Verifying 2D Device Potentials with Kelvin Probe Force Microscopy

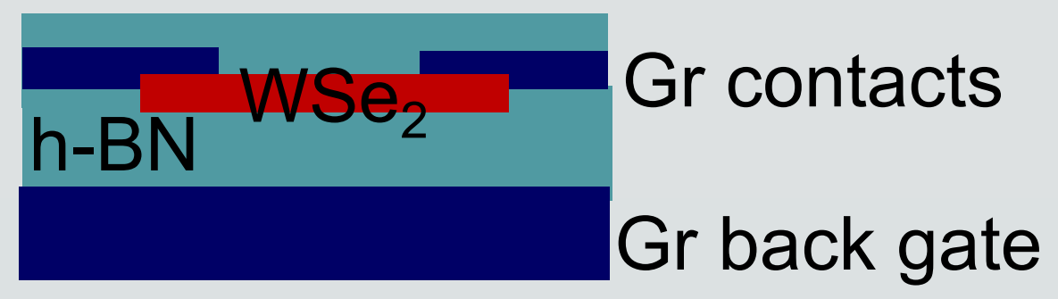
Joel Toledo-Urena, Joseph Murphy, Rebekah Smith, Joseph Simpson, Jennifer Heath
Department of Physics, Linfield College

Introduction

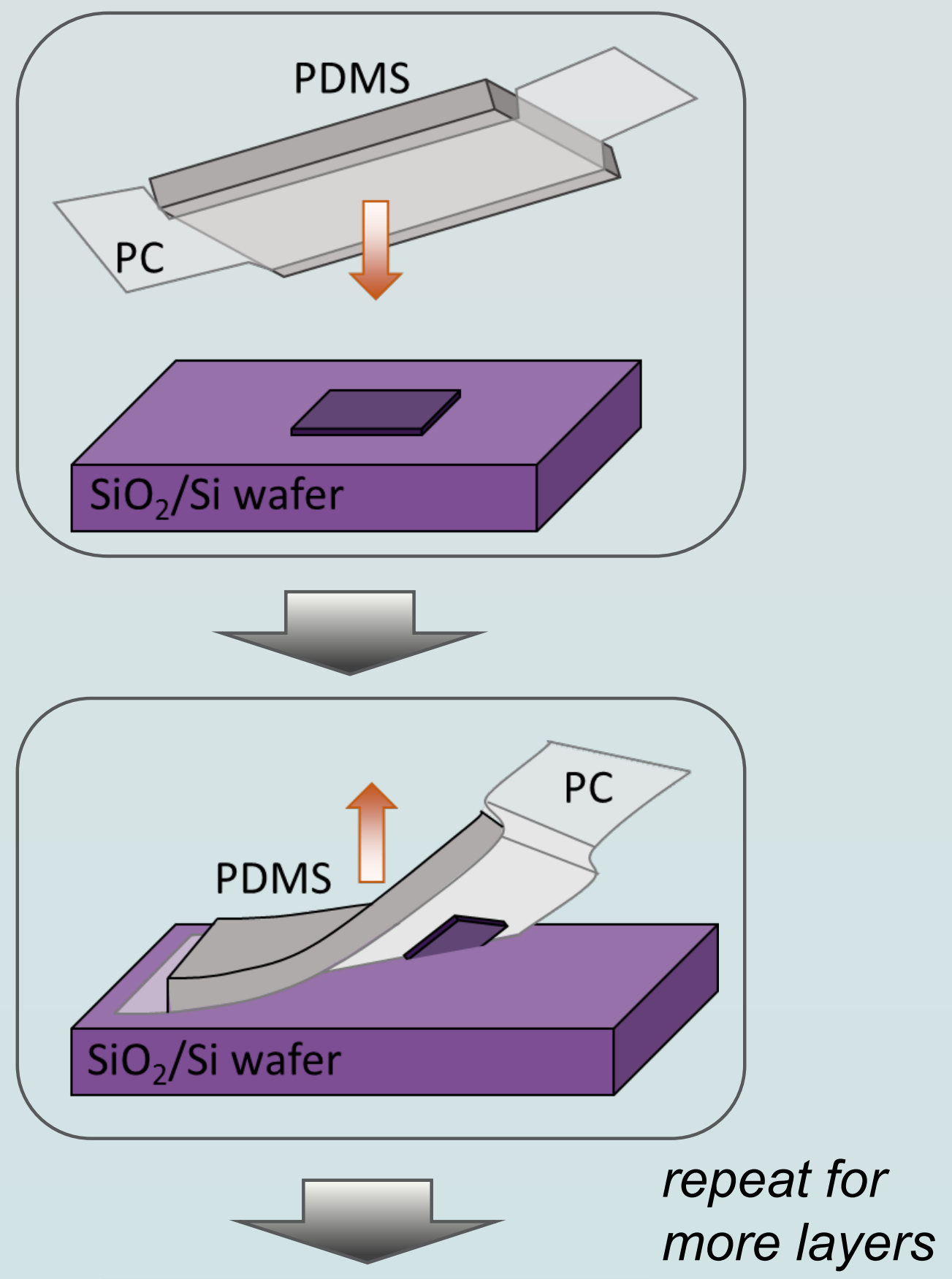
Two-dimensional (2D) materials exhibit properties very different from their 3D counterparts, which affects device design and leads to new opportunities. Understanding the flow of carriers in a 2D device requires knowledge about contact barriers, doping, screening, and tunneling between 2D materials. In 2D field effect transistors (FETs), IV curves show significant quantitative variations in performance, with some FETs being highly conductive, others 'good' and some failing. Given the nature of 2D devices, it makes sense to explore microscopic characterization techniques.

