Excited States in Atomically Thin Semiconductors: Any relevance to semiconductor metrology?

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Funding: Welch, NSF-MRSEC, NSF-EECS, AFOSR, DOE

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What Could We Do with Layered Structures with Just the Right Layers?

– Richard Feynman, 1959, “There’s Plenty of Room at the Bottom”

Stacking different functional layers

Superconductors

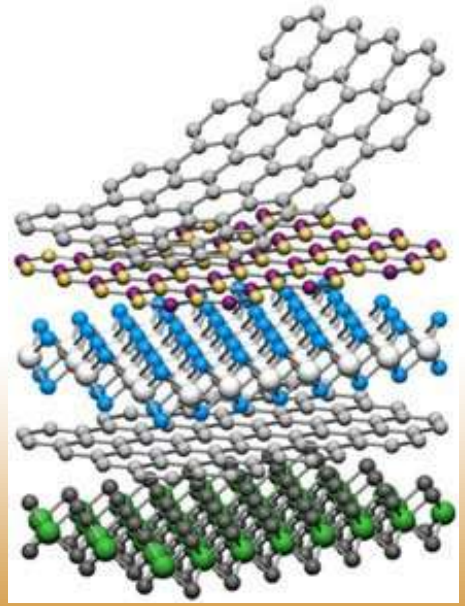
Magnetic Mat.

Ferroelectrics

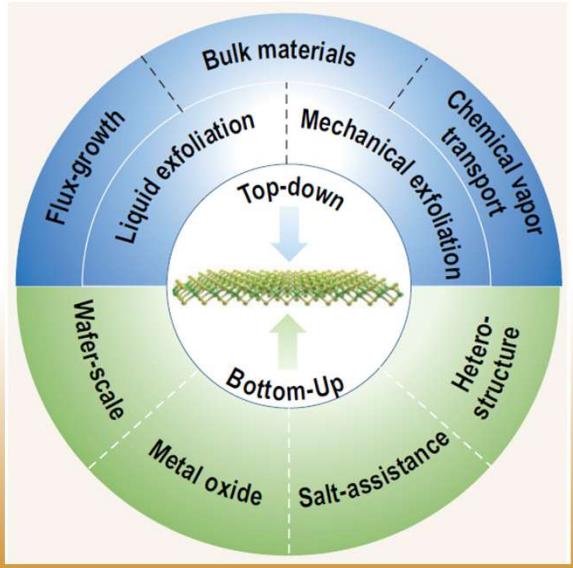
Insulators

Semiconductors

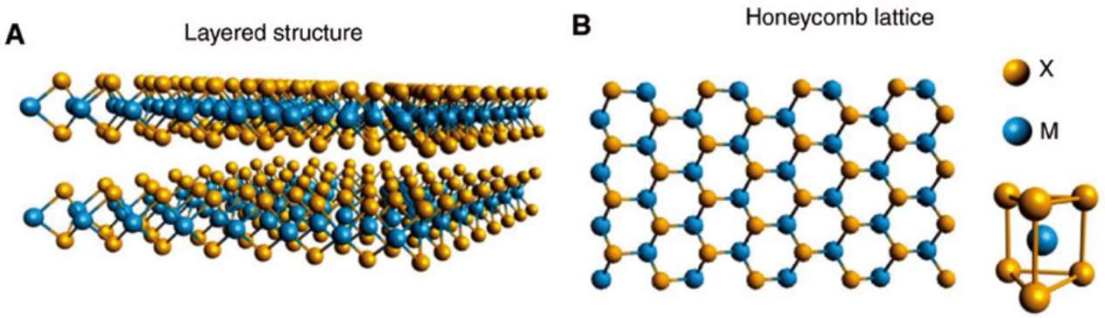
Conductors

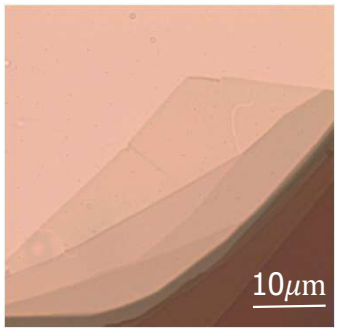


Different growth and assembly methods

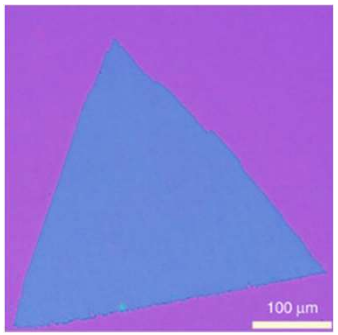


Atomically Thin Semiconductors: TMD

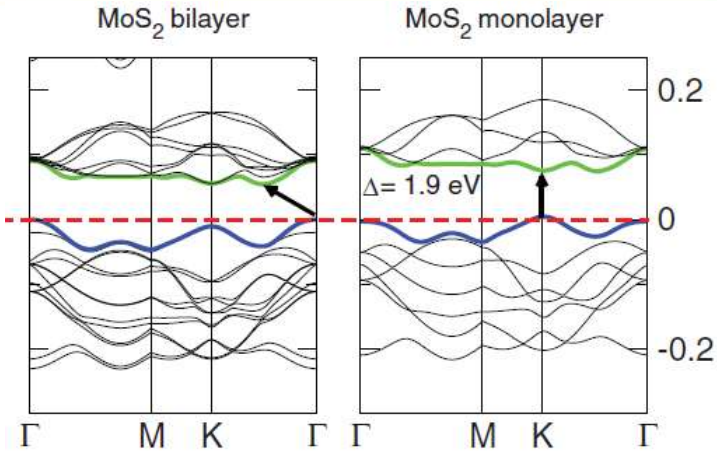




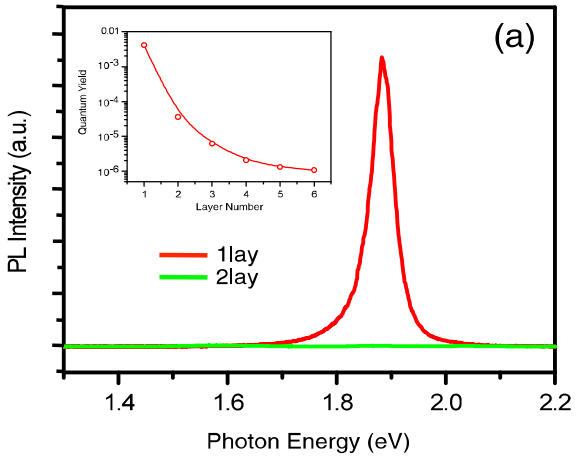
Mechanical Exfoliation



CVD sample

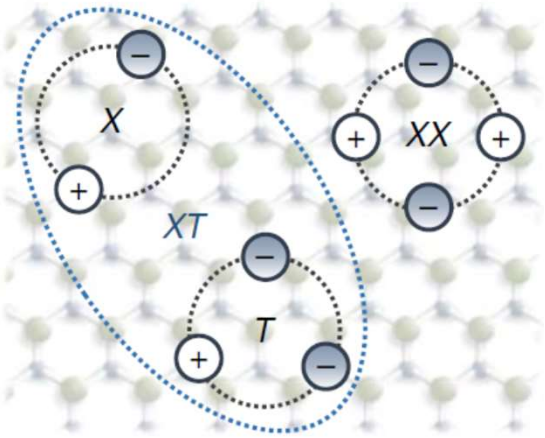


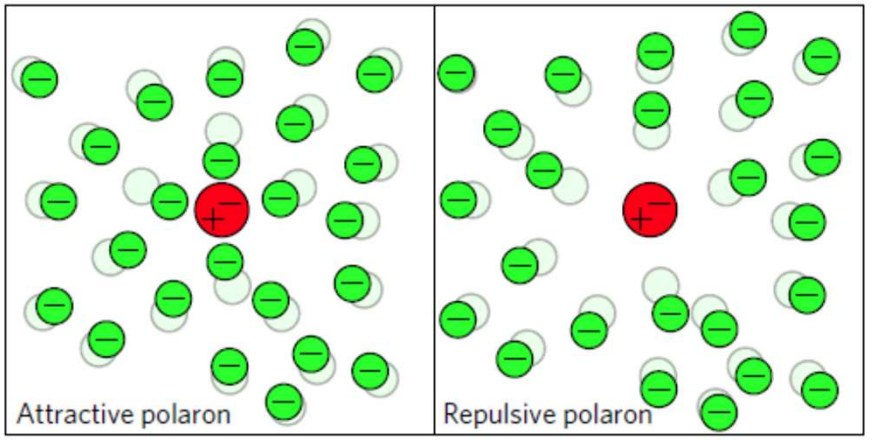
A. Kuc, PRB **83**, 245213 (2011).



