Novel device behaviors at low dimensional heterojunctions in 2-D materials

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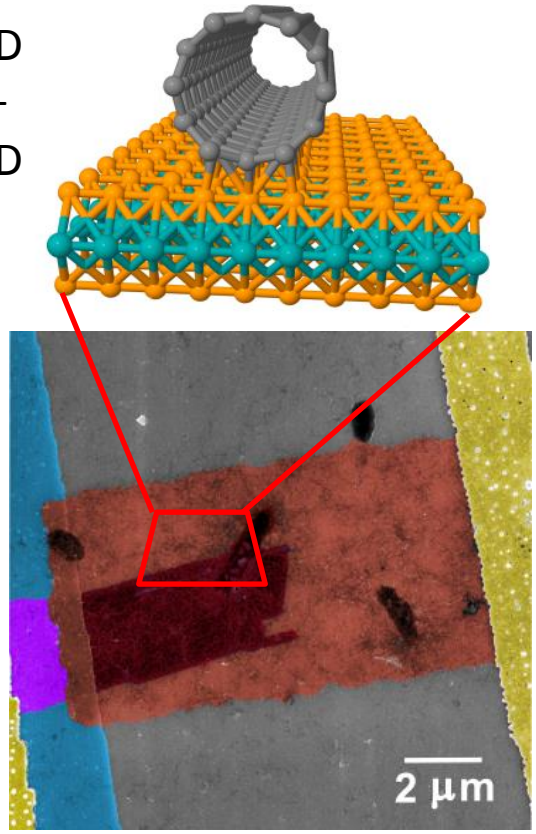
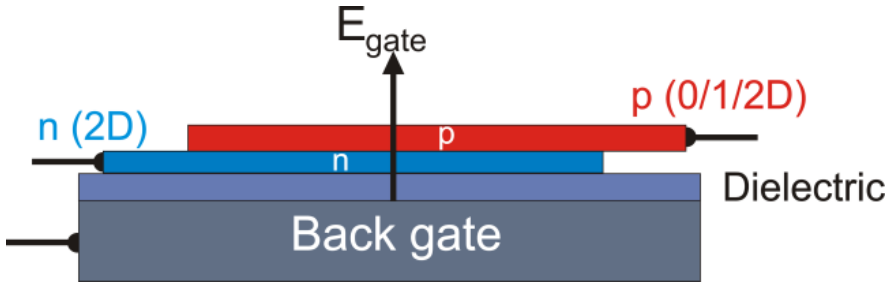
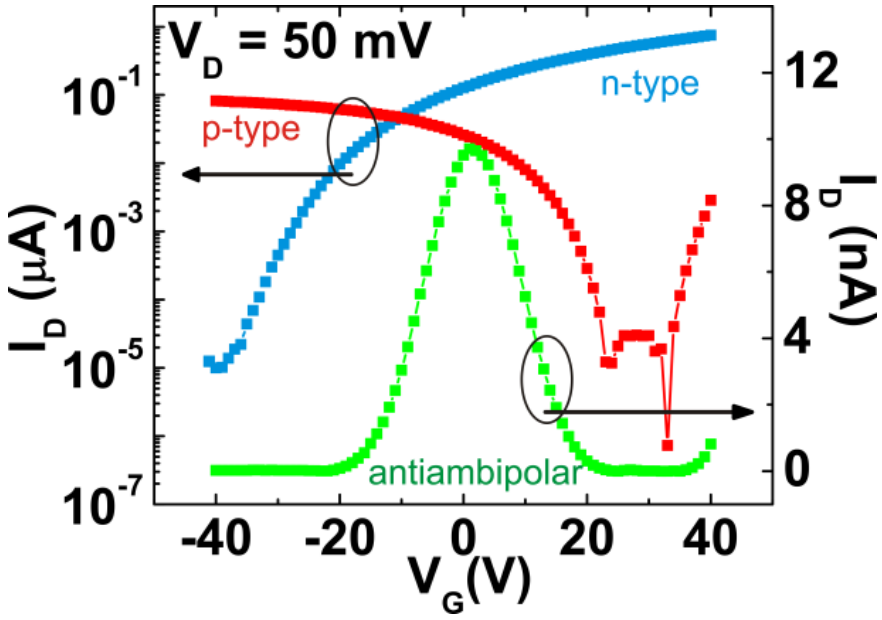
2-D Geometry Produces New Functions

Hersam, Marks, Lauhon *et al*, *PNAS USA*, **110**, 18076 (2013).

1D
+
2D







Concept generalized in Hersam, Marks, Lauhon *et al, Nano Letters* **15**, 416 (2015).

Degrees of Freedom to Explore

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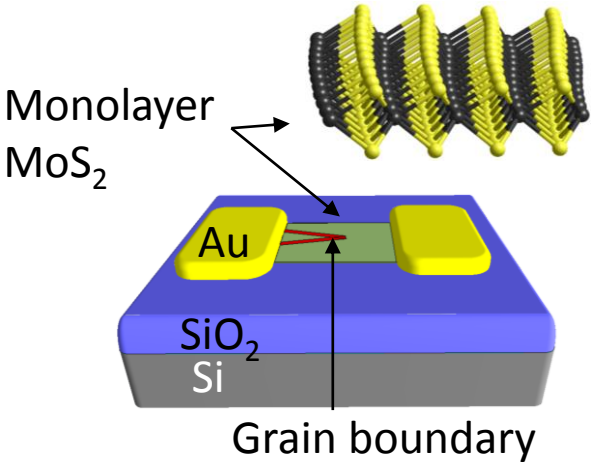
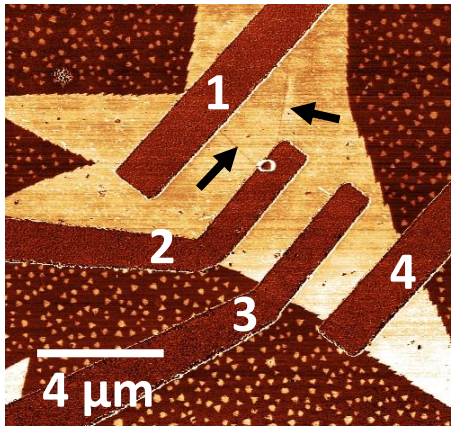
Defects