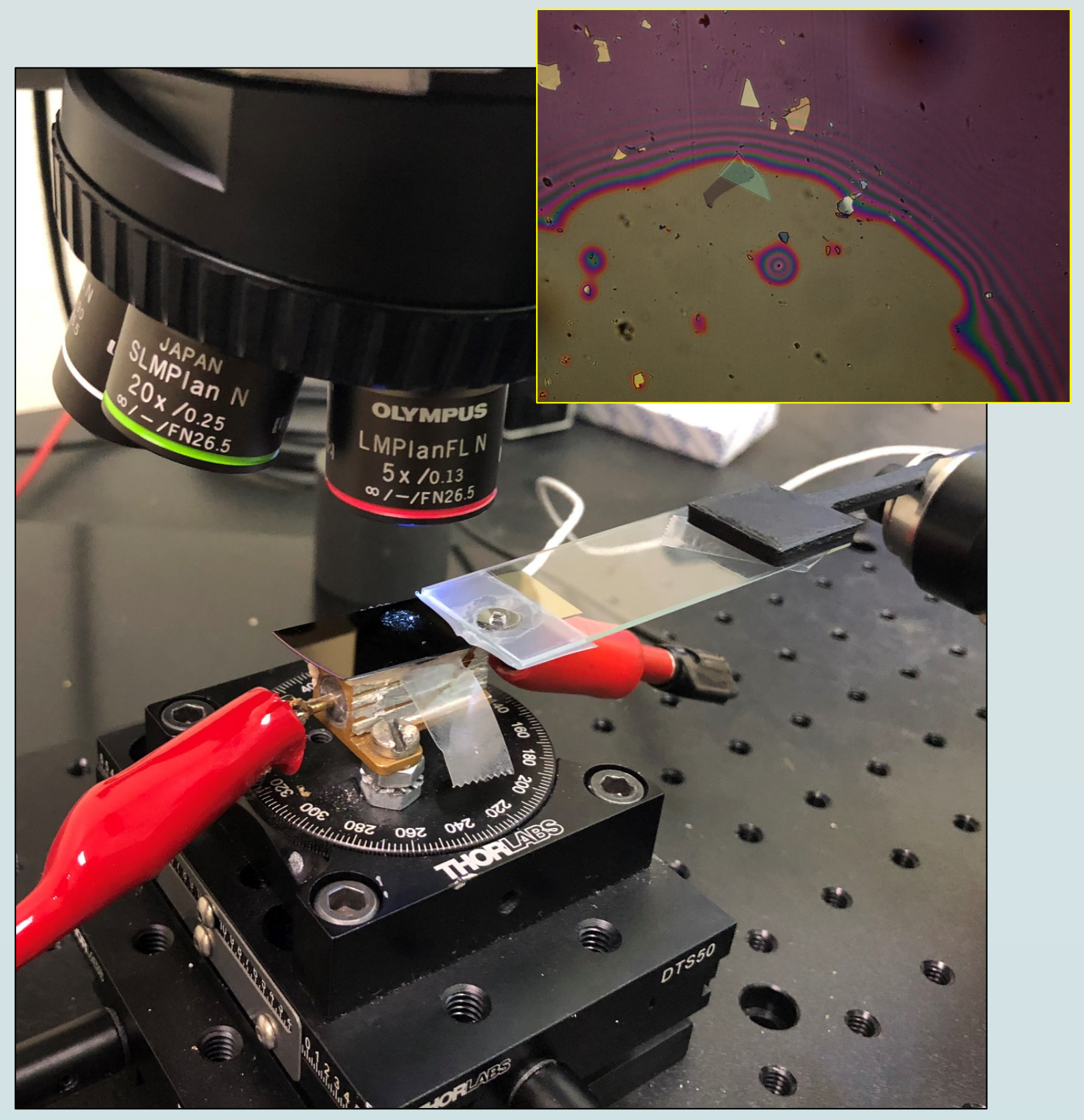
Using Kelvin Probe Force Microscopy (KPFM) we visualize potentials across the entire device. This enables detailed study of the FET including potentials of the channel and contacts as the back gate varies. It also allows us to make correlations between microscopic and macroscopic performance, and to study failure mechanisms.

