Advanced Photodetectors for High Energy Physics Particle Astrophysics and Medical Imaging

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Abstract. This article is a survey of advanced major photodetectors for High Energy Particle Physics, Particle Astrophysics and Medical Imaging. It is intended to give a broad background to ICFA level students. Description, operation and some applications of such photodetectors will be described.

INTRODUCTION

There have been major advances in photodetectors in the last two decades due to advancements in High Energy Particle Physics, Particle Astrophysics and Medical Imaging. Advancements in Solid State technology, rapid advances in electronic circuitry and computer technology helped in this advancement. Photon Detectors are so many types that we will select some of them due to their specific applications.

A human eye is the most incredible photon detector in image forming in color to a resolution of $2 \times 2 \mu m^2$, about 60 times a second (Encyclopedia Britannica 1999). A human eye may have about $1.3 \times 10^4$ by $1.3 \times 10^4$ pixels (sensors). Detection threshold of an eye is about 2500 photons per cm$^2$. Such a threshold can only be achieved by staying in a very dark room for at least half an hour. Then we need to slowly increase exposing our eyes to light, not to damage the retina.

Photon Detectors

A photon detector is a device that converts photons to electronic signals. We can classify them as vacuum photon detectors, solid-state photon detectors and hybrid photon detectors. Some of them convert photons into electrons and holes without internal multiplication (photodiodes), and some of them have internal multiplication of electrons by cascade processes (photomultipliers, PMTs). They can measure time from picoseconds to seconds, energy from eV to multi GeV, and positions from $\mu m$ to meters. Commercially available photodetectors can be sensitive to wavelengths, $\lambda$, from UV (200-300nm) to far infrared (IR up to 50 $\mu m$).
Vacuum Photodetectors

All vacuum photodetectors have windows inner surface coated with low work function materials (e.g. bialkali coating). When a photon enters through the window it may free an electron from the low work function material (photocathode). This process is formulated well by Einstein. Albert Einstein wrote a paper about the quantum nature of the photoelectric effect in 1905 and awarded his Nobel Prize in 1921 for the photoelectric effect,

\[ E = h \nu - \phi \]

Where, \( E \) is the energy of the exiting electron from the photocathode, \( h \) is the Planck Constant, \( \nu \) is the frequency of the incoming photon and \( \phi \) is work function of the photocathode material. It is clear from the formula that the photon has to carry more energy than the work function of the photocathode material. The photon may not produce a detectable electron due to the reason that photocathode material has to be very thin, otherwise the electron may not get through the material. This thickness is very precisely adjusted. The efficiency of producing detectable electron is expressed in quantum efficiency (QE),

\[ QE (\lambda) = \frac{\text{number of detected photoelectrons}}{\text{number of incident } h \nu} \]

QE in percent can be expressed as a function of radiant sensitivity \( S_R \) and wavelength \( \lambda \) as,

\[ QE = S_R \left( \frac{1239.5}{\lambda} \right) \times 100 \% \]

A typical QE for a bialkali photocathode and for \( \lambda = 420 \) nm wavelength is about 20 %. The QE drops off rapidly for larger \( \lambda \), and the window has to be made of quartz for the UV photons to penetrate and produce photoelectrons from the photocathode. Among them are single anode PMTs, multi-anode PMTs (MAPMTs), multi channel plate PMTs (MCP-PMTs). They will be briefly described here. A most commonly used PMT is shown in Figure 1.

![Figure 1. The most commonly used type of photomultiplier tube.](image-url)
In a vacuum PMT the photoelectron is accelerated to the dynodes and cascade multiply and collected by the anode. Depending on the electric fields between the dynodes and the number of dynodes one photoelectron may become up to few times $10^6$. This is an exponential multiplication process. There are variety of PMTs, Venetian-blind, metal dynode, wire mesh dynode and multianode (MAPMTs). They come in various shapes and sizes.

MAPMTs have been mainly manufactured by Hamamatsu Company, Japan. They may be produced with multi-wire anode or multi-anode pads. They are also produced having wire-mesh dynodes or with Venetian-blind dynodes. Figure 2 shows a multi wire anode MAPMT that was assembled with amplifiers close to the base. Some of these tubes were used for a double Compton Scattering Camera [1].

![Figure 2](image)

**FIGURE 2.** An assembled multi wire anode MAPMT that was used for a double Compton Scattering Camera. It had 16 X and 16 Y cross-wire anodes. 32-channel preamplifiers are mounted close to the base.

Figure 3A illustrates a cutaway view of a MCP (Multi Channel Plate) PMT together with one of the channels. Lead Glass channels are highly resistive, therefore high electric field gradient is developed in the channels, when a high voltage is applied between the two ends of the MCP. When a photoelectron is entered in one the channels, it is cascade multiplied, forming an avalanche of electrons. A gain of $10^3$-$10^6$ can be obtainable depending on the channel length and the applied high voltage. This feature of the MCP can be used for boosting photo-image as illustrated in Figure 3B.
FIGURE 3A. A cut schematic view of a MCP-PMT together with a view of a micro channel showing the avalanche multiplication process.

