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Symmetry Breaking and Friction in Few Layer Phosphorene

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Methodology

- **Applying strain to 2D Materials:**
  - Example Samples
  - Sample Cross Section
  - Pressure Vessel
  - Holes RIE into substrates
  - Phosphorene exfoliated directly onto substrate
  - h-BN transferred over holes via Van der Waals Assembly Process
  - Phosphorene exfoliation, storage and measurement done in argon gas

- **Probing Local Strain with Raman:**
  - h-BN Schematics of the process
  - Phosphorene Schematic: Argon or N₂

Strain Induced Peak Splitting

- **Splitting not predicted by Group Theory!**
  - Raman at Center of Microchamber vs. Pressure
  - Data Fit Dbl. Lorentzian
  - Peak for Ext. Mat. Prop.
  - Scan Position [µm]

Extracted Material Properties

- **h-BN E₂g Peak Splitting**
  - Peak Center [cm⁻¹]
  - Peak Intensities
  - Scan Position [µm]

Friction

- **Phosphorene**
  - Strain response parameters found for low energy peaks (L)
  - Mode Experiment DFT
  - Friction Force [MPa]
  - Pressure [MPa]

Theory

- **Generated Strain Distribution:**
  - Analytic Solution ⇒ Extract fundamental properties from data
  - Membrane approximation
  - Fourier Series in Azimuthal Coordinate
  - Effective 2D elastic constants

- **Phonon Strain Response:**
  - Taylor Expand Phonon Secular Equation in Strain:
  - Use Group Theory to Determine Non-Zero Matrix Elements:
  - For h-BN (Point Group D₃₃)
  - For Phosphorene (Point Group C₂ᵥ)

- **Hypothesis Testing has ruled out a second laser spot, material de-lamination, and grain boundaries**

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