Radiation tOlerant THz SensOR (ROTOR)

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ABSTRACT

ROTOR aims at developing THz detector that shows beyond the state-of-the-art key performance indicators for space applications. Being ultralight and having remarkable radiation tolerance ROTOR detector is based on submicron thick stacks of exfoliated graphene and other 2D layered materials and utilizes thermo-electric and Dyakonov-Shur effects. Proof-of-concept realization of the tunable, submicron thick and radiation-tolerant THz detector brings ROTOR to TRL 4, i.e. the Component Laboratory Validated. In response to the societal challenges, within ATTRACT Phase 2 extended consortium will build a prototype and validate in the real environment the THz bio-sensor of revolutionary sensitivity (real-time single biomolecule detection and identification) based on the validated ROTOR technology.

Keywords: Terahertz; bio-sensor; graphene; 2D materials

1. INTRODUCTION

THz fingerprints of astronomical objects are of a great value as they offer insights into history of the Universe, formation and evolution of galaxies and their central supermassive black holes, and other fundamental questions raised by astrophysics.

ROTOR aims at developing THz detector for space applications that shows beyond the state-of-the-art key performance indicators (KPIs), being ultralight and having remarkable radiation tolerance. For that we employ submicron thick stacks of graphene and other 2D layered materials including hexagonal boron nitride (hBN) and transition metal dichalcogenides (TMD).

Specific ROTOR objectives achieved are (i) the development of feasible and easy to use techniques for fabrication of van der Waals heterostructures composed of exfoliated graphene and 2D materials multilayers; (ii) proof-of-concept demonstration and prototyping of a tunable, submicron thick and radiation-tolerant 2D materials based THz detector, approaching Technology Readiness Level (TRL) 4 – Component Laboratory Validated.

Along with a strong investment into the fundamental astrophysics, the ROTOR technology will provide contribute to the sustainable development of the European society via novel THz see-through imaging techniques and systems tackling challenges of utmost importance, e.g., non-destructive testing, medical imaging/diagnosis, health monitoring, quality control, food inspection, environmental control, chemical and biological identification.

2. STATE OF THE ART

Detection and decoding of ultra-weak signals conventionally employ thermo-electric (bolometer) and Dyakonov-Shur effects[1]. To operate in open space, THz detector must be durable, robust, and ionizing radiation resistant.

Atomically thin graphene sheets provide an ideal material base for THz detector, because they possess a high THz absorption ability[2], record-low heat capacity[3], and short thermal relaxation time[4]. Recently project team demonstrated the perfect THz absorber based on graphene multilayers[5]. Suppression of the reflection ability can be achieved by placing graphene/dielectric bilayer on the top of metal back reflector[6].

Plasmon-assisted detection of THz radiation by combining graphene antenna and transistor, i.e. plasmonic Fabry-Perot cavity and rectifying element, has been recently manifested[7]. The responsivity of graphene THz device can be adjusted because the plasmon frequency of 2D electron ensemble is determined by its Fermi energy[8], which can be tuned via chemical or electrostatic doping[9], mechanical stress or other external forces.

Moreover, graphene is promising for space applications because of its outstanding tolerance in respect to irradiation with intermediate energy (0.1 keV - 1 MeV) ions beams that leads to formation of only isolated single vacancies at low fluence and complex defects coalescence at elevated fluence[10].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Tab. 1. Bolometer state-of-the-art KPIs.