Mak, PRL **105**, 136805 (2010)

Quasiparticles in TMDC





Hao et. al. Nat. Comm, 2017
Sidler et.al. Nat. Phys. 2017

- Reduced dielectric screening leads to large binding energy of excitons (X), trions (T), and biexcitons (XX)
- Binding energy is 10-100 X larger than GaAs-based compound semiconductors
- Relevant to room-temperature optoelectronic device operation
- Large dipoles: Ultrafast dynamics and CQED

Outline

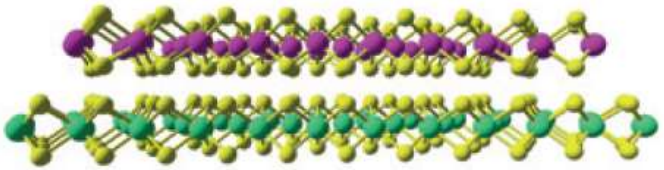
- Background:
  - moiré potential
  - different types of excitons and selection rules

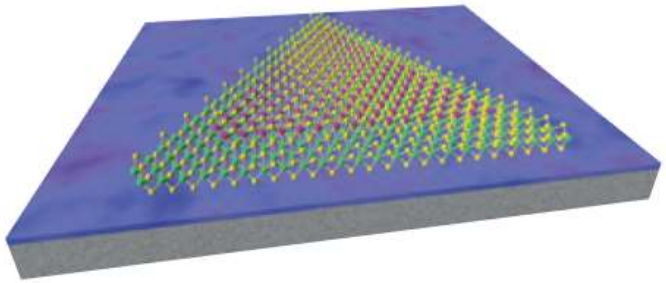
- Excitons tunable by twist angles
  - Resonance
  - Lifetimes
  - Diffusion

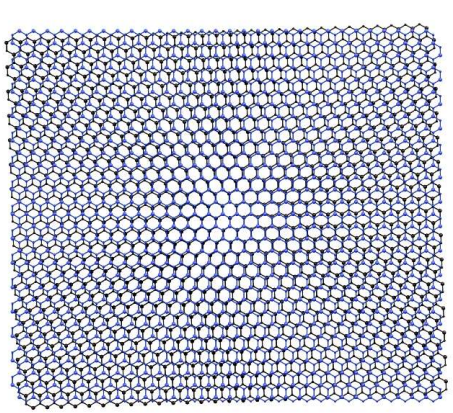
- Separating the generation of moiré potential from the functional layer

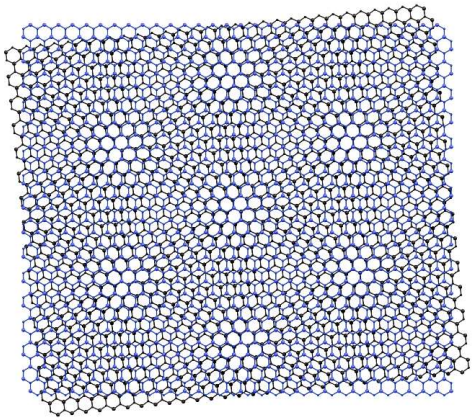
- Ultrafast spectroscopy and its application in compound semiconductor metrology

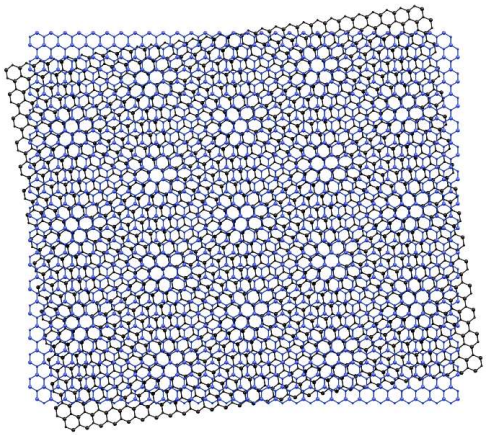
Moiré Superlattices



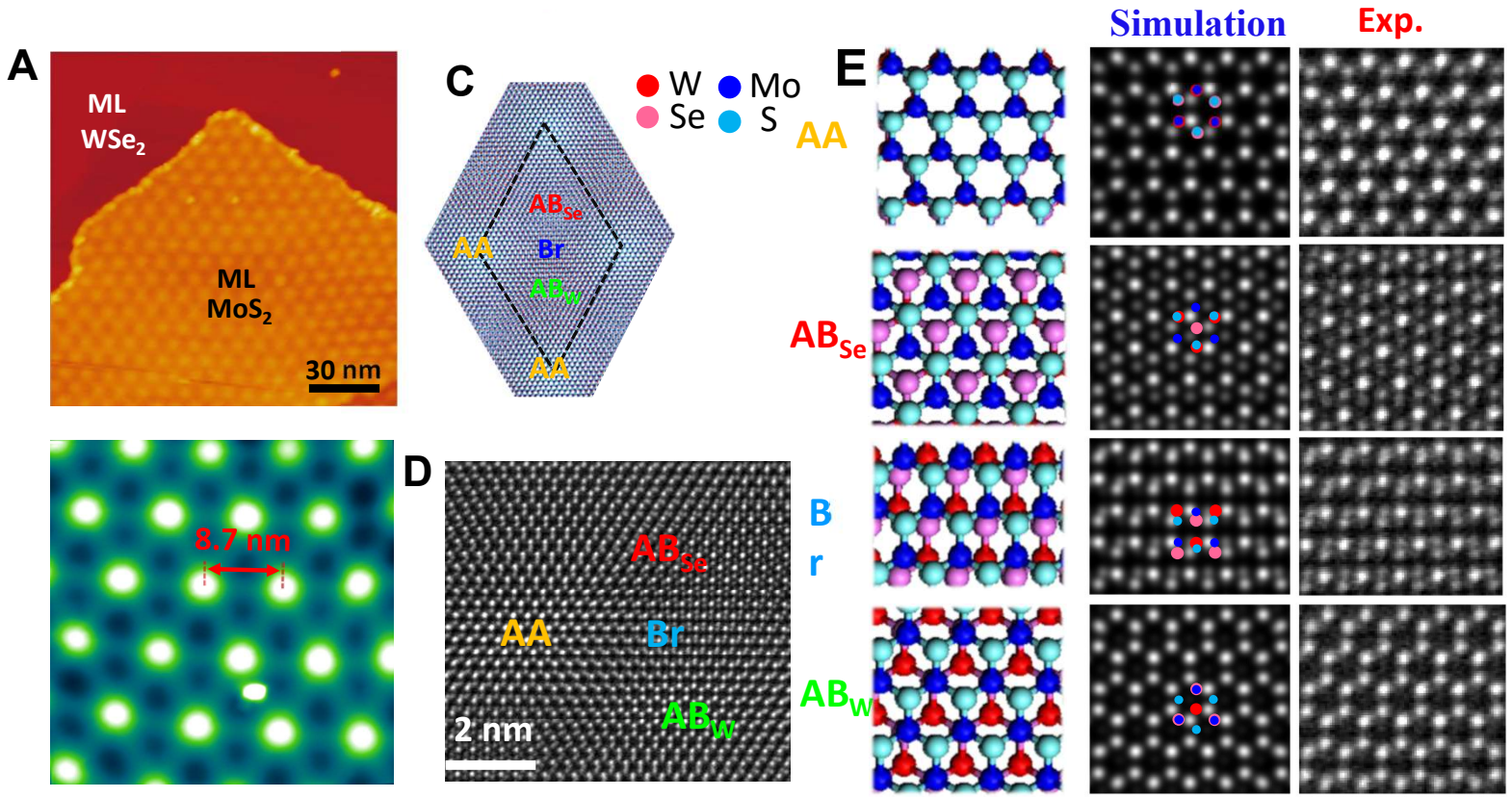






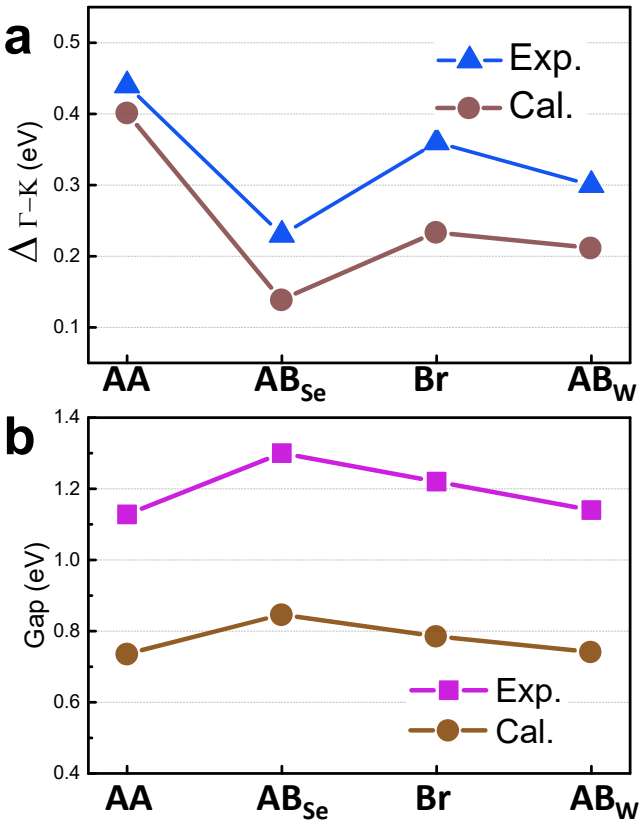


Rotationally Aligned MoS_2/WSe_2 bilayers



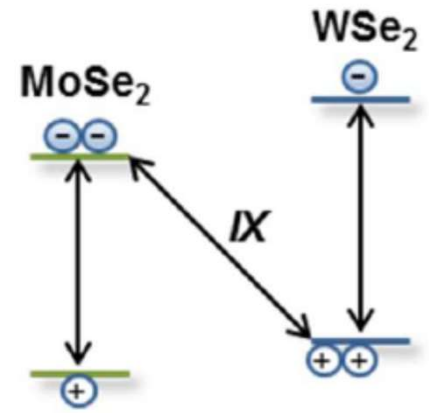
CVD grown MoS_2/WSe_2
Science Advances **3**, *1601459* (2017)