FIGURE 3B. Illustrates how a MCP-PMT can be used for boosting an optical image.
Solid State Photodetectors

Among them are PIN-junction diodes, Charge Coupled Devices (CCD), Avalanche Photodiodes (APD), and Visible Light Photon Counters (VLPC). The first two do not have electronic charge gain, but the APD and the VLPC can produce substantial internal electronic gain. The first three of them are manufactured by several companies, but the VLPC is made exclusively by a branch of Boeing Co. in Los Angeles, California.

All of these devices above are made of semiconductors. There are two types of semiconductors: intrinsic semiconductors and extrinsic semiconductors, and there are two types of photo-effects, intrinsic photo-effect and extrinsic photo-effect. In the case of intrinsic photo-effect, a photon creates an electron hole pair from a bound semiconductor lattice. For the case of extrinsic photo-effect, a photon creates a free electron and a bound hole by interacting with an impurity atom in a semiconductor lattice. The effects are described in the Figures 4-a and b. An electron-hole pair in a semiconductor can be created if,

\[ h\nu \geq E_g \text{, another way of writing } \frac{hc}{\lambda} \geq E_g \]

where, \( h \) is the Planck constant, \( \nu \) is the frequency of the photon, \( \lambda \) is the wavelength of the photon, \( c \) is the speed of light, and \( E_g \) is the bandgap of the semiconductor.

FIGURE 4A. A schematic diagram for the intrinsic photoeffect.

FIGURE 4B. A schematic diagram for the extrinsic photoeffect.
PIN-JUNCTION DIODES

These photodiodes converts the photons into electrical currents with no internal gain. They can be used for detecting burst of photons of sufficient intensity possibly from scintillating crystals in detecting gamma-rays. They can have good quantum efficiencies around 70% to visible photons with silicon oxide antireflective coating. A cross section sketch of a PIN diode is shown in Figure 5-a and b. It is a n-type silicon wafer with p-layer doping as shown in the Figure 5a. Figure 5b shows the energy level diagram. The photons are absorbed in the valence band giving rise the electrons into the conduction band.

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CHARGE COUPLED DEVICES (CCD)

Charge coupled devices are imaging devices that are very widely used in video cameras, as charge particle tracking devices for High Energy Particle Physics, for medical imaging and Astronomy. They are mainly Silicon based devices. GaAs – CCD is being developed for X-ray imaging. Pixel size and thickness of a CCD may vary depending on the applications. As small as 10 micron pixel size CCDs have been manufactured. They are they are slow devices. Electronic charges from the photo conversions are collected in the pixels and read out typically 50-60 times a second to form images. The readout speed very much depends on the size of the CCD and the clock rate of the readout. Figure 6 shows a block diagram of a relatively old type CCD with two-phase clock operational Fairchild CCD202. It shows pixels(charge storage wells), vertical and analog transport registers, clock lines, amplifier, gate and video output. The charges accumulated in the storage wells are first moved to vertical analog transport registers, and then shifted out from pixel to pixel to the horizontal analog registers and from there shifted out by using the two-phase clock system. Typical clock rate is around 15 MHz. More information about the operation of CCD can be found in [2].
ELECTRON BOMBARDED CCD (EBCCD)

A cross-section view of an EBCCD is shown in Figure 7. In this case, photoelectrons produced from the photocathode can be electrostatically focused under a substantial electric field. About 8 to 12kV potential may be applied between the cathode and anode depended on the required gain. These electrons with substantial kinetic energy hit the CCD and produce gain by ionizing the silicon of the CCD. It is an image intensifier where charge gain is required [3]. The fiber optic window reduces the image distortion.
FIGURE 7. A schematic diagram of an electrostatically focused EBCCD that can boost an optical image.

AVALANCHE PHOTO DIODES

Avalanche photo diodes (APD) are silicon base devices that can run in the avalanche mode and the Geiger (breakdown) mode. A cross-section view of an APD together with bias-voltage gain characteristics are shown in Figures 8a and b. Typical gain in the avalanche mode is 50-100 and the gain may reach $10^7$ in the Geiger mode of operation. They are used mainly in the avalanche mode for optical coupling of fibers in communication and in High Energy Particle Physics experiments for detecting photons from scintillating crystals with electromagnetic calorimeters [4].
FIGURES 8A AND 8B. (A) Cross section of the API APD. Note the beveled edge which prevents early breakdown. (B) Photon absorption, charge drift, and multiplication under bias in the APD.

