Photodetectors

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*On leave from INR RAS (Moscow)
Outline

• *Photon and photoelectric effect*
• *Photodetectors and their parameters*
  - Vacuum
  - *Solid state*
  - Hybrid
  - Gaseous
• *Photodetector #1*
Sources

Most important sources were borrowed from the web pages of:
- Photonis: http://www.photonis.com/
- Delft Electronics Products: http://www.dep.nl/
- Photonique: http://www.photonique.ch/
- SensL: http://www.sensl.com/
- ...

And from many other lectures and presentations, in particular by:
Philippe Mangeot (CEA/DSM/DAPNIA)
Dieter Renker (PSI)
Katsushi Arisaka (UCLA)
Eckart Lorenz (ETHZ/mpi)
Christian Joram (CERN)
Amos Breskin (Weizmann Institute of Science)
Thomas Patzak (IN2P3/APC)
Jerry Blazey (Northern Illinois University)
Bayarto Lubsandorzhiev (INR)

Thank you and many apologizes (overall for the ones I forgot to cite!)
The photon

The photon is the elementary particle responsible for electromagnetic phenomena. It is the carrier of electromagnetic radiation of all wavelengths, including gamma rays, X-rays, ultraviolet light, visible light, infrared light, microwaves, and radio waves. Like all quanta, the photon has both wave and particle properties ("wave–particle duality").

Some properties (see PDG Review):

- **Mass:** \( m < 6 \times 10^{-17} \text{ eV} \)
- **Velocity:** \( c = 299,792,458 \text{ m/s} \)
- **Electric charge:** \( q < 5 \times 10^{-30} \text{ e}^- \)
- **Mean life time:** Stable
- \( I(J^{PC}) = 0,1(1^- - ) \)
- **Energy:** \( E = hc/\lambda \)
- **Momentum:** \( p = h/\lambda \)
- ...
Humans can see only the wavelengths of electromagnetic radiation between about 380 and 760 nanometers...this is visible light. Our eyes do not have detectors for wavelengths of energy less than 380 or greater than 760 nanometers.
How to detect a photon

I will discuss photodetectors which are based on photoelectric effect (discovered by H.R. Hertz in 1887): a quantum phenomenon in which atomic electrons (photoelectrons) are ejected after the absorption of photons by atom.

**Photoelectric effect:**
- external photo-effect (photoelectron is emitted out of material)
  The maximum energy of the outgoing electron is:

\[ E_{\text{max}} = \frac{hc}{\lambda} - \phi_0, \]

Where \( \phi_0 \) – is the work function, the minimum energy required to remove a delocalized electron from the surface of any given material (metal).
- internal photo-effect (photoelectron is inside of material)

An intrinsic photoconduction: if \( \lambda < \frac{hc}{E_g} = 1.24/E_g (eV) \), [\( \mu \text{m} \)]
  \( \lambda \) – is wavelength of light, \( E_g \) – semiconductor energy bandgap
An impurity band photoconduction: photo-ionization of shallow impurities (non-ionized at low temperature)
**Photoelectric effect**

External photo-effect (electrons ejected from material). H. Hertz (1887), A. Stoletov (1888) and P. von Lenard (1902) helped establish the external photoelectric effect.

Internal photo-effect (electrons do not leave the media). In 1839, A. Becquerel observed the photoelectric effect via an electrode in a conductive solution exposed to light. In 1873 W. Smith found that selenium is photoconductive.
Heinrich Rudolf Hertz (February 22, 1857 – January 1, 1894) helped establish the photoelectric effect (which was later explained by Albert Einstein) when he noticed that a charged object loses its charge more readily when illuminated by ultraviolet light.