Bolometer Type/ Temperature	Responsivity, V/W	NEP, $W/Hz^{1/2}$	TCR, %/K	Response time	Frequency range
Semiconducting/4.2K	$2.4\ 10^{5}$	$1.2\ 10^{-13}$	0.4	1-10 ms	20 THz to 150 GHz
Metal/1.6K	$7.5\ 10^{5}$ - $1\ 10^{7}$	$3.6\ 10^{-15}$ - $4.3\ 10^{-14}$	2-4	8 ms	Far-IR
Superconducting Nb_5N_6/ room temperature (RT)	100.5	8.5×10^{-11}	>10	0.17 ms	Near IR
Cavity-coupled graphene /5K	Not provided	2×10^{-9}	< 0.15	30 ps	Mid-IR
Pyroelectric, graphene-$LiNbO_3$/10K-RT	> 10^{2}	10^{-9}	>100	10 ms	Mid-IR

Temperature coefficient of resistance (TCR), which represents the percentage change in resistance per Kelvin around the operating temperature, noise-equivalent power (NEP), responsivity and response time are the key parameters of bolometers, which can be based on metals (Ti, Ni, Pt), semiconductors (polysilicon, amorphous silicon, or vanadium oxide) or superconductors (see Tab. 1). The parameters of the mid-infrared room-temperature bolometer listed in the bottom row of Table 1 have been used for benchmarking of the ROTOR THz detector.

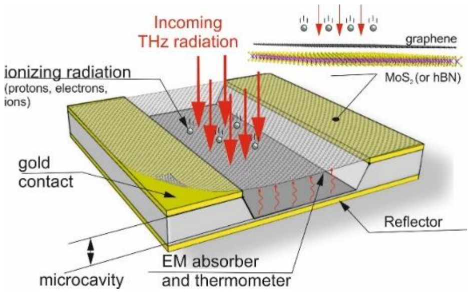

Fig. 1. Schematic presentation of the ROTOR graphene based THz detector.

Graphene[11] and other 2D monoatomic layers[1] are able to withstand damage from Earth's radiation belts' ions and hot magnetospheric plasma. Thus, replacing the standard substrate with 2D materials multilayers will ensure radiation hardness of the absorber keeping it ultralight and broadband. The submicron stack thickness ensures also outstanding sensitivity (it is inversely proportional to the absorption layer thickness) of the bolometer.

The proposed by *ROTOR breakthrough* approach enables detectors (Fig.1) having a 100-500 times lower weight and a 10-50 times smaller footprint in comparison with existing ones at the same sensitivity, and, because of a high tunability, covering the frequency range of interest.

4. PROJECT RESULTS

Based on the results of *ab initio* calculations of graphene/2D materials heterostructures carried out using Density functional theory (DFT) implemented in ORCA and Gaussian 09 packages through the optimizing of the heterostructure geometry by molecular mechanics, semi-empirical methods and DFT via a basic set of MIDI level or 6-31G ** ++, graphene sandwiched between hexagonal boron nitride (hBN) and TMD MoS_2 multilayers have been chosen for experimental realization of effective graphene based ROTOR THz sensor.

This is because TMDs and hBN multilayers possess (i) a high dielectric permittivity, which enables perfect matching conditions and suppressed reflection at very small substrate thickness; and (ii) strong spin-orbit coupling[12], which enables tuning of the perfect absorption frequencies in graphene/TMD/hBN stacks by applying electric field.

Graphene based device fabrication and THz characterization[13]: hBN/graphene/hBN and MoS_2/graphene/MoS_2 heterostructures were fabricated using dry transfer technique[14] starting from micromechanical cleavage. The quality of the flakes, its surface and thickness were monitored by Raman spectroscopy and atomic force microscopy. To shape the device and to open graphene edges obtained heterostructures were then patterned using electron beam lithography with MMA/PMMA resist film (Fig. 2a,b). After plasma etching (CHF_3/O_2) the source and drain metal electrodes were formed by electron beam evaporating Ti and Au, 5 nm and 30 nm respectively. SEM image of the fabricated graphene-based channel before top gate deposition is shown in Fig. 2b. Using optical lithography the source and drain terminals were extended to the µm-scale and patterned in the shape of a bowtie antenna (Fig. 2c). To prevent short contact between top gate and graphene, before gate formation the thin AlO_3 (50 nm) layer was evaporated on the channel area (Fig. 2d).

