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Photosensors

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Abstract

The real-time detection of photons became an important tool in biomedical sciences during the last decades. New techniques like PET are not possible without digital signal processing. The review covers the most common photosensors: photomultipliers, solid-state devices, hybrid detectors and devices based on electron amplification in gas.

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1. Introduction

In biomedical science photographic plates were for a long time the only choice for memorizing images. Still they are the best choice when very high localization resolution is needed but even in this respect real-time digital apparatus become competitive and photographic films will slowly disappear.

New developments in the detection of photons, triggered by particle and nuclear physics, resulted in devices which are orders of magnitude more sensitive than photographic films. The detection of single photons became possible with high efficiency. This offers the possibility to create an image of an—in biomedicine mostly living—object with much lower dose of ionizing radiation.

The high sensitivity together with the excellent time resolution of these devices allow the registration of coincident events and made the Positron Emission Tomography (PET) possible where two X-rays have to be detected simultaneously with a small probability of random coincidences.

Dynamic processes, even if they are varying rapidly, can be observed and registered with limitations only due to the detection mechanism which is, with state of the art detectors, in the range of a few nanoseconds.

A large variety of detectors have been constructed with properties that match a wide range of individual needs. They can be grouped in vacuum devices, solid-state devices, a combination of the two which then is called a hybrid device and gaseous detectors.

2. Basic physical processes

Two processes are used for the detection of photons. Both are based on the transfer of the photon energy to an electron in a collision.

When a photon impinges on the surface of any material it can liberate an electron provided the

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energy of the photon is higher than the photoelectric workfunction ϕ. This was first formulated by A. Einstein in the year 1905 [1]

$$W_{\mathrm{kin}} = h\nu - \phi.$$

The kinetic energy W_{kin} of the electron can be sufficient to bring the electron not only from the surface but also from the volume of the material to the free space. Semiconductors have a very small workfunction ϕ and consequently the threshold wavelength of the incoming photon can be in the near infrared. Standard bialkali photocathodes in photomultipliers (SbKCs) have a threshold at 630 nm (red light).

The other process needs less energy. It is sufficient to lift an electron in a semiconductor from the valence band to the conducting band. Therefore, a silicon crystal (band gap 1.1 eV) can be a very efficient photon detector in the whole range of visible light. When the electron cannot recombine with the hole in the conductive band due to the electric field of a silicon photodiode it can be collected and the signal amplified.

3. Vacuum devices

The first photoelectric tube was produced 90 years ago in 1913 by Elster and Geiter but it took more than 20 years until the first photomultiplier tube was invented by the RCA laboratories in 1936 and became a commercial product. Further innovations such as metal-channel dynodes, mesh dynodes and microchannel plates together with the development of new photocathode materials have led to higher sensitivity and new capabilities.

Photomultipliers have a light transmitting window (mostly glass and very often the whole vacuum container is made of glass) covered at the inner side by a semitransparent photocathode which is made from a thin layer of semiconductor material, some focusing electrodes and a number of so-called dynodes for the electron multiplication. Other constructions are possible and will be discussed later. The mechanics is complicated, need hand work and makes photomultipliers rather expensive. In Fig. 1 the cross-section of a typical photomultiplier is shown.

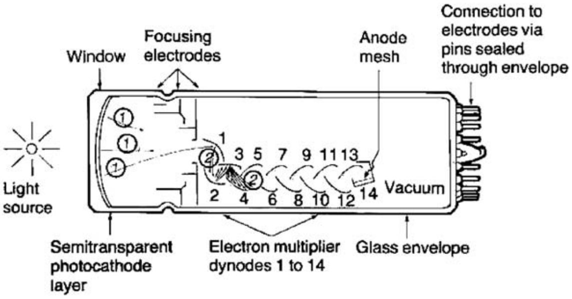

Fig. 1. Cross-section of a photomultiplier tube. ① indicates the electrons liberated by photons from the photocathode and ② shows the cascade of secondary electrons in the first stages of the multiplier dynodes.

The main characteristic of a photomultiplier is its quantum efficiency (QE) which describes the probability that a photon creates an output signal. Several effects influence the QE: the photon can be reflected by the glass of the window, it can pass through the photocathode without interaction and it can produce an electron in the volume of the photocathode but this is stopped inside of the material. The overall effect limits the QE to typical 25%.

The amplification in a photomultiplier depends on the number of dynodes, the dynode material and the electric potential between the dynodes. A rather cheap and easy to produce material is a metal sheet made of copper and beryllium. In this material an incoming electron creates 3–4 secondary electrons when the electric field is bigger than 200 V. A photomultiplier with 12 stages has thus a gain of 1–10 $\times 10^6$, giving an output signal which is big enough to be processed by standard electronic circuits.

