NanoUV - A High-Efficiency Ultraviolet Light Detector Based on Aligned Carbon Nanotubes

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ABSTRACT

We present a novel, high-efficiency ultraviolet light detector based on vertically-aligned carbon nanotubes. Carbon nanotubes are 1D cylinders made of graphene, a 2D material. Therefore, the incoming radiation ejects electrons from the Carbon lattice directly into the vacuum. This minimizes photo-electron re-absorption, which is the leading cause of inefficiency in today's detectors. We report on the design and construction of a NanoUV prototype, and the characterization of its key technological components; on the construction and commissioning of a state-of-the art nanotube-growing facility in Rome; and on the road towards achieving the NanoUV proof-of-concept.

Keywords: Carbon nanotubes; UV light; sensors.

1. INTRODUCTION

Detection of ultraviolet (UV) light with high single-photon quantum efficiency (QE) is required in many fields, from dark matter experiments, to astronomical surveys, and even air pollution monitoring. Traditional detection techniques are based on the use of photo-multiplier tubes (PMTs), which have typical QE of 20-25% for UV photons, and are susceptible to thermal noise. The leading cause of inefficiency comes from the photocathode, where incident photons are turned into electrons through the photoelectric effect. These photo-electrons have very short range in matter, and are typically re-absorbed before they can produce a signal.

NanoUV aims to revolutionize UV-light detectors thanks to photocathodes made of vertically-aligned carbon nanotubes (CNTs), which are sheets of graphene wrapped into straws with internal diameter of a few nm, and length of up to a few hundreds of µm. CNTs can be single-walled or multi-walled, depending on how many tubes share the same axis. Graphene is a two-dimensional form of matter; therefore, electrons are ejected directly into the vacuum. Aligned CNTs have close to vanishing density in the direction of the tube axes, therefore electrons would be able to exit the photocathode without being re-absorbed. Furthermore, the relatively large work function of graphitic carbon (4.7 eV) would make the detector practically unaffected by thermal noise, even at room temperature.

In the NanoUV detector concept, once the photo-electrons leave the nanotube photocathode they will be accelerated in vacuum by an external electric field and reach an energy of about 1 keV before hitting an electron counter. A schematic view of the NanoUV concept can be found in Fig. 1.

Our results can be summarized as follows.

- Identification of a suitable technology for the detection of keV electrons: we have successfully employed both silicon avalanche photo-diodes (cost-effective) and silicon drift detectors (for ultimate energy resolution).
- Design, construction and commissioning of a CNT-growing facility in University 'Sapienza' of Rome. The first growths were successfully performed in August 2020, yielding multiple batches of vertically-aligned CNTs of up to 100 µm in length.
- Design and construction of a NanoUV prototype, which started taking data in August 2020.
- The NanoUV proof-of-concept (60% complete) will be finalized during the months of September and October 2020. The main measurement will consist in illuminating the CNT photocathode with UV light and observing the emission of photo-electrons into the vacuum.

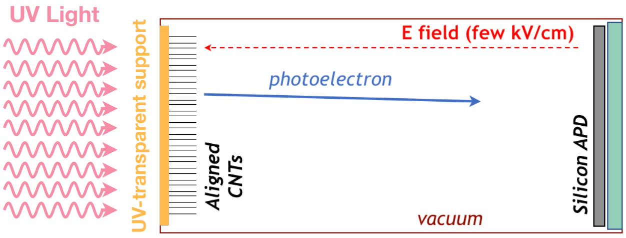

Fig. 1. Schematic view of the NanoUV detector concept.

2. STATE OF THE ART

Current UV-detection technologies can be classified broadly into two categories. The first is made of solid-state devices based on silicon junctions. These detectors are typically sensitive only to the visible or near-UV regions of the light spectrum, with typical QE that rapidly drops below 20% for $\lambda < 300$ nm. Furthermore, because of the relatively small (1.1 eV) band-gap energy of silicon, they are sensitive to thermal noise, and therefore often need to be operated at low temperatures. Attempts to increase the QE of these devices have been made, by developing new coatings [1], or new hetero-junctions [2]. While in some of these cases higher (>50%) values of QE have been achieved, none of these solutions have led to breakthroughs in the field, because of their high manufacturing complexity, and, consequently, their high costs.

