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The Tipsy single soft photon detector and the Trixy ultrafast tracking detector

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ABSTRACT: We present a new and generic type of detector for photons, electrons and energetic charged particles: a stacked set of curved miniature dynodes in vacuum, created through Micro Electro Mechanical System (MEMS) fabrication techniques on top of a CMOS pixel chip. This combination in itself is an efficient single free electron detector. By capping the system with a traditional photocathode, a highly sensitive timed photon counter can be realized. By capping it with an electron emission membrane 'e-brane', a timed MIP tracking detector is realized with a time resolution far superior to current particle detectors. The core innovation, i.e., the stacked curved dynodes on top of a pixel chip, is also relevant for solid-state, atomic and molecular physics experiments.

KEYWORDS: Particle tracking detectors; Timing detectors; Vacuum-based detectors; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others)

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1 Introduction

We propose a new family of detectors consisting of a stacked set of curved miniature dynodes in vacuum, created through Micro Electro Mechanical System (MEMS) fabrication techniques, placed on top of a CMOS pixel chip. This combination in itself is an efficient single free electron detector with a good spatial resolution (determined by the pixel pitch) and superb time resolution. By capping the system with a traditional photocathode, a highly sensitive Timed Photon Counter TiPC or 'Tipsy' can be realized. By capping it with an electron emission membrane 'e-brane' a timed energetic charged particle counter 'Trixy' is realized with a time resolution much better than current particle detectors.

Tipsy will have ps time resolution, very low noise, excellent spatial resolution and rate capabilities. It will have impact on the field of medical imaging (notably PET scanning), optical communication, night-vision equipment and even truly 3D image recording. The time resolution of Trixy is orders of magnitude better than planar Si avalanche detectors presently applied in particle physics experiments, opening new horizons for (vertex) tracking, time-of-flight spectrometers, track pattern recognition and trigger detectors. The core innovation of Tipsy and Trixy (i.e. the stacked curved dynodes on top of a CMOS pixel chip) will revolutionize electron detection in solid-state, atomic and molecular physics experiments.

2 The Timed Photon Counter 'Tipsy' single soft photon detector

Principle. A soft photon ($0.1\,\mu\mathrm{m} < \lambda < 2\,\mu\mathrm{m}$), entering through Tipsy's window, interacts with the photocathode. Due to the photo-effect, an electron is emitted into the evacuated space under the window. This electron is accelerated towards the first dynode, put at positive potential of 150–400 V with respect to the photocathode. This dynode is an ultra-thin i.e. silicon-nitride layer with cone-shaped protrusions, shown in figure 1. These cone shapes create an electric field between the following dynode, focusing the electrons towards the top of the cones, away from the non-active support areas.

