Employment of nanodiamond photocathodes on MPGD-based HEP detector at the future EIC

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On behalf of INFN, Trieste & INFN, Bari collaboration

Outline

- Motivation
- Coating unit & QE Setup in Bari
- QE measurement in Bari
- ASSET @ CERN
- Preliminary measurement with ASSET
- Employment of ND on THGEMs
- Conclusion
Motivation of this specific R & D

• Demand of a compact RICH for the future EIC ► short radiator length (Limited number of Photons)

• As standard quartz window is opaque below 165 nm ► windowless RICH is a possible approach ► Gaseous detectors

• CsI most used, however ageing due to humidity and ion bombardment ► quest for novel PC with sensitivity in the far UV region

• H-ND powder as possible more robust alternative photocathode of CsI

• Our R & D; H-ND coupled to THGEM

• We report here some preliminary results on the initial phase of these studies
Why and which Nano Diamond

- Microwave Plasma Enhanced Chemical Vapour Deposited (MWPECVD) diamond films are used for thermionic current generation and for UV photocathodes, because they exhibit a better stability than CsI.
- Production of diamond films by MWPECVD technique at 800°C. Peculiarity: hydrogenated surface!! Moves down Negative Electron Affinity (N.E.A.) to -1.27 eV. A crucial parameter for electron photo and thermo emission. Maximum Q.E. achieved for the MWPECVD based diamond is 12% at 140 nm.

<table>
<thead>
<tr>
<th>Comparison CsI to Nano Diamond</th>
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<tbody>
<tr>
<td>H – ND</td>
</tr>
<tr>
<td>• Low electron affinity ➤ 0.35 – 0.5 eV</td>
</tr>
<tr>
<td>• Wide band gap ➤ 5.5 eV</td>
</tr>
<tr>
<td>• Preliminary measured QE ➤ 30 – 40% @ 140 nm for Hydrogenated samples. (We mes 7.7% after one year H – ND in H₂O).</td>
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<tr>
<td>• Chemically inert</td>
</tr>
<tr>
<td>• Radiation hard</td>
</tr>
<tr>
<td>• Good thermal conductivity</td>
</tr>
<tr>
<td>CsI</td>
</tr>
<tr>
<td>• Low electron affinity ➤ 0.1 eV</td>
</tr>
<tr>
<td>• Wide band gap ➤ 6.2 eV</td>
</tr>
<tr>
<td>• Typical Quantum Efficiency ➤ 35 – 50% @ 140 nm</td>
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<tr>
<td>• CsI has hygroscopic nature</td>
</tr>
<tr>
<td>• Aging ➤ Ion Accumulation ➤ Degradation in QE of PC</td>
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</tbody>
</table>

Comparative QE: CsI: ND/HND

- ND [APL-108 (2016) 083503]
- HND [APL-108 (2016) 083503]
Photocathode coating & photocurrent measurement @ Bari
Pulsed spray thin film coating setup:
No of Shots determine the coating thickness

Figure: The pulsed spray technique for thin film coating, equipped with an ultrasonic atomizer and with a heater at INFN Bari, Italy
Pictorial view of photoemission measurement setup:

High voltage power supply
Display unit of vacuum pump
Vacuum pump control unit
TMP vacuum pump
Kiethley Picoammeter
Sample photocathode interchangeable via NIST
Gate valve with MgF₂ window
KF40 SS bellow
VUV Monochromator controller
Ar gas cylinder
Entrance Slit (0.01 to 3mm)
Exit Slit (0.01 to 3mm)
Reflective Collimator
Vacuum pump unit

Figure: McPherson VUV monochromator for the photocurrent measurement at INFN Bari, Italy
Quantum Efficiency Formula Bari

\[ QE_{PC}(\lambda) = \frac{N_e}{N_{ph}} = \frac{Calibration_{NIST}(\lambda)}{e} \times \frac{I_{PC}(\lambda) - I_{DC(PC)}}{I_{NIST}(\lambda) - I_{DC(NIST)}} \]

\[ N_{ph} = \frac{I_{NIST}}{e} \times \frac{1}{Calibration_{NIST}} \]

\[ N_e = \frac{I_{PC}}{e} \]

Where:
- \( QE_{PC}(\lambda) \) = Quantum efficiency of the photocathode
- \( I_{PC}(\lambda) \) = Measured photocurrent value of the photocathode
- \( I_{NIST}(\lambda) \) = Measured photocurrent value of the NIST Photodiode.
- \( Calibration_{NIST}(\lambda) \) = Known calibration factor to estimate number of incident photons from \( I_{NIST} \).
- \( I_{DC} \) = Estimated dark current.