Albert Einstein (March 14, 1879 - April 18, 1955) received the 1921 Nobel Prize in Physics "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."
Types of photodetectors

**Vacuum photodetectors**
- PMTs
- Microchannel plate PMT

**Solid state photodetectors**
- Photodiodes, phototransistors and PIN diodes
- Avalanche photodiodes (APDs)
- Multipixel Geiger-mode APDs (SiPMs)

**Hybrid photon detectors**
- Hybrid phototube with luminescent screen
- HPD
- HAPD

**Gaseous photodetectors**
- Photodetectors with gas photocathode
- Photodetectors with solid photocathode
Typical photodetector parameters

- Quantum efficiency and spectral response: \( \text{QE}(\lambda) = \frac{N_e}{N_\gamma} \)
- Geometric size (sensitive area, dimensions, weight)
- Operating voltage
- Power consumption
- Gain: \( M(U), M(T) \)
- Excess noise factor: \( \text{ENF}(M) = 1 + \frac{\sigma_M^2}{M^2} \)
- Noise (Equivalent noise charge or ENC) as a function of signal integration time (for some photodetectors: dark count)
- Linearity(M)
- Time resolution (signal rise time, spread of p.e. transit time)
- Gain vs. signal rate dependence
- Lifetime
- ...
Vacuum Devices: PMT

In 1902, Austin and Starke reported that the metal surfaces impacted by cathode rays emitted a larger number of electrons than were incident. The use of secondary emission as a means for signal amplification was proposed as early as 1919. The first photomultiplier tube was invented in August 1930 by L.A. Kubetsky from USSR (see presentation of B. Lubsandorzhiev at Beaune-2005, NIM A567 (2006) 282). In 1936 Zworykin, Morton and Malter of RCA also reported on multistage PMT. It was used to pickup sound for movies.

“Kubetsky tube” (1930)
Some important parameters:
Gain: up to $10^7$
QE: $20 \div 30 \%$ for 400 nm light (peak)
Excess noise factor: $1.1 \div 1.15$
Time resolution: $\sim 1$ ns
Operating voltage: $1000 \div 2000$ V
PMTs

Different shapes and sizes: up to 20 inch in diameter
Photocathods

Response of conventional alkali photocathode

- CsTe
- Bi-alkali
- Multalkali
- Extended red Multalkali

Wavelength (nm)

Multalkali: Sb-Na-K
Bialkali: Sb-K-Cs, Sb-Na-K

Transmission mode photocathodes

<table>
<thead>
<tr>
<th>Cone Code</th>
<th>Photocathode Material</th>
<th>Window Material</th>
<th>Spectral Range (nm)</th>
<th>Peak Wavelength (nm)</th>
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<tr>
<td>100M</td>
<td>Cs-I</td>
<td>MgF₂</td>
<td>115 to 200</td>
<td>140</td>
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<tr>
<td>200S</td>
<td>Cs-Te</td>
<td>Silicon dioxide</td>
<td>160 to 320</td>
<td>210</td>
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<tr>
<td>200M</td>
<td>Cs-Te</td>
<td>Sb-Te</td>
<td>115 to 330</td>
<td>220</td>
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<td>Cs-Te</td>
<td>Sb-Te</td>
<td>160 to 320</td>
<td>240</td>
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<td>201A</td>
<td>Cs-Te</td>
<td>Single crystal</td>
<td>150 to 320</td>
<td>290</td>
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<tr>
<td>300K (9-11)</td>
<td>Sb-Cs</td>
<td>BOROSILICATE</td>
<td>300 to 650</td>
<td>410</td>
</tr>
<tr>
<td>400K</td>
<td>Bialkali</td>
<td>BOROSILICATE</td>
<td>300 to 650</td>
<td>420</td>
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<tr>
<td>400U</td>
<td>Bialkali</td>
<td>UV</td>
<td>185 to 650</td>
<td>430</td>
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<tr>
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<td>Bialkali</td>
<td>Silicon dioxide</td>
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<td>430</td>
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<td>401K</td>
<td>High temperature bialkali</td>
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<td>375</td>
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<td>300 to 650</td>
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<td>Silicon dioxide</td>
<td>160 to 650</td>
<td>420</td>
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<td>650</td>
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<td>700K (9-1)</td>
<td>Ag-O-Cs</td>
<td>BOROSILICATE</td>
<td>300 to 1200</td>
<td>800</td>
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</tbody>
</table>