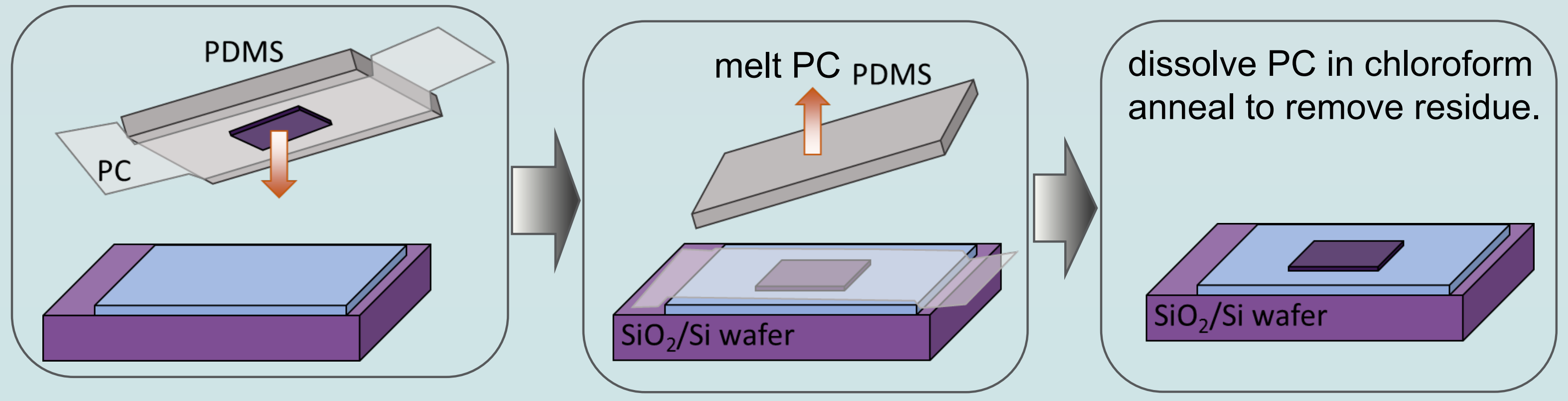
Building a 2D FET



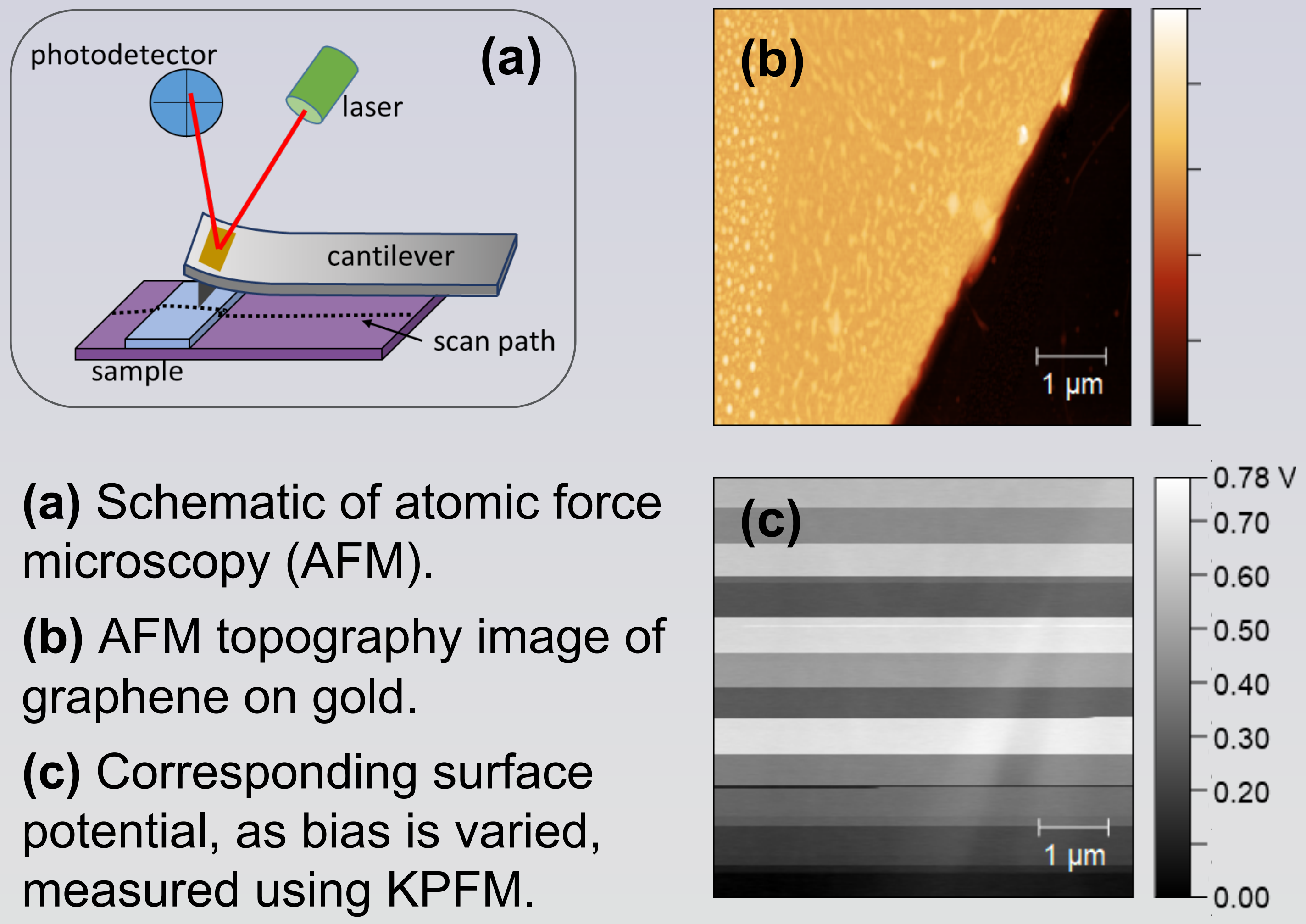
Mechanically exfoliated films are lifted off the SiO_2 substrate and layered together using a polycarbonate (PC) on poly-dimethylsulfate (PDMS) stamp to form device structures. Ultimately, they are melted down over gold contacts.







Kelvin Probe Force Microscopy (KPFM)