Fig. 3 shows the results of the room temperature measurements of photovoltage V_p as a function of top-gate voltage V_{tg} acquired at different power of incident

THz radiation. The zero-level of attenuation corresponds to 300 μW incident power.

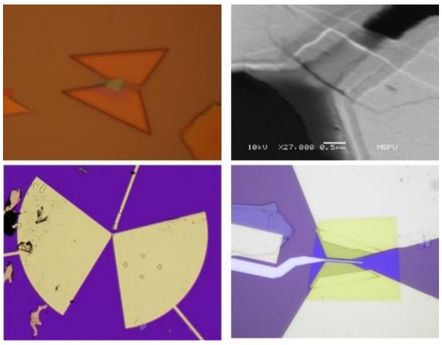

Fig. 2. (a) Optical image of hBN/graphene/hBN stake on SiO_2/Si substrate after electron beam lithography. (b) SEM image of channel of THz detector after patented and metal deposition. (c), (d) Optical images of obtained THz device.

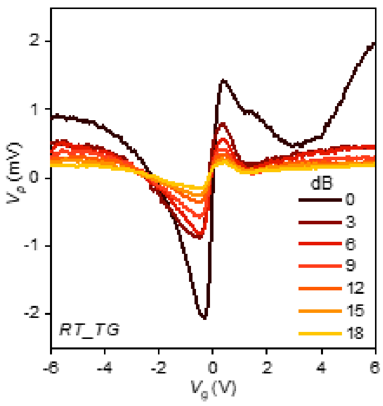

Fig.3. Room-temperature photovoltage as a function of top-gate voltage V_{tg} measured at 0.13 THz using line-level attenuator. 3 dB pad reduces power to one half, 6 dB to one fourth, 10 dB to one tenth, 20 dB to one hundredth, 30 dB to one thousandth and so on.

The following ROTOR KPIs have been achieved: Sensor thickness < 1μm, Detection range 0.1-1.5 THz, Sensor tunability vs electrostatic doping >± 0.2 THz, Responsivity V/W > 10^2 (work is still in progress), TCR %/K > 100, NEP, W/Hz$^{1/2}$ ~10^{-10}, and a record response time of ~10 ps.

In order to enhance responsivity we evaluated a number of sensor's geometries and graphene plasmon-polariton structures. Coupling the incident THz wave to graphene plasmon-polariton, which spatial dimension is much less than the wavelength, provides a tremendous concentration of electromagnetic energy within an atom-thick layer leading to outstanding responsivity.

The investigation of possible effects of ionizing radiations on a graphene based THz detector to be deployed in space has been carried out in the worst case when the remains of PMMA used for graphene handling is still presented in the device[15]. A hydrogen/carbon ion beam was used to simulate the action of protons and secondary ions on the device. We showed that the graphene sheets remain intact after irradiation with an intense 290 keV ion beam, $1.5 \cdot 10^{12}$ ions per cm^2. However, the ability of the graphene/PMMA multilayer for THz absorption can be substantially lowered due to heating damage of the topmost PMMA slabs produced by carbon ions. By contrast, protons do not have this negative effect due to their much longer mean free path in PMMA. Since the particles flux at the geostationary orbit is significantly lower than that used in our experiments, we may conclude that it cannot cause a tangible heating of the graphene/PMMA based THz absorber. Numerical simulations reveal that the performances of the graphene/PMMA multilayer as *THz detector will remain unchanged for more than ten years due to the predicted low damage of graphene produced by the existing ionizing radiations at the geostationary orbit.*

5. FUTURE PROJECT VISION

ROTOR offers a highly promising route towards broadband THz detector. In response to the societal challenges, the next steps within ATTRACT Phase 2 is working out THz bio-sensor of revolutionary sensitivity (real-time single biomolecule detection and identification) based on the achievements of the ROTOR technology. *We propose on-chip THz bio-sensor (Fig.4) that will enable a stable and tunable label- , bleaching- and blurring-free detection by using graphene plasmonic interferometry*[7] *in conjunction with plasmon-polariton slowing-down in graphene based van-der-Waals heterostructures*[16]. Sharp resonances in the THz response of graphene heterostructures will provide high selectivity in bio-objects recognition at extraordinary sensitivity.

