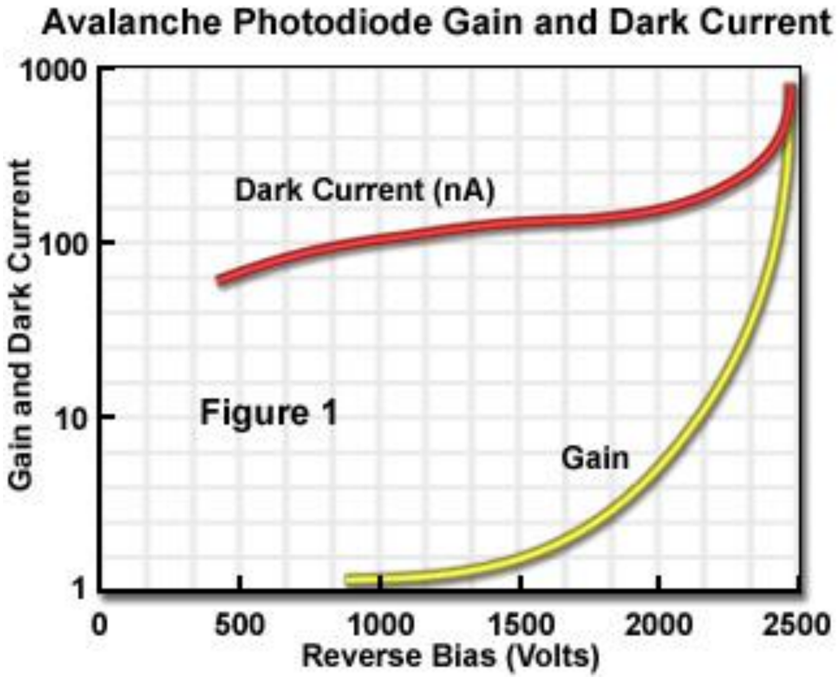
InGaAs photodiodes have typical sensitivity range 900–1700 nm with maximum sensitivity at 1550 nm. The diodes have high quantum efficiency and sensitivity (typically 0.95 $\mathrm{A \cdot W^{-1}}$ at peak sensitivity). The dark current can be smaller that nano Ampere, which provides good NEP, e. g. 2×10^{-15} $\mathrm{W \cdot Hz^{-\frac{1}{2}}}$ for G8376-1 (Hamamatsu) with active area diameter 0.04 mm.

Peak Quantum Efficiency (tip. 40-90%) is typically higher than PMT, but no internal amplification.

❑ Avalanche Photodiode

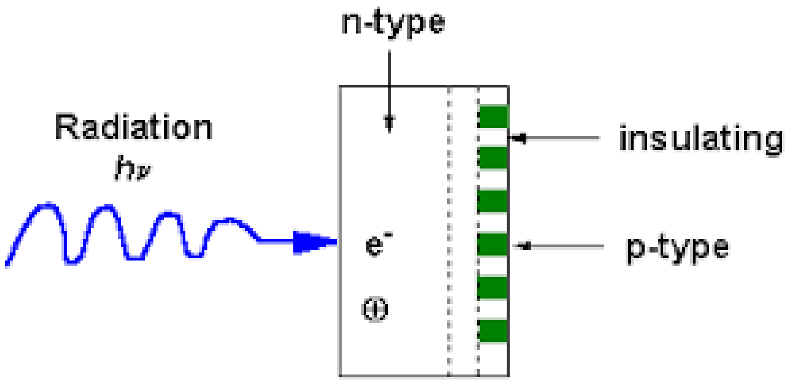
Amplification can be achieved in special designed photodiodes under high reverse bias voltage (1-2 kV).

