Borys Group at Montana State University

Experimental optical spectroscopy and nano-optics of quantum materials

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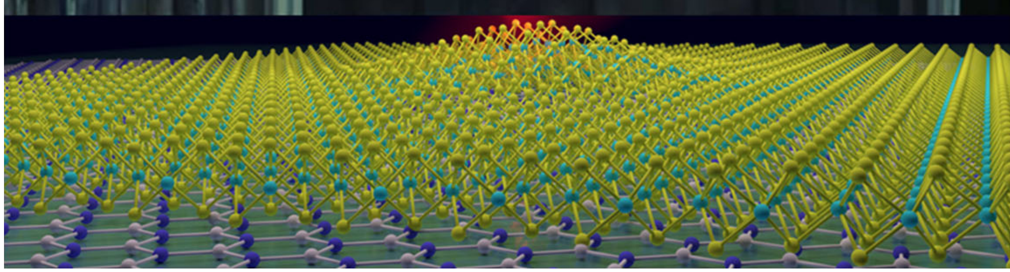
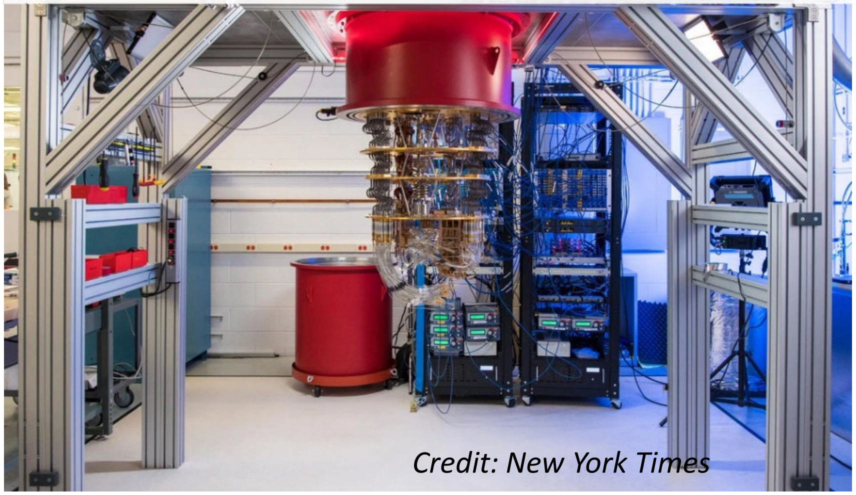


http://www.boryslab.com

Quantum technologies need new quantum materials

Google quantum computer w/ 53 qubits

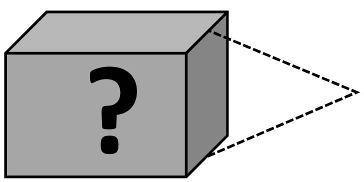


~3 meters

Boson sampler: 50-photon states in a 100 mode interferometer

~1 meter

Quantum materials



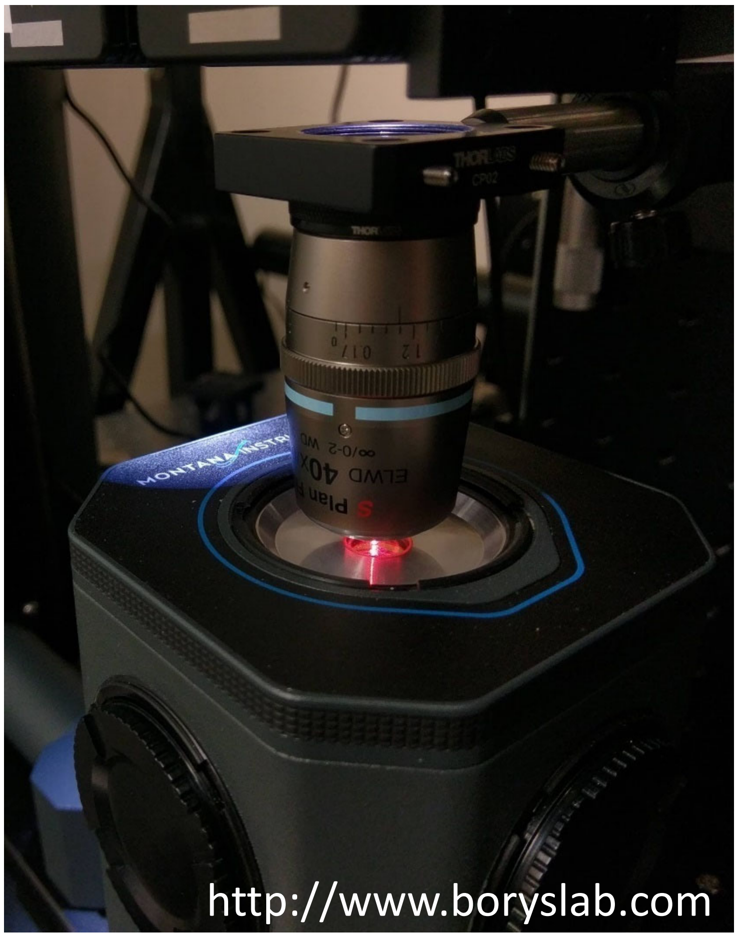
Optical, electrical, and magnetic behavior that can create, store, transport, and/or manipulate quantum states of light and matter

What will future quantum devices be made from?