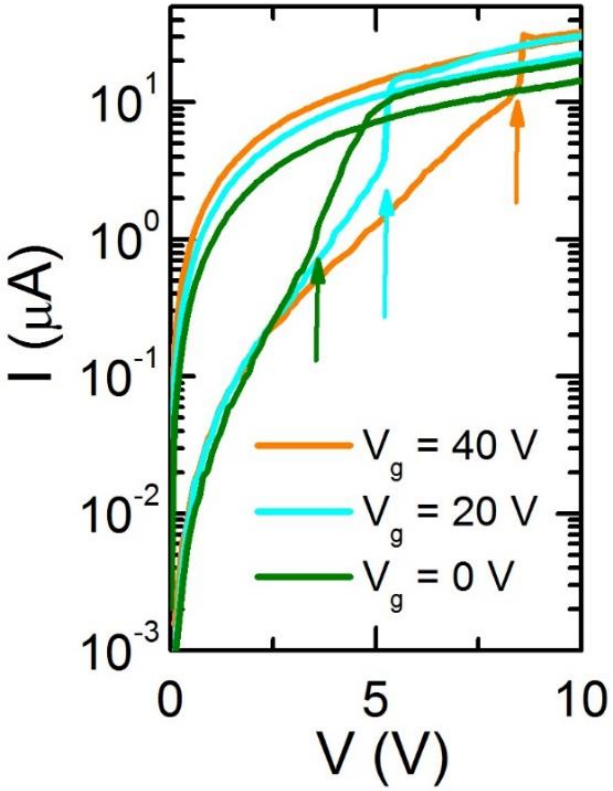
Explore, Understand, Control

Grain boundaries lead to memristive behavior

Hersam, Marks, Lauhon, *Nature Nanotechnology* **10**, 403 (2015)



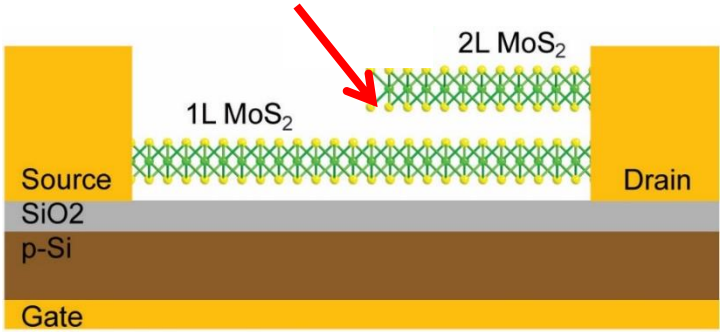


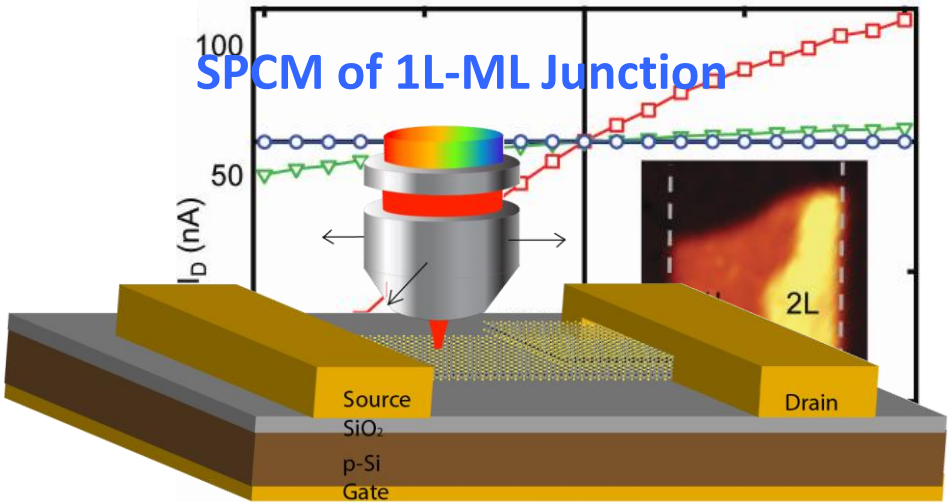


- Hysteretic I-V curve with low and high resistance states → memristor.
- Switching ratio (ON/OFF) ~ 10^3
- Observed in devices with grain boundaries *and* sulfur vacancies.

