Contribution ID: **155** Type: **not specified**

The project 2-SPaCE: 2-dimensional materials for Single Photon CountErs

The far-infrared region (wavelengths in the range 10 μm –1 mm) is one of the richest areas of spectroscopic research, encompassing the rotational spectra of molecules and vibrational spectra of solids, liquids and gases. Both basic research studies and applications in this spectral region are hampered by the absence of sensitive detectors. Moreover, for certain applications an ultimately high sensitivity reaching a photon-counting level is indispensable. For instance, the single photon detection in the sub-THz spectral range may allow direct detection of dark matter in a region of the parameters space difficult to reach with different techniques, but particularly interesting from a theoretical point of view (axions, ALPs, dark photons, etc.).

However, in THz range photon energies are far smaller (hν < 124 meV for λ > 10 μm) and the single-photon detection is no longer trivial, in marked contrast to the visible and near-infrared regions (wavelengths shorter than about 1.5 μm), in which single-photon counting is possible.

Despite recent efforts to improve the available detector technologies, attainable sensitivities are currently far below the level of single-photon detection, In the last decade, a variety of novel detection schemes have been proposed [1-3]. Among them, semiconductor quantum device have used as single-photon detectors. The experimentally achieved noise equivalent power (NEP), less than 1×10^{-19} W/Hz$^{-1/2}$, is by several orders of magnitude lower than typical state-of-the-art detectros operating in the THz range. Such ultra-high sensitivity reaching singe-photon detection level, as well as ultra-broad dynamic range are consequence of the unconventional detection mechanism in a nanometric phototransistors.

The unique physical properties of graphene, like high carrier mobility, robustness and stability, make this material of potential use for several forefront applications in detector R&D [4,5]. Beyond graphene, there are many other 2D materials that due to confinement of electrons and to the lack of strong interlayer interactions usually exhibit optical and electronic properties different from their analogous 3D systems [6]. The size-dependent properties can be exemplified by molybdenum disulphide (MoS_2) that is semiconducting with an indirect bandgap as bulk material, and becomes a direct gap semiconductor in the 2D form. The functional flexibility offered by 2D atomic crystals is considered to be a key property for next device generation.

The proposed project (2SPaCE, 2-dimensional materials for Single Photon CountErs) is aimed at the development of a technological platform for advanced detectors based on 2D materials, graphene and MoS_2, to be employed as single photon counters in the sub-THz and THz regions.
The main goal of the project will be the investigation of novel detector schemes where 2D materials may play a potentially revolutionary role, by designing and fabricating proof-of-concepts devices. Different device architectures will be explored to achieve efficient detection in the spectral range of interest, by combining the different key concepts which are generally considered for future device generation based on this class of materials:

-Many of the appealing properties of 2D materials arise from the combination of strong light-matter interaction, and electronic transport dominated by hot-carriers effects and collective interactions, like the plasmonic effects that can be activated in the FETs canne [7]. Nowadays, plasmonics in 2DES is one the key concepts for the realization of novel optical devices working in different spectral ranges - from THz to visibile. In particular, the spectroscopic studies on the hydrodynamic response of a 2D electronic plasma confined in the transistor micrometric channel have demonstrated that 2D-based FETs can be used to realize a frequency-tunable THz detectors based on plasmonic micro-cavities[8].

-The remarkable electrodynamics and thermal properties of grahene, at present very well understood at room-T [9], are much less explored at low-T [10]. However, several reports indicated the possibility to reach very high sensitivity as both a bolometer and as a calorimeter [11].

For all the proposed 2D-based devices, one crucial point will be the integration of the 2D materials into the device technology needed for the addressed detector type. With the aim of fabricating detectors using the 2D layered materials, we will propose and develop novel solutions for the microfabrication of future electronic devices, contributing to the advancement of 2D materials science and device technology, whose foreseen applications will be not only in field of dark matter studies. The focus will be the study of the properties that could make 2D layered materials usable in detectors, but the results are expected to be relevant for the knowledge on 2D materials in general.

To date, CVD revealed to be a suitable method to growth controlled quality graphene[12] on large area, a least at R&D level. However, for future device applications, reliable solutions for the integration of the graphene-platform at wafer-scale level are still to find, as they are within the objectives of the "Graphene Flagship" started in 2013. Beyond graphene, the controlled synthesis and fabrication solutions for other 2D-based devices is still lacking or just emerging, hence a fundamental understanding of the processes involved and intensive work at R&D level are still required.

Among the goals of the 2-SPaCE project is the implementation of new equipments and the strengthening of pre-existing facilities for the growth and the analysis of graphene and MoS2. Graphene will be grown at the Laboratori Nazionali di Frascati (LNF) of the INFN (the host institution), by using the expertise developed and facilities set-up within a research program funded by the host institution in the 2014-2015 period and involving the proponents.

As the 2-SPaCE project is concerned with the fabrication and study of novel devices, the final results will be constituted by the demonstration of the proposed detectors concepts. The final deliverables could be possibly both in the form of experimental proof-of-principle prototypes or in the form of ready-to-use demonstrators, together with material synthesis methods, fabrication process solutions and experimental results. The project aim is demonstrating physical principles and indicating the pathways towards optimization of the proposed concepts.

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Summary

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