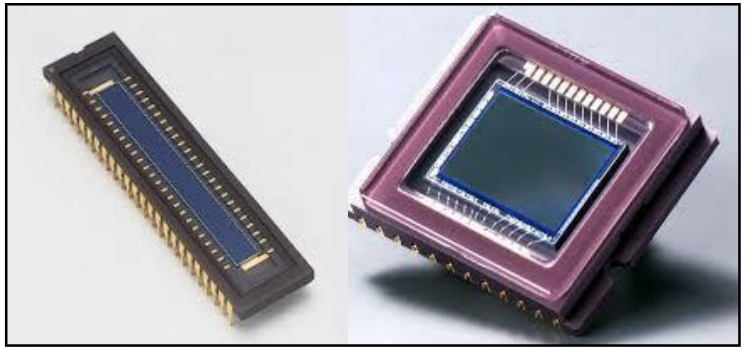




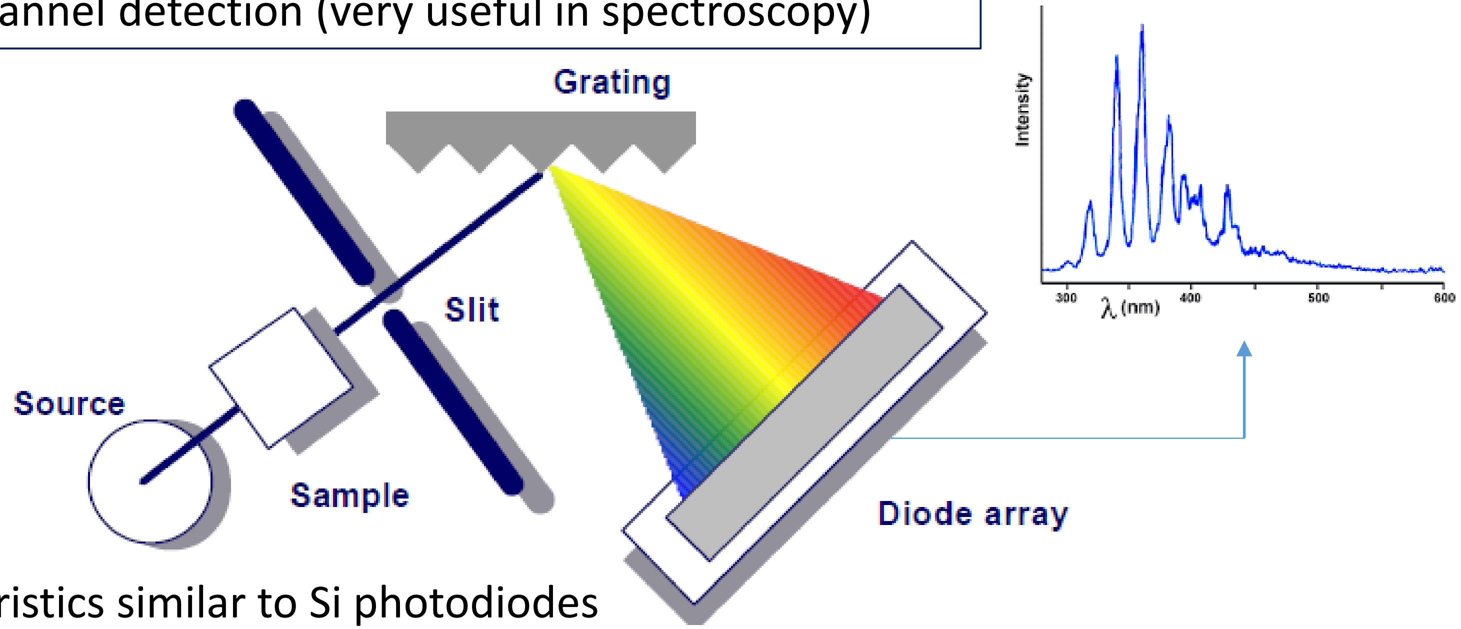
- ✓ Amplification can be as high as 100-1000, contrary to PMT (~ 10^6).
- ✓ Can be used in Photon counting mode

❑ Si Photodiode linear array and CCD (charge coupled device)