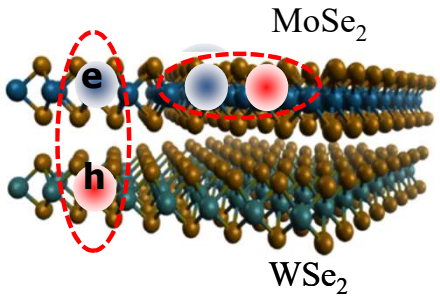
2D electronic superlattices



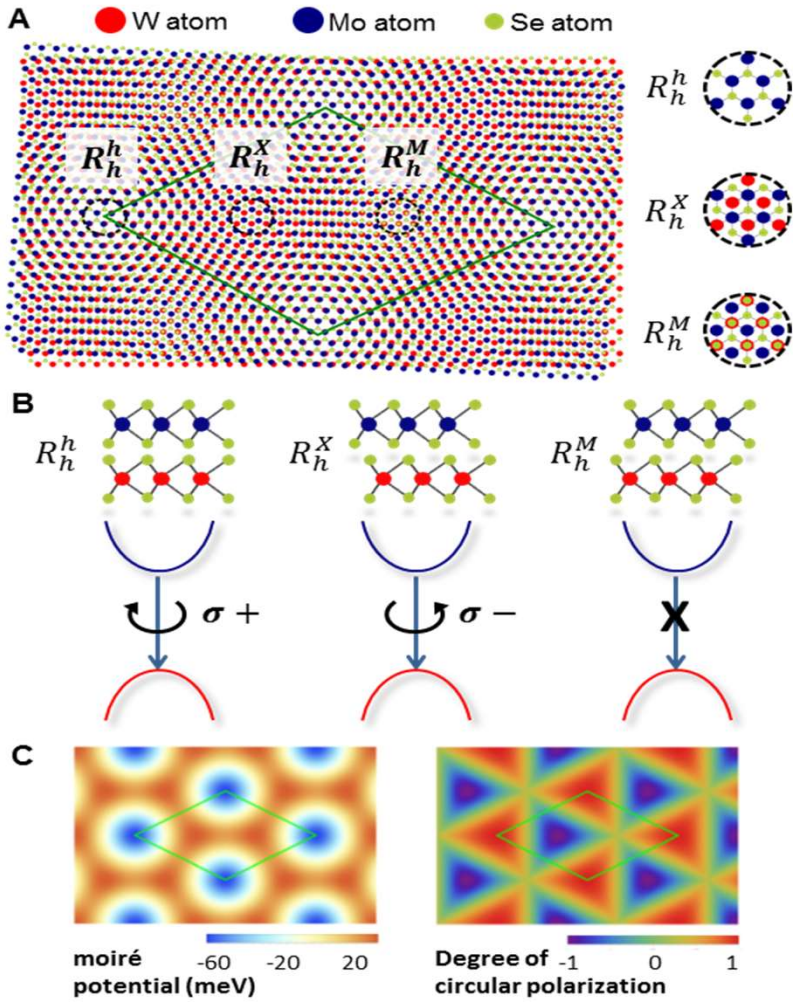
Band Gap is modulated periodically following the Moiré pattern