Figure 3-3: Spectral transmittance of window materials

NDIP-08, Aix-les-Bains, 15/06/2008

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New photocathods

From M. Suyama, PD07
Electron affinity is the energy required for an electron at the conduction-band level to escape to the vacuum level. By suitably treating the surface of a p-type semiconductor material, the band levels at the surface can be bent downward so that the effective electron affinity is actually negative. Thermalized electrons in the conduction band are normally repelled by the electron-affinity barrier; the advantage of the NEA materials is that these electrons can now escape into the vacuum as they approach the surface.
PMT Energy Resolution

\[
\frac{\sigma}{E} = \sqrt{\frac{N_\gamma}{N_\gamma}} = \sqrt{\frac{1}{N_\gamma}}
\]

\[
\frac{\sigma}{E} = \left( \frac{\text{ENF}}{N_\gamma \cdot \text{QE} \cdot \text{CE}} \right) + \left( \frac{\text{ENC}}{N_\gamma \cdot \text{QE} \cdot \text{CE} \cdot G_p} \right)^2
\]

\[
\left( \frac{\sigma}{E} \right)_{\text{Single PE}} = \sqrt{\frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n}} = \sqrt{\text{ENF} - 1}
\]

\[
\text{ENF}(M) = 1 + \frac{\sigma_M^2}{M^2}
\]

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

\[
\text{ENF} \approx 1.1
\]
Different PMT dynode geometries

Circular-cage: very compact
Box-and-grid: good collection efficiency, slow
Venetian-blind: good collection efficiency and gain stability, slow
Linear focusing: small transit time spread, fast, sensitive to magnetic fields
Fine-mesh: fast, compact, operate in magnetic fields ~ 1 T, collection efficiency low
Metal channel: compact, high collection area, operate in magnetic field ~10 mT

Table 3-2: Typical time characteristics (2-in. dia. photomultiplier tubes)
PMTs in magnetic field

Fig. 4.36 Relative gain variation as a function of magnetic field: (a) for a tube with linear focusing dynodes, (b) for a tube with venetian-blind dynodes.
- curve 1: field aligned with y-axis (Fig. 4.35)
- curve 2: field aligned with x-axis
- curve 3: field aligned with z-axis

Require μ-metal shield!!!

Fine-mesh PMT

Figure 6.25: Gain vs. magnetic flux density
MCP PMT

Core: hard etchable glass
Cladding: lead glass

(a) Schematic structure of an MCP
(b) Principle of multiplication

Figure 2 – Comparison of 5micron pore and 2 micron pore MCP’s (same magnification)

- Monofiber draw
- Multifiber stack and draw
- Billet stacking
- Slicing (6~ 5 to 10°)
- Etching of core glass
- Reduction of lead glass
  - $H_2 @ 250$ to $450°C$
  - => Semiconductive layer
- Vacuum deposition
  - NiCr electrodes

Philippe Mangeot  CEA/DSM/DAPNIA

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MCP PMT

- Structure and principle
  - Glass window
  - Photocathode
  - Photon
  - Photoelectron
  - Dual MCP
  - Gain ~ 10^6
  - ΔV ~ 300 V
  - ΔV ~ 3000 V
  - ΔV ~ 300 V
- Chevron structure:
  - Reduces space charge
  - Reduces ion feedback
  - Increases gain
- Anode may be pixilated

Gain vs. voltage

Gain vs. mag. field

Single p.e. response

TTS spread

NDIP-08, Aix-les-Bains, 15/06/2008

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Solid state photodetectors: internal photoelectric effect in Si

Internal photoeffect

Figure 5a: Internal quantum efficiency in the wavelength range from 150 nm to 1000 nm. Below 300 nm a quantum yield above unity is achieved, i.e. more than one electron-hole pair is generated per incident photon. The drop beyond 950 nm is due to the beginning transparency of silicon in the infrared. The detector thickness for these measurements was 300 µm (from [5]).
Solid state photodetectors: light absorption in silicon

The absorption coefficient vs. photon energy in silicon at different temperatures.
1. and 2. - (Sze [1981]);
3. - (Jellison and Modine [1982]).

