Nuclear Instruments and Methods in Physics Research A 809 (2016) 171–174

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Potential applications of electron emission membranes in medicine ☆

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ARTICLE INFO

Available online 2 November 2015

Keywords:
Electron multiplication
Dynode
Transmission Dynode
Photomultiplier
PET scanner
Cherenkov radiation

ABSTRACT

With a miniaturised stack of transmission dynodes, a noise free amplifier is being developed for the detection of single free electrons, with excellent time- and 2D spatial resolution and efficiency. With this generic technology, a new family of detectors for individual elementary particles may become possible. Potential applications of such electron emission membranes in medicine are discussed.

1. Introduction

For the detection of individual elementary particles, the charge, left after the process of absorption and ionisation, is usually too small to activate digital electronic circuitry directly. The charge must be amplified, and this can be achieved by *multiplication*. Examples are electron multiplication in gaseous proportional detectors, and vacuum electron multiplication in photomultipliers. The photomultiplier (PMT), although developed 80 years ago, is still widely used, in spite of its volume, weight, poor functioning in magnetic field, and costs. In the dynode chain of a PMT, amplification-by-multiplication of single (photo) electrons is achieved without adding noise to the output, albeit that the charge avalanche is subject to statistical fluctuations. For *digital* detectors, sensitive to single particles, such fluctuations are irrelevant. In PMTs, however, they contribute to the fluctuation of the analogue output signal. In addition, some dark current is introduced by thermally generated electrons from the photocathode.

In the last decade, electron multiplication in solid-state avalanche detectors has been successfully developed, and now PMTs are gradually replaced by Silicon photomultipliers (SiPM) thanks to their planar geometry, 2D-spatial resolution, their capability to operate in B-fields, and decreasing costs. In these devices, the amplification-by-multiplication comes with shot noise, dark current, bias current, and the noise associated with these currents.

There is a fundamental difference between multiplication as it occurs in PMTs and in SiPMs. In PMTs, secondary electrons are created by the impact of an energetic ($\sim$150 eV) electron on a dynode, whereas in SiPMs, electron–hole pairs are created by charge carriers, with energy levels in the order of the mean ionisation potential or higher. The noise-free amplification, in vacuum, by means of dynodes, is in that sense superior to the amplification as it occurs in SiPMs. The 3D construction of the dynode chain used in PMTs, however, makes them voluminous and expensive. In an on-going project, *transmission* dynodes in the form of planar, ultra-thin, electron emitting membranes are being developed: here, electrons impinging on the top surface cause the emission of several (secondary) electrons at the *bottom* side [1]. These secondary electrons are accelerated by the homogeneous electric field towards the next transmission dynode. The planar geometry, if miniaturised, can be integrated onto a pixel chip, resulting in a

☆This work is supported by the ERC-Advanced Grant 2012 MEMBrane 320764.
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http://dx.doi.org/10.1016/j.nima.2015.10.084
0168-9002/

new generic single free-electron detector, or, when capped with a photocathode, a new mm-thin and planar PMT with ground-breaking single photon time resolution and 2D position resolution (Tipsy: see Fig. 1). The dark current of this device will be determined by the emission of thermal electrons from the photocathode, as in classical PMTs.

With Tipsy, time-of-flight (TOF) measurements of single photons to levels below 10 ps seem feasible, allowing direct 3D object imaging (photography). For this, a camera based on Tipsy, is equipped with a light source emitting picosecond light pulses. By registering the ToF of the reflected photons arriving in a pixel, the distance between that pixel and the object area represented by that pixel is known, with mm precision.

Another application would be in detectors for positron emission tomography (PET) scanners: the planar and thin geometry of Tipsy enables the readout of a (scintillation/Cherenkov) cube at all six sides. This could improve their spatial- and time resolution by an order of magnitude [2,3,4,5,6,7,8,9].

2. Transmission dynodes

In principle, a transmission dynode has the form of a thin membrane, placed in vacuum, supported at its edges. Its thickness is in the order of the penetration depth of electrons with energy of 100–500 eV; for most membrane materials the optimal thickness will be between 10 nm and 100 nm. Since the maximum area of thin and free-standing membranes is limited to $\sim 1\ mm^2$, a transmission dynode in practice takes the form of an array of smaller circular sections, supported by a carrier substrate. There are advantages in giving these individual sections the shape of a dome (instead of a flat surface): a dome just deforms if the membrane contracts or expands, where a flat surface may be ripped, or may wrinkle. A cone-shaped dynode section results, in addition, in focussing of incoming electrons towards the centre of the dome, and in focussing of secondary electrons, emitted from the bottom side, towards the centre of the subsequent dynode section. This is essential for attracting all photoelectrons, emitted by the planar and continuous photocathode towards the active dome sections of the top (first) dynode, and it allows operating the dynode stack in a magnetic field of certain strength (see Fig. 2).