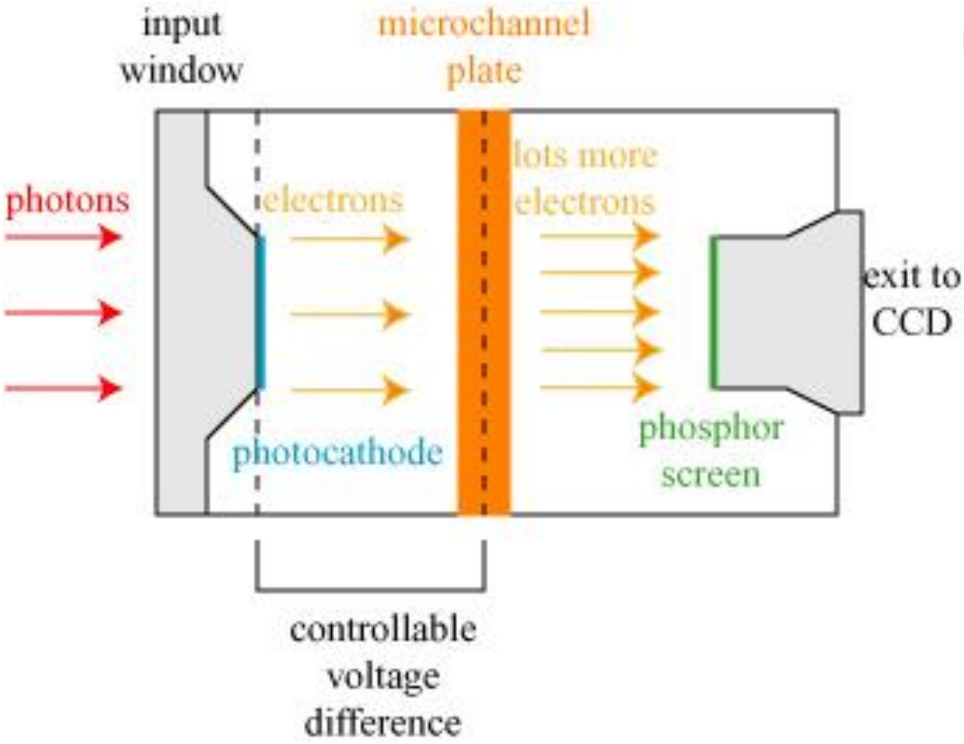


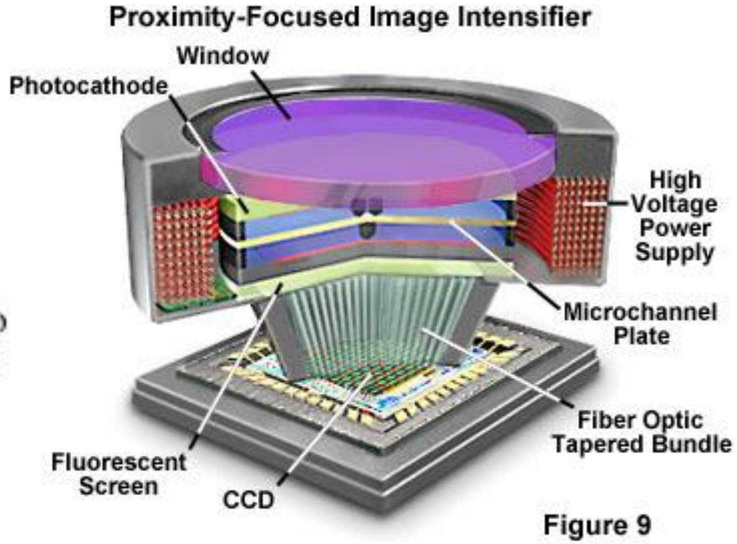
Multichannel detection (very useful in spectroscopy)



- ✓ Charateristics similar to Si photodiodes
- ✓ Longer time transfer of the signal from internal registry to external electronics (board and PC)

☐ Intensified CCD (ICCD)

