Terahertz Nano-detectors Exploiting Novel Two-Dimensional Materials and Van der Waals Solids

Miriam S. Vitiello[1] and Leonardo Viti[1]
[1] *NEST, Istituto Nanoscienze – CNR and Scuola Normale Superiore, Piazza San Silvestro 12, Pisa, I-56127*

The ability to convert light into an electrical signal with high efficiencies and controllable dynamics is a major need in photonics and optoelectronics. In the Terahertz (THz) frequency range, with its exceptional application possibilities in high data rate wireless communications, security, night-vision, biomedical or video-imaging and gas sensing, detection technologies providing efficiency and sensitivity performances that can be "engineered" from scratch, remain elusive [1]. These key priorities prompted in the last decade a major surge of interdisciplinary research, encompassing the investigation of different technologies in-between optics and microwave electronics, different physical mechanisms and a large variety of material systems [1,2] offering *ad-hoc* properties to target the expected performance and functionalities.

The talk will provide an overview on our recent developments on THz photodetectors from graphene [1] to novel and fascinating 2D material systems, never exploited before for any active THz device, as topological insulators (TI) black-phosphorus (BP) and bi-dimensional Van der Walls heterostructures combining hexagonal borum nitride (hBN) and BP in a multi-stack configuration.

By exploiting the inherent electrical and thermal in-plane anisotropy of a flexible thin flake of BP, we devised plasma-wave, thermoelectric and bolometric nano-detectors with a selective, switchable and controllable operating mechanism [3,4] as well as near-field THz detection probes. All devices operates at room-temperature in the 0.3- 3.8 THz range and are integrated on-chip with planar nano-antennas, which provide remarkable efficiencies through light-harvesting in the strongly sub-wavelength device channel. The achieved selective detection (~5-8 V/W responsivity) and sensitivity performances (signal-to-noise ratio of 500), are here exploited to demonstrate the first concrete application of a phosphorus-based active THz device, for pharmaceutical and quality control imaging of macroscopic samples, in real-time and in a realistic setting.

We furthermore combine the benefit of the heterostructure architecture with the exceptional technological potential of 2D layered nanomaterials; by reassembling the thin isolated atomic planes of hexagonal borum nitride (hBN) with a few layer phosphorene we stacked mechanically hBN/BP/hBN heterostructures layer-by-layer in a precisely chosen sequence, to devise high efficiency photodetectors operating in the 0.3-0.65 THz range from 4K to 300K with record S/N = 20000.

As a very intriguing alternative, we explored TIs which represent a novel quantum state of matter, characterized by edge or surface-states, showing up on the topological character of the bulk wave-functions. Allowing electrons to move along their surface, but not through their inside, they emerged as an intriguing material platform for the exploration of exotic physical phenomena, somehow resembling the graphene Dirac-cone physics, as well as for exciting applications in optoelectronics, spintronics, nanoscience, low-power electronics and quantum computing. Investigation of topological surface states (TSS) is conventionally hindered by the fact that, in most of experimental conditions, the TSS properties are mixed up with those of bulk-states. We devised a novel tool to unveil TSS and to probe related plasmonic effects. By engineering $Bi_2Te_{(3-x)}Se_x$ stoichiometry, and by gating the surface of nanoscale field-effect-transistors, exploiting thin flakes of $Bi_2Te_{2.2}Se_{0.8}$ or Bi_2Se_3, we recently provided the first demonstration of room-temperature Terahertz (THz) detection mediated by over-damped plasma-wave oscillations on the "activated" TSS of a $Bi_2Te_{2.2}Se_{0.8}$ flake [5]

References

[1] F.H.L. Koppens, T. Mueller, Ph. Avouris, A.C. Ferrari, M.S. Vitiello, and M. Polini "Photodetectors based on graphene, other two-dimensional materials, and hybrid systems", Nature Nanotech. 9, 780 (2014).
[2] M. S. Vitiello et al. "One dimensional semiconductor nanostructures: An effective active-material for terahertz detection" APL Materials, 3, 026104 (2015).
[3] L. Viti et al. "Black Phosphorus Terahertz photodetectors" Advanced Materials, 27, 5567 (2015).
[4] L.Viti et al. "Efficient Terahertz detection in black-phosphorus nano-transistors with selective and controllable plasma-wave, bolometric and thermoelectric response" Scientific Reports, (2016).
[5] L. Viti et al. "Plasma-Wave Terahertz Detection Mediated by Topological Insulators Surface States", Nano Letters 16, 80-87 (2016).