Photomultipliers have a shape which is dictated by technical restrictions in the fabrication of the vacuum container but active areas in the wide range of 10–500 mm diameter are possible. They are in the standard configuration very sensitive to magnetic fields and give no information about the position of the incoming photon. The first problem was solved to some extent by making the dynodes from meshes with small distance and high field between them [2]. The latter is addressed by the metal-channel devices: the single chain of dynodes

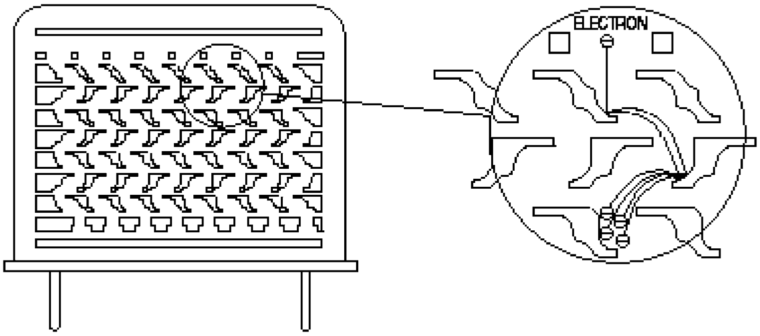

Fig. 2. Cross-section of a metal-channel photomultiplier.

is replaced by many chains in parallel and a segmented anode (Fig. 2) [3].

The multiplication in a chain of dynodes is the best low noise amplification. There is only a contribution to the noise due to the stochastic character of the emission of secondary electrons which is described in literature by the excess noise factor *F*. The consequence is that photomultipliers can detect single photons and provide a very good energy resolution in calorimeters with scintillating crystals.

4. Semiconductor devices

Solid-state devices have the big advantage that they can be produced in standard fully automated processes and therefore can be cheap, that they can be tailored to individual needs in a short time of few months and they open new areas of applications because of their low mass and their very small space consumption. The detector by itself is only some 0.3 mm thick and the housing can be made with a thickness of less than 0.5 mm. In addition they are insensitive to magnet fields with a theoretical limit of some 15 T. The quantum efficiency is very high in all solid-state devices because basically only the reflection at the surface reduces the detection probability. A silicon photodiode has a QE of 85% in almost the whole range of visible light [4]. In the blue, where most scintillating crystals have their peak emission, the QE is still 70–80% (Fig. 3a).

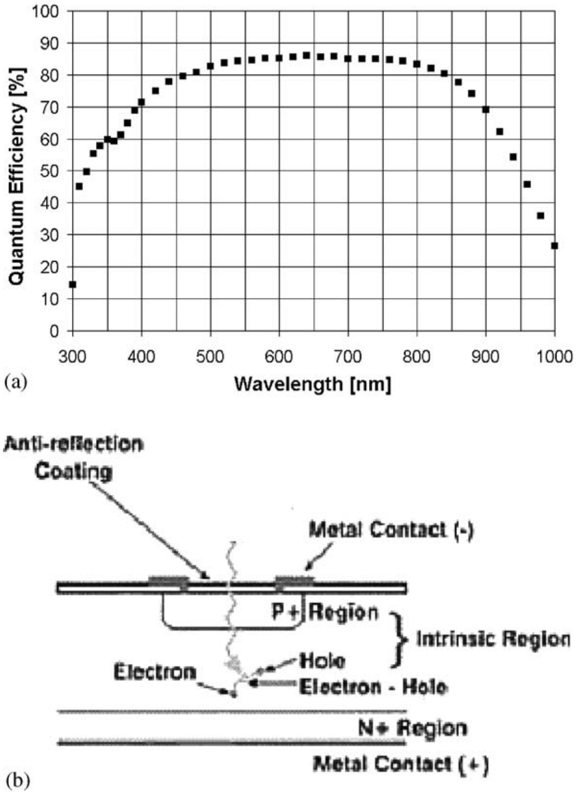

Fig. 3. Quantum efficiency of a PIN photodiode (a) and basic structure (b).

5. Silicon PIN photodiode

The silicon PIN diode is a very successful device. All major experiments in high-energy physics used it in big numbers in the last 2 decades. It has a rather simple structure and is produced by standard semiconductor processes: boron diffusion on one side and phosphor diffusion on the other side of a high purity silicon wafer and at the end contacts are made by aluminium deposition (Fig. 3b). The operation is simple and reliable but since it has no gain it needs a charge-sensitive amplifier that adds to the cost and creates noise in the readout system. Single photon detection with silicon photodiodes is therefore not possible and the very good timing properties (1–2 ns) are destroyed by the signal rise time of the amplifier which is 10 ns or more.