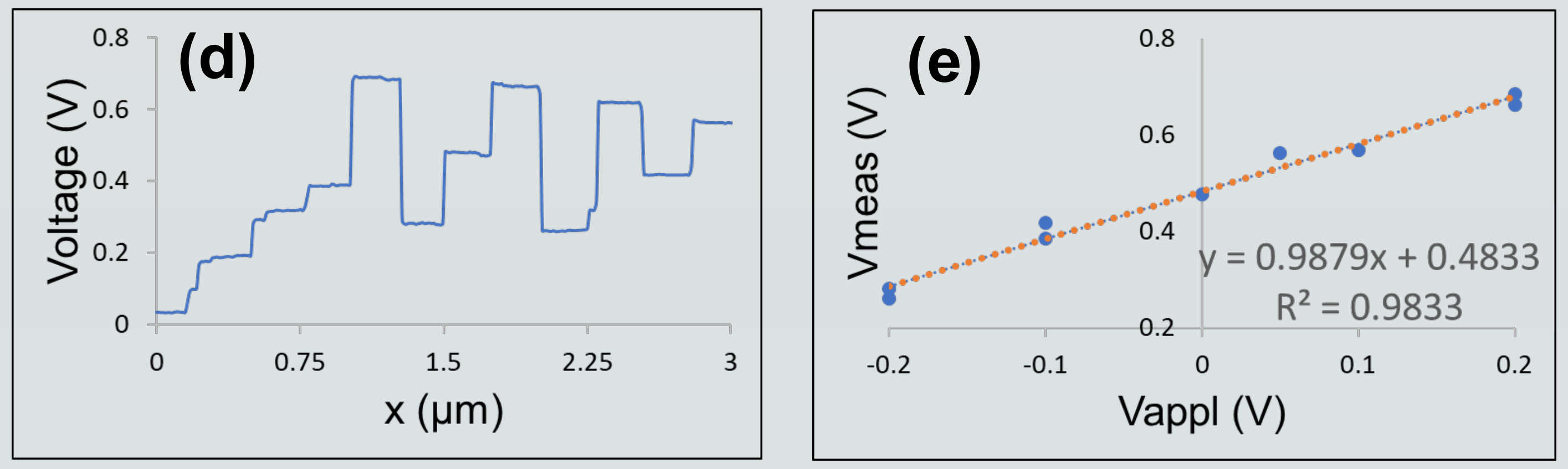


(a) Schematic of atomic force microscopy (AFM).

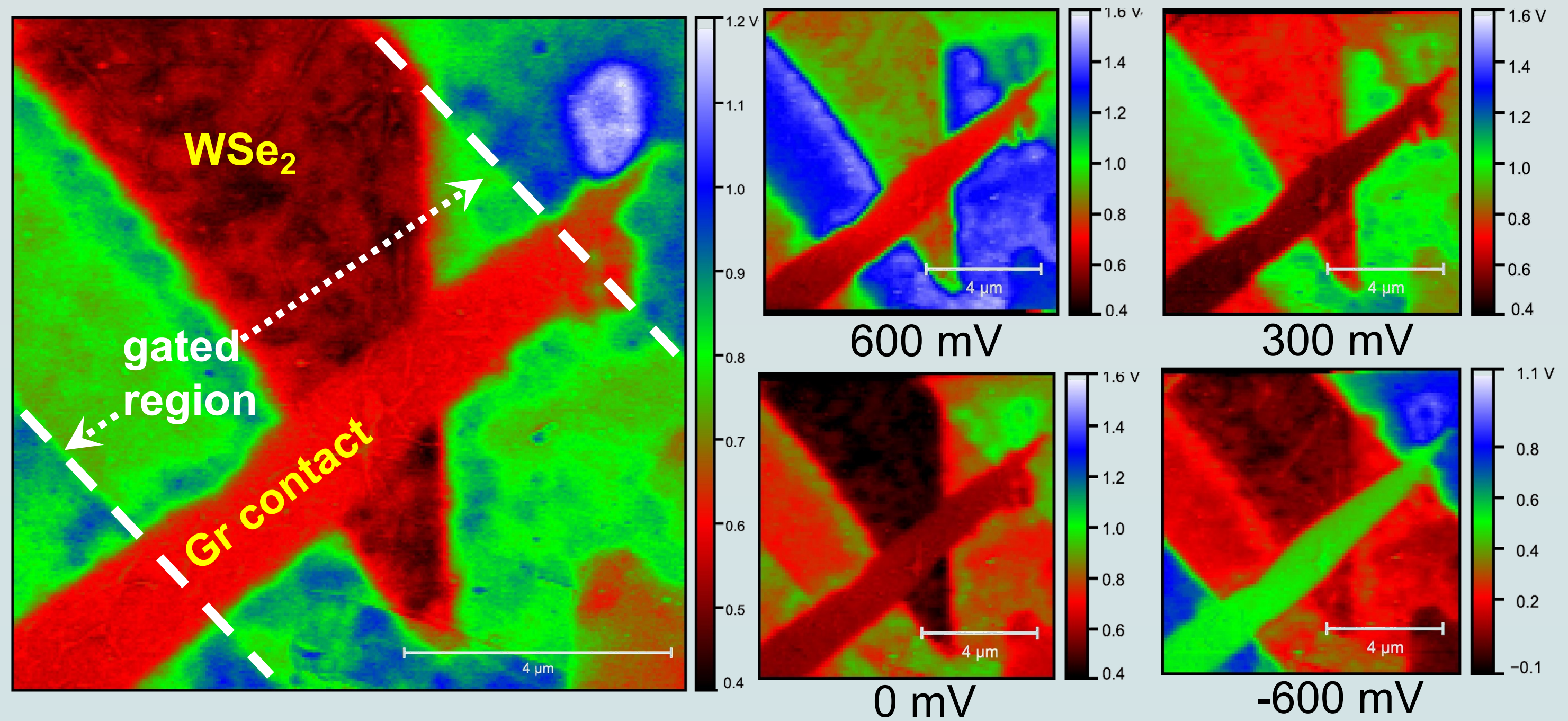
(b) AFM topography image of graphene on gold.

