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## NanoMechanics: Elasticity and Friction in Nano-Objects

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### Highlights of Research:

- \* Discovery of **metastable diamene** by pressurizing **two-layer** epitaxial graphene grown on SiC(0001), presenting a **stiffness upon indentation similar/larger than bulk diamond** and **an increase in hardness of bare SiC of 30%**. The associated 2L-graphene/SiC toughness also increases by 10-15% compared to bare SiC.
- \* Discovery of  **$sp^2$  -  $sp^3$  phase transformations** in 2D materials such as graphene and h-BN.
- \* Demonstration of the **first Å-Indentation (ÅI)** measurements to measure the stiffness (up to 1 TPa) of ultra-thin (down to 1 atomic layer) films on substrates.
- \* Demonstration of **the first measurements of interfacial transverse shear modulus of an atomic layer** on a substrate.
- \* Demonstration of a **universal inverse relationship between nanoscale friction and interfacial atomic shear modulus**.
- \* First measurement by ÅI of the stiffness of **Q-Carbon** nano-filaments.
- \* Discovery of an **oscillatory behavior in friction forces** and work function values for even and odd number of layers in polycrystalline **MoS<sub>2</sub>** films, associated to the **oscillatory piezoelectricity of the grains**.
- \* **First measurements of the transverse inter-layer elasticity of 2D materials**.
- \* **First Studies of the friction properties of individual nanotubes**.

### 1. Publications during DoE Funding Period:

#### Publications 2019 – 2023 acknowledging DoE support

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1. Impact of metastable graphene-diamond coatings on the fracture toughness of silicon carbide, M Rejhon, V Dedič, M Shestopalov, J Kunc, E Riedo\*, **Nanoscale** (2024), DOI: 10.1039/D3NR06281C
2. Ryan M Khan, Martin Rejhon, Yanxiao Li, Nitika Parashar, Elisa Riedo, Ryan R Wixom, Frank W DelRio, Rémi Dingreville, "Probing the Mechanical Properties of 2D Materials via Atomic-Force-Microscopy-Based Modulated Nanoindentation", **Small Methods** (2023) <https://doi.org/10.1002/smtd.202301043>

3. Martin Rejhon, Xinliu Zhou, Francesco Lavini, Alessandra Zanut, Filip Popovich, Lorenzo Schellack, Lukasz Witek, Paulo Coelho, Jan Kunc, and Elisa Riedo\* "Giant increase of hardness in silicon carbide by metastable single layer diamond", **Advanced Science** (2023), 2204562 <https://doi.org/10.1002/advs.202204562> .
4. Martin Rejhon, Francesco Lavini, Ali Khosravi, Mykhailo Shestopalov, Jan Kunc, Erio Tosatti, Elisa Riedo\*, "Relation between Interfacial Shear and Friction Force in 2D Materials" **Nature Nanotechnology** (2022), <https://doi.org/10.1038/s41565-022-01237-7> .
5. F. Lavini, M. Rejhon, E. Riedo\*, "Two-dimensional diamonds from sp<sup>2</sup>-to-sp<sup>3</sup> phase transitions", **Nature Reviews Materials** (2022) doi.org/10.1038/s41578-022-00451-y
6. Xiangyu Liu, Alessandra Zanut, Martina Sladkova-Faure, Liyuan Xie, Marcus Weck, Xiaorui Zheng, Elisa Riedo\* Giuseppe Maria de Peppo, "Cost and Time Effective Lithography of Reusable Millimeter Size Bone Tissue Replicas With Sub-15 nm Feature Size on A Biocompatible Polymer", **Advanced Functional Materials** (2021) <https://doi.org/10.1002/adfm.202008662> (Cover Article)
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10. F. Cellini, F. Lavini, C. Berger, W.d. Heer, E. Riedo\*, Layer dependence of graphene-diamene phase transition in epitaxial and exfoliated few-layer graphene using machine learning, Last Round of Revisions in **2D Materials**, arXiv:1901.09071 [cond-mat.mtrl-sci], (2019).
11. F. Cellini, Y. Gao, E Riedo\*, "Å-Indentation for non-destructive elastic moduli measurements of supported ultra-hard ultra-thin films and nanostructures", **Scientific Reports** 9, Article number: 4075 (2019) <https://doi.org/10.1038/s41598-019-40636-0>
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14. Y. Gao, T. Cao, F. Cellini, C. Berger, W. Heer, E. Tosatti, E. Riedo\*, A. Bongiorno "Ultra-hard carbon film from epitaxial two-layer graphene" **Nature Nanotechnology** 13, 133–138 (2018), doi:10.1038/s41565-017-0023-9 (Highlighted in several media and full article in Newsweek)
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18. Edoardo Albisetti, Daniela Petti, Giacomo Sala, Raffaele Silvani, Silvia Tacchi, Simone Finizio, Sebastian Wintz, Annalisa Calò, Xiaorui Zheng, Jörg Raabe, Elisa Riedo, and Riccardo Bertacco, "Nanoscale spin-wave circuits based on engineered reconfigurable spin-textures", **Nature Communications Physics**, 1 (1), 56 (2018) <https://doi.org/10.1038/s42005-018-0056-x>
19. E. Albisetti, D. Petti, Annalisa Calò, Xiaorui Zheng, R. Bertacco, E. Riedo\*, "Thermal scanning probe lithography: from spintronics to biomedical applications", **Proc. SPIE** 10584, **Novel Patterning Technologies** 2018, 1058405 (2018); doi: 10.1117/12.2301253; <https://doi.org/10.1117/12.2301253>
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- Kyung Duk Koh, Hsiang-Chih Chiu, Elisa Riedo\* and Francesca Storici "Measuring the elasticity of ribonucleotide(s)-containing DNA molecules using AFM", book chapter in *Methods in Molecular Biology with the topic of RNA nanotechnology*, Springer Protocols, (2015).
- Ricardo Garcia, Armin Knoll, and Elisa Riedo\* "Advanced Scanning Probe Lithography", **Nature Nanotechnology**, 9, 577 (2014) DOI: 10.1038/NNANO.2014.157.
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