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### Coating Details

<table>
<thead>
<tr>
<th>Coated Substrate/THGEMs</th>
<th>Type of ND</th>
<th>#Shots</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB IX</td>
<td>ND</td>
<td>300</td>
</tr>
<tr>
<td>TB VIII</td>
<td>H-ND</td>
<td>140</td>
</tr>
<tr>
<td>TB III</td>
<td>H-ND</td>
<td>43</td>
</tr>
<tr>
<td>TBVII</td>
<td>H-ND</td>
<td>55</td>
</tr>
<tr>
<td>TB XIX</td>
<td>H-ND</td>
<td>59</td>
</tr>
<tr>
<td>TB XI</td>
<td>H-ND</td>
<td>250</td>
</tr>
<tr>
<td>PCB9</td>
<td>H-ND</td>
<td>25</td>
</tr>
<tr>
<td>PCB7</td>
<td>H-ND</td>
<td>50</td>
</tr>
<tr>
<td>PCB10</td>
<td>H-ND</td>
<td>100</td>
</tr>
<tr>
<td>PCB11</td>
<td>H-ND</td>
<td>200</td>
</tr>
<tr>
<td>PCB8</td>
<td>H-ND</td>
<td>400</td>
</tr>
<tr>
<td>PCB1</td>
<td>ND</td>
<td>100</td>
</tr>
<tr>
<td>PCB2</td>
<td>ND</td>
<td>100</td>
</tr>
<tr>
<td>PCB3</td>
<td>ND</td>
<td>200</td>
</tr>
<tr>
<td>PCB4</td>
<td>ND</td>
<td>200</td>
</tr>
<tr>
<td>PCB5</td>
<td>ND</td>
<td>50</td>
</tr>
<tr>
<td>PCB6</td>
<td>H-ND</td>
<td>50</td>
</tr>
</tbody>
</table>

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**Coated THGEMs and PCB Coins:**

- ND & H-ND coted on 14 PCB coins
- Non-hydrogenated ND full THGEMs (One)
- Hydrogenated ND full THGEMs (Five)

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THGEM (AA) : 30 mm X 30 mm

PCB Coin : 25 mm diameter
Figure details: (A) Au_PCB of 01 inch diameter substrate used for the QE measurement. (B) Uncoated THGEM of active area 30 mm x 30 mm. (C) Half uncoated and half coated THGEM with ND powder, mounted into the test chamber and zoomed view of the both coated (D) and uncoated (E) parts are shown. (E) Test chamber with readout pad where the THGEMs are tested. (G) The test chamber after installation of a THGEM, with gas flow and X-ray source.
Noise, Reproducibility and Electric field scan @INFN Bari
Noise and Reproducibility

PCB7 [50 Shots] photo current vs. wavelength

Estimated dark current of substrate ~ \(0.1 \pm 0.02\) pA

NIST photo current vs. wavelength

DC ~ 20 pA

Estimated dark current of substrate ~ \(0.1 \pm 0.02\) pA
Photocurrent vs Electric field in Vacuum & Gas @ 160 nm

- Vacuum
- CH₄
- Ar:CH₄ 50:50

Photocurrent [pA] vs Electric field [kV/cm] for different gas mixtures.
Photocurrent Results
Quantum Efficiency vs. H-ND Shots @ 160 nm @ 2 kV/cm
Quantum Efficiency of ND and H-ND

Quantum Efficiency vs. Wavelength ($\lambda$)

- PCB8 H-ND (400 shots) 500V
- ND Al Substr [2019]
Photocurrent measurement @ CERN
Schematic & Pictorial view of photoemission measurement setup: ASSET
Quantum Efficiency Formula CERN

\[ QE_{PC}(\lambda) = \frac{N_{pe}}{N_{ph}} = \frac{(I_{PC}/e)}{(factor(\lambda) \times I_{ref}(abs))} \]

\[ I_{ref}(abs) = I_{ref} \times \frac{I_{PMT(Top)}}{I_{PMT(Bottom)}} \]

where \( I_{ref} = I_{PMT(Bottom/withPC)} \)

\[ factor(\lambda) = \frac{h \times c \times radiant\ sensitivity}{\lambda} \]

\( \lambda \) = wavelength; \( h \) = Planck’s constant; \( c \) = velocity of light in vacuum

ET Enterprise Calibration for PM 9403 [S.N. 88]

Photocurrent vs. wavelength

Quantum Efficiency vs. wavelength

Where:
- \( QE_{PC}(\lambda) \) = Quantum efficiency of the photocathode
- \( factor(\lambda) \) = extrapolated as shown from data sheet
- \( I_{PC}(\lambda) \) = Measured photocurrent value of the photocathode
Comparison of Bari and CERN results

- **Photocurrent on the substrate vs. wavelength**
- **Quantum Efficiency vs. wavelength**
- **Ratio of QE [CERN/Bari]**

ASSET is in building up state, comparative analyses are useful

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Comparison with literature

- Deposited by Miranda and Thomas in CERN.
- Substrate used: Au PCB coin
- Measured in ASSET @ GDD lab.
- QE: $\sim 23.6\%$ @ CERN & $\sim 34.8$ in literature for $\lambda = 160$ nm
Reproducibility @ CERN