(c) Corresponding surface potential, as bias is varied, measured using KPFM.

(d) A line cut through these KPFM data and **(e)** its 1:1 correspondence to applied voltages confirm the KPFM measurement accuracy.



KPFM Data on WSe$_2$ Transistor

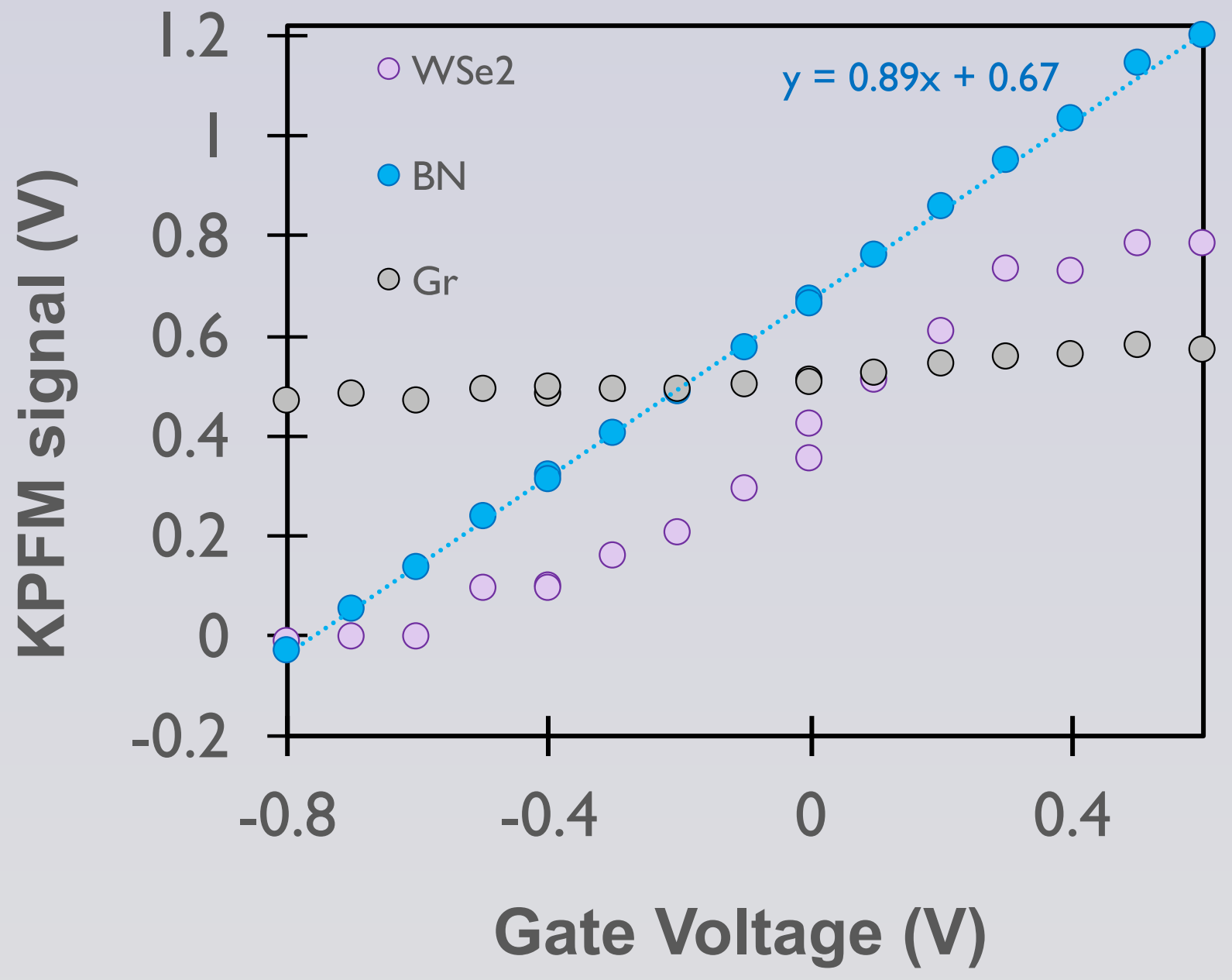


- Monolayer WSe$_2$ channel, Gr contacts and gate. Contact held at 0V bias, gate bias (V_{gate}) varied.
- Average signal from each region was analyzed as a function of V_{gate}: gated and ungated BN, gated and ungated bilayer graphene contact, gated WSe$_2$.
- A slight signal drift due to evolution of the tip was corrected using data from ungated regions.

Results and analysis

- Work function changes with gate bias reflect shifts in chemical potentials and charge densities in the FET.

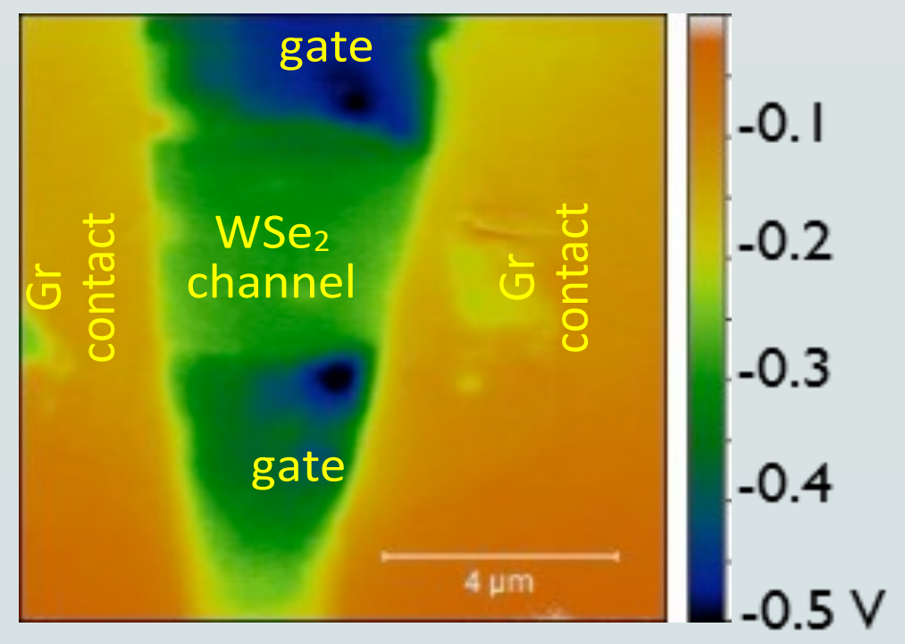
$$e\Delta V_G = \Delta E_F + e\Delta\phi$$
$$= \Delta E_F + \frac{e^2 n}{C_G}$$



- Expect a linear KPFM response with gate, over insulators.
- KPFM signal over WSe$_2$ saturates, apparently showing band edges and ambipolar doping.
- Slope of BN data (0.89±0.02) is slightly suppressed from expected 1:1 response.
- Changes in KPFM signal with gate bias are similar in 'clean' and contaminated regions.

Conclusions and future directions

- Successfully observed microscopic response of FET to gating using KPFM; data includes information about doping, contact barriers, and other effects.
- Ambipolar doping appears to be observed. Will confirm with transistor I-V measurements.
- FM-KPFM measurements have better spatial sensitivity; some suppression of signal can be expected in these AM-KPFM data due to averaging effects.
- This approach can also be applied to a fully encapsulated FET.



KPFM image shows the device underlying a BN encapsulating layer.

References

D. Braga et. al., NanoLett. **12** (2012) 5218.
K. Kim et al. ACSNano **9** (2015) 4527.
Y. Yu et al. NanoLett **9** (2009) 3430.

Acknowledgements

The M.J. Murdock Charitable Trust, Natural Sciences Program
The National Science Foundation grant #1433496
Tianbao Xie and Michael Crosser, Linfield College
David Cobden, Tauno Palomaki, Paul Nguyen -U. Washington
We also thank the Linfield physics alumni community, for both expertise and direct financial support.

Linfield College