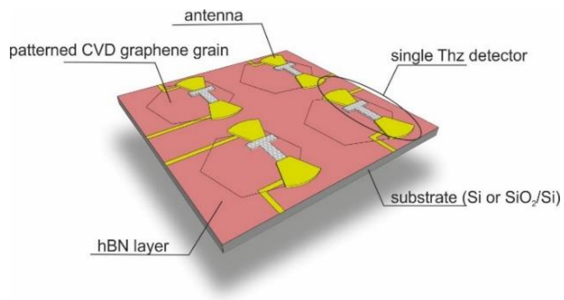

Fig. 4. Schematic presentation of ATTRACT Phase 2 CVD graphene based THz bio-sensor.

The developing technology will grant disruptive solutions for *high precision detection of biological and chemical species, instantaneous genetics tests, and real time environment monitoring to be used, e.g. for bacteria and viruses.*

5.1. Technology Scaling

In the framework of the ROTOR sub-project we have developed a prototype of a tunable, submicron thick and radiation-tolerant THz detector, which is based on exfoliated 2D materials, approaching TRL4. *To bridge from fundamental astrophysics to real-life applications ATTRACT Phase 2 project will make efforts to switch from the exfoliated graphene and other 2D materials to much more technological route based on chemical vapour deposition (CVD) processes.* This will be achieved by solving the following tasks:

Controlled *in situ* **CVD growth of hBN encapsulated graphene domains.** The targeted fundamental graphene parameters will be achieved by tuning the synthesis conditions (based on the UEF know-how).

Design of the on-chip THz bio-sensor having the maximum performance in terms of broadband response, high sensitivity, selectivity and efficiency. THz sensor will be modelled as an IoT system describing each device in terms of signal level, bandwidth, signal-to-noise ratio. The system performance and the data transmission protocols will be described by the relevant model in terms of data loss, missed detection, false alarms for both the detection and classification.

Fabrication of THz bio-sensor based on CVD grown 2D materials. System calibration. Prototyping. Validation of device performance with available biomolecules (including RNA/DNA, certain bacteria and viruses).

The ATTRACT phase 2 project will need 3 years and 2 millions Euro distributed between the following work packages: 1. **Theory and Modelling**. **Proof of the concept experiment** (50 person-months), 2. **Robust design of the THz bio-sensor** (30 person-months), 3. **BIO-experiments for THz bio-sensor validation** (50 person-months), 4. **Technology demonstration in real environment** (30 person-months).

5.2. Project Synergies and Outreach

Along with the partners of ROTOR, i.e. **UEF** as widely recognized in the field of 2D material photonics and nanofabrication, CVD synthesis know-how; **INP** posseting unique modelling expertise in graphene THz electromagnetics, establishment necessary for successful biomolecules THz detection physical parameters of CVD graphene / heterostructures; **UniSa** known as an expert in the robust design of electrical engineering nano- and microdevices made of graphene, *ATTRACT Phase 2 consortium will be reinforced* by Center of Physical Science and Technologies, **FMTC, Vilnius, Lt,** together with Lithuanian industrial partner **TeraVil** (http://www.teravil.lt/t-spec.php) an expert in the THz spectroscopy design and technology validation and commercialization, **StabVida, Lisbon, Pt,** https://www.stabvida.com/company as a European SME with vast experience in genetics/genomics, leading the production and characterization of biomolecules; Moscow Physics-Technical Institute, **MIPT, Moscow, Russia** as unique globally recognized expert in the field of graphene-based THz detectors, and THz technology (MIPT costs are paid using internal resources; no contribution from EC is expected).