Absorption length of light in Si (T~300 K)

Lifetime of carriers generated by light in good quality silicon >10^-3 sec
Solid state photodetectors: Photodiode

Applying reverse voltage to the p-n junction we can collect these photocarriers.

Si photodiode

N-region can have very high resistivity and be very thick ~300-500 μm → PIN photodiode

Advantage: very high QE for visible light (up to 95% with antireflective layer)
Disadvantage: no gain
Solid state photodetectors: phototransistor

Photoelectric signal can be amplified
Solid state photodetectors: avalanche multiplication

Another way to amplify photoelectric signal: applying high electric field in uniform p-n junction may cause an avalanche multiplication of electrons created by absorbed light.

![Ionization coefficients as a function of electric field in silicon](image)

Silicon is a good material for APD construction: high sensitivity in visible and UV range, significant difference between ionization coefficients for electrons and holes – smaller positive feedback and smaller multiplication noise.
Solid state photodetectors: APDs

Avalanche photodiodes are photodiodes with built-in high electric field region. With increasing reverse bias voltage, electrons (or holes) are accelerated and can create additional electron-hole pairs through impact ionization.

Excess Noise Factor:
\[ F = k \cdot M + (1-k)(2-1/M) \]
\[ k = \frac{\beta}{\alpha} \] (k-factor)
\( \beta \) - ionization coefficient for holes
\( \alpha \) - ionization coefficient for electrons
(see R.J. McIntyre, IEEE Tr. ED-13 (1972) 164)

5x5 mm² APDs developed by Hamamatsu and CMS collaboration for the CMS ECAL: “reverse rich-through structure”
Solid state photodetectors: APD parameters

Advantages: high QE, gain up to 1000, area up to 1 cm²
Disadvantages: ENF and temperature coefficient increases with the increase of gain
Solid state photodetectors: “beveled edge” APDs

It is made by growing the p-type epitaxial layer on n-type neutron transmutation doped silicon. The broad gain region enables device operation at high gain with low excess noise and excellent gain uniformity. The APD edge (perpendicular to the junction) is beveled in order to reduce the field along the device edge, enabling the device to sustain the high biases necessary for APD operation.

_Schematic cross-section and electric field profile, according to Advanced Photonix Inc._
(from M.Moszynski et al., NIM A485 (2002) 504)
Solid state photodetectors: “beveled edge” APDs-II

- High gain > 100
- Large area – up to 16 mm in diameter
- High QE
- Low excess noise factor

(measured by Advanced Photonix, Inc.)
Solid state photodetectors: Planar APDs from RMD

Planar APDs from RMD

- Manual Bevel Process
  - Deep Diffusion into Si wafer, p-n-p
  - Si Removal
  - Bevel Formed

- Planar Process
  - Wafer Diced

- 64-pixel APD array
  - 0.9x0.9 mm² pixel size

This APD is really large!

- 13 cm² APD on a 2 inch diameter silicon wafer
Solid state photodetectors: Avalanche photodiodes: Arrays

Arrays of APDs can be produced with a very good fill factor.

The biggest problem is the connection to the readout electronics.

16 CsI(Tl) crystal coupled to the array and illuminated by a $^{22}$Na source

R. Farrell et al., NIM A442 (2000) 171

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**Solid state photodetectors: APD’s operated in Geiger mode**

*High gain → operate APDs over breakdown → Geiger mode APDs*

Single pixel Geiger mode APD’s developed long time ago
(see for example: R.Haitz et al, J.Appl.Phys. (1963-1965))

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- Single pixel devices are not capable of operating in multi-photon mode
- Sensitive area is limited by dark count and dead time (few mm² Geiger mode APD can operate only at low temperature, needs “active quenching”)

**Solution: Multipixel Geiger mode APD (MPGM APD)**
Solid state photodetectors: Multipixel Geiger-mode APDs (SiPMs): Structure and principles of operation

- Geiger avalanche is quenched by an individual pixel resistor (from 100kΩ to several MΩ).
- It contains 100÷20 000 pixels/mm², made on common substrate and connected together.
- Each pixel works as a binary device.
- MGAPD is pixellated silicon avalanche photodiode operated in Geiger mode (~10-20% over breakdown voltage).
- For small light pulses \(N_γ < N_{\text{pixels}}\) device as a whole works as an analog detector.

