Ion Beams Through Nanopore Masks: A Platform for Nanoscale Patterning and Defect Dynamics in Two-Dimensional Materials

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In this presentation, we demonstrate that ion irradiation through nanopore masks not only offers a route to patterning at a truly nanoscale, but also enables fundamental studies of defect dynamics in two-dimensional (2D) materials.Deterministic patterning of 2D materials at the nanoscale is essential for applications in electronics, photonic metasurfaces, and separation membranes. However, established top-down approaches face a persistent trade-off between resolution, throughput, and cleanliness: electron-beam lithography and other resist-based patterning typically introduce residues that are difficult to fully remove from atomically thin membranes, while high-resolution focused ion/electron beams deliver excellent precision but limited scalability. Motivated by these limitations, we demonstrate a resist-free, contactless approach in which energetic Ar^+ ions transmitted through a suspended Si nanopore mask transfer exactly predefined patterns into self-supporting graphene using a broad ion beam. The method enables large-area patterning with demonstrated feature sizes down to $\sim$15 nm. Simultaneously, the irradiation drives local cleaning by coupling surface diffusion and sputtering of hydrocarbon contaminants, improving membrane cleanliness in and around patterned regions in a single step. Using the same nanopore-mask platform, we also establish an experimental geometry for fundamental defect studies by spatially separating where defects are created from where they are later analyzed. This controlled confinement of irradiation allows us to probe defect propagation in graphene under ambient conditions using selected area electron diffraction (SAED), high resolution TEM (HRTEM), and electron energy loss spectroscopy (STEM-EELS). In both uniformly irradiated and nanopore-masked samples, ion damage produces a global lattice expansion, with tensile strain reaching $\sim$0.8% at intermediate defect densities before relaxing at higher damage levels. Strikingly, we observe reduced crystallinity and clear defect-density gradients in regions outside the directly irradiated areas, indicating room-temperature migration of irradiation-induced vacancies over distances of order $\sim$100 nm. These observations support a strain-assisted vacancy migration mechanism, in which ion-induced lattice strain lowers the effective migration barrier. In addition, the data point to an active role of mobile adatoms, which can partially heal the lattice through vacancy - adatom recombination.

[1] TT Tran, H Bruce, NH Pham, D Primetzhofer, *2D Materials* **10**, 025017 (2023).
[2] TT Tran, POÅ Persson, N Pham, R Holenak, D Primetzhofer, *Small* **21**, 2504370 (2025).