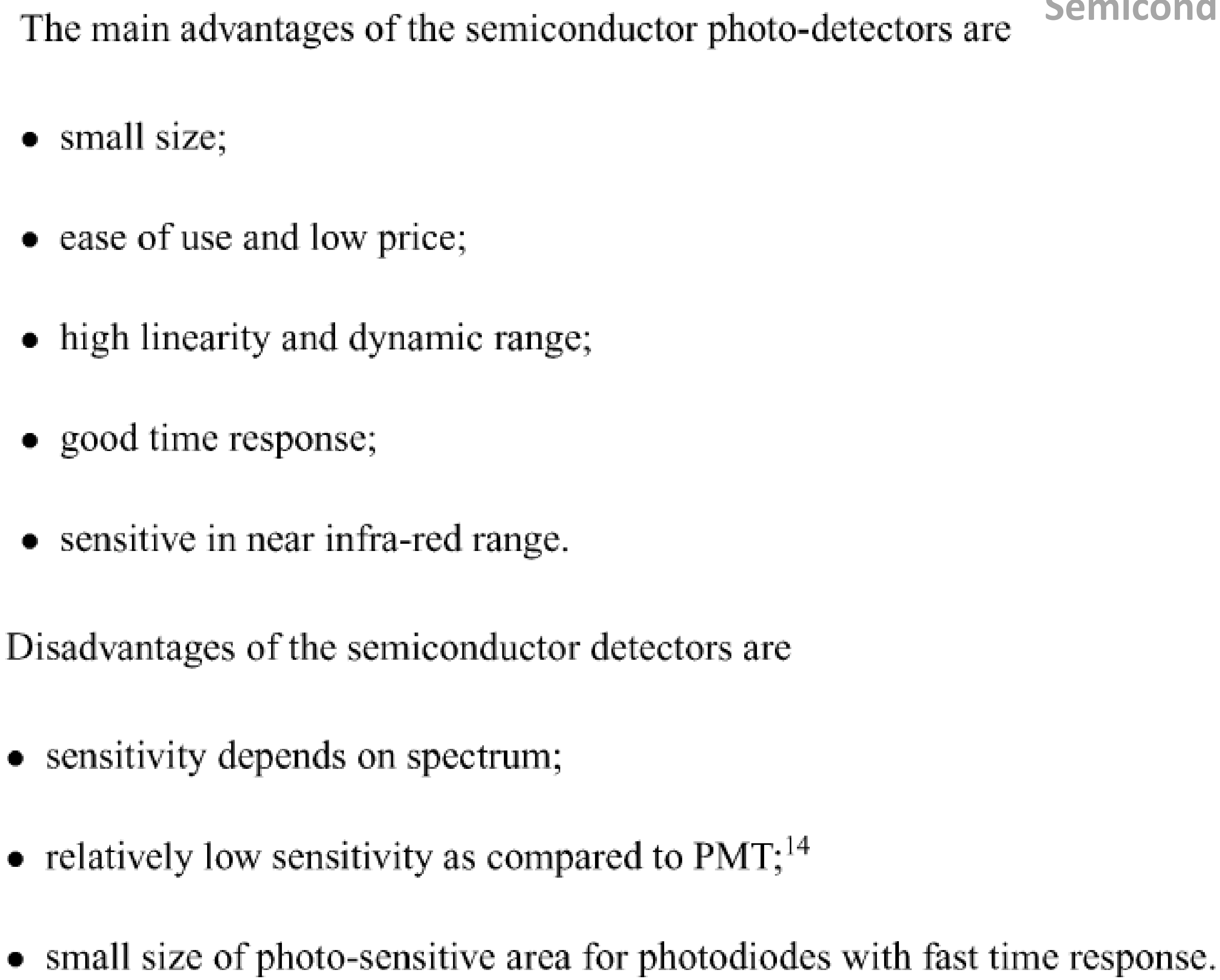




Voltage Gating of the MCP allows obtaining multichannel detection with good time resolution (min. ~ 1 ns) and variable gain to carry out temporally resolved measurements at lower light level.

Typically used in emission spectroscopy with time gating (we will see examples in Laser Induced Breakdown Spectroscopy).

Semiconductor Photodetectors



The main advantages of the semiconductor photo-detectors are

- small size;
- ease of use and low price;
- high linearity and dynamic range;
- good time response;
- sensitive in near infra-red range.

Disadvantages of the semiconductor detectors are

- sensitivity depends on spectrum;
- relatively low sensitivity as compared to PMT;[14]
- small size of photo-sensitive area for photodiodes with fast time response.

Measurement of light power and pulse energy

Light power

- ☐ High level : Powermeter

- ☐ Low light power: Photodiode

<u>Example</u>

$S=0.5\ \mathrm{A/W};\ R=10\ \mathrm{k\Omega} \rightarrow S_U=SR=5\times10^3\ \mathrm{V/W}$

$P=0.1\ \mathrm{mW} \leftrightarrow U_{out}=0.5\ \mathrm{V}$

Dark current of PD $I_{dark}\approx 100\ \mathrm{nA}$

$U_{out\ dark}\ (R=10\ \mathrm{k\Omega}) = I_{dark}\times R \approx 1\ \mathrm{mV}$

$U_{out\ dark}\ (R=1\ \mathrm{M\Omega}) = I_{dark}\times R \approx 0.1\ \mathrm{V}$

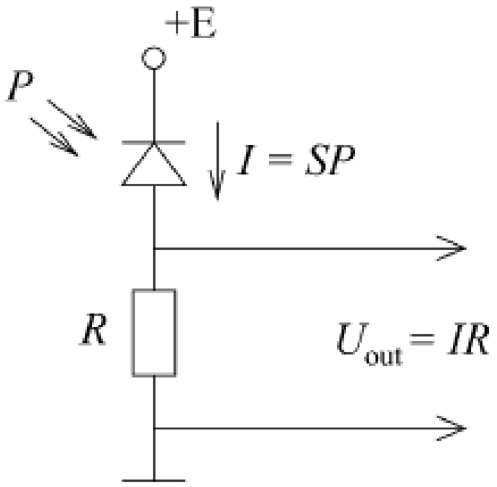


Figure 4.6: Electric circuit for measurements of the light power with photodiode.