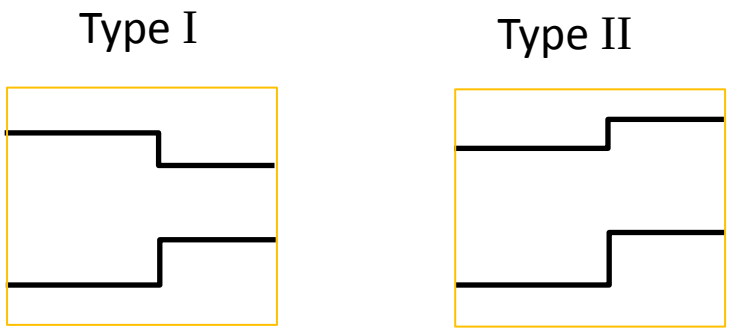
Unique opportunity for neuromorphic computing

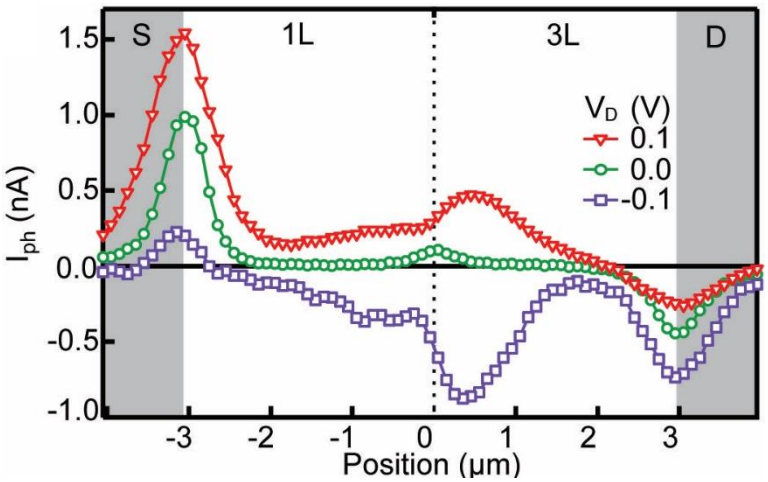
A new type of heterojunction in MoS_2





Thickness-dependent bandstructure results in fundamentally new type of semiconductor junction.

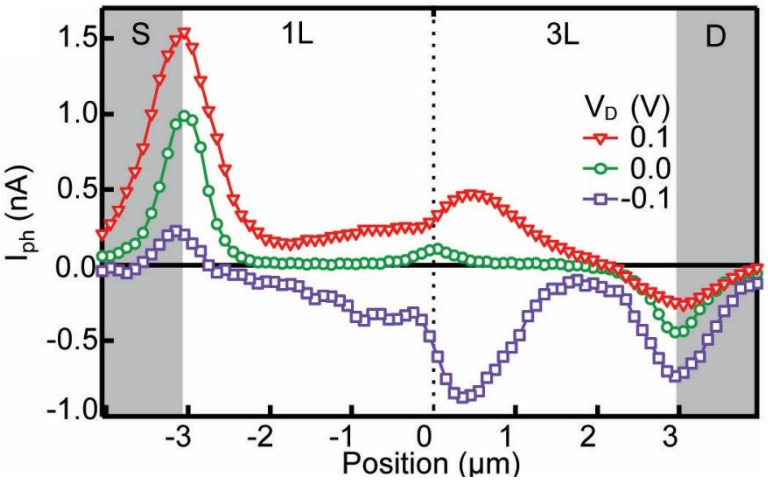




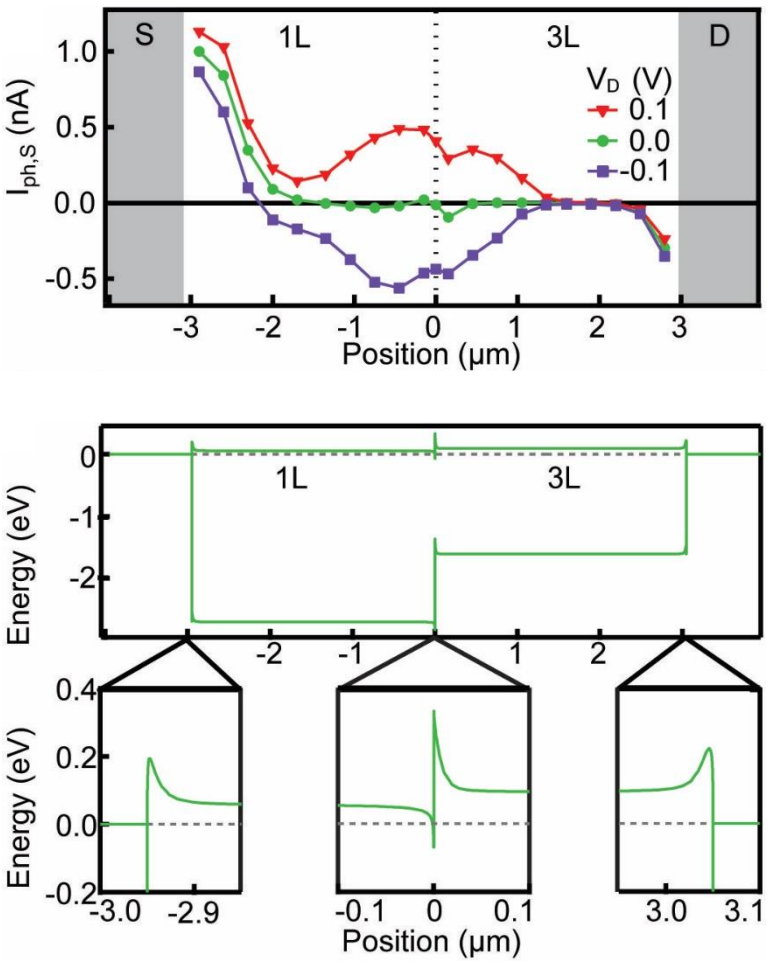
Howell, Jariwala, et al., *Nano Lett.*, **15**, 2278 (2015)

SPCM modeling extracts band profiles

Measured



Simulated



FE modeling based on material parameters determined from uniform thickness devices.