Interlayer excitons confined in a Moiré potential

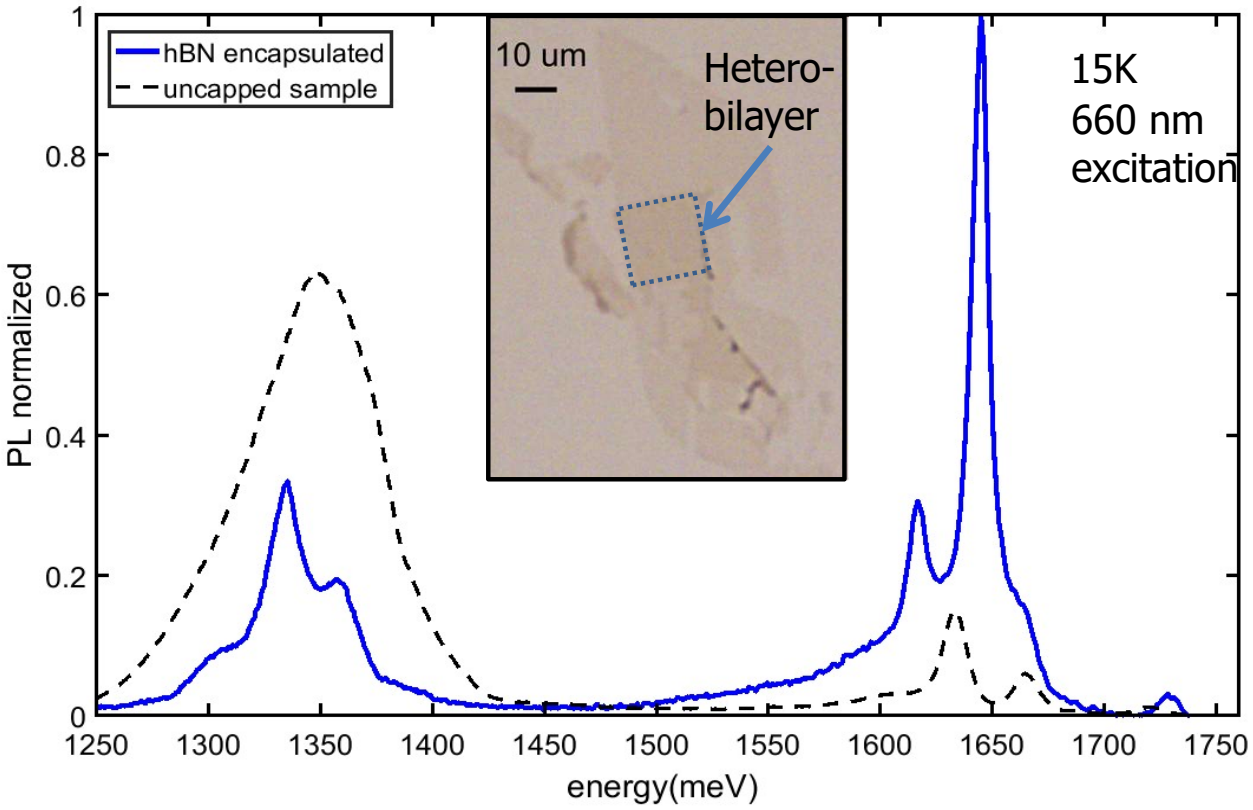




Yu et al., Sci. Adv. 2017;3:e1701696

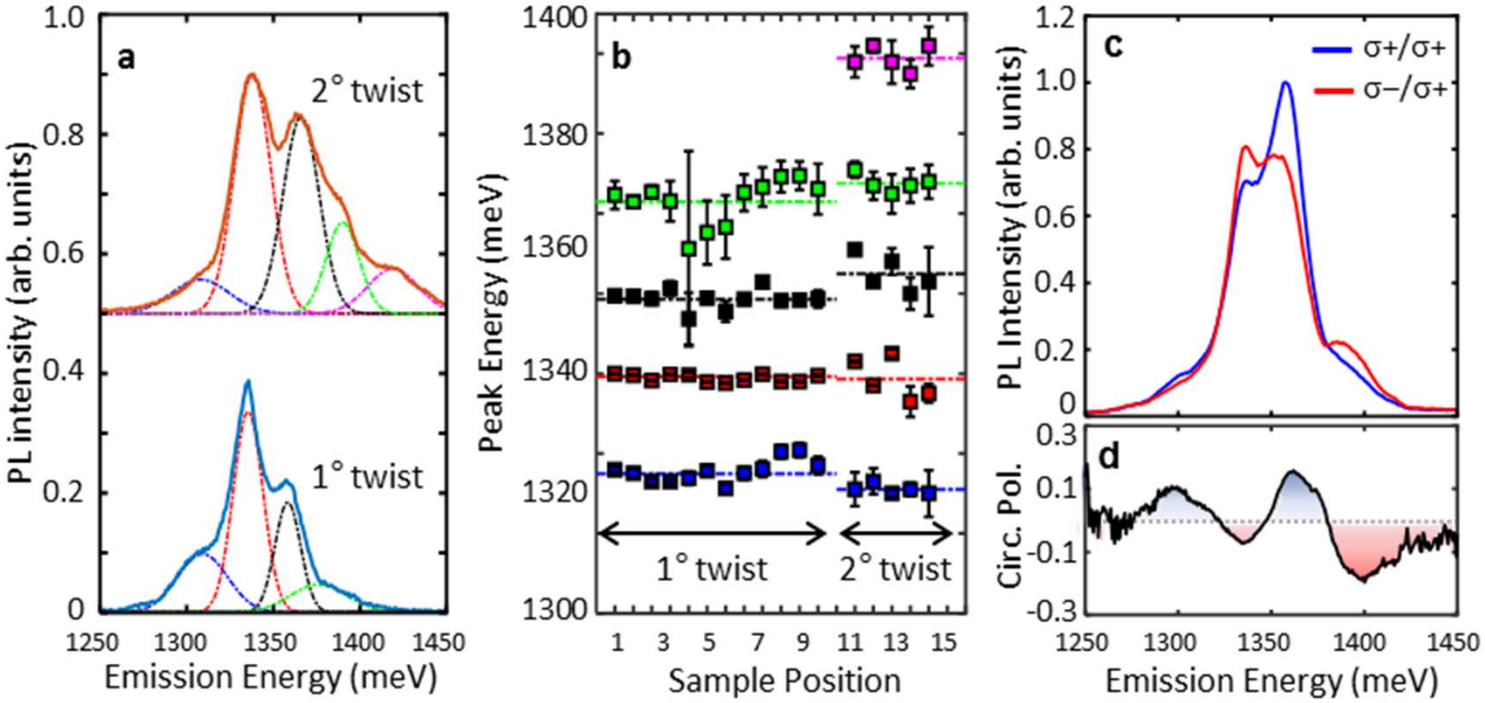


Ground State and Excited Excitons in a Moiré potential



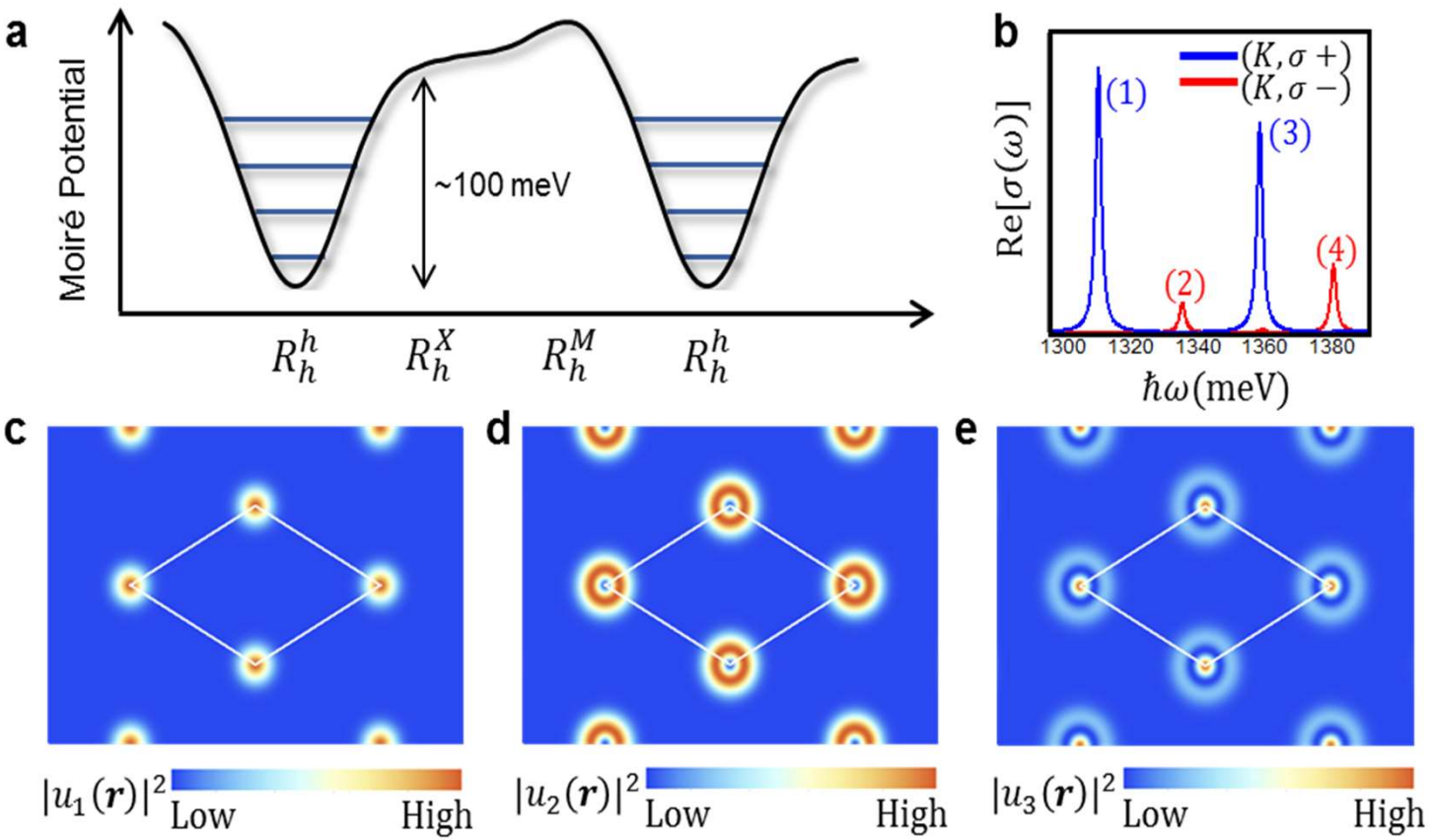
Rivera et. al., Nature communications **2015,** 6, 6242

Ground State and Excited Excitons in a Moiré potential



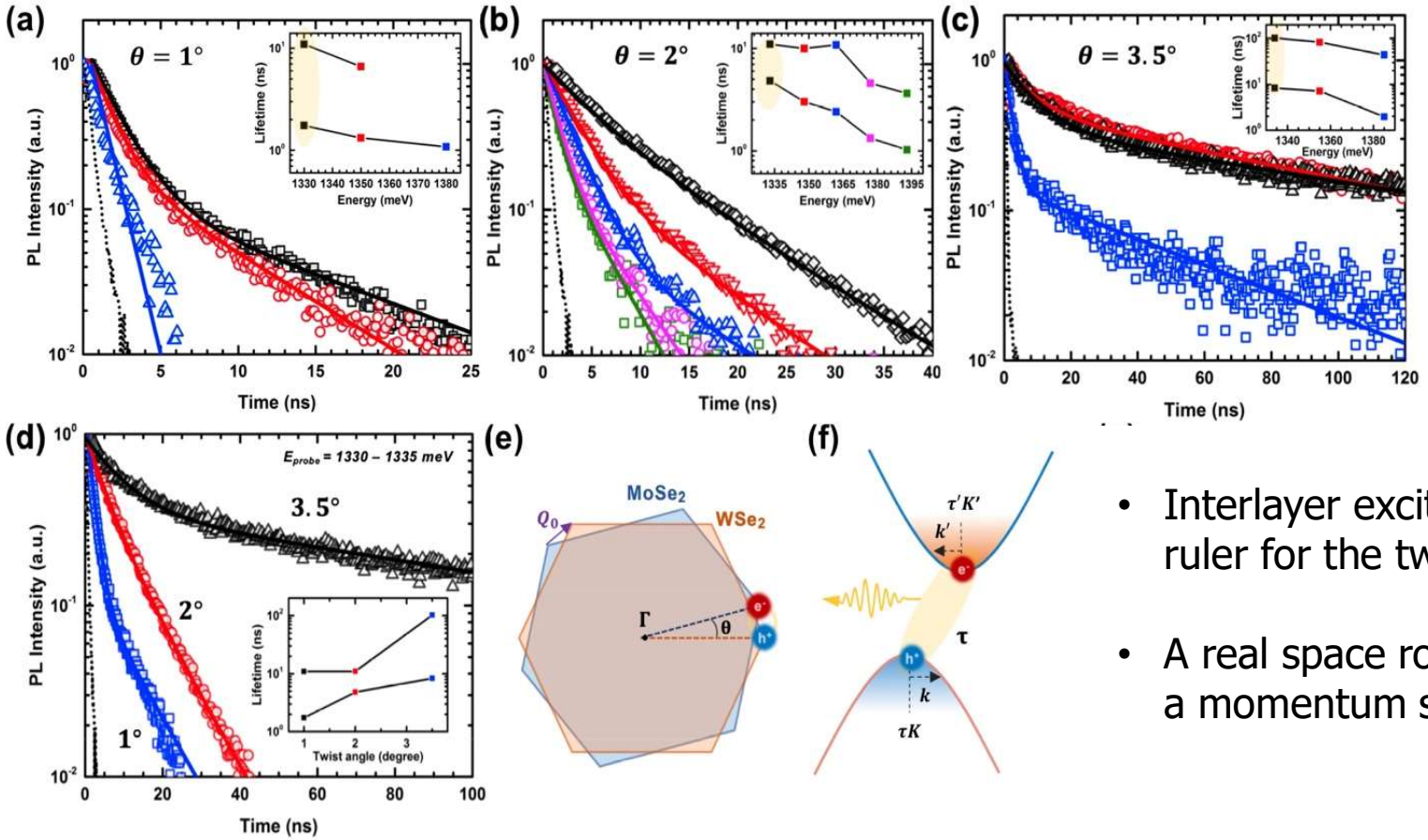
Tran K, Moody G, et.al., Nature 567, 71, 2019