Pulse energy

$$U_d \sim \int I_p(t)dt$$

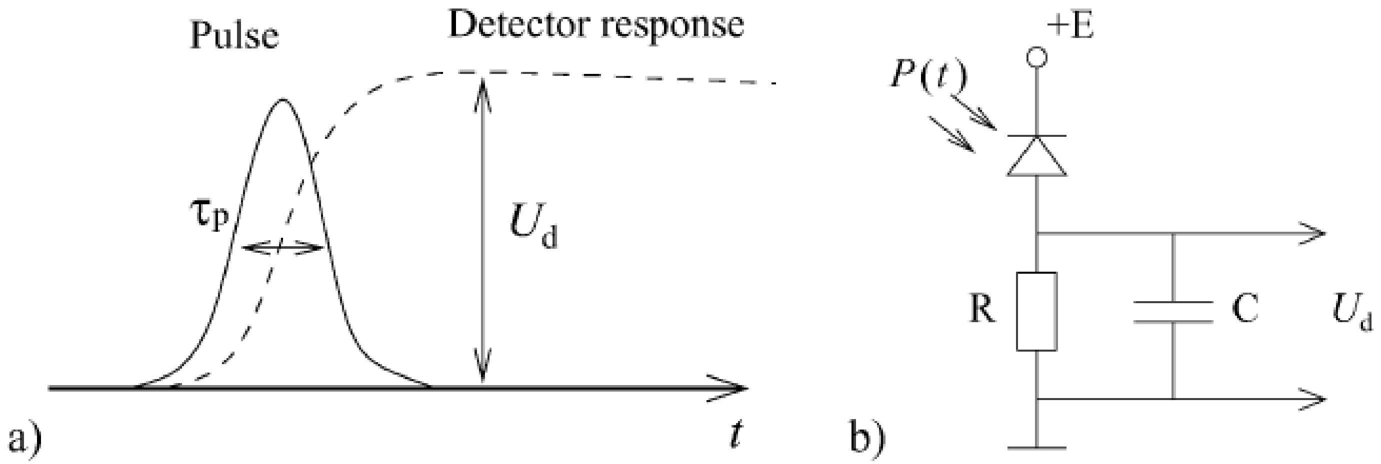


Figure 4.7: Pulse energy measurements: a) integration of the pulse intensity by a slow photo-detector, and b) electric integration circuit for a photodiode.

$$E = \int P(t)dt = \int \frac{I(t)}{S}dt = \frac{1}{S}\int I(t)dt \quad \Longrightarrow \quad U_d = Q/C$$

Example

S=0.5 A/W (@800 nm)

C=10 nF → S_p=S/C=5×10^7 V/J

E=1 μJ ↔ U_d=50 V

C=10 μF → S_p=S/C=5×10^4 V/J

E=1 mJ ↔ U_d=50 V

Energy meter or calibrated PD

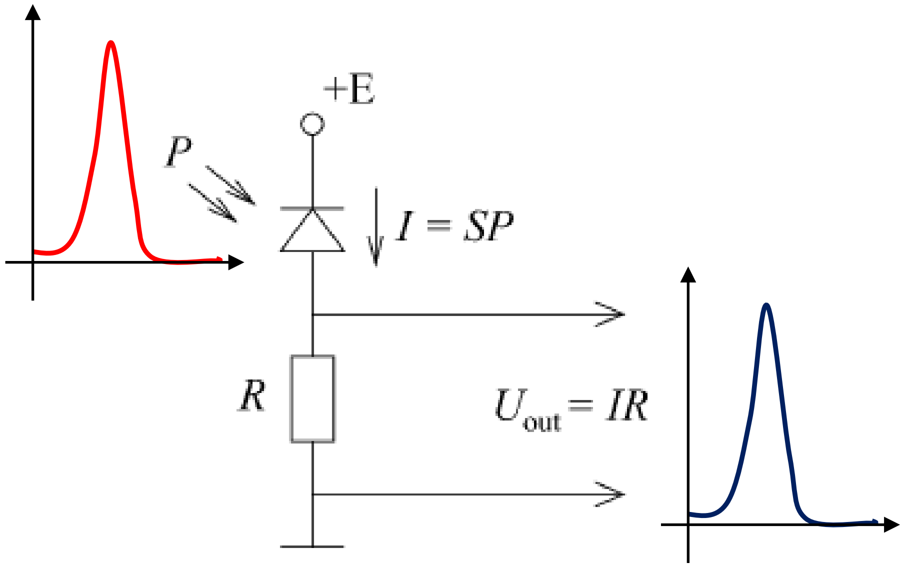
Repetition rate can be limited by the integrating circuit

