CALL FOR PROPOSALS
OF JOINT LAB PROJECTS
FOR THE YEARS 2015-2019

RESEARCH AREA	TITLE	ITALIAN COORDINATOR (NAME, E-MAIL, PHONE N.)	ITALIAN INSTITUTION (NAME, ADDRESS, PHONE N.)	USA COORDINATOR (NAME, E-MAIL, PHONE N.)	USA INSTITUTION (NAME, ADDRESS, PHONE N.)
Nanotechnology, 2D materials	Silicene Field Effect Transistors (SFET)	Alessandro Molle, alessandro.molle@mdm.imm.cnr.it, +39 039 603 2884	Istituto per la Microelettronica e Microsistemi (CNR), U.O.S. di Agrate Brianza, via C. Olivetti 2, Agrate Brianza	Deji Akinwande, deji@ece.utexas.edu, +1 (512) 471-4345	University of Texas – Austin, Austin, TX, 78758

(*) = ***Please name the Partner Country***

THIRD YEAR REPORT

The third year was focused on the consolidation, optimization and exploitation of the research achievements aiming at a technology transfer scheme.

1) Consolidation and optimization efforts were intended to standardize silicene processing in reliable schemes to be generally extended to the class of epitaxial Xenes. In this respect, samples incorporating silicene on Ag-mica substrates were exchanged between partners in order to develop reliable etching procedures and subsequent device patterning. Alternatively, silicene samples were produced by fabricating templates of epitaxial Ag(111) on Si(111) substrates at CNR-IMM (under supervision by Dr. Grazianetti) in order to facilitate a reproducible etching process of the template from the silicene sheet in a glove box environment at UT-Austin. Other optimization steps in the process flow were concerned with the growth of an additional encapsulation Al_2O_3 layer by atomic layer deposition at the UT-Austin. The full approach was rationalized in the review article: A. Molle, C. Grazianetti, L. Tao, T. Deepyanti, Md. H. Alam, and D.Akinwande, "Silicene, silicene derivatives, and their device applications", *Chem. Soc. Rev.* 2018 47, 6370 with the aim to consolidate our priority in the topic and to establish future directions for the Xene technology.

As a follow-up to carry out the silicene processing as outlined in the above-mentioned article and to strengthen the scientific connection between partners in agreement with the previously signed Memorandum of Understanding, the PhD student, Gabriele Faraone from CNR-IMM and Università di Milano-Bicocca (Dr. A. Molle being the CNR supervisor), spent a 6 months internship at the UT-Austin in order to get trained in the clean-room processing activity. Main task of Faraone's activity was to optimize the etching solution, oxide encapsulation layer, and transfer methodologies, and test them on silicene samples supplied by CNR-IMM. At the same time, optimized device structures were designed, fabricated, and tested at UT-Austin. The internship was also meant to assess pre-established device fabrication strategies in the nanoelectronics framework. In addition to the transistor structure, non-volatile memory devices based on silicene of this kind were designed with the aim to realize first prototypes in this context. To this purpose, consideration was given to

epitaxial phosphorene samples that were originally exchanged between partners as an alternative of silicene. Dr. C. Grazianetti, Post-Doc at the CNR-IMM for the project, was committed to develop the epitaxial synthesis of phosphorene on gold substrates and exchange them. This kind of samples are currently under test.

2) Processing of silicene was subject of technology transfer as reported in the achievement of the US Patent US10242884B2 "Integration of air-sensitive two-dimensional materials on arbitrary substrates for the manufacturing of electronic devices" that include C. Grazianetti and A. Molle from CNR-IMM, and L. Tao and D. Akinwande (UT-Austin) as inventors. On top of the tough evaluation of the patent application, the delamination of silicene developed at UT-Austin on encapsulated silicene sample produced by CNR-IMM was recognized as an original invention enabling the handling and the device integration of similar silicene-like air-sensitive materials like germanene, stanene, epitaxial phosphorene, and so on. In particular, the patent shows how the declared methodology results in an operation field effect transistor working at room temperature. As corroborating fact, the methodology was successfully standardized on multilayer silicene with superior environmental stability (see: C. Grazianetti, E. Cinquanta, L. Tao, P. De Padova, C. Quaresima, C. Ottaviani, D. Akinwande, and A. Molle, ACS Nano 2017, 11, 3376). Exploitation of the invention was carried out by UT-Austin and CNR. The patent finalization was the result of negotiation between the legal representatives of the CNR and the UT-Austin ultimately leading to an agreement between the parts in terms of the contributed costs. The achievement is consistent with the initial purpose of the SFET project to create value on the research products with global impact on the scientific and technology fields.

During 2018, the project activity contributed to parallel grants (including the national grant "Crystel" from Fondazione CARIPLO-Regione Lombardia and the ERC-COG 2017 "XFab" grant) with an overall substantial benefit for the CNR.

List of scientific and technology products.

- Li Tao, Deji Akinwande Carlo Grazianetti, Alessandro Molle (inventors), "Integration of air-sensitive two-dimensional materials on arbitrary substrates for the manufacturing of electronic devices", US Patent US10242884B2 (2019).
- Li Tao, Eugenio Cinquanta, Carlo Grazianetti, Alessandro Molle, and Deji Akinwande, "Encapsulated Silicene Field-Effect Transistors" in *Silicene*, NanoScience and Technology, P. Vogt and G. Le Lay (Eds.), © Springer Nature Switzerland AG 2018
- A. Molle, C. Grazianetti, L. Tao, T. Deepyanti, Md. H. Alam, and D.Akinwande, "Silicene, silicene derivatives, and their device applications", *Chem. Soc. Rev.* 2018 47, 6370 (Impact factor 2018: 40.443)
- C. Grazianetti, E. Cinquanta, L. Tao, P. De Padova, C. Quaresima, C. Ottaviani, D. Akinwande, and A. Molle, "Silicon Nanosheets: Crossover between Multilayer Silicene and Diamond-like Growth Regime", *ACS Nano* 2017, 11, 3376 (Impact Factor 2017: 13,709)

Date: July 29th, 2019 **Signature (Alessandro Molle):**