MEMS-made Photocathodes with high Quantum Efficiency [HighQE]

Harry van der Graaf [1*], John Smedley [2], Gert Nützel[3]

[1]Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[2]Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA
[3]Photonis Roden, Dwazziewegen 2, 9301 ZR Roden, The Netherlands

*Corresponding author: vdgraaf@nikhef.nl

ABSTRACT
The goal of our project is to raise the state-of-the-art quantum efficiency, now 35 %, of a photocathode, to a much higher value, approaching unity. The quantum efficiency is determined by three processes: electron emission by a specific surface facing vacuum is considered to be the crucial one. Progress made in tools for studying this process is reported.

Keywords: Photocathode; Quantum Efficiency; Transmission Dynode; Tynode

1. INTRODUCTION

- The efficiency of a new generation of soft photon detectors is determined by the quantum efficiency of their photocathodes. With HighQE we expect to raise this efficiency from 35 % to 90 % or higher.

- We propose the ***active*** photocathode, favouring the emission of photo-electrons, created in the layer material, into the vacuum.

- We have developed:
    1. MEMS technology for creating electron-emitting multilayer films (tynodes).
    2. Two systems for measuring the emission of electrons by specific surfaces.
    3. We performed a (solid state physics) study about applying ab-initio simulations on doped (terminated) surfaces, exposed to a strong extracting field, stimulating electron emission.

2. STATE OF THE ART.

The photomultiplier has been the ultimate single soft photon detector since its invention in 1934. During the last two decades, solid state Si detectors were developed, resulting in Si-Photomultipliers (SiPM) such as the single-photon avalanche diode (**SPAD**). Now, SPADs are widely applied because of their planar shape, granularity, efficiency, time resolution, and cost.

Parallel to the SPAD development, the Micro Channel Plate (MCP) was greatly improved [1], and the new Tynode [2,3] was developed. The great advance of these vacuum electron multipliers is the high level of charge amplification in absence of dark current noise. In addition, the spread in time of electrons emitted by a stack of tynodes is estimated to be of order 1 ps. A tynode stack, combined with a photocathode would form the ultimate soft photon detector, only lacking efficiency. For that reason we intend to develop the High QE photocathode: the new Timed Photon Counter TiPC would outperform SiPMs also in the future.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The quality of a single soft photon detector is determined by the following properties:

1. efficiency: the probability to detect an incoming soft photon
2. spatial 2D resolution: usually determined by the granularity of the pixelized active surface
3. time resolution
4. noise, in terms of dark current or dark counting rate
5. max. counting rate, possibly per pixel; pixel dead time
6. form factor, volume, weight, mass (radiation length)
7. power dissipation
8. cost

Add 1: the efficiency of future SiPMs will reach unity. The basis of our project lies in the efficiency of TiPC and MCP-based photodetectors, determined by the QE of photocathodes.
Add 3: The charge signal of TiPC is determined by the crossing of a cloud of electrons of the gap between the last tynode and the pixel imput pad. This signal is completed in ~ 5 ps, while the geometry of the electron cloud may cause a spread of ~ 1 ps. The potential time resolution of TiPC is, for the near future, limited to what is electronically possible. We claim that TiPC has the potential to become is the fastest detector possible. The fundamental physics in TiPC lies in free electrons moving in vacuum, having the largest possible electron mobility.
Add 4: The single-electron response of vacuum electron multipliers exhibit well-known fluctuations. With sufficient gain, after discrimination, there is a simple digital output. This output is free of dark noise events, so the vacuum electron multiplies is free of dark current noise. This is a fundamental advantage with respect to SiPMs. It should be noted, however that a classical PM has noise due to thermal electrons emitted from the photocathode. It is expected that a new high QE photocathode has a higher emission of thermal electrons. We anticipate to operate new photocathodes at lower temperature. In fact, their noise as a function of temperature reveals important information about the electron emission process.
Add 5: For TiPC, the functionality of the pixel electronics is purely digital, providing time stamps. In SiPMs, avalanches must be generated, requiring additional bias power (**Add 7**) and pixel fiducial area.

4. PROJECT RESULTS

We have realised MEMS procedures for making Tynodes. We realised a breakthrough by creating an MgO 10 nm thick membrane using Atomic Layer Deposition (ALD), with a 3 nm thick TiN conductive layer on top, avoiding charge-up effects [4,5]

We measured the electron emission of our membranes in a SEM based setup. By scanning the tynode samples, a SEM image of the tynode appears, in parallel to an image displaying the local value of the transmission secondary electron yield (TSEY) [6,7].

In the TyTest set up, the electron emission of surfaces, back-bombarded with 2 keV electrons from an e-gun, is imaged by means of a readout with a quad TimePix-1 chip. Previous measurements were confirmed. With TyTest, electron emission can be measured of object surfaces in general [8].

Graphene. In order to drift photoelectrons towards the emission (vacuum) side, the photon absorption layer could be sandwiched by two graphene layers. We have studied the deposition of graphene on ALD Alumina. [9].

We have studied the application of density functional theory (DFT) using ab-initio simulation programs. Previously, we worked with the Vienna ab-initio Simulation Package VASP [10]. With results of these simulations, the emission (tunnelling) of electrons into vacuum could be optimised by applying additional ALD layers, or by surface doping and termination, and by a strong extracting field [11, 12].

5. FUTURE PROJECT VISION

5.1. Technology Scaling

The first action for raising the TRL level is to install a team of solid-state physicists. Their task is to develop models predicting electron emission work functions. Photocathodes are to be made from suitable materials, being the result of their simulations. In an iterative process, the practical photocathode with desired properties should be realised and the method can directly be transferred to industry, in this case Photonis.

5.2. Project Synergies and Outreach

The HighQE project is closely related to the following ATTRACT-1 projects: NanoUV, Gisiphod, FastICPix, FastPix. We are looking forward to collaborate.

Photonis is the essential commercial partner in our project: Photonis has the facility to make in-situ photocathodes. Their knowledge is classified. This does not hamper our plans to develop the procedures for making HighQE photocathodes, but the details of the implementation of the inventions in Photonis' detectors will not be made public.
We would like to collaborate with the group of Jon Lapington, University of Leicester. This group is performing studies on surface effects using the VASP simulation program [12].

5.3. Technology application and demonstration cases

Our research will result in a groundbreaking new generic single soft photon detector, to the benefit of Science in general, and more specific to particle & nuclear physics, astronomy, photonics, applied quantum physics, the instrumentation for gravitational wave experiments, and lab instrumentation in general.

5.4. Technology commercialization

Commercial aspects are fully covered by Photonis. This multinational is active, since many years, in developing, producing and selling photodetectors. Their Planacon single soft photon detector is widely used. This Planacon detector is the ideal testing object for new photocathodes.

5.5. Envisioned risks

First, we will focus on Ge as layer material for our new photocathode, since two out of three processes are known to be under control. A layer thickness of 100 nm will absorb more than 90 % of incoming soft photons with wavelength 0.4 µm $< \lambda <$ 1.0 µm. The second process in which photo-electrons in the conduction band drift towards the emitting surface, is also know to occur well. The third process, namely the emission of photo-electrons into the vacuum, is known to be problematic. If this turns out to be a showstopper, we will turn to GaAs as absorbing material.

5.6. Liaison with Student Teams and Socio-Economic Study

Our HighQE ATTRACT 1 project has been chosen as subject for a group of 5 students participating to the CERN IdeaSquare summerschool. Future activity like this will be well supported.

6. ACKNOWLEDGEMENT

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