Simulations reproduce bias dependence assuming a type-2 band offset.

Howell, Jariwala, et al., *Nano Lett.,* **15**, 2278 (2015)

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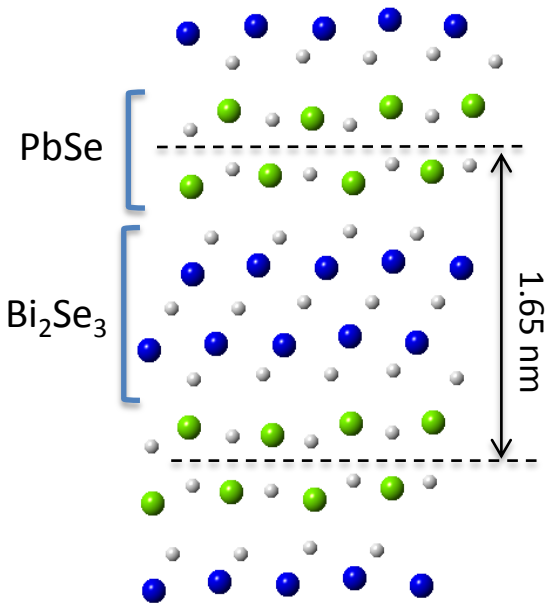
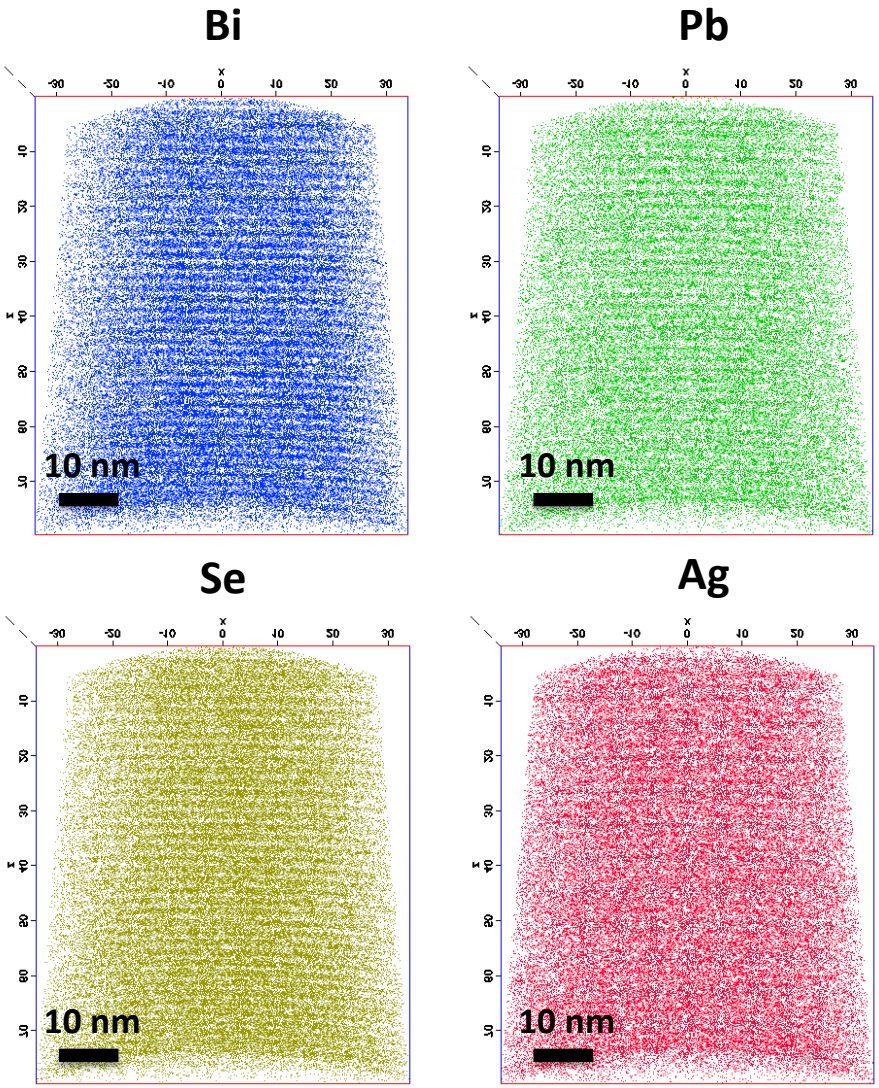
*Explore, **Understand**, Control*