Arrays of photodiodes are easy to produce and are commercially available.

6. Avalanche photodiodes

This device combines to some extent the advantage of photomultipliers with those of solid-state detectors. An avalanche photodiode (APD) provides gain due to the high internal field at the junction of positive and negative doped silicon. The electrons in this field gain enough energy that they can create in an interaction a second free electron which then creates a third – an avalanche starts (Fig. 4). The multiplication is moderate between 50 and 200. A gain of 10^4 is possible but at values higher than a few hundreds the environment (e.g. temperature and voltage supply) needs to be very stable [4].

The signal from an avalanche photodiode is big enough to open new possibilities: two APDs can be mounted on both ends of a crystal. A comparison of the signal amplitudes provides information on the depth of interaction [5]. The probability that an X-ray with an energy of 511 keV interacts with the APD is very small.

Another possibility is the position determination when an array of thin crystals is mounted on a big APD. A thin layer of metal with well-defined resistivity on the back of an APD with an area of $28 \times 28\,\text{mm}^2$, four amplifiers connected to the 4 corners and a comparison of the amplitudes, provides a position resolution of 0.3 mm [6].

7. APDs operated in Geiger mode

When an APD is operated at a bias voltage higher than the breakdown voltage any photon or thermally liberated electron will start an avalanche which persists until the voltage is lowered actively or when the voltage drops on a properly chosen serial resistivity. The output signal is proportional to the overvoltage and the capacitance of the APD. Clearly there is a long dead time of microseconds after each breakdown. This problem

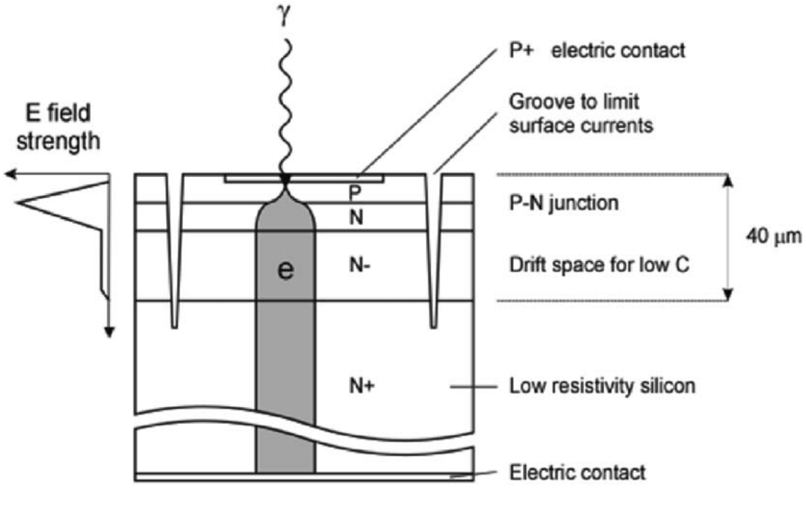

Fig. 4. Structure of an avalanche photodiode (Hamamatsu type S8148).

was overcome by a new development, the so-called silicon photomultiplier.

The sensitive area of $1 \times 1\,\text{mm}^2$ of this device is made of 576 small APDs (pixels) which are all individually connected to the bias voltage via a serial resistivity of 400 kΩ. Now only the pixel that actually was hit breaks down and needs time for recovery. Due to the smaller capacitance the recovery time is in the order of 100 ns.

These devices have single photon response, excellent energy resolution (Fig. 5) and a time resolution of 50 ps [7]. The geometric fill factor, the sensitive area divided by the overall area, is some 25% for the best device of this type [8] but it can be improved by a factor of 2. Then the detection probability of Geiger mode APDs will be 40–50% even for single photons. Scintillating crystals with rather poor light output but low price or very fast response could be used with these devices.

Since thermally liberated electrons can trigger an avalanche, the APDs operated in Geiger mode have a high dark count rate of 1 MHz per mm^2. The probability for accidental coincidences in PET would be high. This can be significantly reduced by operating them at low temperatures. A temperature of −50°C, easily achievable with Peltier elements, would be enough to reduce the dark count rate by 3 orders of magnitude.