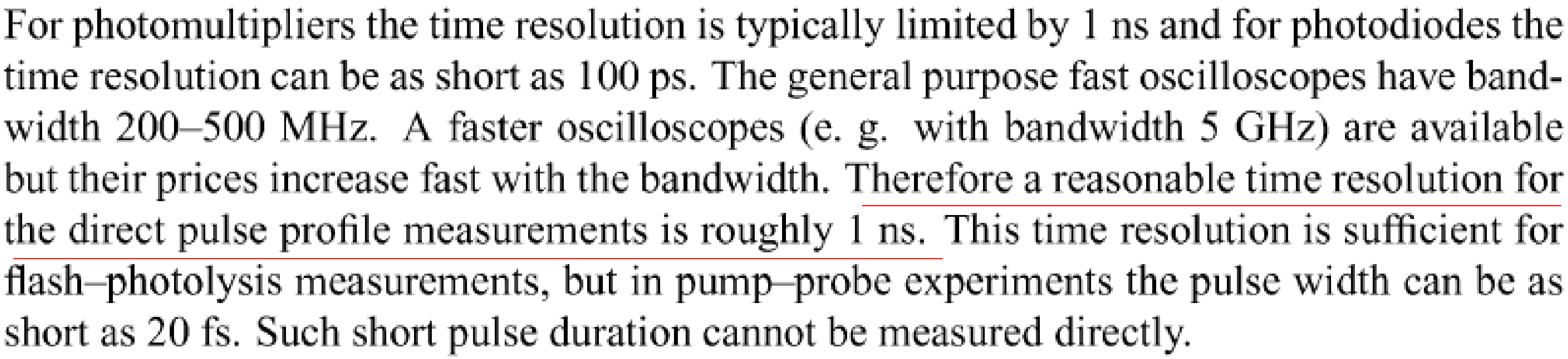
Spectral sensitivity implies calibration at different wavelengths