Atom Probe Tomography of a 2D Material: Ag doped $(PbSe)_5(Bi_2Se_3)_{3m}$





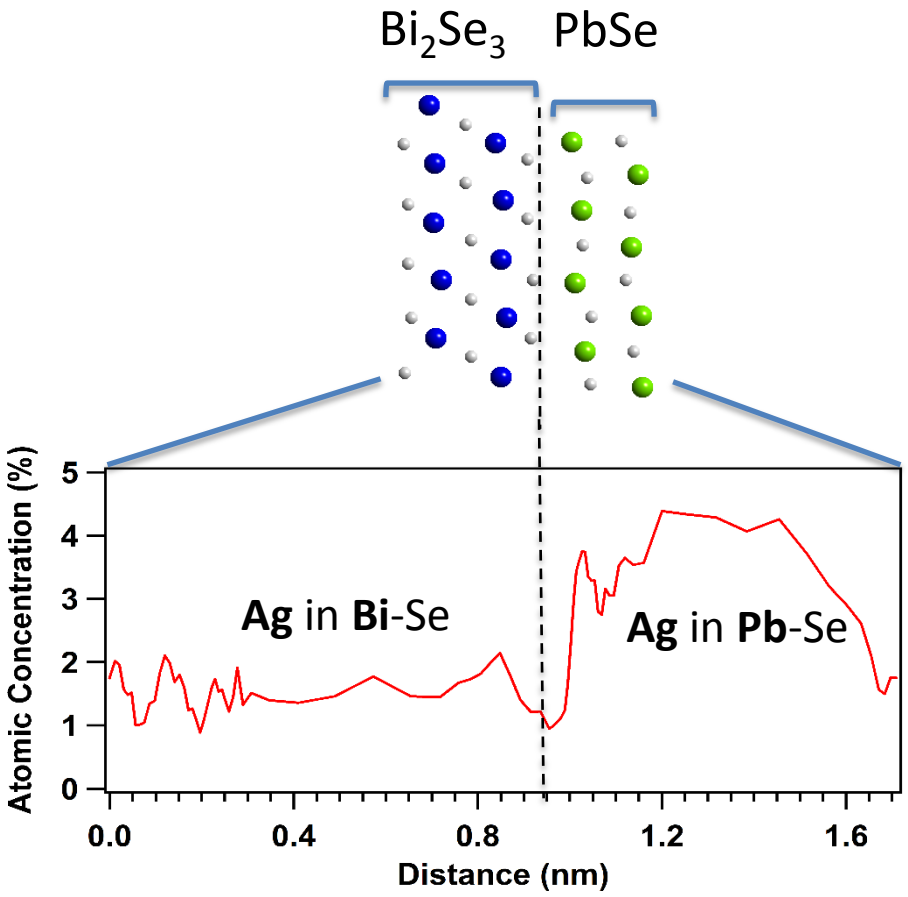
- Ag doping changes *m*=1 phase from metallic to superconducting.
- Ag is expected to dope only the PbSe layer. ***Can dopant location be resolved by APT?***

Ren, Lauhon et al, *unpublished*.

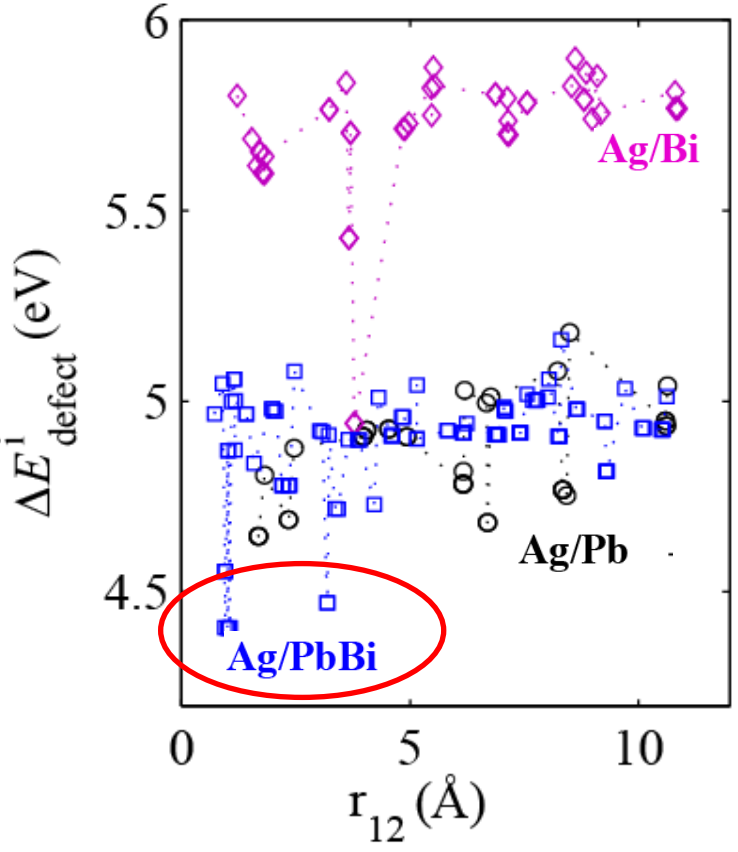
NU: Mercouri Kanatzidis

NIST: Singh, Tavazza

Atom probe shows Ag dopes both Pb and Bi layers



First Principles Calculations: Defect Formation Energies



Significance: Validation of ability to predict and measure dopant locations in 2-D materials.

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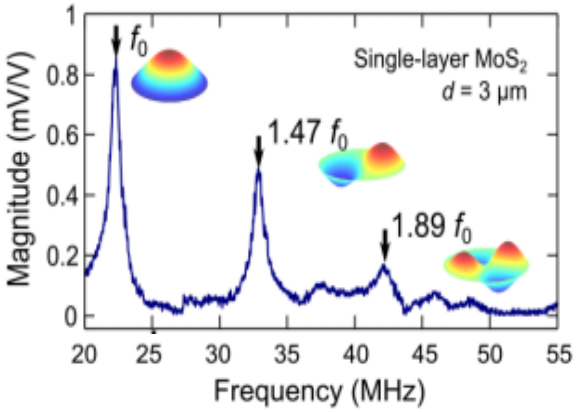
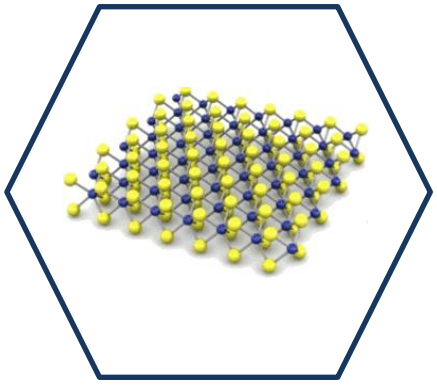
Mechanical Properties of MoS_2 Membranes