**Picture from talk of E. Grigoriev at Como 2001**

**MPGM APDs/SiPMs have very good pixel-to-pixel signal uniformity.**

Green-red light sensitive APD, low amplitude light signals, \(U=43\,\text{V}, \, T=-28\,\text{C}\)
Solid state photodetectors: SiPM structure for green/red light


Absorption length for light in silicon

(Y. Musienko, PD-07, Kobe)

(Y. Musienko, Beaune-05)

MEPhI/PULSAR APD, T=22C, U=59 V

PDE [%]

0 2 4 6 8 10 12

400 450 500 550 600 650 700 750 800

Wavelength [nm]

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Solid state photodetectors: Blue sensitive SiPM

Another solution: “reversed” APD structure. In “reversed” structure electrons initiate the avalanche breakdown.

Measured using technique described in NIMA 567 (2006) 57

(Y. Musienko, PD-07, Kobe)

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Solid state photodetectors: Optical cross-talk in SiPM

Hot-carrier luminescence:
$10^5$ carriers produces ~3 photons with an wavelength less than $1 \mu m$
Increases with the gain!

Optical cross-talk causes adjacent pixels to be fired $\rightarrow$ increases gain fluctuations $\rightarrow$ increases noise and excess noise factor!

Optical cross-talk increases the excess noise factor and dark count at high electronics thresholds

(E.Popova, CALICE meeting)
Solid state photodetectors: Optical cross-talk reduction

Solution: optically separate pixels with grooves

(E. Grigoriev Como 2001)

CPTA/Photonique SSPM with trenches
Solid state photodetectors: After-pulsing in SiPMs

Solution: “cleaner” technology or longer pixel recovery time

Events with after-pulse measured on a single micropixel.

After-pulse probability vs bias
Solid state photodetectors: SiPM linearity

Linearity of SiPM is determined by its total number of pixels:

\[ N_{\text{fired cells}} = N_{\text{total}} \cdot (1 - e^{-\frac{N_{\text{photon}} \cdot \text{PDE}}{N_{\text{total}}}}) \]

This equation is correct for light pulses which are shorter than pixel recovery time, and for an “ideal” SiPM (no cross-talk and no after-pulsing).

(B. Dolgoshein, TRD05, Bari)
Solid state photodetectors: SiPM timing

SiPMs have excellent timing properties

Measured with MEPhI/Pulsar SiPM using single photons (B. Dolgoshein, Beaune-02)

Measured with 100 μm SPAD using single photons

35 ps time resolution at room temperature with large area single photon avalanche diodes

A. Guiliani, P. Maccagnini, L. Rech, M. Ghioni and S. Cova
Solid state photodetectors: Large area SiPMs

SiPMs with up to 3x3 mm² area produced by many companies: Hamamatsu, CPTA/Photonique, Pulsar, Zecotek, SensL, FBK-irst

FBK-irst SiPMs, C. Piemonte: June 13th, 2007, Perugia
Solid state photodetectors: VLPC

Visible Light Photon Counter (developed by Rockwell):
- Impact ionization of As doped
- Impurities (E~54 mV)
- Impurity band conduction (at low T)

Advantages: QE(520 nm)~70%, M~50 000, pulse width ~1 ns
Disadvantages: Dark count rate ~20 kHz, very sensitive to IR photons, T_{op}=6-9 K
Hybrid photodetectors: Hybrid phototube with luminescent screen

A.E.Chudakov 1959 - hybrid tube with luminescent screen
Van Aller et al. 1981 - prototypes of «smart tube»
Van Aller et al. 1981-1986 - XP2600
L.Bezrukov, B.Lubsandorzhiev et al. 1985-1986 - Quasar-300 and Quasar-350 tubes
L.Bezrukov, B.Lubsandorzhiev et al. 1987 - Tests of XP2600 and Quasar-300 tubes in Lake Baikal
L.Bezrukov, B.Lubsandorzhiev et al. 1990 - Quasar-370 tube.