Measurement of pulse duration

- ❑ Direct measurement

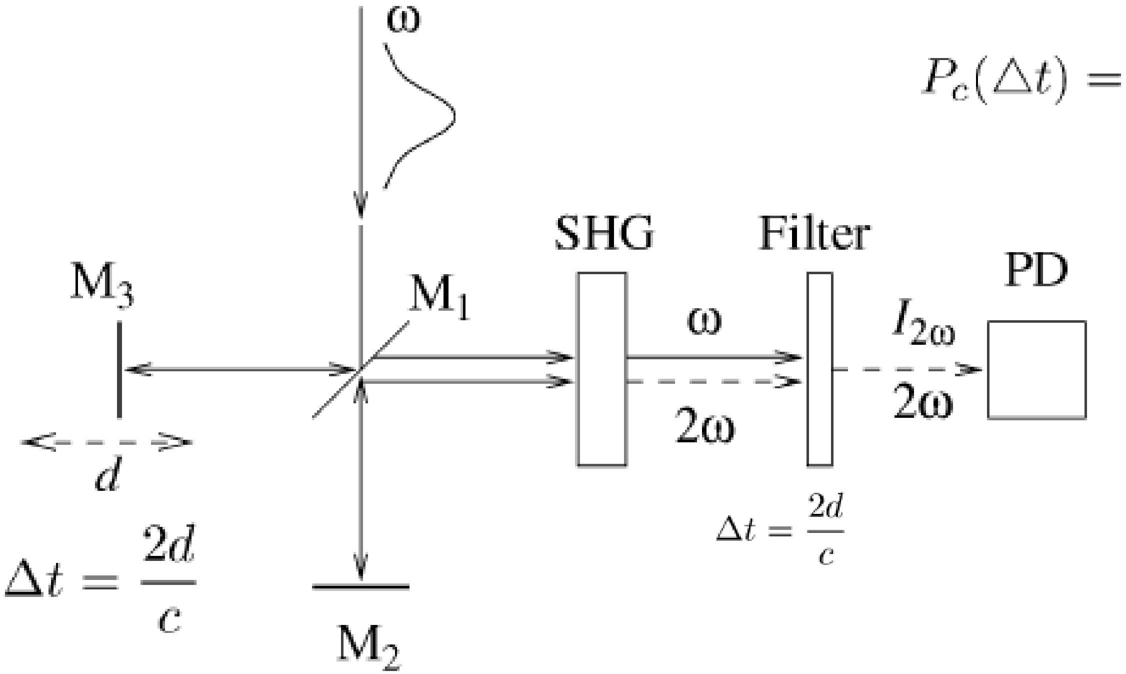
The sensitive element can be PD or PMT




For photomultipliers the time resolution is typically limited by 1 ns and for photodiodes the time resolution can be as short as 100 ps. The general purpose fast oscilloscopes have bandwidth 200–500 MHz. A faster oscilloscopes (e. g. with bandwidth 5 GHz) are available but their prices increase fast with the bandwidth. Therefore a reasonable time resolution for the direct pulse profile measurements is roughly 1 ns. This time resolution is sufficient for flash–photolysis measurements, but in pump–probe experiments the pulse width can be as short as 20 fs. Such short pulse duration cannot be measured directly.

❑ Indirect measurement (Autocorrelation)

$$P_c(\Delta t) = 2\alpha \int_{-\infty}^{+\infty} I(t)I(t+\Delta t)dt$$



The measured value is the total pulse energy at the second harmonic (at 2ω)

$$P_{2\omega} = \int_{-\infty}^{+\infty} I_{2\omega}(t)dt$$

$$= \overbrace{\alpha \int_{-\infty}^{+\infty} I^2(t)dt + \alpha \int_{-\infty}^{+\infty} I^2(t+\Delta t)dt}^{P_o(\Delta t)} + \overbrace{2\alpha \int_{-\infty}^{+\infty} I(t)I(t+\Delta t)dt}^{P_c(\Delta t)}$$

The results of the measurements using devices presented in Fig. 4.8 is the autocorrelation function of the input signal, therefore these devices are called autocorrelators.

If the function $I(t)$ is a pulse, then its autocorrelation function is a pulse too. For example, for a Gaussian pulse $I(t) = e^{-t^2}$ the autocorrelation function is

$$\begin{aligned} P_c(\triangle t) &= \int\limits_{-\infty}^{+\infty} e^{-t^2-(t+\triangle t)^2} dt = \int\limits_{-\infty}^{+\infty} e^{-\left(\sqrt{2}t+\frac{\triangle t}{\sqrt{2}}\right)^2 - \left(\frac{\triangle t}{\sqrt{2}}\right)^2} dt \\ &= e^{-\frac{\triangle t^2}{2}} \int\limits_{-\infty}^{+\infty} e^{-\frac{(2t+\triangle t)^2}{2}} dt = Ce^{-\frac{\triangle t^2}{2}} \end{aligned} \tag{4.45}$$

which is the Gaussian pulse, but it is $\sqrt{2}$ times broader than the original pulse. This is shown in Fig. 4.9, where autocorrelation function was normalized to fit the scale.

