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The Challenge of Complexity in Nanotechnology

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The big bang of nanofabrication techniques from the narrow area of electronics to the wider applications in energy, health and environment areas has been accompanied with a change in the geometrical characteristics of nanostructures. From the well-defined lithographic patterns used largely in semiconductor manufacturing, we have moved to more complex geometries to enhance surface properties and functionalities. These surfaces morphologies range from the almost periodic self-assembled nanostructures to the more random biomimetic morphologies usually characterized by hierarchical organization and multiscale structures. However, despite the extensive use of such complex nanostructured surfaces, a well-founded and concise mathematical characterization and metrology is still missing undermining their quantitative evaluation and large-scale production. The aim of this talk is to address the challenge of nanocomplexity with emphasis on the mathematical characterization and metrology. The key idea is to put this challenge in the perspective of the complexity science and get inspiration by its mathematical concepts and methods. In the first part, we will show plenty of real-world examples to identify the specific appearances of nanocomplexity in microscopy images of micro- and nanostructures. Then we will summarize the current approaches to their analysis found in recent literature. In the second part, we will elaborate three mathematical routes to the characterization of spatial nanocomplexity inspired by complexity and chaos science. The first quantifies the complexity of a nanosurface by the deviation of its morphology from the average symmetry case (fully periodic and fully random) using mulltiscale entropy and information concepts [1] . In the second, the focus is shifted to the scaling symmetry and an alternative to the multifractal formalism is proposed to provide robust and reliable measurements of multifractal spectra of nanosurfaces [2]. Thirdly, we will present an alternative approach to chaos according to which the chaotic evolution of a microscopy image is used to quantify its distance from full order and randomness and therefore to define a chaos-based measure of spatial complexity of depicted nanostructures [3]. Several applications will be presented in wet and plasma etched surfaces of polymers and metals to reveal the benefits and limitations of three methods while emphasis will be given on their link to surface functionality.

References

[1] A. Arapis, V. Constantoudis, D. Kontziampasis, A. Milionis, C.W.E. Lam, A. Tripathy, D. Poulikakos, E. Gogolides, *Materials Today: Proceedings* **54**, 63-72 (2022).

[2] V. Constantoudis, K. Poulios, M. Chatzigeorgiou and G. Papavieros , "Computational nanometrology of nanostructures: the challenge of spatial complexity", International Congress of Metrology, 13001 (2017).