Marie Curie ITN cQOM
Summary of the Scientific Achievements

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Description of research work and achieved goals

Our research objective is to study the electromechanical properties of graphite nanostructures in order to push the current performance limitations related to nano- electromechanical devices. Due to the layered structure of graphite, it is enough to comprise only two or more graphene layers in order to realize large anisotropic material properties, both electronic and mechanical. During the two years' project time, we have made continued progress towards the understanding of some of the more important properties of thin graphite samples. This progress is mainly thanks to our unique experimental setup which allows us to mechanically manipulate graphite nanostructures with sub-nanometer resolution and to measure the charge transport properties in conjugation with the interlayer mechanical properties in between two individual layers of graphene. Overall, we have published four manuscripts based on our recent results:

1) Direct observation of thermally activated stalking faults scattering in HOPG meso-structures, shining light over one of the long standing mysteries of charge transport in graphite (Fig. 1); In essence, this work discussed the origin of the large anizotropical material resistivity between the in-plane and out-of-plane axes, caused by the presence of 2D potential barriers in the form of stacking-faults along the c-axis.

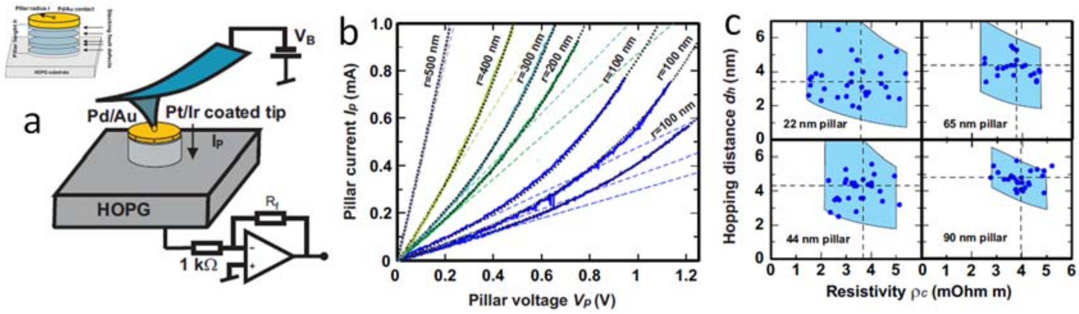

Figure 1. **(a)** Measurement setup, inset shows the presence of individual stacking faults along the c-axis. **(b)** i-V plots of graphite nanostructurs of different radii. **(c)** Hoping distance vs. resistivity for different pillar height.

2) First direct measurement of interlayer displacement forces in graphite nanostructures, enabling novel applications in the MEMS domain (Fig. 2); In essence, we directly measure the exfoliation energy and the required forces for displacing one graphitic layer on top of the other. Thus, we obtain values for both the interlayer adhesion energy and for the dynamic friction of 2 MPa (0.31±0.1 J/m2) and 0.06 MPa, respectively. We then demonstrate how these displacement forces can be designed to realize variable, constant and zero applied force mechanical elements.

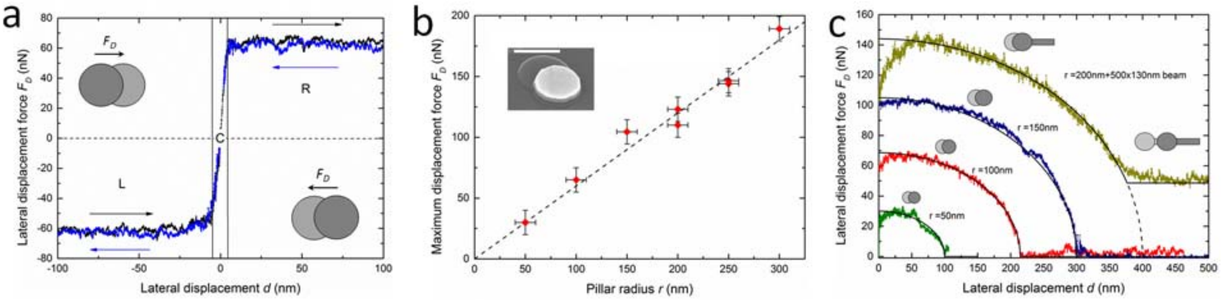

Figure 2. **(a)** Lateral displacement forces of 100nm radius and 60mn height graphite pillar. **(b)** Maximum lateral force of different pillar radii. **(c)** Full displacement force traces for both circular and combined circle beam structure.

