Engineering and Discovering Matter at the Atomic Scale in 2D Materials

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Energy storage, nano-catalysis, ultrathin dielectrics, and quantum materials increasingly rely on single-atom control of defects, dopants, and interfaces — and on identifying emergent atomic configurations that govern phase formation and transformation in 2D materials. Research is shifting from structural characterization only to engineering and discovering matter at the atomic scale. This requires electron microscopy that combines atomic resolution with controlled interaction while controlling beam-induced transformations. Using low-voltage Cc/Cs-corrected TEM (SALVE) [1,2], we establish a platform that unites sub-ångström imaging with interaction-energy control. Applied to TMDs, TMPTs, confined nanoparticles, ultrathin oxides, and carbon layers [3–8], this approach reveals defect-mediated functionalization pathways and atomic-scale reactivity. Most strikingly, we observe a previously unrecognized atomic state in liquid metals: stationary atoms coexisting with liquid atoms during solidification [9]. The latter challenges the classical description of liquids and illustrates that low-voltage aberration-corrected TEM can reveal fundamentally new atomic-scale physics.

Extending these concepts to beam-sensitive organic 2D systems, we resolve defects and crystallization pathways in imine-based polymers and covalent organic frameworks at sub-2 nm resolution. The realization of single-crystalline two-dimensional poly(arylene vinylene) COFs [10] and monolayer nanocrystalline graphene derived from Langmuir films [11] demonstrates that optimized 120 kV operation often is decisive for preserving chemical integrity while maximizing structural insight [12-14]. We further identify design principles for enhanced beam stability in conductive MOFs and reveal unexpected growth pathways in Cu_3(BHT), where in-situ liquid-cell TEM uncovers the formation of Cu_4(BHT) instead of the anticipated phase [14]. At atomic resolution and controlled interaction energies, TEM transforms from an observational tool into a platform for materials discovery — revealing phases, mechanisms, and states of matter previously beyond experimental reach.

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