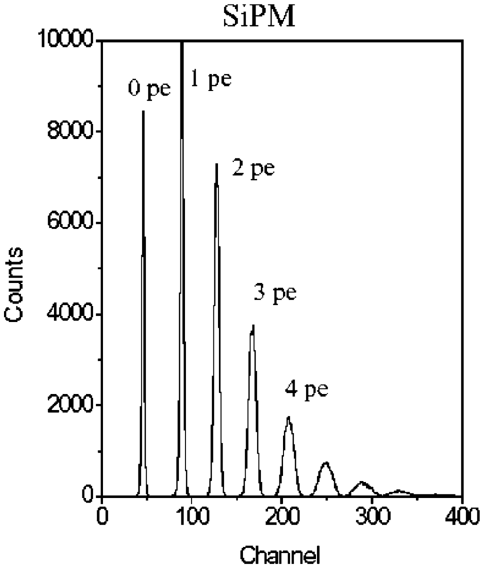

Fig. 5. Response of an avalanche photodiode operated in Geiger mode to light with very low intensity. The number of photons can be counted for each event.

8. Hybrid photodetectors

These devices are a variant of the photomultiplier. The vacuum container and the photocathode are the same but the multiplication is not done in a chain of dynodes. The electrons liberated in the photocathode by a photon are accelerated in a high electric field (10–15 kV) and are focussed onto a silicon PIN photodiode or onto an APD. In the silicon the electrons lose their energy by ionization, and they produce electron–hole pairs that can be collected. On average an energy of 3.6 eV is needed to create one electron–hole pair. Ignoring the very thin protection layer on the surface of the silicon diode an amplification of 4000 is achieved with a field of 15 kV. With an APD as anode a gain of more than 10^5 may allow the use of simple readout electronic circuits.

Like the APDs operated in Geiger mode, the hybrid photodetectors have a very good energy resolution even for light of very low intensity [9]. When the anode, the silicon diode, is segmented they can provide position information.

9. Gaseous photodetectors

Gaseous detectors have been developed for high-energy physics experiments whenever large areas needed to be covered. Square meters can be made for a very low price. They are based on photoconversion and subsequent multiplication in a gas avalanche. The photoconversion can be in the gas itself but the state-of-the-art detectors use a photocathode (like photomultipliers) made of cesium iodide (CsI), which can be made in large areas. A recent development is the gas electron multiplier foil (GEM) that reduces to a large extent the problems of photodetection in gas, the ion and photon feedback [10,11]. This gas electron multiplier consists of a foil of insulating material which is covered on both sides with metal. Small holes are made with a regular pattern. When the two metal films are connected to

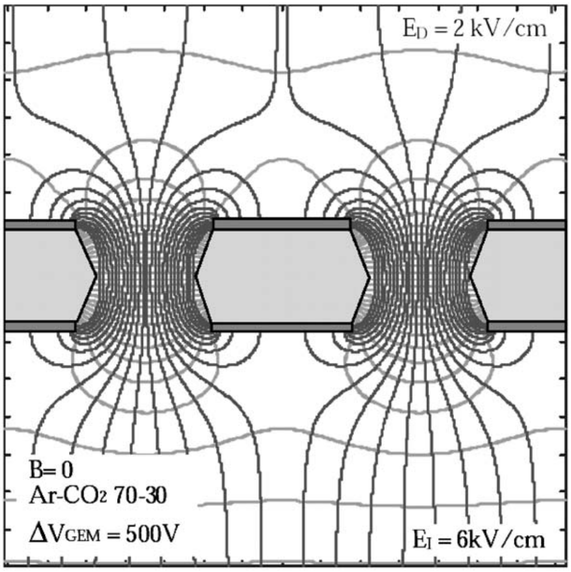

Fig. 6. Field distribution in a gas electron multiplier foil.

different potentials the electric field inside the holes can be made big enough that electrons can ionize the gas and initiate an avalanche (Fig. 6). With wires or pads behind the GEM foil the electrons can be collected and amplified.

10. Conclusions

The detection and image memorization of photons and X-rays was dominated for a long time by photographic plates. The localization resolution is very high but there is no or very poor information on the time and therefore measurements of coincident events are not possible.

In 1924, Geiger, Rutherford and their colleagues used phosphor screens to detect X-rays. Coincidences were found by two observers watching two screens. The rate capability and the time resolution was rather poor.

We have now detectors that can easily handle million events per second with a resolution of less than 1 ns. The localization resolution is improving and reaches 1/10 of a millimeter. In real-time the information or in an integrating device like a CCD-camera a full image can be stored and digitally processed.

Still there is a wide field for improvements and rapid progress can be expected.

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