3) Exploiting our nano-fabrication and manipulation technology, we studied the out-of-plane electrical conductivity as a function of twist angle of a single twisted interface which is created in mesoscopic cylindrical HOPG pillar structures (figure 3). The measurements reveal that the electrical transport across the interface is dominated by a phonon assisted channel which enables momentum conservation of the conduction electrons passing between the twisted Dirac bands at the interface. Most intriguingly, the conduction is significantly enhanced within a narrow angular range of less than 0.5º at “magic” angles of 21.8º and 38.2º providing the first experimental confirmation for the existence of a novel 2-dimensional interface state originating from the coherent coupling of electronic states in the twisted sheets due to the commensurate superlattice.

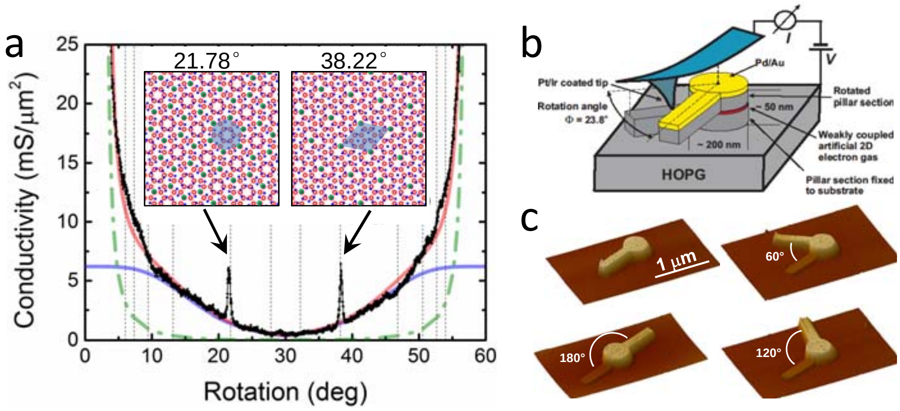

Figure 3. **(a)** Angular dependant iterface conductivity (black curve). Inset : superlattice structures. **(b)** AFM based actuation of rotational bearing structures. **(c)** AFM images of stable rotational configurations both prior and after the mechanical actuation.

List of conferences attended

a. Diavolezza, 10.-14. February 2013, ITN cQOM workshop.
b. Monte Verità, 21.-25. July 2013, Conference on Quantum Nano- and Micromechanics.
c. ETH Zurich, 12. December 2013, Quantum Engineering Day.
d. Seminar, 15. March 2014, Tel Aviv University, physical electronics department, Israel.
e. MRS fall meeting, November 2014, Boston, Massachusetts, USA.
f. Diavolezza, 1.-5. February 2015, ITN cQOM workshop.

Publications

1. Koren, E.; Knoll, A.; Loertscher, E.; Duerig, D.; “Measurement of the spreading resistance of meso-scale circular contacts on HOPG”, *Applied Physics Letters* **2014**, 123112, (105). Link
2. Koren, E.; Knoll, A.; Loertscher, E.; Duerig, D.; “Direct experimental observation of stacking fault scattering in HOPG meso-structures”, *Nature Comm.* **2014**, 5, 5837. Link
3. Koren, E.; Knoll, A.; Loertscher, E.; Duerig, D.; “Adhesion and friction of mesoscopic graphite sliding contacts”, *Science*, **2015**, 348, 679. Link
4. Koren, E.; Leven, Itai.; Knoll, A.; Loertscher, E.; Hod, Oded.; Duerig, D.; “Observation of coherent commensurate electronic states at a twisted graphene interface”, *Nature Nanotech*, **2016**, accepted.