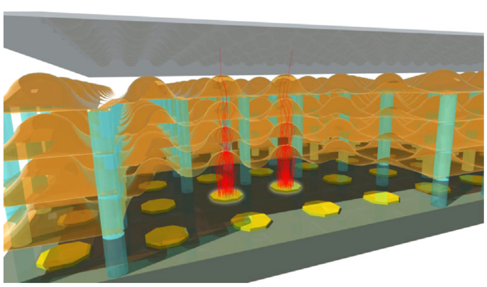

Fig. 1. The Tipsy photomultiplier. By absorption in the photocathode, a soft photon is converted into a photoelectron. This electron is accelerated towards the first transmission dynode (carrying an array of dome-shaped ultra-thin membranes), put at an accelerating potential. The impinging electron causes the emission of, on average, M secondary electrons at the bottom side of the dynode, which will be accelerated towards the next dynode. With a secondary electron yield (SEY) of M, and a number of dynodes of N, a charge of M^N will arrive in the pixel input pad, sufficiently large for digital processing.

The essential property of a transmission membrane is the emission of a sufficient number of (secondary) electrons. With the secondary electron yield (SEY) M and a number of N dynodes, the expected number of electrons entering the pixel input pad equals M^N. With 8 dynodes and a SEY of 4, 65 k electrons appear at the (clipped) pixel input pad, depositing a charge of 1×10^{-14} C. Assuming a capacitance of 10 fF seen by this charge, the potential change of 1 V can drive digital circuitry directly. The rise time of this (charge) signal is determined by the few ps it takes for the electrons to cross the gap between the last dynode and the (anode) pixel input pads. To this end, the last dynode should have a low ‘horizontal’ resistivity, so as to avoid charge-up effects. We propose to cover the topside of the transmission dynodes with a continuous conductive layer, for instance a few nm thick carbon layer. Although the layer is very thin, its specific resistivity should be sufficiently low to avoid charge-up effects. Ultra thin membranes of sufficient area can be created in MEMS technology applying LPCVD-deposited Silicon Rich Nitride (SRN) [10]. We study the transmission secondary electron yield (TSEY) of SRN by Monte Carlo simulations and by direct measurements with beams of electrons and photons. From low-energy GEANT4 extensions developed by FEI [11,12], and VASP [13], we conclude:

1. The TSEY strongly depends on the electron affinity (or work function) of the emitting surface (see Fig. 3).

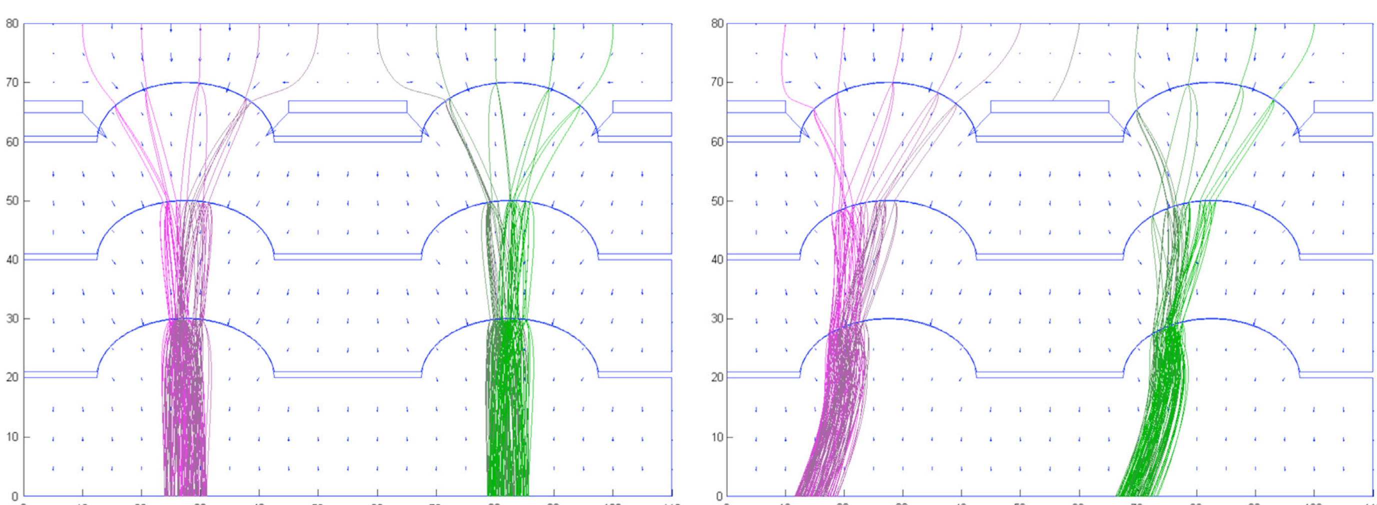

Fig. 2. The effect of a magnetic field (1T) on the trajectories of secondary electrons. Note the focussing effect of the dome-shaped dynodes. Dome pitch (square) 55 μm; dynode layer pitch 20 μm; potential difference between subsequent dynodes: 150 V. Assuming the secondary electrons being at rest at the moment of emission, they arrive after 5 ps onto the next dynode. The transition time between the arrival of a single electron at the first dynode and the completion of the avalanche on the pixel input pad is ~40 ps, but here the spread is less than 1 ps due to the uniformity of the electron trajectories. The time resolution of this electron amplifier is determined by the time for electrons to cross the last gap between the last dynode and the pixel input pads (2–5 ps).