Slips and Polarization Flips in Deformed 2D Heterostructures

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ABSTRACT

Mechanical strain and deformation offer an unprecedented ability to tailor the symmetry and structure of 2D materials, enabling a host of quantum phenomena like electronic and ferroic phase transitions, exciton trapping, pseudomagnetic fields, and moire engineering. Yet, in many applications of 2D materials, strain is an unknown or uncontrolled parameter. Here, we demonstrate new fabrication techniques and atomic to microscale imaging to design the mechanics of 2D materials and unravel the breakdown of continuum mechanics, role of interfacial slip, and new scaling laws of 2D materials under strain and 3D deformation.

First, we demonstrate designable strain by depositing patterned stressor layers of magnesium oxide onto 2D monolayers and heterostructures. We use Raman hyperspectral mapping to extract the spatially heterogeneous strain in the 2D materials under and near the stressors. We observe complex strain profiles with magnitudes of up to 1%, and fit the profiles using a traction separation model of interfacial slip. We use the stressors to demonstrate patternable bandgap engineering in monolayers with a rate of 93 meV/%, interfacial heterostrain tuning of the moire superlattice.

Second, we use scanning transmission microscopy to image the nanoscale shape of bends in 2D multilayers, and heterostructures. Aligned 2D multilayers display angle dependent bending stiffness due to a transition between shear and superlubric slip at the van der Waals interface. We intentionally introduce misalignment between the layers through twist or heterointerfaces, and demonstrate the resulting 2D heterostructures reach the theoretical limit of stiffness, scaling as the linear sum of the individual layers. Finally, we demonstrate how 3D bending may be used to induce polarization changes in 2D ferroelectrics, and define a critical bending angle of 33 degrees at which point polarization changes become energetically favorable.

These experiments show that interfacial slip strongly affects the mechanics of 2D heterostructures and leads to membranes orders of magnitude more deformable and tunable than conventional 3D materials. We leverage these insights to demonstrate the feasibility of strain and deformation engineering for mobility enhancement in 2D transistors, stretchable electronics and tunable nanoelectromechanical systems.