B.K.Lubsandorzhiev, Ringberg Castle 23-28 September 2007

The PMT used in the Quasar-370LSO had ~17% η(efi)

Single electron resolution ~35% (fwhm)
Hybrid photodetectors: HPD

- Hybrid photo diodes (HPD)

Photo cathode + p.e. acceleration + silicon det. (pixel, strip, pads)

Photo cathode like in PMT, $\Delta V$ 10-20 kV

$$G = \frac{e\Delta V}{W_{Si}} = \frac{20 \text{ keV}}{3.6 \text{ eV}} \approx 5 \cdot 10^3 \quad \text{(for } \Delta V = 20 \text{ kV)}$$

Single photon detection with high resolution

Poisson statistics with $\bar{n} = 5000$

Background from electron backscattering from silicon surface

5” HPD
Bialkali KCsSb UV extend
Si 2048 ch 1x1mm²
HV = 20 kV
C. Joram Beaune 2002
Hybrid photodetectors: HAPD

![Diagram of Hybrid Photodetector: HAPD](image)

**Gain Characteristics**

- **Electron Bombarded Gain**
  - 1600 at -8 kV
- **Avalanche Gain**
  - 110 at 405 V
- **Total Gain**
  - 180,000

**Time Response**

- **Rise Time**: 360 ps
- **Fall Time**: 340 ps

From M. Suyama, PD-07

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Hybrid photodetectors: HAPD-II

144 multi-anode HPD

Blalkali Effective area: 60x60mm

AD 5x5mm pixel 12x12 pixels

Nagoya Univ., KEK, Tokyo metropolitan Univ.

73mm

28mm

Please refer to Adachi-sensei’s presentation

Proximity focused HPD

Multi-pixel AD 16x16 mm² 8x8 pixels

For operation in magnetic fields

High QE HAPD for MAGIC camera

From M.Suyama, PD-07

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Gaseous photodetectors: Why?

Why GPMs?

- large area
- flat geometry
- Moderate cost
- Operation in high magnetic fields
- Operation at very low temperatures
- Sensitivity to single photons
- Spectral range from UV to visible
- Fast (ns range)
- High localization accuracy (sub-mm)

Applications:
RICH, calorimetry, astroparticle physics, medical, plasma, atomic...etc.

Beaune 2005

A. Breskin
Gaseous photodetectors: principles of operation

Cathode pad read-out with fully integrated electronics over the back side → reduced cabling, less dead space
Gaseous photocathodes

- Photon conversion directly on gas molecule
- $E_{\lambda}$ must be > Ionization potential of gas
- Most gas have $E_{ion} > 10$ eV => $\lambda = 1240/10 = 124$ nm far UV
- But
  - $TEA$ triethylamine $[(C_2H_5)_3N]$ $E_{ion}=7.5$ eV
  - $TMAE$ tetrakis(dimethylamino)ethylene $[C_{10}H_{24}N_4]$ $E_{ion}=6.1$ eV

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Gaseous photodetectors: TEA

**Multistage chamber**
- First RICH in operation
- E605 at FNAL
- 15 m He radiator
- 2 chambers
- 40 x 80 cm²
- Ar +TEA
- 3% TEA (bubbling @ 10°C)
- Gain $4 \times 10^6$ to $10^7$

**Advantages of TEA**
- High vapor pressure
- Good QE
- Small free mean path for UV

**Disadvantages of TEA**
- Too high threshold 7.5 eV (165 nm)
- Need UV optic (mirror, windows)
- Needs very high transmission Cerenkov medium

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Gaseous photodetectors: TMAE

drift chamber (DELPHI, SLD, OMEGA)