The second category are two-stage devices, composed by a photocathode, where the incident photons are converted, through the photoelectric effect, into electrons; and a gain component, where the electrons are accelerated and multiplied into a detectable current. This category of devices is spearheaded by PMTs, which have been successfully employed in the detection of UV light over the past decades, albeit with low QE. The main limiting factor of the QE of a PMTs comes from the photocathode: because of the very short range of low-energy electrons in matter, there is a high probability that they are re-absorbed in the photocathode without being able to reach the gain component, and therefore without producing any signal. Widely-used photocathode materials for UV-sensitive PMTs are alkali (*e.g.* Cs-Te or Cs-I) and bialkali compounds (*e.g.* Sb-K-Cs or Sb-Rb-Cs), which have typical QE of 30-35% and 15-25% for UV photons, respectively. Just like silicon devices, also PMTs are sensitive to thermal noise, therefore need to be kept at low temperatures for best performance.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Since the discovery of graphene in 2004, and of carbon nanostructures in the following years, there has been widespread excitement for the unique chemical, physical and mechanical properties of these materials. The introduction of carbon nanostructures has led to technological breakthroughs in a many fields, including electronics, biotechnologies, and chemical sensors.

NanoUV intends to introduce carbon nanotubes (CNTs) to the field of UV light detection. The key technological advancement is constituted by the replacement of traditional photocathodes with vertically-aligned CNTs. Nanotubes are one-dimensional cylinders made of wrapped graphene, a two-dimensional material; therefore, photo-electrons are ejected directly into the vacuum. Furthermore, they have close to vanishing density in the direction of the tube axes [3]. These unique properties would allow to **minimize electron re-absorption** in the photocathode, the leading cause of inefficiency of today’s UV light detectors.

In addition, the relatively high work function of graphitic Carbon (4.7 eV) would make NanoUV devices (i) **insensitive to thermal noise**, even at room temperature; and (ii) insensitive to visible light (**visible-blind**). A UV detector with these features would have immediate use in many fields: from dark matter searches, to space telescopes, and even air-pollution monitoring.

Current state-of-the-art **dark matter** detectors employ large masses of liquid Xenon [4,5] or Argon [6] as active target. A dark matter event would produce scintillation light, which for these liquids is entirely in the UV. A UV light detector with higher QE would increase the detector sensitivity, therefore increasing the reach of these searches.

In recent years, UV spectral analysis has opened new possibilities in astronomical research, as it is populated by atomic and molecular emission lines that are highly relevant for the study of stars, supernovae, black holes, and in searches for habitable exoplanets. Next-generation **space telescopes** are being planned to carry out surveys of the universe [7], or extensive searches for habitable exoplanets [8], and high QE is the key feature that would improve their capability of detecting faint deep-space objects. Furthermore, visible-blindness would shield the telescope from starlight, avoiding costly alternative solutions (such as ‘starshades’ [8]).

Lastly, NanoUV could benefit **air pollution monitoring**, currently regarded as one of the largest environmental threats to the health of EU citizens. Ground level ozone, in particular, is recognized as one of the most harmful to human health [9], and needs to be constantly monitored in large cities. This is done by using UV light detectors to measure the intensity of the 254 nm emission line of mercury lamps. A portable, high-efficiency UV light detector such as NanoUV could offer an interesting technological solution.

4. PROJECT RESULTS

4.1. Detection of keV electrons

Photoelectrons emitted by the CNT photocathode will be accelerated to ~1 keV energy before reaching the other side of the device, where they need to be detected. The detection of keV electrons with a portable technology is not a trivial task; yet we have successfully employed to this end both silicon avalanche photo-diodes and silicon drift detectors.

Avalanche photo-diodes (APDs) are silicon *p-n* junctions operated in reverse bias mode, widely employed as visible light detectors. We have

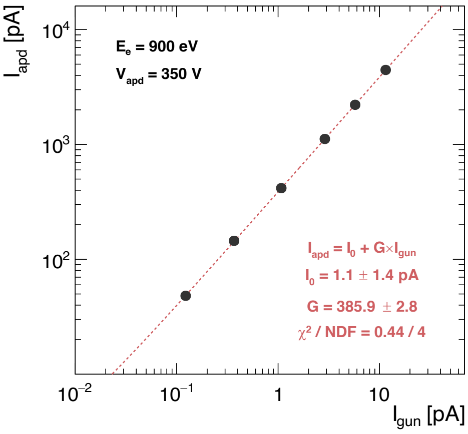

Fig. 2. APD bias current (I_{apd}) as a function of the electron gun current (I_{gun}), for electrons with energy E_e = 900 eV.

