Introduction

FUNDAMENTALS AND MAIN DESIGNS OF SINGLE PHOTON DETECTORS

This book is dedicated to gaseous photomultipliers—gas filled devices able of recording single ultraviolet (UV) and visible photons with a high position resolution. Nowadays, such detectors are mainly used in various research areas as electronic imaging devices. Combined with computers they are capable of treating and storing imaging information of UV-light. Serious efforts are ongoing currently aiming to commercialize some of these designs. This will allow them to greatly expand their applications into various fields in the nearest future.

Before we identify the place for gaseous detectors among other types of ultraviolet and visible photons sensors, it will be useful to give a short historical review of the developments in the field of single photon detection.

There are various detectors for single photons. Their design depends on photons energy, the required sensitivity.

The first electronic detector of single photons (visible and UV) was the photomultiplier tube (PMT). The first prototypes of the PMTs were developed around 1930 by Kybetsky and his group, according to (Lubsandorzhiev, 2006 and Summer, 1957). This detector became a commercial product after the famous work of Zworykin and his team (Zworykin, 1936). In this device, primary electrons are produced by photoelectric effect between the photons and the cathode. These primary photoelectrons are attracted towards a second cathode where secondary electron emission of electrons occur which are attracted towards a third cathode and so on. The specially designed dynode system is capable of multiplying the single initial photoelectron by a factor of $10^3$-$10^6$. This multiplication makes it possible to with a high efficiency detect single primary electrons, and hence single photons.

For a long time vacuum photomultiplier tubes were the only devices capable of detecting single ultraviolet and visible photons. Typically, these photodetectors had sensitive areas between 5 and 50 cm$^2$ and they were not position-sensitive.

The next major step appeared in the form of television (TV) tubes and image intensifiers. The TV-tubes was also developed based on Zworykin’s efforts. They were the main imaging detectors of visible and infrared light at this time. However, due to various technical reasons they were not capable of recording electronically individual photons, and they were not sensitive to UV light.

In the 1950’s another single photon UV detector appeared, the Geiger gas counter (Friedman, 1951). Although this type of electron multiplier had been invented already in 1908, and was widely used for the detection of high energy particles and X-ray photons, it was the first time it was exploited to detect UV photons. The first photosensitive Geiger gas counter was also based on the principle of photoelec-
tric effect between the UV photons and a metal cathode. Later the metallic cathodes were replaced by
photoionization of vapors with a low ionization potential, offering much higher sensitivity for ultraviolet
light (Chubb, 1955).

In both these detectors, primary electrons are created from the UV photons. In the photomultiplier tube
it is via photoelectric effect in a metallic cathode, and in the Geiger gas counter it is via photoionization
of a photosensitive gas. In the Geiger gas counter, each primary photoelectron trigger a short (~1 ms)
burst of corona discharges in the strong electric field applied in the gas, and as a result in that up to 10^8
secondary electrons are created and collected on an anode wire (see Chapter III for details). This results
in a large amplitude electrical pulse which is fed into the input electronics and allows efficient detection
of single photoelectrons and hence single photons. These detectors were not position sensitive either.

A new page in the development of photosensitive detectors was written after the invention of the posi-
tion sensitive gaseous photomultiplier in the late 1970ies. This device is operating in avalanche mode
in a gas mixture at a pressure of 1 atmosphere (Séguinot 1977, Bogomolov 1978). These detectors also
exploited photoionization of vapors having a low ionization potential, but had two important new features:

1. They were multiwire proportional chambers (MWPC). These are detectors having a planar geometry
   with a multiwire anode instead of a single wire as used in the cylindrical Geiger gas counter.
2. In contrast to Geiger gas counters they operated at sufficiently low voltages between the anode and
   the cathode electrodes to still allow the primary photoelectrons to trigger Townsend avalanches, but
   not to trigger a corona discharge. Depending on the applied voltage, each primary photoelectron
   can create between 10^4 and 10^6 secondary electrons. Even with the electronics of that time, they
   could be detected with efficiency close to 100%. At these conditions avalanches are well localized
   in space and induce signals on the anode wires in the vicinity of the avalanche. This enables the
   position of the avalanche, and hence the initial photon, to be determined in the direction perpen-
dicular to the anode wires with an accuracy of better than a few mm. The initial position sensitive
gaseous photomultipliers could not determine the position along the wires.