• TMAE
  – Use of quartz windows
  – High QE

• Thick detector
  – Improve absorption

• Drift zone
  – Eliminate parallaxe

• End detector
  – $X$, $Z$ detection
  – Time => $Z$ coordinate

• Drawback of TMAE
  – Low vapor pressure
  – Long absorption range
  – Could need to warm up
  – Aggressive stuff
Gaseous photodetectors: solid photocathode

Solid photocathode

✓ CsI first choice
  - Quartz windows
  - Good QE
  - Gas resistant
    - If no H2O or pollutants
Micro pattern GPMs

✓ Micromegas

- Photon transmission
- Microwave photocathode
- 800 V
- Drift space
- Phototransmission space
- 500 V
- Amplification space
- 0 V

CsI photocathode may be deposited under the drift electrode (transmission mode) or on top of the micromesh (reflection).

High gain reachable:
- Low ion/photon feedback
- Optical screening

Single photon amplitude spectrum
CsI photo cathode
Y. Giomataris

✓ GEM

- Semi-transparent PC
- Reflective PC

- Fast signals [1-10 ns]
- High gain (>10^5)
- Sensitivity to single photoelectrons
- Operation in noble gases (mixtures)
- High 2D precision

- Largely reduced photon feedback compared to "open" geometry
- No photon feedback
- Easier production of thick PC
GMP for visible light

Sealed detector package with semitransparent K-Cs-Sb PC

Sealing in gas: In/Sn; 130-150°C

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>QE %</th>
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<tbody>
<tr>
<td>300</td>
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<tr>
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<tr>
<td>500</td>
<td>15</td>
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<tr>
<td>600</td>
<td>5</td>
</tr>
</tbody>
</table>

13% = best QE measured after sealing.
2 weeks stability

Best sealed GPMT: QE = 6% @ 365 nm stable for 1 month

under development:
Silicon (with Glasgow Univ.), ceramic
Expected higher stability

Beaune 2005
D. Mörmann et al. NIM A504 (2003) 93
M. Balcerzyk et al. IEEE TNS 50 (2003) 847

A. Breskin
The Eye – photosensor #1

The first proto-eyes evolved among animals 540 million years ago. The human eye is about 2.5 cm in length and weighs about 7 grams. Light passes through the cornea, pupil and lens before hitting the retina. The iris is a muscle that controls the size of the pupil and therefore, the amount of light that enters the eye. Also, the color of your eyes is determined by the iris. The vitreous is a clear gel that provides constant pressure to maintain the shape of the eye. The retina is the area of the eye that contains the receptors (rods and cones) that respond to light. The receptors respond to light by generating electrical impulses that travel out of the eye through the optic nerve to the brain.

The cone cells (for color) and the rod cells (for low-light contrasts) in the retina detect and convert light into neural signals. The visual signals are then transmitted to the brain via the optic nerve. The optic nerve contains 1.2 million nerve fibers. This number is low compared to the roughly 100 million photoreceptors in the retina.
The Eye – photosensor #1: Rods and cones

**Rods cells**
- There are ~100000000 rods in human eye
- Used for night vision
- Highly sensitive to light; sensitive to scattered light (they have more pigment than cones)
- Loss causes night blindness
- Low spatial resolution with higher noise
- Not present in the fovea
- Slower response to light; rods need to be exposed to light over time
- One type of photosensitive pigment (monochromatic stimulus)
- Confer achromatic vision, with more emphasis on detecting motion

**Cone cells**
- There are ~5000000 cones in human eye
- Used for day vision
- At least 1/10th of the rods' light sensitivity; sensitive only to direct light
- Loss constitutes legal blindness
- High spatial resolution with lower noise
- Concentrated in the fovea
- Quicker response to light; can perceive more rapid changes in stimuli
- Three types of photosensitive pigment in humans (trichromatic stimulus)
- Confer color vision, with more emphasis on detecting fine details

Rods&cones. Spectral sensitivity

It was found that human eye can detect light pulse of 10-40 photons. Taking into account that absorption of light in retina is \( \sim 10\text{-}20\% \) and transparency of vitreous is \( \sim 50\% \) \( \Rightarrow \) \( \sim 2\text{-}8 \) photoelectron give signal is detected.