Ground State and Excited Excitons in a Moiré potential



Physical Review B **2018,** 97, (3), 035306

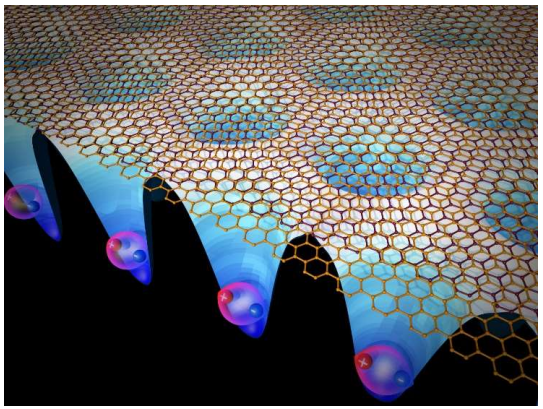
Angle Dependent Interlayer Exciton Lifetimes

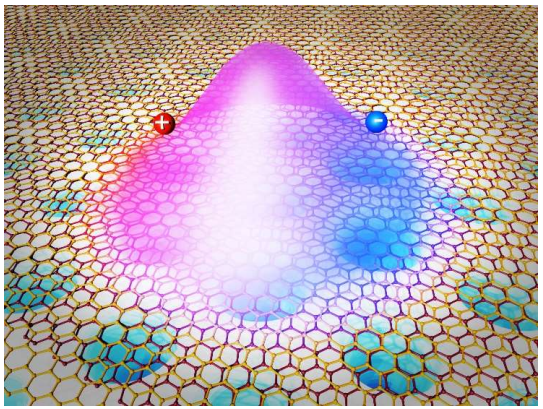


- Interlayer exciton lifetimes: a ruler for the twist angle
- A real space rotation leads to a momentum space rotation

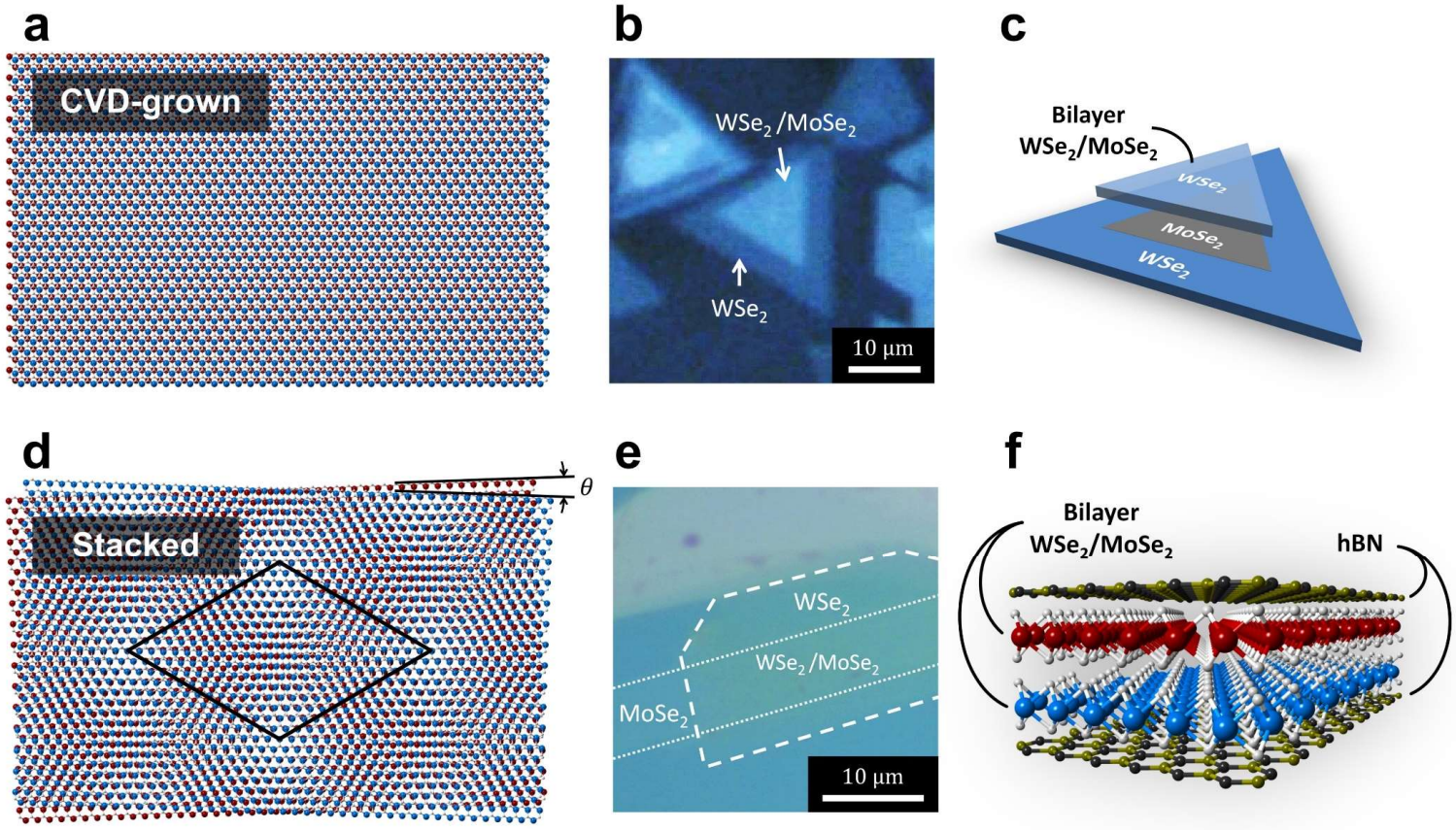
Choi, PRL, 126, 047401, 2021

Are excitons localized in moiré superlattices?

