Potential applications of electron emission membranes in medicine

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Abstract

With a miniaturized 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.

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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 (~ 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 ionization 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 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 Topsy, 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 Topsy, 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 Topsy 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 eV – 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 $\sim 1 \text{ mm}^2$, 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).

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 $1 \times 10^{-14} \text{ C}$. 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:

- The TSEY strongly depends on the electron affinity (or work function) of the emitting surface (see Fig. 3).
- Surface hydrogen termination, known to result in a very high SEY for diamond reflection dynodes [14], should have a similar effect on SRN dynodes [15].

We measured SRN samples in the National Science Light Source (NSLS) low-energy synchrotron radiation facility in Brookhaven BNL, confirming the increase in (reflective) SEY after H-termination [16]. Measurements with scanning electron microscopes (SEM), with samples placed in a dual Faraday Cup (see Fig. 4), are on-going, and new test facilities are being developed in Brookhaven BNL and at ImPhys at Delft University of Technology, including in-situ bake-out facilities.

3. Applications in medicine

Assuming the realisation of MEMS-made micro transmission dynodes with sufficient TSEY, an essentially noise-free, highly compact free-electron multiplier (amplifier) with unprecedented time resolution and 2D granularity becomes available as a generic base for the detection of individual elementary particles. As such, it may replace the multiplication section in PMTs and X-ray detectors in medical applications.

The Time Photon Counter ‘Topsy’ detector (see Fig. 1) combines a photocathode, the dynode stack and a charge sensitive readout pixel chip. When combined with a lens system and a ps pulsed light source, a TOF camera is formed capable to create direct 3D images of objects by recording the time-of-flight of photons emitted by the source, reflected by the object, and projected onto the photocathode by the lens system. This requires a time measurement per individual pixel (using a local TDC and memory).

The performance of PET scanners could be greatly improved when Topsy detectors would be applied as a soft photon readout device [3, 4, 17, 18, 19]. In addition to excellent single-photon time resolution, Topsy could have a high photodetection efficiency (PDE) over a broad wavelength range, including the UV, which enables the efficient detection of (prompt) Cherenkov photons in addition to, or instead of scintillation photons [20, 21, 22, 23, 24]. Following the method presented by Brunner et al [20], a GEANT4 simulation for lead glass resulted in an average of ~ 13 Cherenkov photons created by 511 keV photons. A potential implementation of a Cherenkov detector for PET could consist of a lead glass cube optically coupled on all six sides to Topsy photodetectors [19, 22]. A schematic illustration of this concept is shown in Fig. 5. In fact, the photocathodes could be applied on the cube's edge planes directly, reducing losses due to reflection. This would be even be more relevant for cube materials with a higher Cherenkov photon yield, often associated with a higher index of refraction. If we assume that only a small number of Cherenkov photons will be affected by absorption, scattering and reflection, and assuming a quantum efficiency (QE) of 0.3 of the photocathode, the probability to detect at least four photoelectrons can be estimated to be 0.6 (see Fig. 6). These Cherenkov photons originate from the conversion point of the 511 keV photon in the glass cube. This point can be reconstructed accurately even from such a low number of photons if their times of detection are measured precisely and used as the input parameters for position reconstruction [2], as is e.g. also done in a global positioning system (GPS). That is, the conversion point lies on a sphere with the hit pixel at the centre and the radius defined by the time-of-flight of the Cherenkov photon. With four spheres, the conversion point of the 511 keV photon is known with sub mm precision in 3D, given that the timing obtained with Topsy photosensors could be as good as a few ps. It is noted that the sensitivity for Compton events is reduced since Compton electrons with an energy below 120 keV do not create Cherenkov radiation in lead glass, and the remaining Cherenkov photons created in multi-interaction events may not provide consistent information for position reconstruction.

Another application of Topsy is a tracking detector for energetic charged particles [25]. By placing a stack of thin, transparent, equidistant and parallel foils in the volume of the tracks, Cherenkov photons are created in the intersection points of tracks and foils, and being emitted under a fixed angle between the track and the photon direction. By means of Topsy detectors covering the inside of the volume boundaries, track reconstruction and timing seems feasible with a low mass, thus low scattering tracking detector.

4. Conclusion

If transmission dynodes can be made with a secondary electron yield of 4 or higher, a new generic charge amplifier for free electrons in vacuum can be realised. Given the recent discovery of the high secondary electron yield of diamond, theoretical support, and material characterisation measurements, the chance to develop such a dynode is high. Based on this amplifier, a new generation of detectors for single, elementary particles emerges, improving the performance of instrumentation for medicine by an order of magnitude.

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Fig. 1. The Topsy 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.

Fig. 2. The effect of a magnetic field (1 T) on the trajectories of secondary electrons. Note the focussing effect of the dome-shaped dynodes. Dome pitch (square) $55\text{ }\mu\text{m}$; dynode layer pitch $20\text{ }\mu\text{m}$; 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 $\sim 40\text{ ps}$, 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).

Fig. 3. The Transmission Secondary Electron Yield (TSEY) of a 20 nm thick membrane of β - Si_3N_4 as a function of the electron affinity of the emitting (bottom) surface, shown for incoming electrons of 500 eV and 1500 eV. For this, the low-energy GEANT4 extensions developed by FEI were applied [12].

225 Fig. 4. The Dual Faraday Cup. Placed in a SEM microscope, the electron beam enters via the hole in the top electrode. A dynode sample is
 226 placed at the centre. Above and under the sample, a mesh electrode and a half sphere electrode are placed, respectively. These in total 5
 227 electrodes can be put at any potential and their currents can be measured. This enables the measurement of current components such as punch-
 228 through electrons, back-scattered electrons, reflective secondary electrons, and transmission secondary electrons. Left: exploded view of the
 229 Dual Faraday Cup. Right: simulation of secondary electron trajectories for a specific setting of the potentials of the 5 electrodes.
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Fig. 5. A PET scanner detection element with Timed Photon Counter Tipsy soft photon detectors as readout. Cherenkov photons, created after the absorption of a 511 keV annihilation photon in a lead glass cube are read out at all six sides.

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240 Fig. 6. The probability of the emission of a specific number of Cherenkov photons due to the absorption of a 511 keV photon in lead glass.
241 Assuming a QE of 0.3, and no other losses, the probability to have at least four photoelectrons is about 60 % [15].
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