Sensitive to small forces

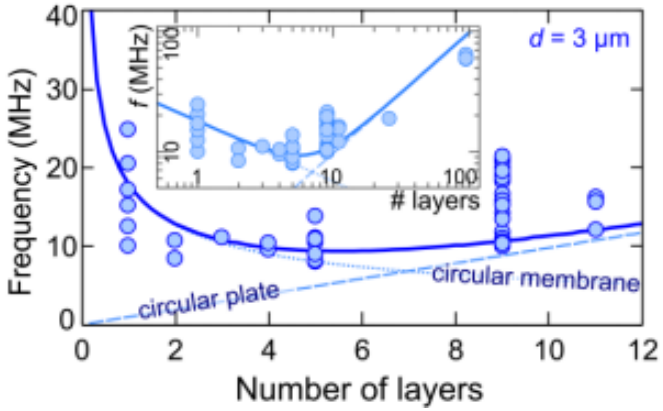


Adv. Mater. **25**, 6719 (2013)

$$f = \frac{2.4048}{\pi d}\sqrt{\frac{T}{\rho t}}$$

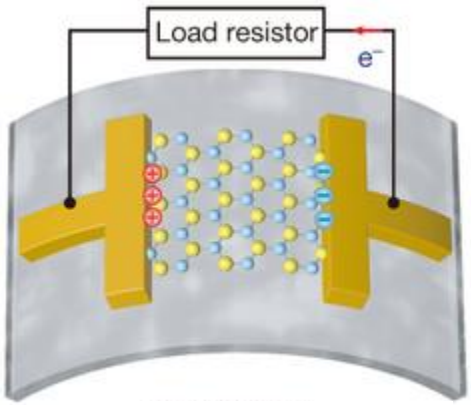


Membrane-like below ~6L



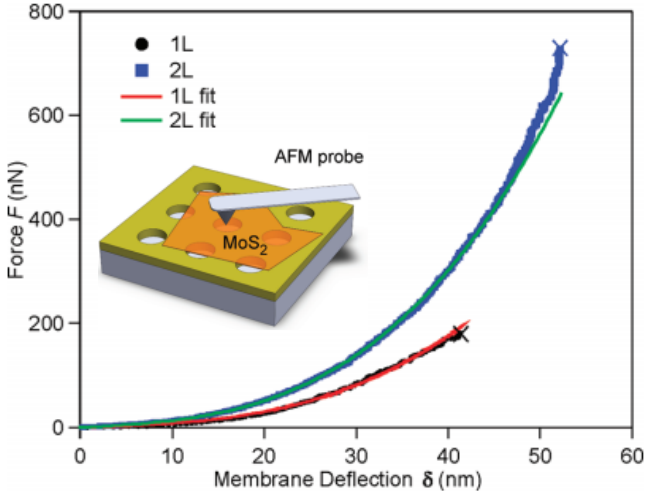
ACS Nano **7**, 6086 (2013)

Piezoelectric Monolayer



Nature **514**, 474 (2014)

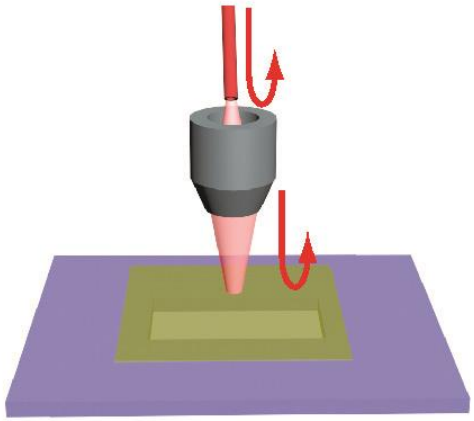
Nonlinear force vs. displacement



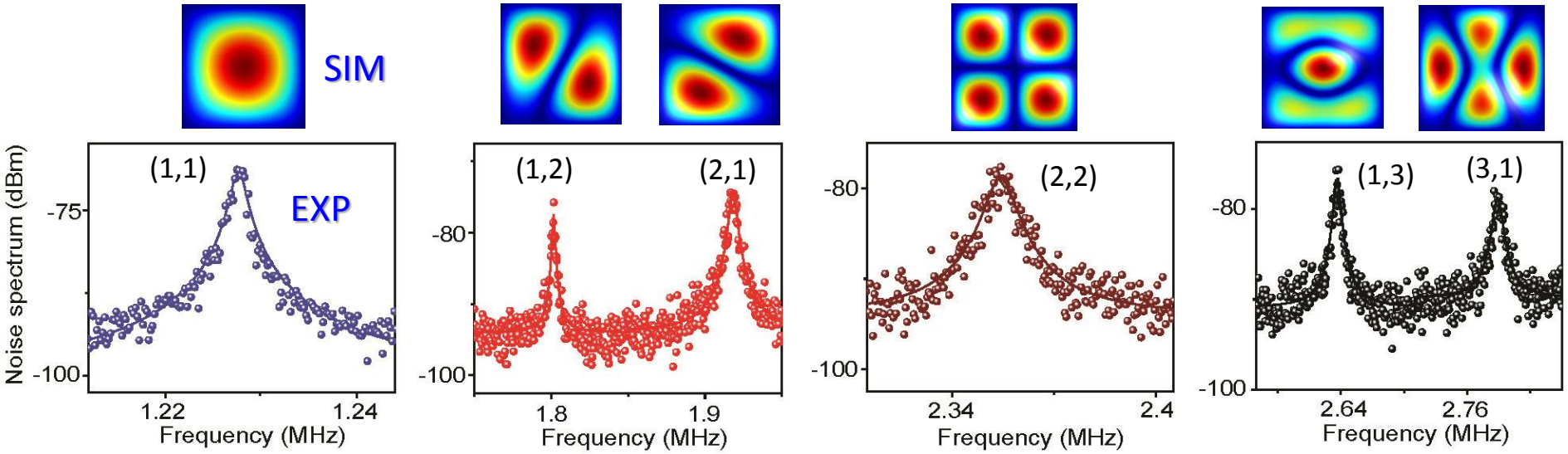
ACS Nano **5**, 9703 (2011)