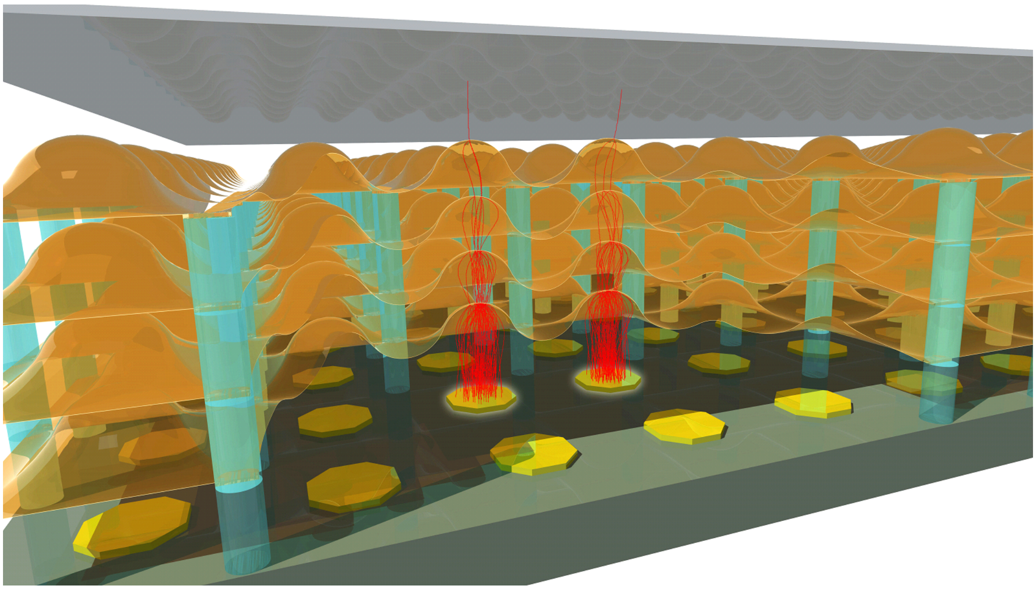

Figure 1. The innovation at the heart of the proposed detectors: a stack of dynodes in vacuum placed on top of a CMOS pixel chip. By capping the assembly with a classical photocathode or e-brane, a photon detector (Tipsy) or energetic charged particle detector (Trixy) can be realized, respectively. The Tipsy detector, for example, is sensitive for individual (soft) photons, which are converted into photoelectrons in the photocathode and multiplied in the stack of dynodes. The resulting electron avalanche is detected by the circuitry in the individual pixels of the CMOS chip.

The electrons arrive at the first dynode with an energy of 150–400 eV. At the point of impact, secondary electrons are emitted not only from the top of the layer, but also from the bottom, due to the thickness of this *transmission dynode* of only 15 nm. Secondary electrons emitted from the top will fall back; those emitted from the bottom accelerate towards the next dynode. With a *secondary electron yield* Y and a number of sequential dynodes N, a gain $G = Y^N$ is reached. With $Y = 4$ (typical for dynodes in a classical PM), and five dynodes, an average charge of 1 k electrons is collected onto the pixels' input pad, which is sufficient for detection [1]. With seven dynodes, a charge of 16 k electrons causes a potential change of the input pad of one volt, which can be considered as a digital signal.

Performance. The *response time* of the Tipsy detector, determined by the time it takes for the electrons to pass through the gaps between the photocathode, dynodes and pixel chip, is of the order of 50 ps. The *time resolution* to detect a single soft photon is mainly determined by the time the electrons take to cross the last gap between the last dynode and the pixel anode, and can be of the order of a ps. The *spatial resolution* of $\sim 10\,\mu$m, in both planar directions, is determined by the pixel pitch. The high granularity of the independent pixels allows a *high multiplicity* of coincident multi-photon detection while keeping the *occupancy* low. The maximum *event rate* of the device can be extremely high because of the short response time of 50 ps. Since Lorentz forces, acting on the free moving electrons are orders of magnitude smaller than the electrostatic forces, the operation of Tipsy detectors is little affected by a magnetic field, as opposed to classical PMs. In addition, the repetitive focusing throughout the dynode stack positively contributes to this.

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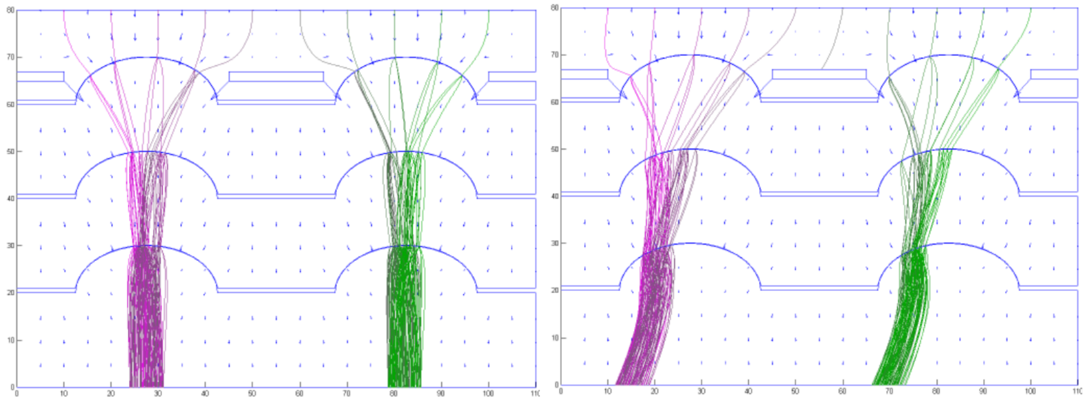

Figure 2. Left: first results of a simulation of (2D) electron trajectories in Tipsy. The potential step between the electrodes is 150 V. Spacing dynodes: 20 μm, cone pitch is 55 μm. Incoming single electrons are generated in horizontal steps of 10 μm along the cathode, and the tracks are colored in order to follow them towards the anode. Note the focusing effect of the cone shaped dynode structure. Here, the first dynode has an additional electrode in the support area in order to focus the incident single electrons towards the active multiplication area. Right: the effect of a magnetic field of 1 Tesla, demonstrating that the Tipsy photomultiplier could operate well in this magnetic field.