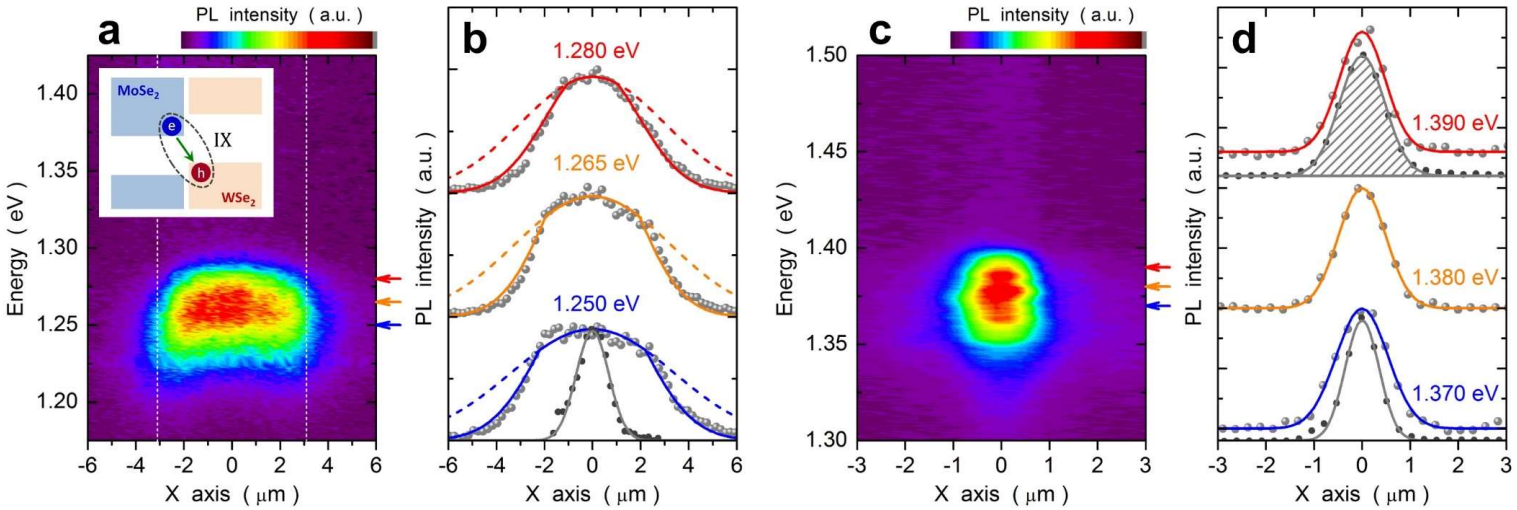




CVD vs. stacked samples

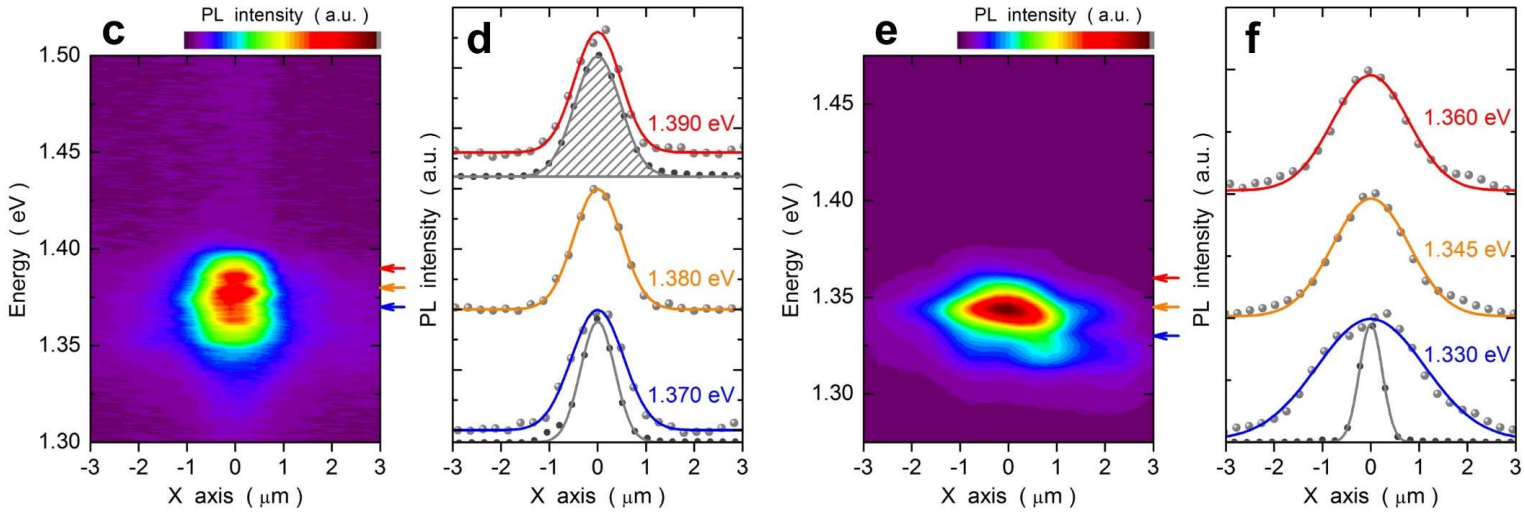


CVD vs. 1 degree samples



Choi, Hus, Li, Chang et. al. Science Advances 6 (39), eaba8866

1 vs. 3 degree samples



Exciton diffusion depends on twist angle, excitation density….

Other experiments: Kis, Xiaoyang Zhu, Libai Huang, Chernikov…

Take home message

- Different types of excitons and selection rules in moiré superlattice

- Excitons tunable by twist angles
  - Resonance
  - Lifetimes
  - Diffusion

A recent development in moiré engineering

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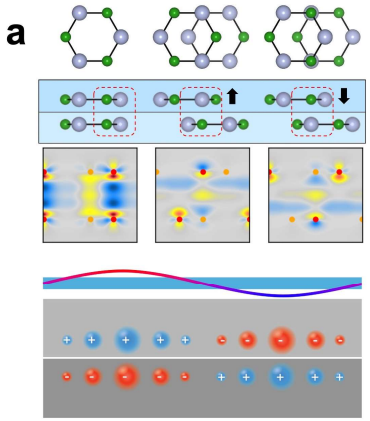
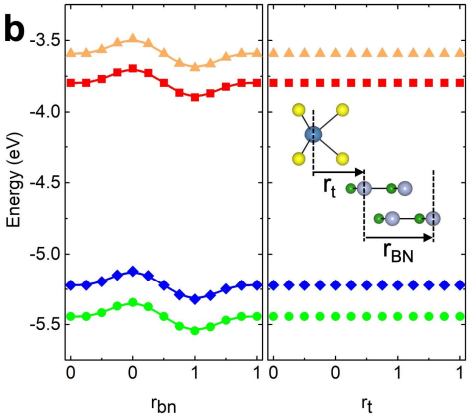
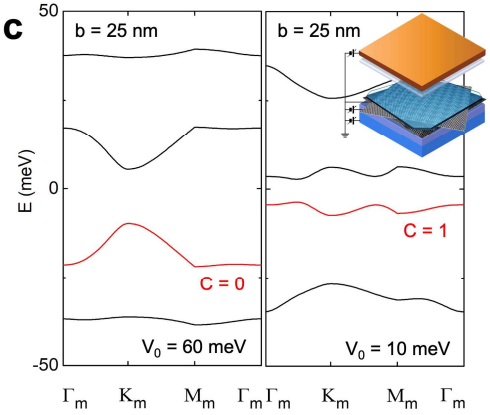
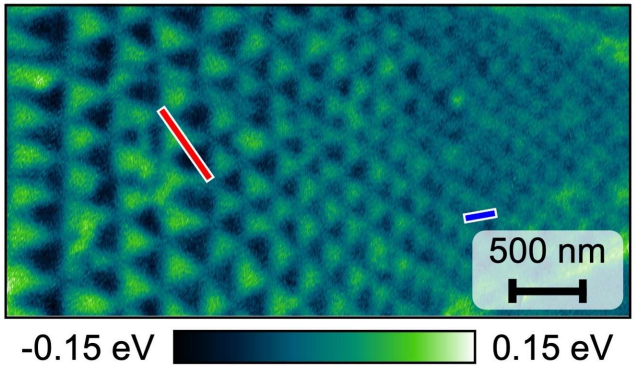
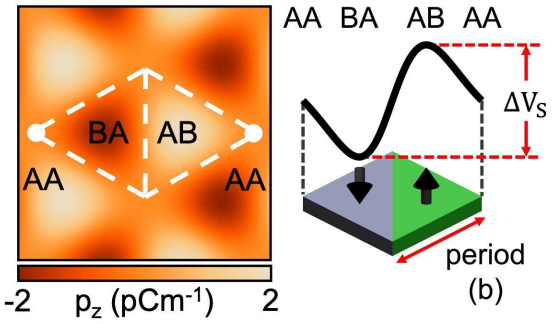
Twisted hBN imposes a universal potential