Annalen der Physik **527**, 27 (2015)

Modes identified from thermal fluctuations

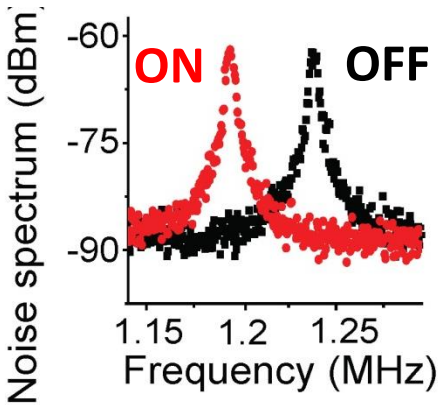


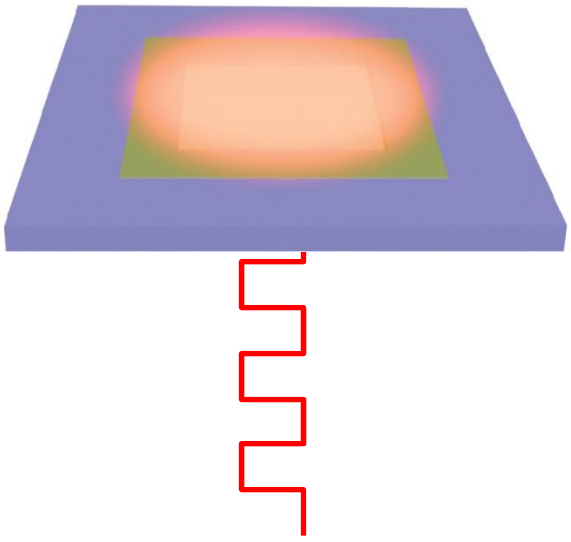
- Thermally excited vibrational modes are observed and identified.
- Nominally degenerate modes are split.
  - Could indicate mode-coupling.



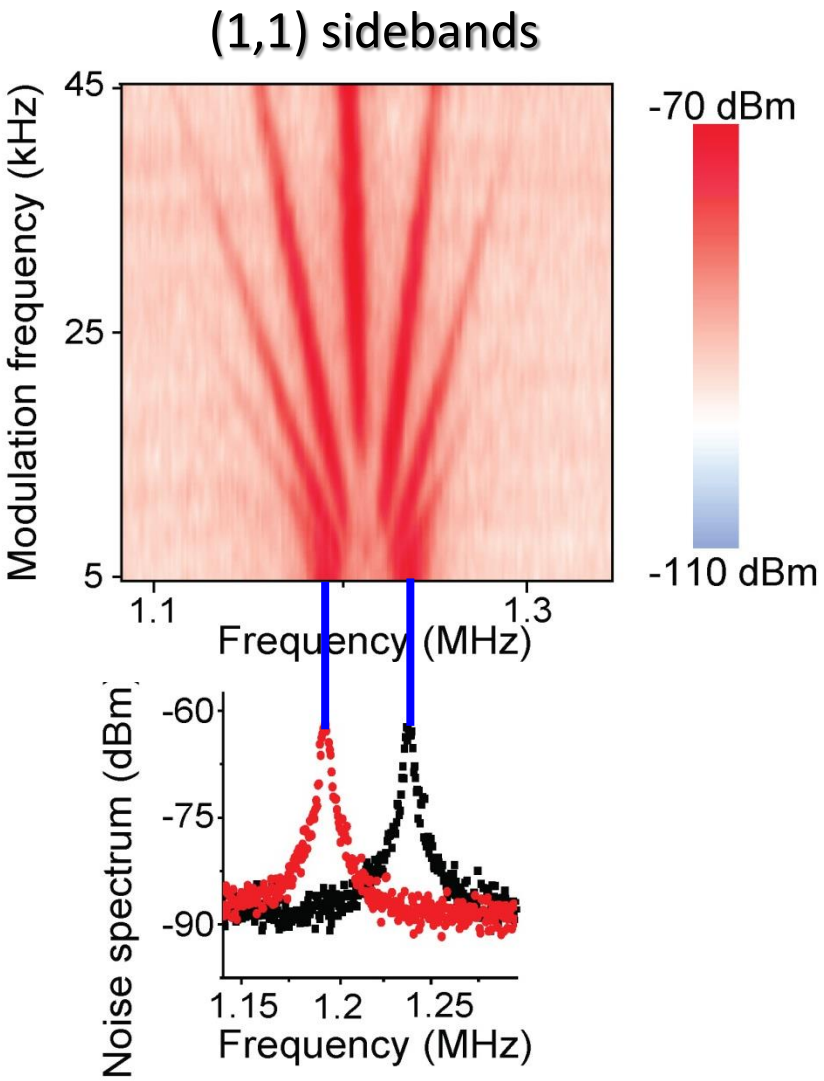
Liu and Lauhon, *Nano Lett ASAP.*

Distribution of thermal energy in mechanical modes depends on modulation frequency