In Tipsy's discrete multi-dynode system the energy of an electron-to-be-multiplied (order 200 eV) is much higher than the binding energy of electrons in the dynode material (0.5–5 eV). In Si-PMs, this energy is of the order of the band gap energy, and multiplication generates bias current and, consequently, noise. Another drawback of Si-PMs is the electron/hole mobility, limiting the effective speed of charge displacement, and therefore the charge signal speed.

The separation of the functionalities of photon absorption/conversion and electron multiplication of Tipsy, and the passive electron multiplication of the thin membranes makes it intrinsically superior in terms of noise, speed (time resolution, signal duration and detector response time), in photon spatial resolution, in detector occupancy, and in radiation hardness. The fundamental advantage of Tipsy over current photon detectors is the fact that its fast (charge) signal is generated by a small displacement of free, accelerated electrons in vacuum. The vacuum electron multiplier is free of bias current and noise. Furthermore, the fine granularity allows a good spatial resolution and a low occupancy even at high counting rates with multiple hits.

The first dynode. The focusing of the field above the cone array is of special interest for the first dynode: the efficiency of the Tipsy and Trixy detectors is proportional to the *acceptance* of the photo electrons and emission electrons, respectively. Electrons arriving at the non-active area between two adjacent cones will not be detected. This is not relevant for the next dynodes where a limited efficiency results in a reduction of the effective secondary electron yield, which can simply be compensated for by a higher *secondary electron yield* (SEY), thus increased potential difference between the dynodes, or a larger number of dynodes. One way of focusing is depicted in figure 2.

Tipsy's efficiency to detect photons is determined by the Quantum Efficiency (QE) of the state-of-the-art photocathode (20–40%) while future Si-PMs may achieve even higher efficiency. In this project we will develop theories and practical methods (i.e. surface processing) that may result in the development of novel high QE photocathodes.

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3 The Trixy tracking detector for charged energetic particles

While Tipsy is sensitive for soft photons, Trixy detects fast charged particles. Instead of a photocathode, Trixy has an electron emission membrane 'e-brane'. The unique property of e-brane is that it is highly likely to emit at least one electron after the passage of a charged particle, at the crossing point of the membrane and the particle's track. The time resolution of Trixy can be of the order of a ps, and its (track) position resolution would be limited only by the pixel size of its CMOS readout pixel chip.

The electron emission membrane 'e-brane'. The essential property of this foil is the emission of *at least one electron* after the passage of a fast charged particle, close to the crossing point of the particles' track and the foil surface.

By means of photon exchange, the fast charged particle interacts with mainly the electrons in the foil. An electron with sufficient energy may cross the foil material and escape from the foil surface into the vacuum space, away from the foil. With the electron multiplier, as in Tipsy, the position of this electron, and its time of creation can be measured precisely. The emission efficiency (yield) of plain aluminium or copper foils is known to be 2–4% [2]. We intend to develop a foil with electron emission yield larger than 50%: 1) by applying a material or coating with a low or negative work function; 2) by applying a multilayer with specific charge carriers transport properties [3]; 3) by applying a strong extracting electric field; and 4) by *surface treatment*: since only the skin (depth $\sim 20\,\mathrm{nm}$) of the surface contributes to electron emission, the yield increases when the emitting surface is increased. The ultimate yield increase by surface roughening would be reached by means of *fractalising* [4].

Applications. The Trixy detector would outperform state-of-the-art (Si) semiconductor tracking detectors, now widely applied in particle physics experiments, in terms of time resolution, rate capability, and radiation hardness. This opens a new horizon for (vertex) tracking, for Time-of-Flight spectrometers, for track pattern recognition and trigger detectors.

4 The electron multiplier: transmission dynodes

In a photomultiplier, electron multiplication occurs in the successive dynodes, resulting in a detectable charge pulse after the last dynode. We intend to develop, by means of Micro Electro Mechanical System (MEMS) technology, a stack of miniature *transmission* dynodes, placed on top of a pixel chip as charge sensitive, segmented sensor. Instead of *reflective* dynodes, typical for photomultipliers, secondary electrons are emitted here from the bottom of the ultra-thin layers, after the impact of accelerated incoming electrons at the top [5]. The layout of such an electron multiplier is depicted in figure 3. With state-of-the-art MEMS technology, ultra thin membranes can be made [6]. We intend to create for the first time a stack of *curved* thin layers forming the dynodes by the deposition of CVD silicon nitride onto a sacrificial template: the template is removed by dry etching.