We also plan to take advantage of the already well-established connections within groups of the **intra ATTRACT THz alliance** (established on a meeting in Pisa on December 17, 2019), i.e. T-CONVERSE and ROTOR projects for the optimization of the illumination arrangement and the selection and characterization of the component best suited for the system, GRANT project for design and optimization of the imaging architecture, TACTICS project for application of the THz hyperspectral imager to the industrial monitoring.

5.3. Technology application and demonstration cases

ATTRACT Phase 2 project breakthroughs target radically new **technology** of **ultra-sensitive in-situ THz precise characterization** of macromolecular components, and bacteria and viruses. Implementation of the ATTRACT Phase 2 project can lead to *commercial device that will transform the future industry standards performing biochemical analysis with better accuracy, faster processing and at lower costs*.

Some of already funded European research infrastructure projects might benefit from the results and outcomes of ATTRACT Phase 2 project initiated by ROTOR, such as[17] Aerosols, Clouds and Trace gases Research Infrastructure, Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure from the Environment domain; Industrial Biotechnology Innovation and Synthetic Biology Accelerator, Infrastructure for System Biology Europe from Health & Food domain.

5.4. Technology commercialization

The potential of ATTRACT Phase 2 step from lab validation of THz detector (TRL4 by ROTOR) to ***THz technology bio-sensing*** demonstrated in relevant environment (TRL6) is estimated by the project team as very high as multiple industries and social areas will be positively impacted by the technologies developed, including biosensing instrumentation ~ \$20 billion by 2025[18], global microbiology ~ \$6 billion per year by 2021[19], genetics/genomics ~ \$0.5 billion[20].

Our strategy to address market needs is commercializing both single technological products and overall THz bio-sensor device. Consortium foresees three technologies that can be patented/licensed, and take-up by industry: (i) methods, algorithms and software for THz bio-identification, (ii) scalable CVD high-quality encapsulated graphene synthesis, (iii) on-chip integrated THz bio-sensor based on CVD graphene.

It will require close collaboration with industry, addressing high-tech **SMEs**' needs (consortium partners **StabVida and TeraVil**) and wider. To scale up the developed technology uptakes to wider industrial level, highly effective tools provided by **Business Finland** will be used [https://www.businessfinland.fi/en/for-finnishcustomers/home/]. **EKSPLA, EU photonics manufacturer since 1992** https://ekspla.com/about-us/company-profile/, has already expressed its interest in the outcomes of both ROTOR and ATTRACT Phase 2 project, as End User.

5.5. Envisioned risks

Consortium envisages the following R&I risks and their mitigation measures: (1) CVD graphene parameters do not provide stable device operation by particular sensing/tuning mechanism (medium level, mitigation: ►concentrate on combination of two or more mechanisms for detection / tuning). (2) *In situ* CVD synthesis of hBN/graphene is not achieved in time (medium level, mitigation: ►*Ex situ* CVD growth of graphene large domains followed by transfer to hBN will be adopted).

Possible insufficient personnel resources to perform the work (medium risk) will be mitigated by ►Involving highly motivated FTMC and UEF PhD students of H2020 MSCA ITNs TERAOPTICS and GREAT networks.

5.6. Liaison with Student Teams and Socio-Economic Study

ATTRACT THz alliance organizes THzBio2020 workshop in Erice (Sicily) on March 14–19, 2021, http://www.eisbem.eu/index.php/2020-thz-workshop/, to involve MS and PhD students to R&I. This initiative will be supported during the next phases of ATTRACT project implementation.

UEF will be in charge of developing the MSc level explanation material of ROTOR technology. This material will be exploited by UniSA to organize a MSc student competition to provide ideas and prototypes inspired by ROTOR.

The consortium communication channels will be available for the expert-driven socio-economic study of the ATTRACT initiative and ecosystem, furnishing a large number of possible people to interview (e.g. UniSA mailing-lists reaches more than 50,000 users).

6. ACKNOWLEDGEMENT

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