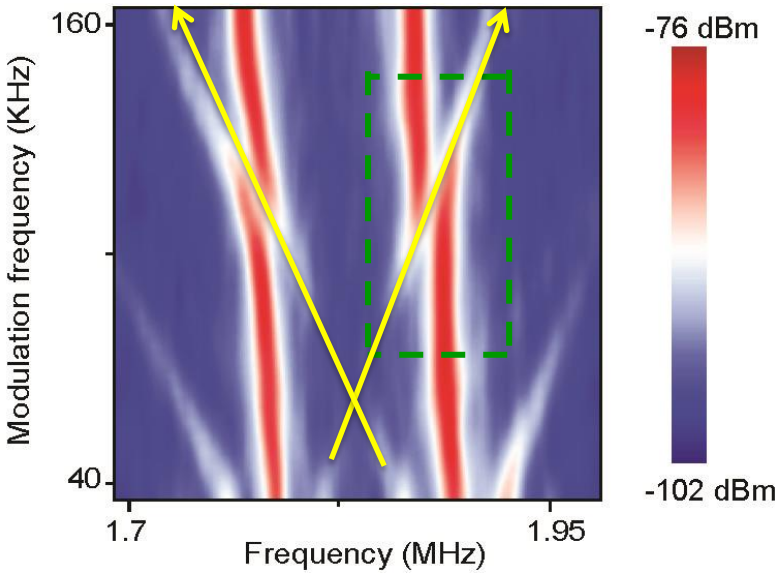


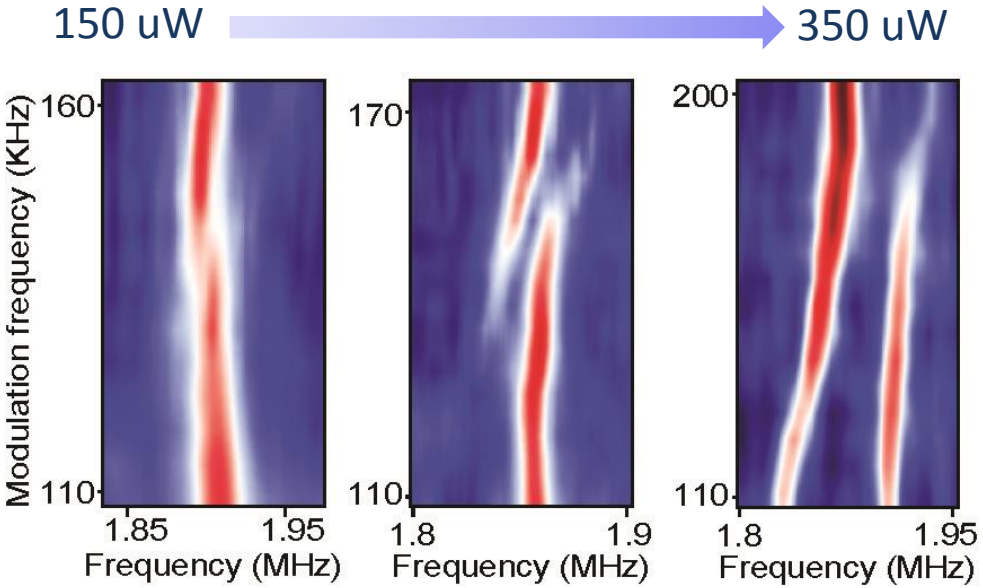
VISIBLE

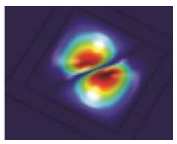


Liu and Lauhon, *Nano Lett ASAP.*

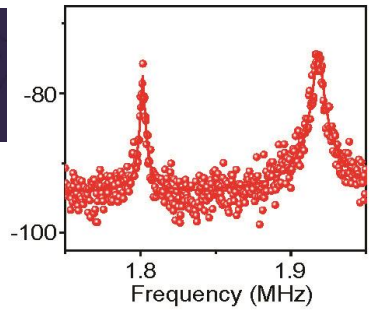
Normal-mode splitting is observed

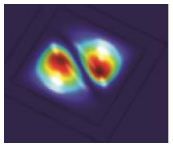






(1,2)





(2,1)

- Peak splitting → coupling rate g.
- g is 10 X the decay rate γ.

Strong coupling enables coherent energy exchange.

Liu and Lauhon, *Nano Lett ASAP.*

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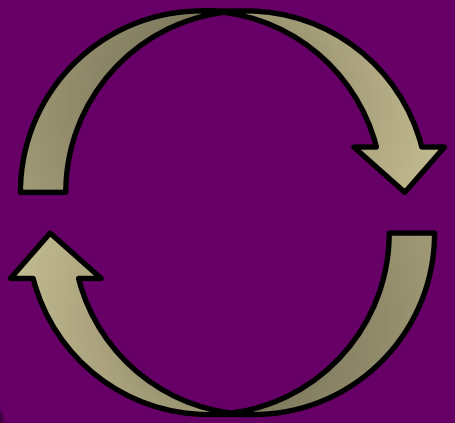
Challenges in 2-D Materials & Devices



Integrated approach to 2D MSE

Lauhon Research Group

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Ryan Paull	(G-1)
Xiaochen Ren	(G-3)
Zhiyuan Sun	(G-2)
KunHo Yoon	(G-5)

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M. Kanatzidis	Northwestern
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