The conical shape of the protrusions has several positive aspects: a cone is more rigid, stable and stronger than a flat membrane with the same projected area. The electric field above a cone focuses the incoming electron(s), but also the emitted electrons at the bottom surface are focused

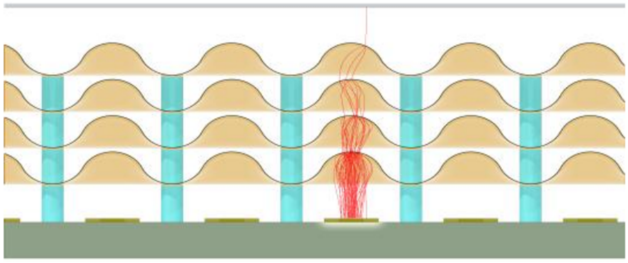

Figure 3. The electron multiplier is a stack of basically identical dynodes. A dynode is an ultra thin layer of i.e. Si-doped silicon nitride (Si_3N_4), shaped in an array of cone-shaped protrusions, supported by insulating pillars. The spacing between two dynodes is $\sim 20\,\mu$m, and the distance between the pillars is $\sim 55\,\mu$m.

onto the following cone (or pixel input pad). This focusing of the field above the cone array is of special interest for the first dynode: the efficiency of the Tipsy and Trixy detectors is proportional to the *transmission efficiency* of the photo- or EEM-emitted electrons. Electrons arriving at the inactive area between two adjacent cones will not be detected. This is not relevant for the next dynodes where a limited efficiency results in a reduction of the effective secondary electron yield (SEY), which can easily be compensated for by a higher potential difference between the dynodes, or a larger number of dynodes.

As layer material we intend to apply doped silicon nitride; crucial is the SEY as a function of the layer thickness and the energy of the incoming electrons [7]. Since this energy is of the same order as required in photomultipliers (~ 150 eV), the sequence of potentials of the dynodes is also comparable. As a result, the electric field in a gap between two dynodes is quite strong, but still orders of magnitude away from discharge risks (Fohler & Norheim limit for cold emission in vacuum [8]). A compromise must be found for the (distribution of the) electron emission work function: a low value favours the yield, but also limits the impact energy of the electrons. If sufficient yield cannot be reached, the layer could take the form of a multilayer, with better emission properties [9].

The dynode material must be slightly conductive: since more electrons leave a dynode than arrive, the vacancies must be compensated. The compensating current is largest for the last dynode. The horizontal voltage drop over a dynode due to the compensation current should not exceed ~ 5 V. The *horizontal resistivity* may be reduced by the deposition of a metal layer onto the dynode layer, in the area of the support pillars. There is a special requirement for the last dynode: the compensation of vacancies must occur within ps in order not to induce positive charge on the pixel input pad, reducing the effective (electron) charge signal.

5 Prototype MEMS made ultra thin dynodes

At the MEMS-lab DIMES of Delft University of Technology, ultra thin windows made of Si_3N_4 had been made: see figure 4. Based on this technology, a first prototype dynode has been realised: see figure 5.

This dynode prototype will be tested in a vacuum container in which free electrons are generated by shooting electrons from an *electron gun* onto the dynode under test (see figure 6). The

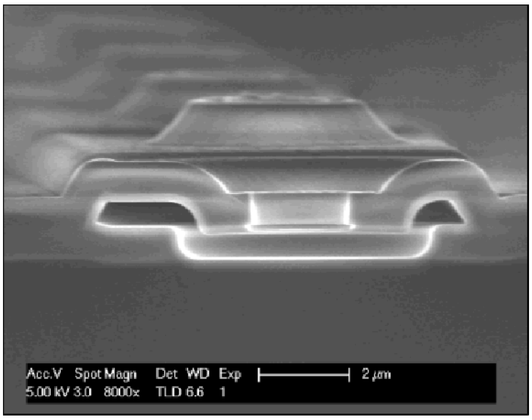

Figure 4. Ultra thin silicon nitride membranes: the central chamber has two windows with a thickness of 15 nm. The diameters of the windows are 2 and 5 microns, respectively [6].