successfully employed them as electron detectors, by directing a current I_{gun} of electrons coming from a mono-energetic gun on their sensitive area and studying the bias current I_{apd} generated by the APD. We find I_{apd} to be proportional to I_{gun}, and the proportionality constant is found to be $G = 385.9 \pm 2.8$, for electrons with energy of 900 eV (see Fig. 2). The knowledge of G will allow us to operate the APD inside the NanoUV prototype with a potential difference $\Delta V = 900$ V between the CNTs and the APD. The use of APDs to detect low (< 1 keV) energy electrons, presented here, is a novelty [10].

Silicon drift detectors (SDDs) have also recently been employed as electron detectors [11]. Compared to APDs they are characterized by significantly improved energy resolution, which makes them sensitive to single photo-electrons. While single-electron sensitivity will play a crucial role in the NanoUV proof-of-concept, a detailed cost-benefit study will be carried out to decide whether it is feasible to employ SDDs in large-scale production.

The SDD we have tested was produced by Fondazione Bruno Kessler (FBK), and its electronics were designed and produced by Politecnico di Milano (PoliMi) specifically for NanoUV. The SDD was installed inside the NanoUV prototype, and in this configuration it was employed to successfully reconstruct of the ^{55}Fe Kα peak (5.9 keV) with a FWHM of 136 eV at 22°C.

4.2. CNT-growing facility

We have designed and constructed a state-of-the-art CNT-growing facility in University 'Sapienza' of Rome, which employs chemical vapor deposition (CVD) to grow vertically-aligned multi-walled CNTs. The chamber is also capable of plasma-enhanced CVD (PE-CVD), which allows to produce single-walled CNTs. The construction was completed at the end of July 2020. Its commissioning began in the first week of August 2020, and we have successfully synthesized vertically aligned CNTs already on the first day of operation. A SEM image of one of the first growths is shown in Fig.3: vertically-aligned nanotubes on a fused silica substrate, between 80 and 100 μm in length, are clearly visible. While we intend to improve on the growth parameters of these nanotubes (length, alignment, density), it should be noted that this is already a remarkable achievement, as the commissioning of a CVD chamber can typically take up to several months. It should also be noted that as of now, ours is the largest and most versatile CNT-growing facility in Italy.

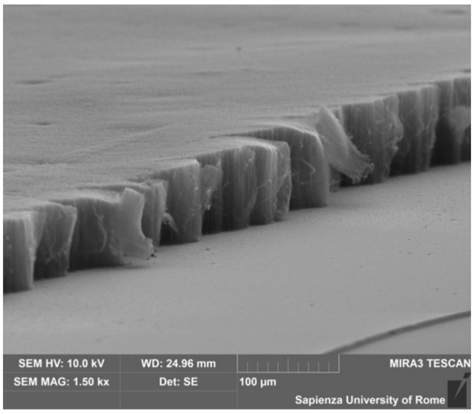

Fig. 3. SEM image of one of the first growths of vertically-aligned CNTs performed at the new CVD facility in Rome.

4.3. NanoUV proof-of-concept (60% complete)

Preliminary measurements on CNT anisotropy have been carried out, and are summarized in Fig. 4, which shows the flux of emitted photo-electrons when illuminating CNTs with a Helium UV lamp, as a function of the incidence angle γ of the UV radiation with respect to the CNT axes. The fluxes are divided by the same fluxes measured on amorphous carbon (aC), and the ratio is normalized to be equal to unity around $\gamma = 40°$. As can be seen, for all different photo-electron energies (shown in different colors), a significant enhancement of the flux of photo-electrons emitted by CNTs is observed around $\gamma = 90°$, which corresponds to photons at grazing angle. These results are a further indication of the anisotropy of this material, and will allow us to define the optimal illuminating angle to maximize the device efficiency.