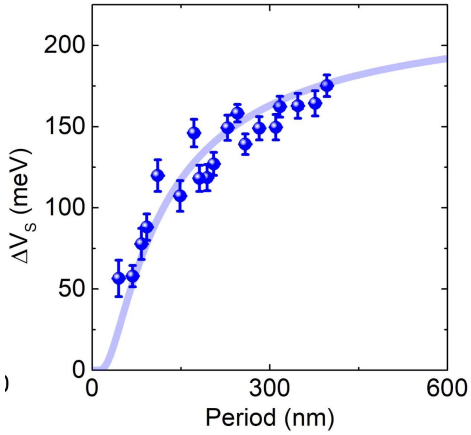






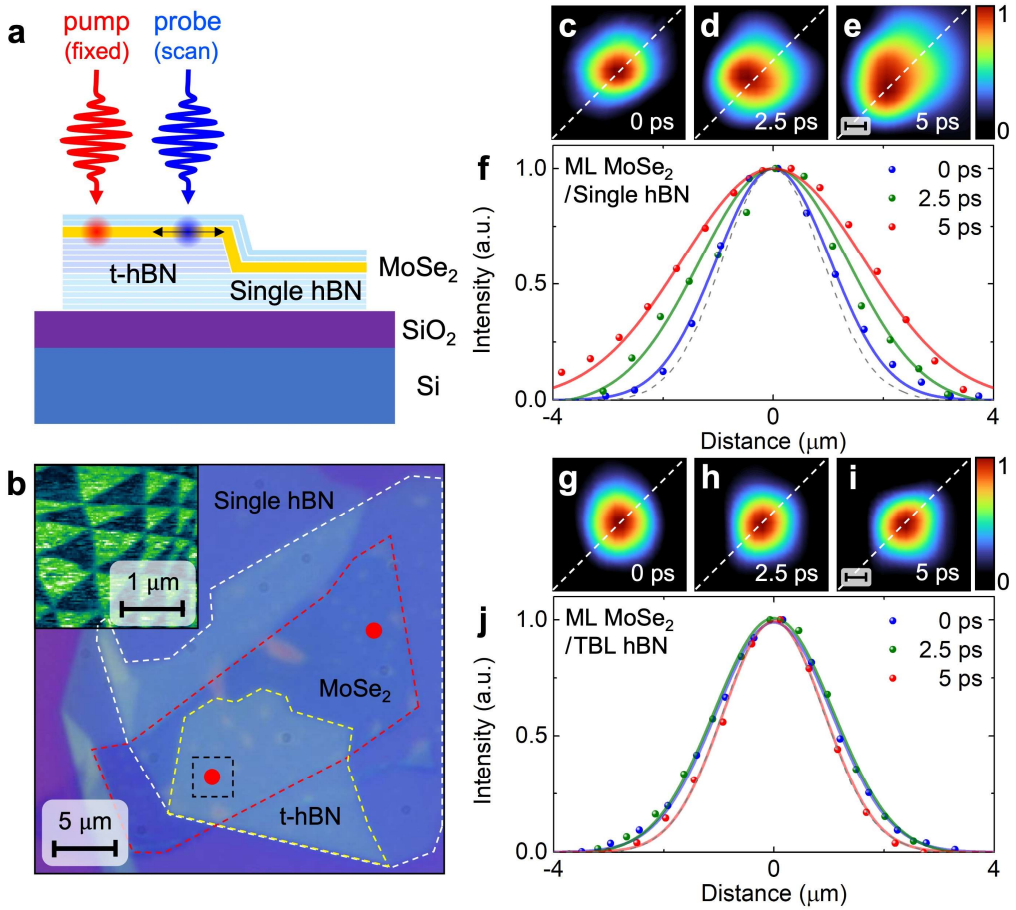






Nature Materials **volume 23**, 65–70 (2024)

Controlling exciton diffusion



Spectroscopy for semiconductor metrology

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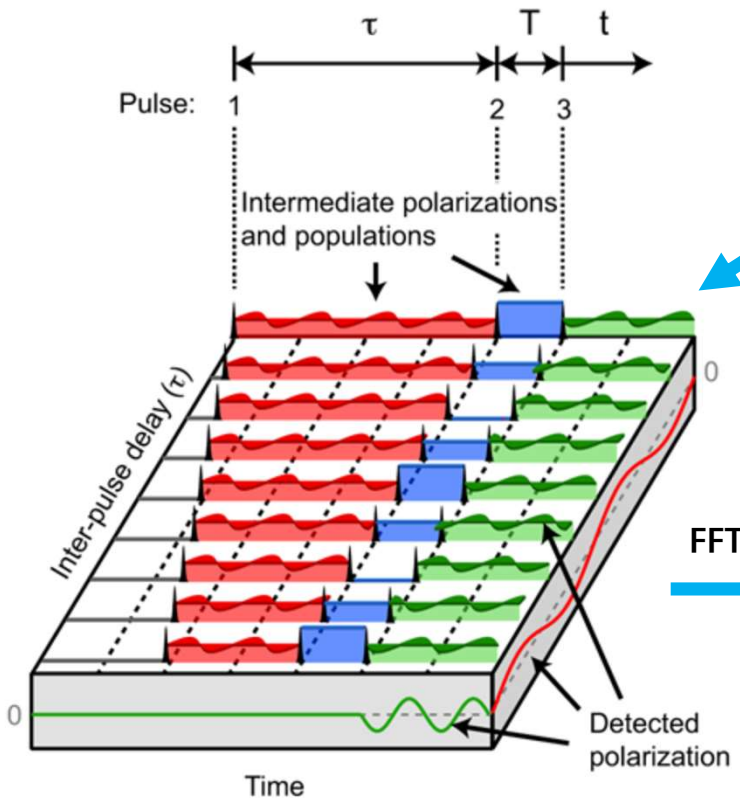
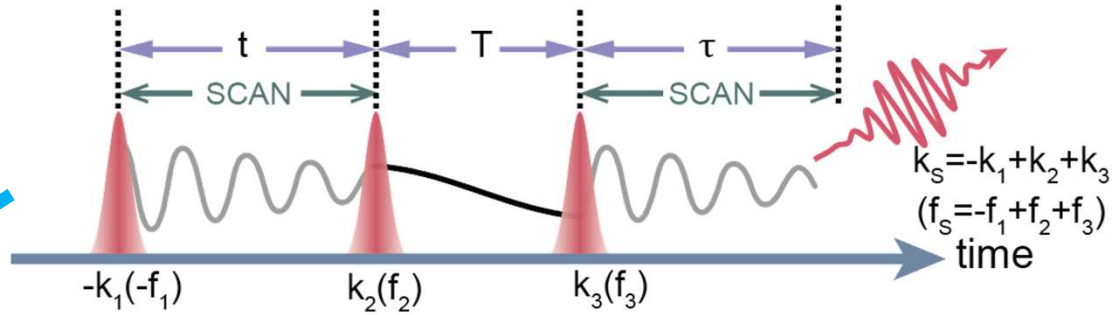
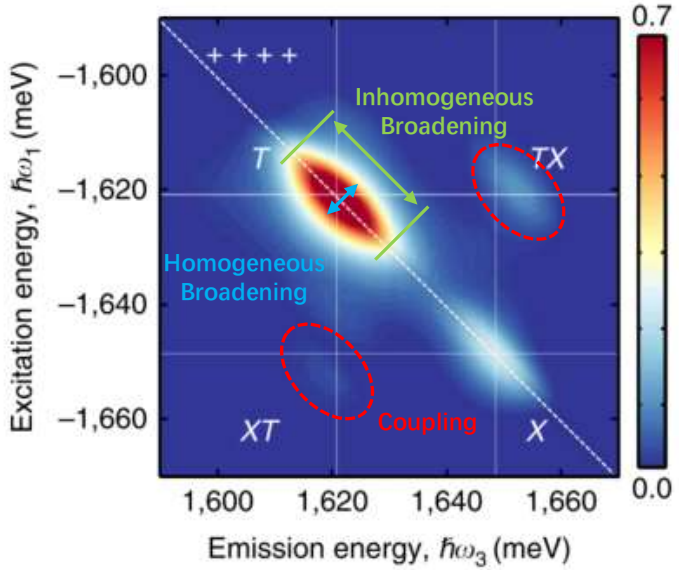
2D coherent electronic spectroscopy





FFT to τ & t



C. L. Smallwood. Laser & Photonics Reviews **12**, 1800171 (2018).

Nonlinear optical microscope – wafer-size compound semiconductor

- Transition absorption imaging
- Coherent Raman spectroscopy imaging
- Multi-dimensional four-wave-mixing imaging