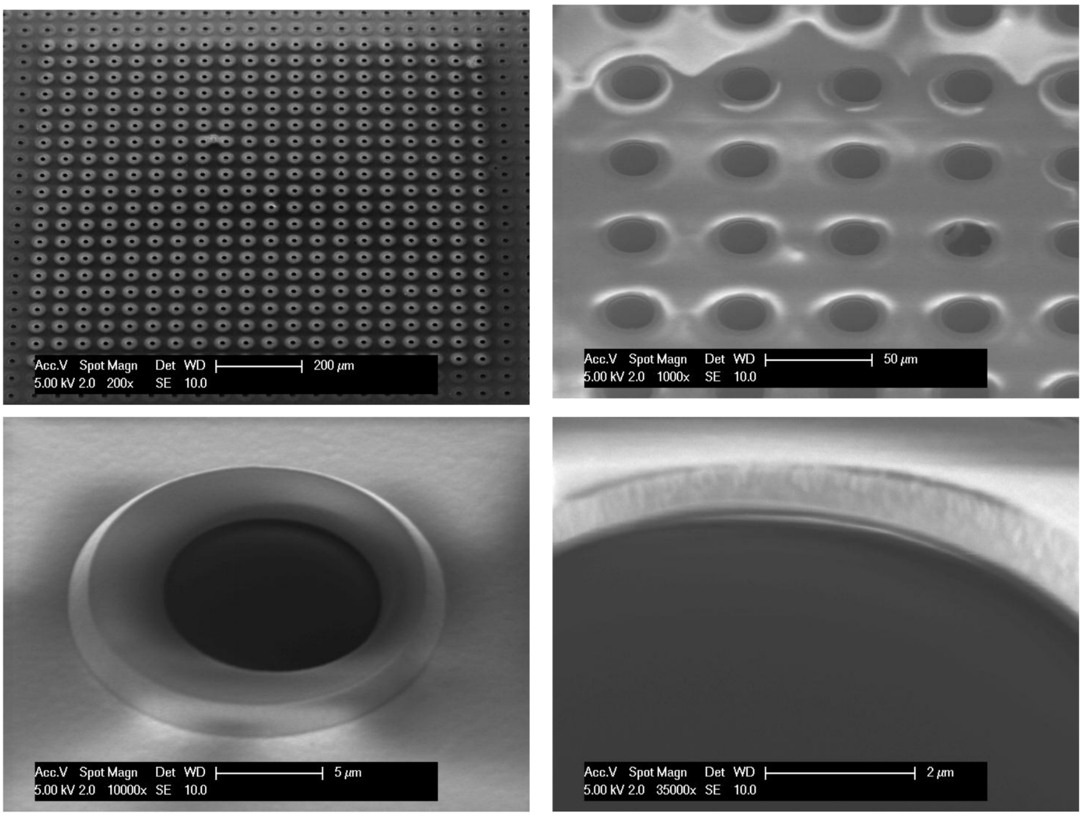

Figure 5. One of the first prototype ultra-thin transmission membranes, displayed with increasing scale. A standard Si wafer is used as carrier. Instead of two cones, an array of 16×16 cones is realised. Bottom right: the cone-shaped membrane is too thin to be visible.

outcoming electrons (transmitted incoming electrons plus secondary emitted electrons) are measured by means of the Timepix chip. Each pixel can detect charge pulses equivalent to $1000\,e^-$. The electron gun will emit electrons in bunches of ~ 100 ns, since the pixel preamps are dc insensitive. In addition, the total charge exposure on the dynode is kept to a minimum.

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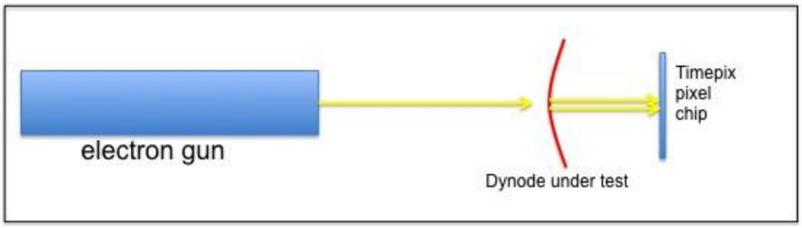

Figure 6. Layout of the test set-up. The vacuum chamber includes a naked Timepix chip facing an electron gun. After careful analysing the Timepix response to the electron beam, the dynode under test is placed in front of the TimePix chip, and the difference in response is a measure for the activity (electron absorption and electron multiplication) of the dynode.

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