To achieve the NanoUV proof-of-concept we have designed and constructed a prototype (Fig. 4), made of a small cylindrical vacuum chamber with a circular LiF window (transparent to UV light) on one side, on the inside of which the nanotubes can be mounted and brought to a potential of $\Delta V \leq 1$ kV; and on the other side an APD or SDD, hosted on a linear translator. The main measurement will be carried out in the months of

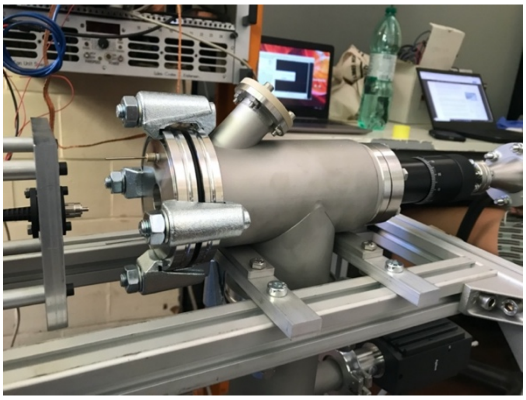

Fig. 4. The NanoUV prototype taking data in Rome.

September and October 2020: UV light will be directed through the LiF window onto the CNT photocathode. The ejected photo-electrons will be accelerated by the applied tension ΔV, and detected by the SDD detector. The measurement will be performed for different values of ΔV, to prove that the signal is linked to electrons.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

By the end of the ATTRACT Phase 1, a successful proof-of-concept will bring the project to TRL 4. By the end of ATTRACT Phase 2 we plan to scale up to TRL 7. The main aim of Phase 2 will be the design and construction of a truly portable and marketable NanoUV device. The main steps required are:

- miniaturization of electrical components;
- engineering of (static) vacuum seal;
- optimization of LiF window and CNT orientation;
- cost-benefit analysis to select silicon technology.

5.2. Project Synergies and Outreach

The NanoUV consortium will expand to six partners, as shown in Tab. 1, where the main role of each partner is also summarized. The three partners which constitute the ATTRACT Phase 1 NanoUV consortium (INFN, Sapienza and Roma Tre) will be joined by three new partners (FBK, PoliMi, TEES). The role of project coordinator will be retained by INFN (project coordinator: F. Pandolfi), which will also be in charge of the synthesis of CNT with the newly commissioned CVD growing facility in Rome (main responsible: I. Rago). Partnership with 'Sapienza' University (main responsible: Prof. G. Cavoto) will ensure access to a scanning electron microscope (SEM), to XPS and Raman spectroscopy analysis facilities and even spatially-resolved micro-spectroscopy (Prof. C. Mariani). The laboratories of University of Roma Tre (main responsible: Prof. A. Ruocco) will continue to provide accurate characterization of silicon detectors and carbon nanostructures with XPS, UPS and monoenergetic electrons.

The three new partners will offer the necessary additional assets to design and produce a portable and marketable NanoUV device: Fondazione Bruno Kessler (FBK, main contact: G. Borghi), a research foundation leader in silicon sensor development, will be in charge of defining the most suitable sensor technology for the application (APD, SDD, or other), and of designing and producing an optimal silicon sensor for the device; Politecnico di Milano (PoliMi, main contact: Prof. C. Fiorini) a leading expert in silicon sensor operation and electronics, will design and construct the detector electronics; and finally T.E.E.S. Srl (teessrl.com/, main contact: M. Alessandroni), a company based in Rome which builds on over 30 years of experience in designing and constructing custom mechanical equipment for research with vacuum technologies, and which has already successfully designed and constructed the NanoUV Phase 1 prototype, will be in charge of the design and construction of the portable NanoUV device. Wide dissemination of our technology to businesses will be ensured by our participation to the TechTransfer program of INFN (web.infn.it/TechTransfer). In addition, our direct connection with major Italian universities will give us high visibility in the academic world: we will organize public seminars at major Italian universities and we will take part in the Share Science program of University 'Sapienza' of Rome (web.uniroma1.it/fac_smfn/share-science), which will let us reach researchers and students from other fields of science, such as Chemistry, Biology, Geoscience and Engineering. To reach the broader public, we will participate to science outreach events such as La Notte Europea dei Ricercatori (www.nottedeiricercatori.it/), MeetMeTonight (www.meetmetonight.it/), Pint of Science (www.pintofscience.it/) and Caffé Scienza (www.formascienza.org/caffe.asp). Finally, we will participate in events with high-school students organized by our universities.