**PCB7 [50 Shots] QE vs. Wavelength**

- **Quantum Efficiency**
  - Y-axis: 0.01 to 0.09
  - X-axis: 120 to 190 nm

- **Wavelength [nm]**
  - 120, 130, 140, 150, 160, 170, 180, 190

- **Data Points**
  - 12-12-19 13.04
  - 13-12-19 10.31
  - 13-12-19 11.37
  - 13-12-19 18.19
  - 13-12-19 19.34
  - 14-12-19 11.17
  - 14-12-19 12.04

**Standard Deviation of the repeated measurements of PCB7 [50 Shots]**

- **Standard Deviation**
  - Y-axis: 0 to 0.005
  - X-axis: 120 to 190 nm

- **Data Points**
  - 0.0005
  - 0.0025
  - 0.0035
  - 0.0045
  - 0.005

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In case of a CsI photocathode, a 25% drop in QE is observed for an irradiation of 0.1 mC/cm² [Nucl. Instrum. Meth. A 574 (2007) 28]

NOTE: This is the first preliminary irradiation ageing study of H-ND photocathodes ever performed.
THGEM Characterization
THGEM parameters

- THGEMs are standard Printed Circuit Boards (PCBs) with holes produced by mechanical drilling.
- Like in GEMs, in the presence of a correct electrical bias and in a proper gas mixture, each hole acts as an electron multiplier.
- The signal generated by the gas multiplication is collected at the anode.
- The geometrical parameters of our THGEMs are: hole diameter (d) = 0.4 mm; hole pitch (p) = 0.8 mm; thickness of the fiberglass (t) = 0.4 mm; and rim around holes < 5 um.

For measurements used:
- Gas mixture: Ar:CH\textsubscript{4} 50:50
- CAEN N1471H HV PS has been used.
- CREMAT CR-110 Preamplifier with CREMAT CR-150 r5 evaluation board has been used to read the signal from the detector.
- Ortec 672 Spectroscopy amplifier with AMPTEK MCA 8000A has been used for processing the signal and for saving the data.
A typical $^{55}\text{Fe}$ X-ray spectrum obtained in $\text{Ar}:\text{CH}_4 = 50:50$ gas mixture for uncoated and H-ND coated THGEM VIII

<table>
<thead>
<tr>
<th>THGEM VIII Characterization</th>
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<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

- THGEM VIII Before H-ND coating [$\Delta V = 1520\text{V}$]
- THGEM VIII After H-ND coating [$\Delta V = 1520\text{V}$]
Uncoated and H-ND coated THGEM VIII in Ar:CH$_4$ = 50:50 gas mixture

THGEM effective gain vs. bias voltage

- • Before H-ND coating
- ▲ After H-ND coating
Conclusion

• A systematic R&D has been started to explore the characteristics and possibilities of ND photocathode.
• H-ND is having comparable QE to CsI @ 140 nm.
• Preliminary measurements have been performed and found promising results.
• Aging studies have been started & preliminary results of QE shows that, H-ND photocathodes are quite stable in comparison with CsI
• H-ND has been applied on THGEMs and a R&D towards a detector of single photon based on hybrid (THGEM + MM) MPGD technology with H – ND photocathode has been started.
• Coated THGEMs show a decrease in electrical stability, in particular, for the H-ND case, however an improvement is observed after heat treatment in electric oven.
• **Hydrogenated Nano Diamond is a potential candidate as CsI substitute after overcoming the observed challenges.**
Backup slides
Quantum Efficiency Formula CERN

\[ QE_{PC}(\lambda) = \frac{N_{pe}}{N_{ph}} = \frac{(I_{PC}/e)}{\left( \text{factor}(\lambda) \times I_{ref(\text{abs})} \right)} \]

\[ I_{ref(\text{abs})} = I_{ref} \times \frac{I_{PMT(\text{Top})}}{I_{PMT(\text{Bottom})}} \]

where \( I_{ref} = \frac{I_{PMT(\text{Bottom})}}{I_{PMT(\text{Top})}} \)

\[ \text{factor}(\lambda) = \frac{h \times c \times \text{radiant sensitivity}}{\lambda} \]

where \( \lambda = \text{wavelength}; h = \text{Planck’s constant}; c = \text{velocity of light in vacuum} \)

Calibration of CsI PMT photocurrent to number of Photons

Where:
- \( QE_{PC}(\lambda) \) = Quantum efficiency of the photocathode
- \( \text{factor}(\lambda) \) = extrapolated as shown from data sheet
- \( I_{PC}(\lambda) \) = Measured photocurrent value of the photocathode

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Estimated dark current of NIST photodiode $\sim 19.4 \pm 1.4 \, \text{pA}$
Position scanning

- We scanned two of our samples with 2 mm @ 0 nm wavelength to see the profile.
- A clear difference between CsI and H – ND can be seen.
- The reduced photocurrent is due to lower QE (?).