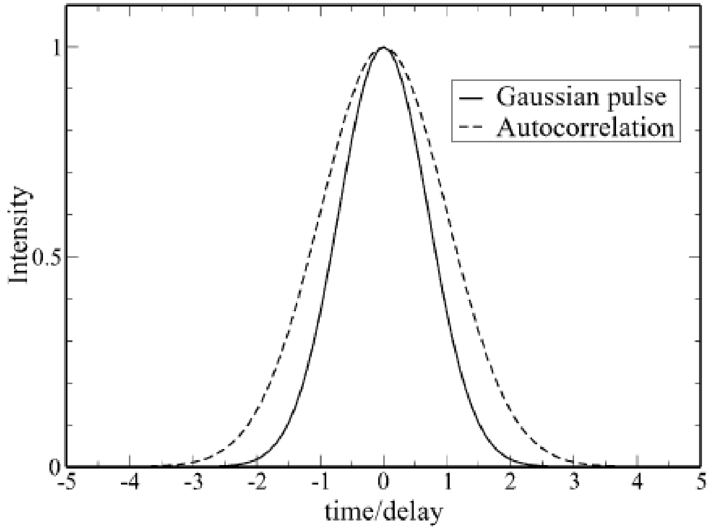
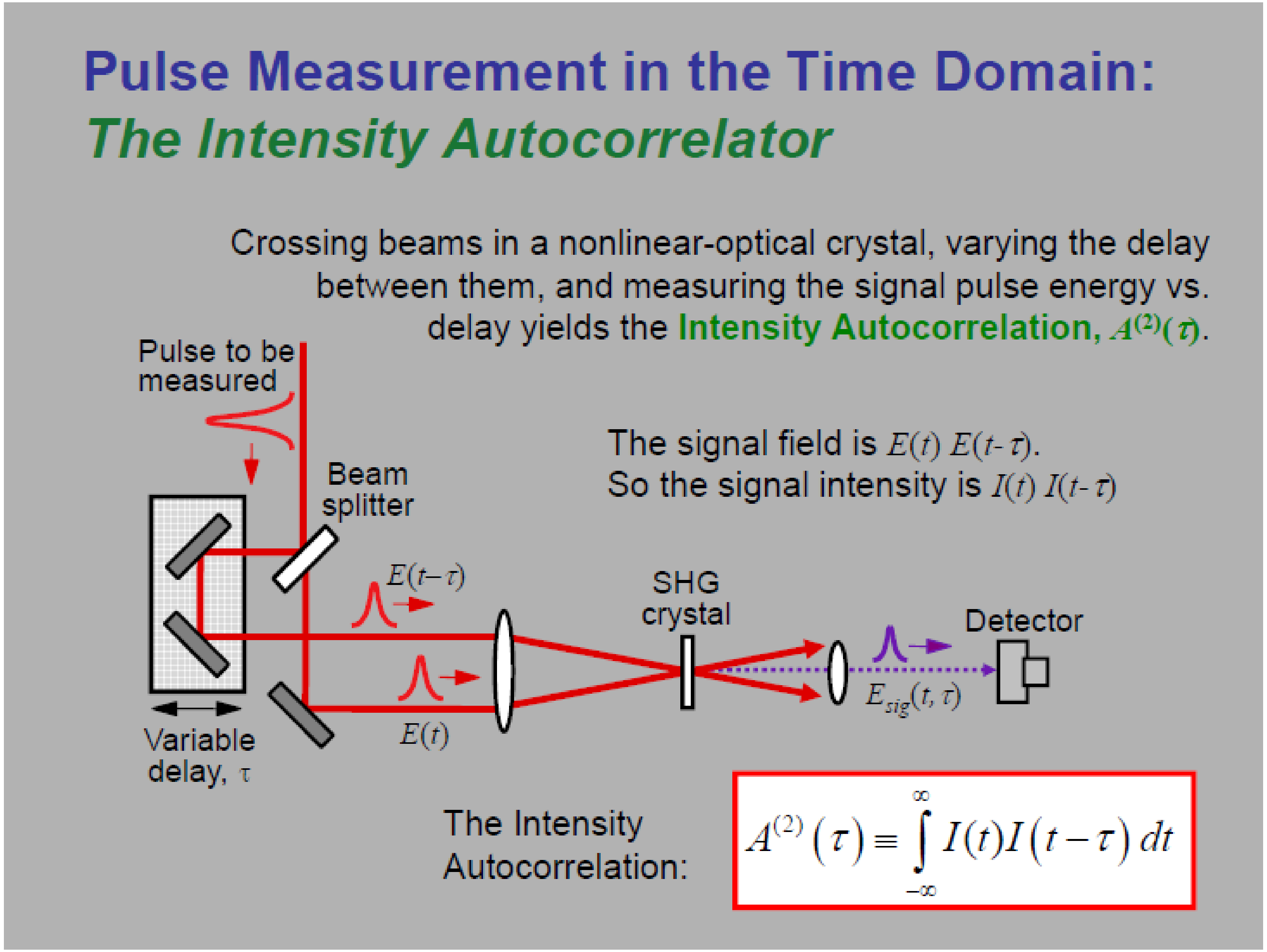


Figure 4.9: Autocorrelation function (dashed line) of a Gaussian pulse, $I = e^{-t^2}$ (solid line)

- Background Free Single Shot Autocorrelators (SSA)



Pulse Measurement in the Time Domain:
The Intensity Autocorrelator

Crossing beams in a nonlinear-optical crystal, varying the delay between them, and measuring the signal pulse energy vs. delay yields the **Intensity Autocorrelation, $A^{(2)}(\tau)$**.

The signal field is $E(t)\,E(t-\tau)$.
So the signal intensity is $I(t)\,I(t-\tau)$

The Intensity Autocorrelation:

$$A^{(2)}(\tau) \equiv \int_{-\infty}^{\infty} I(t)I(t-\tau)\,dt$$

Limits…

- ✓ Autocorrelation function is always symmetric, but this should not be the case for the real pulse.
- ✓ Autocorrelation function and pulse can have different temporal shape, so the method provides only an estimate of the pulse width, but not the actual pulse profile.
- ✓ Pulse broadening in optical components of the autocorrelator and mechanical inaccuracy of e.g. delay line or SHG crystal alignement can affect the measurement.

… and Capability

- ✓ Nevertheless, pulses as short as few femtosecond have been measured with this technique, which is good enough for optical spectroscopy applications.