5.3. Technology application and demonstration cases

The construction of a portable UV detector with high QE will have immediate applications in the field of research (see Section 3). We plan to collaborate with the 'Sapienza' group of Darkside [6], a next-generation dark matter experiment based on liquid Argon. Argon emits its scintillation light entirely in the UV range (λ=128 nm). Currently a small prototype is being built in Rome, consisting of a small tank of liquid Argon, with which R&D studies for Darkside will be carried out. We will use a NanoUV device on this prototype to detect Argon scintillation light and compare its performance with the standard setup planned for Darkside, which is based on

Tab. 1. NanoUV consortium for ATTRACT Phase 2. New partners are marked with an asterisk (*).

Partner name	Organization type	Main role
Istituto Nazionale di Fisica Nucleare (INFN)	Research institute	Project coordination, carbon nanotube synthesis
'Sapienza' University of Rome	University	Access to spectroscopy facilities (XPS, Raman, spatially-resolved micro-spectroscopy) and SEM
University of Roma Tre	University	Characterization of silicon detectors and carbon nanostructures with XPS, UPS, and electron gun
Fondazione Bruno Kessler (FBK) *	Research institute	Development of silicon detectors
Politecnico di Milano (PoliMi) *	University	Development of electronics for silicon detectors
TEES Srl *	Industrial partner	Design and construction of portable NanoUV device

more conventional photo-multipliers. Proving that the employment of a NanoUV device brings significant improvements in the measurement of Argon scintillation light will be a crucial test of this technology, and will give the scientific community an important demonstration of its potential.

We also plan to contact local authorities to explore the possibility of using NanoUV technology in the context of ground-level pollution monitoring. Most large cities monitor the amount of ground-level ozone by measuring the 254 nm emission line of mercury lamps. By offering a portable technology which has high efficiency at that wavelength, NanoUV might prove to be an appealing solution, and could lead to better pollution monitoring in large European cities.

5.4. Technology commercialization

The inclusion of a technical commercial partner in the NanoUV consortium (TEES Srl) already constitutes an important step towards the commercialization of the device. Furthermore we intend to apply for the start-up incubation services provided by Regione Lazio (*lazioinnova.it/incubazione-preincubazione-associazione/*). This would also put us in contact with local administration authorities, which would allow us to gauge the potential market of a NanoUV device in the context of air-pollution monitoring. Finally, the direct contact we have with major Italian research institutes (INFN, FBK) and universities (Sapienza, Roma Tre, PoliMi) gives us a clear understanding of the market such a device would have in research environments.

5.5. Envisioned risks

The key step necessary to the commercialization of a NanoUV device, and hence the area of higher risk, will be the clear identification of a market, the broadness of which will depend also on the cost of a single device. A rough breakdown of the expected manufacturing costs is summarized in Tab. 2. As can be seen CNTs, which are the main technological innovation, are a very small fraction of the total cost of a single device, which is instead dominated by the other components, all of which are based on well-known technologies. This means that by increasing our reliance on standardized industrial solutions, a significant cost reduction would be possible.

Tab. 2. Rough breakdown of the expected manufacturing costs of a single NanoUV device.

Component	Cost
Carbon nanotubes (1 cm^2)	10 €
Silicon sensor	300 €
Vacuum-sealed box	400 €
Read-out electronics and connectors	300 €
LiF window	100 €
Total	**1110 €**

5.6. Liaison with Student Teams and Socio-Economic Study

Our project is already attracting MSc.-level students because of the involvement of many of our collaborators in teaching at university level. Therefore, collaborating with ATTRACT MSc.-level student teams will be a very natural extension of this activity, and we will welcome it with enthusiasm. To this end we will dedicate two persons (F. Pandolfi and G. Cavoto), both with vast experience in teaching at the MSc.-level, to the explanation of our technology to students teams.

We plan to participate in ATTRACT's expert-driven socio-economic study with whatever information is deemed most useful, being it interviews, surveys, technology impact references, etc.

6. ACKNOWLEDGEMENTS

The authors affiliated with Politecnico di Milano, not part of the original NanoUV consortium, have given crucial contributions for the usage of SDD technology in NanoUV, including: the procurement of the SDD sensor, the design and construction of a support compatible with the NanoUV prototype, and the design and construction of a dedicated electronics module.

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