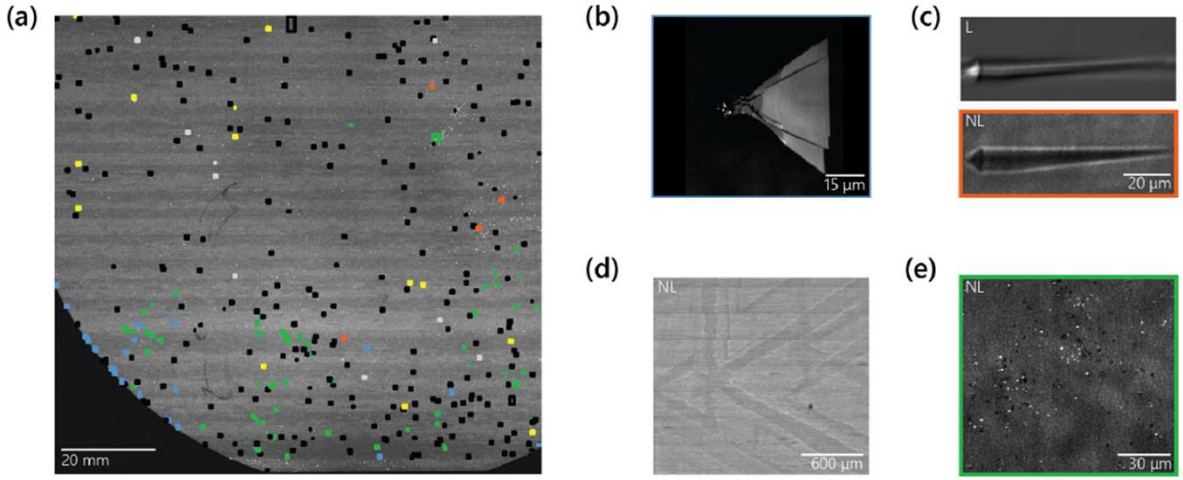
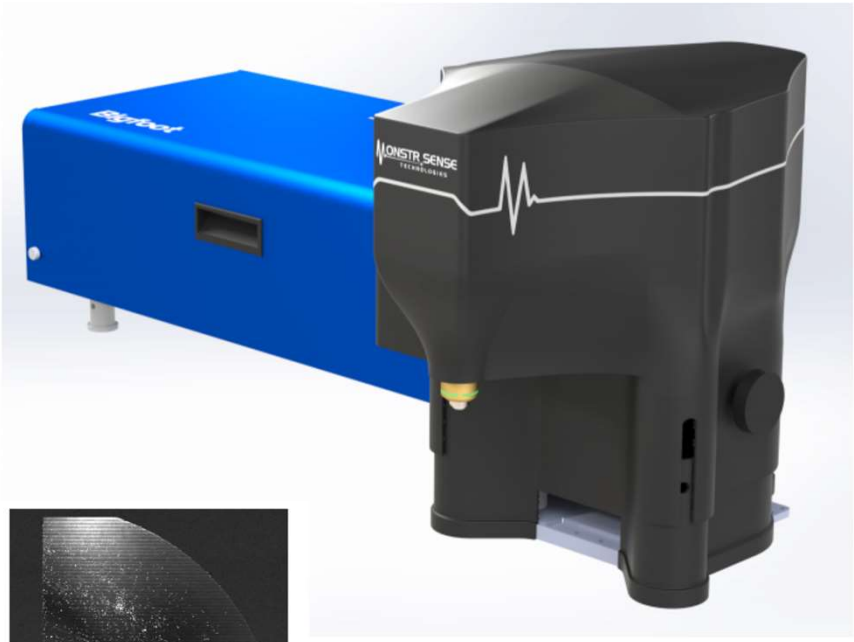
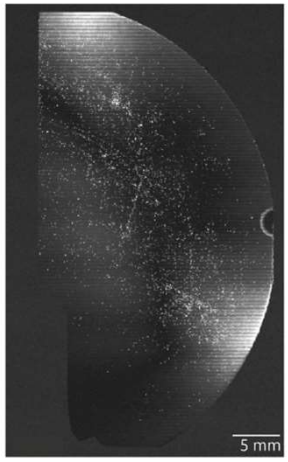


Figure 1: (a) Pump-probe image of a 6" SiC wafer (b) Surface triangle defect (c) Carrot defect (d) Doping variations and crystallographic defects (e) Microclusters of localized defects.



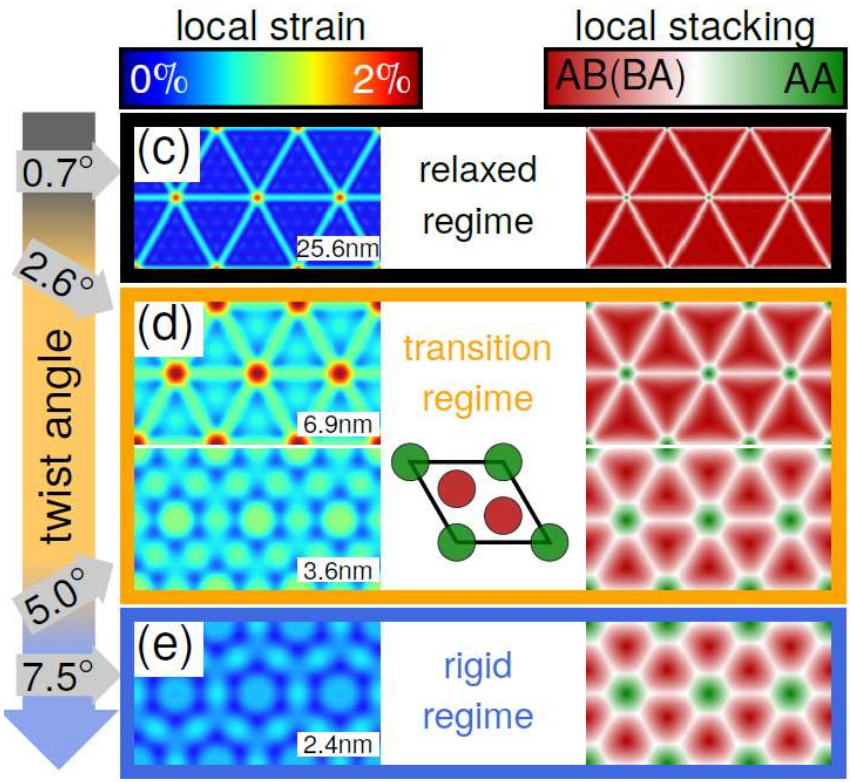
https://monstrsense.com



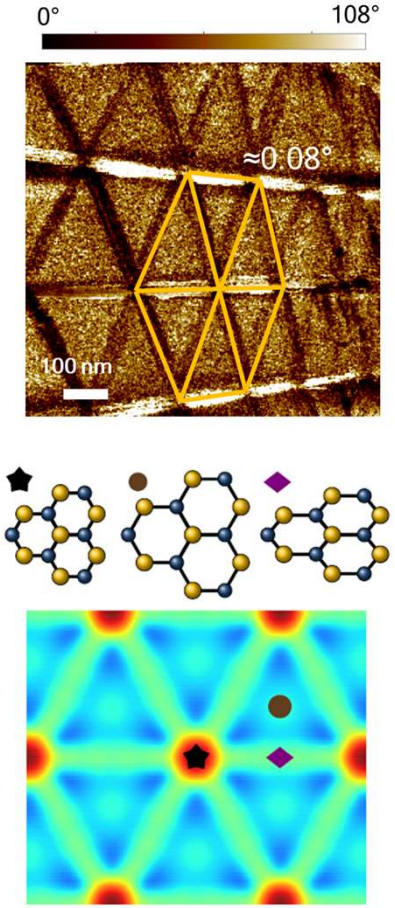
2-inch GaAs multiple quantum well imaging

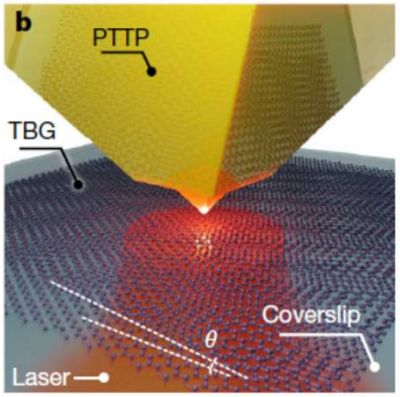
Lattice reconstruction characterized by Raman spectra

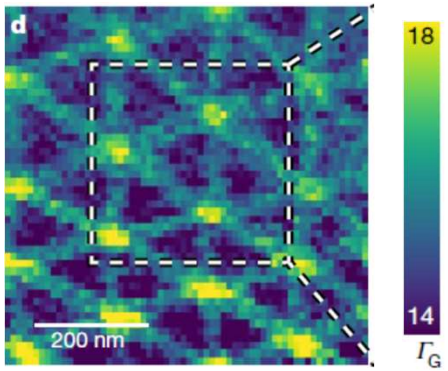
Calculated lattice reconstruction



PFM image of a MoS2 bilayer







Nature **590**, 405–409 (2021); twisted graphene bilayers

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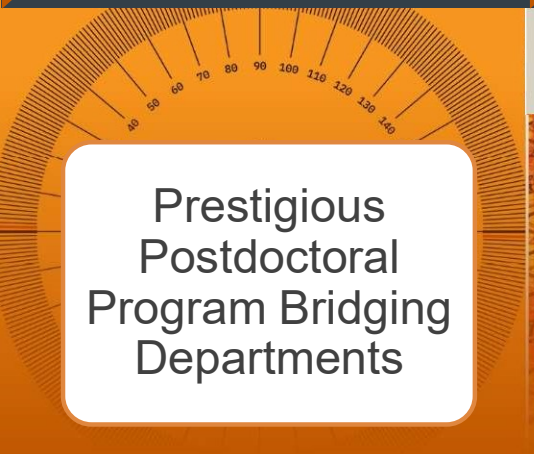
WHAT STARTS HERE CHANGES THE WORLD

TEXAS Quantum Institute (TQI)

Co-directors: Xiaoqin Elaine Li (Physics) and Xiuling Li (ECE)

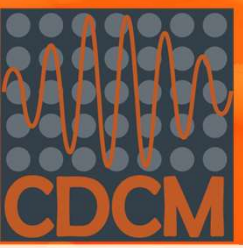
ALGORITHMS	MATERIALS	METROLOGY	SYSTEMS

Propose novel designs and concepts to industry



Prestigious Postdoctoral Program Bridging Departments	Internationally Visible Workshops	New Flagship Metrology Facility	Seed Grant Program (grant planning, seed interdisciplinary projects)
Determining how to operate a quantum computer effectively	**Predict, compute, and create new materials with unprecedented properties**	**Seeing the invisible: invent and apply the most advanced measurement tools**	**Build new sensors, electronics, circuits, and interconnects**

Thank you for your attention!



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