In the early work, Séguinot used benzene vapors which are sensitive to UV light with wavelength λ
< 135 nm (Séguinot, 1977), whereas Bogomolov successfully used toluene vapors which are sensitive
to UV light with wavelengths λ < 146 nm (Bogomolov, 1978).

The quantum efficiency of these detectors defined as the number of created photoelectrons per in-
cident photon reached up to 30% ~40% in a narrow UV wavelength region, which is comparable to the
efficiency of the best PMTs (Séguinot, 1977).

The long awaited first position-sensitive photomultiplier had been developed! For many years these
photosensitive MWPCs were the only position sensitive detector capable detecting single UV photons
with high efficiency. At atmospheric pressure there is no serious mechanical constrains on the window
between the detector and the outside. Hence, the detector size and the active area of this photomulti-
plier can easily be several square meters per detector. Another important feature of the photosensitive
MWPCs, compared to vacuum PMTs, was their low sensitivity to magnetic fields which are often used
in high energy physics experiments.

Photosensitive MWPCs immediately became a very active area of development. This development
is still going on. Various new multiplication structures have been developed, including the recently
invented micropattern detectors (Francke 2002). The development of new photosensitive compounds
Introduction

has increased the sensitivity to single photons, comparable to the PMT, and has extended the sensitive spectrum into the visible range of spectra.

By the end of the 1980ies, microchannel plates (MCPs) were successfully combined with high efficiency photocathodes allowing the detection of single photons with a position resolution close to or better than the photosensitive gaseous detectors (Anashin, 1995, and references therein). The microchannel plates had been invented already in the 1960ies and were used to detect charged particles (Wiley, 1962). In these photosensitive microchannel plates electron multiplication occurs due to the secondary emission of electrons on the inner walls of glass micro-capillary tubes. This type of detector also has a low sensitivity to magnetic fields. However, the active area of such device is small, around 10 cm², and it is very difficult and expensive to produce MCPs with larger active area.

At the same time photonics companies started producing the first vacuum multi-anode PMT which offered a position resolution of few mm (Salomon, 1992).

Some work was also done on so called hybrid photodetectors which used a new principle of generating secondary electrons (Ambrosio 2003). In this device, the primary photoelectrons are accelerated in vacuum to high kinetic energies and hit either a solid state detector or a scintillator. In the first case many secondary electron-hole pairs are produced in the solid state detector allowing detection of primary photoelectron with a high position resolution. In the second case a burst of scintillation light is produced and can be recorded by other means, for example with small PMTs.

The rapid progress in solid state technology offers new possibilities for detecting single UV and visible photons. One of the most exciting among them is the so called SiPM. This is a solid state detector exploiting a Geiger type of discharge in the p-n junction (Renker 2006). The quantum efficiency of such device is about 20%, similar to vacuum PMTs. The multiplication factor in Geiger mode is \( \sim 10^6 \), hence each primary photon produces \( \sim 10^4 \) secondary electron-hole pairs. This detector can be made with high granularity as all semiconductor devices. The individual pixel size can be as small as 25 x 25 \( \mu \)m². Similar to the MWPCs they are insensitive to magnetic fields. However, their price per unit of area is quite high which restricts their applications. The use of electron avalanches in semiconductor devices is a blooming field of development. For example, avalanche charge coupling device (avalanche CCD) for imaging visible and UV photons are under intense development and may end up soon as a commercial device (Holl 2006).

In this book we will do a detailed comparison between various types of photosensitive detectors, and analyze their advantages and disadvantages for different applications. Despite great competition coming from other type of photosensitive detectors, in many applications UV sensitive gaseous photomultipliers offer a simple and cost effective solution allowing one to build large area devices capable operating in strong magnetic fields.

In the last chapters we will also describe and exemplify a wide range of applications for various gaseous photomultipliers, from high energy physics and astrophysics experiments to plasma diagnostics and spectroscopy. From this it will be clear why position sensitive detectors of single photons are so important in science, technology, industry and our daily life.

REFERENCES