FIGURE 9. A cross section view of a 7 silicon pad Hybrid PMT.
HYBRID PMT, HPMT

Hybrid Photomultiplier Tubes are very much needed when there is a strong magnetic field in the region where they are used as photodetectors [5]. DEP Co. in Holland has been developing these with multi-anode structure as proximity focusing devices which makes them operate in strong magnetic fields without large gain drop. Photoelectrons that are produced from the photocathode are accelerated under a high voltage (around 10kV) hit a PIN-Diode (see the earlier pages) and produce large number of electron-hole pairs in the silicon. An electronic gain of 2000-3000 is obtainable in such a device due to the kinetic energy gained by the electrons under the applied electric field. Approximately 3.6eV energy is required for producing an electron-hole pair. Cross-section and multi-pad anode view is shown in Figure 9. HPMT can be used as a photon counter due to the internal gain and long integration time preamplifier. Figure 10 shows a pulse height spectrum obtained by G. Anzivino et.al. [6] at low rates due to the slow low noise amplifier used for obtaining the pulse height spectrum.

![Graph showing pulse-height spectrum of an electrostatically focused HPD exposed to a small number of photoelectrons per light pulse.](image)

**FIGURE 10.** Pulse-height spectrum of an electrostatically focused HPD exposed to a small number of photoelectrons per light pulse.

Visible Light Photon Counters (VLPC)

The Visible Light Photon Counters (VLPC) are the derivatives of the Solid State Photo Multipliers (SSPM) which have high avalanche gain capability, high quantum efficiency (around 80%), and high rate capability Silicon base devices [Refs.7,8,9]. M. Atac has pioneered the development of the VLPC’s, at UCLA working together with M. Petroff of Rockwell International Science Center, now is a subsidiary of Boeing Co. The devices can be used for scintillating fiber tracking and for medical imaging due to their above characteristics.
Operation principles of the VLPCs are given in Reference 8, therefore we will discussed them briefly here. They are Impurity Band Conduction (IBC) devices that are minimized in quantum efficiency in the Infrared (IR) region while maximized in quantum efficiency for the wavelengths around 550 nm relative to the original device, SSPM which was discovered by Rockwell International Science Center. The VLPC's and the SSPMs are silicon based devices with some levels of donor and acceptor concentrations in silicon that are formed by molecular epitaxy technique.

A schematic diagram of the VLPC cross-section is shown in Figure 11.

![Figure 11: Schematic of the operational principles of the VLPC.](image)

In a VLPC, a neutral donor is a substitutional ion with an electron bound to it in a hydrogen-like orbit with an ionization potential of about 0.05eV. Because of this very small energy (band-gap) required for creating electron-hole pair the devices need to run at cryogenic temperatures. Nominally they run at temperatures around 7K. The gain plus the drift region is less than 10μm. When the concentration of impurities is sufficiently high, they form an energy band separated from the conduction band by the ionization potential. When the applied electric field between the substrate and the top contact is sufficiently high, about $2 \times 10^3$ to $10^4$ V/cm, each electron in the gain region starts an avalanche of free electron-hole pairs within 1nsec. The avalanche gain could reach up to $5 \times 10^4$ when applied voltage reaches 7volts. The avalanche may occupy about 10micron diameter area for about few microseconds while the rest of the area of 1mm² is continuously available for detecting photons. The VLPC's are now produced in 2x4 chips having 8 pads for a convenient connection to a ribbon cable. Characteristics of the VLPC's are given in Table I.
Quantum efficiency, avalanche gain and dark count pulse rate as functions of temperature and bias voltage are given in Figure 12. The nominal bias voltage and the temperature settings that are given in the Table I can easily be found from the curves. Neither the quantum efficiency nor the gain is a strong function of the bias voltage and the temperature. We will see in the following paper that achieving 0.1K stability of the temperature is relatively easy by making use of Enthalpy of the boil-off He gas of a liquid Helium dewar.

Table I

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<table>
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<tr>
<td>Quantum efficiency optimized for 530nm</td>
<td>80%</td>
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<tr>
<td>Avalanche gain</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>Thermal electron pulse rate at 6.5K</td>
<td>$-5 \times 10^3$/sec.mm$^2$</td>
</tr>
<tr>
<td>Saturation pulse rate</td>
<td>$5 \times 10^7$/sec.mm$^2$</td>
</tr>
<tr>
<td>Pulse risetime</td>
<td>&lt; 3 nsec</td>
</tr>
<tr>
<td>Average power per pixel</td>
<td>1.5 microwatt</td>
</tr>
<tr>
<td>Optimum operating voltage</td>
<td>~6.5V</td>
</tr>
<tr>
<td>Optimum operating temperature</td>
<td>6-7K</td>
</tr>
<tr>
<td>Dynamic-range (linear)</td>
<td>3000 photoelectrons</td>
</tr>
<tr>
<td>Effect by magnetic field</td>
<td>No effect up to 12kG</td>
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FIGURE 12. Quantum efficiency, avalanche gain and dark count pulse rate as functions of temperature and bias voltage.
REFERENCES

2. Damerell, C.J.S.; Rutherford Appleton Laboratory Preprint, RAL-P-95-008.
5. DEP Co. Catalog, Holland.