- Improved scalability?
- Better performance?
- New quantum effects?

Borys Group at Montana State:

experimental nano-optics and quantum materials research



Optical spectroscopy group:

- How materials **absorb** light.
- How materials **emit** light.

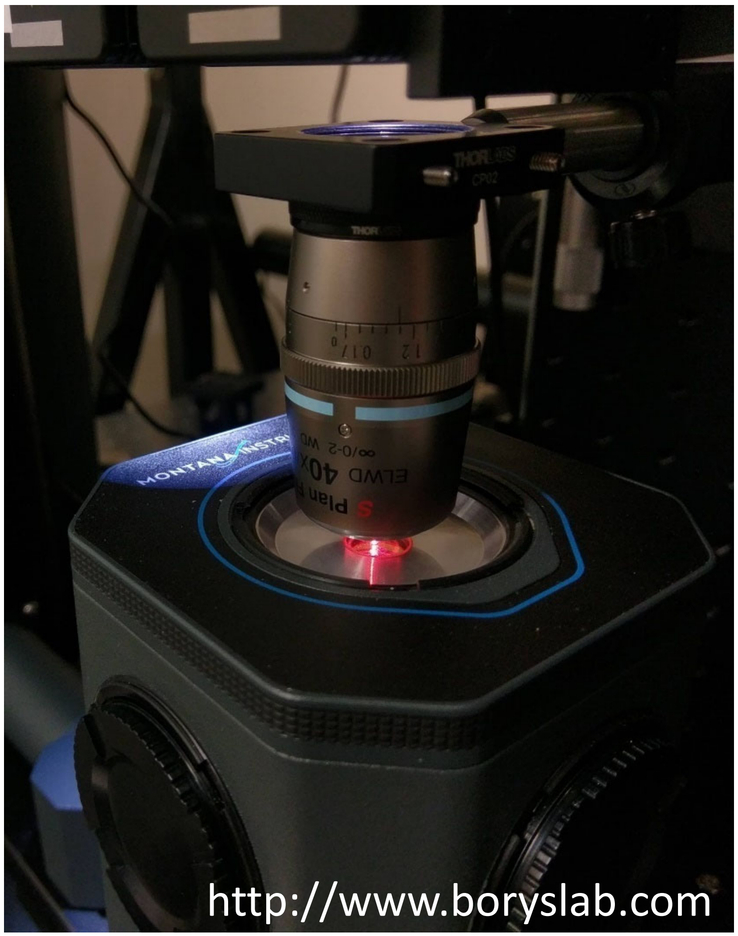
$$1 \text{ femtosecond} = \frac{1 \text{ second}}{1{,}000{,}000{,}000{,}000{,}000}$$

$$1 \text{ nanometer} = \frac{1 \text{ meter}}{1{,}000{,}000{,}000}$$

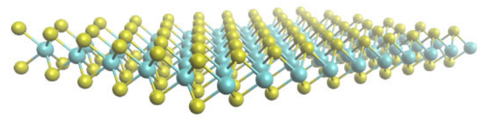
$$3 \text{ Kelvin} = -475\ °\text{Farhenheit}$$

Borys Group at Montana State:

experimental nano-optics and quantum materials research



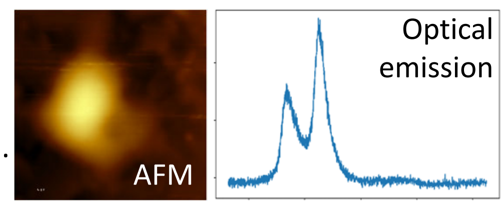
Nanoscale & quantum many-body phenomena in 2D materials



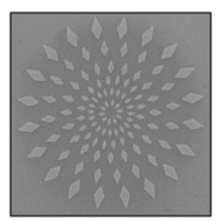
Nat Comm, **6** 7993 (2015).
PRL **119**, 087401 (2017).
ACS Nano **11**, 2115 (2017).

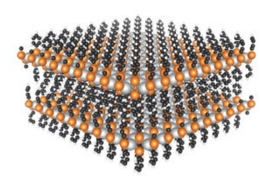
Nano-optical & multimodal characterization at the nanoscale

2D Mater. **4**, 021024 (2017).
ACS Nano **13**, 1284 (2019).

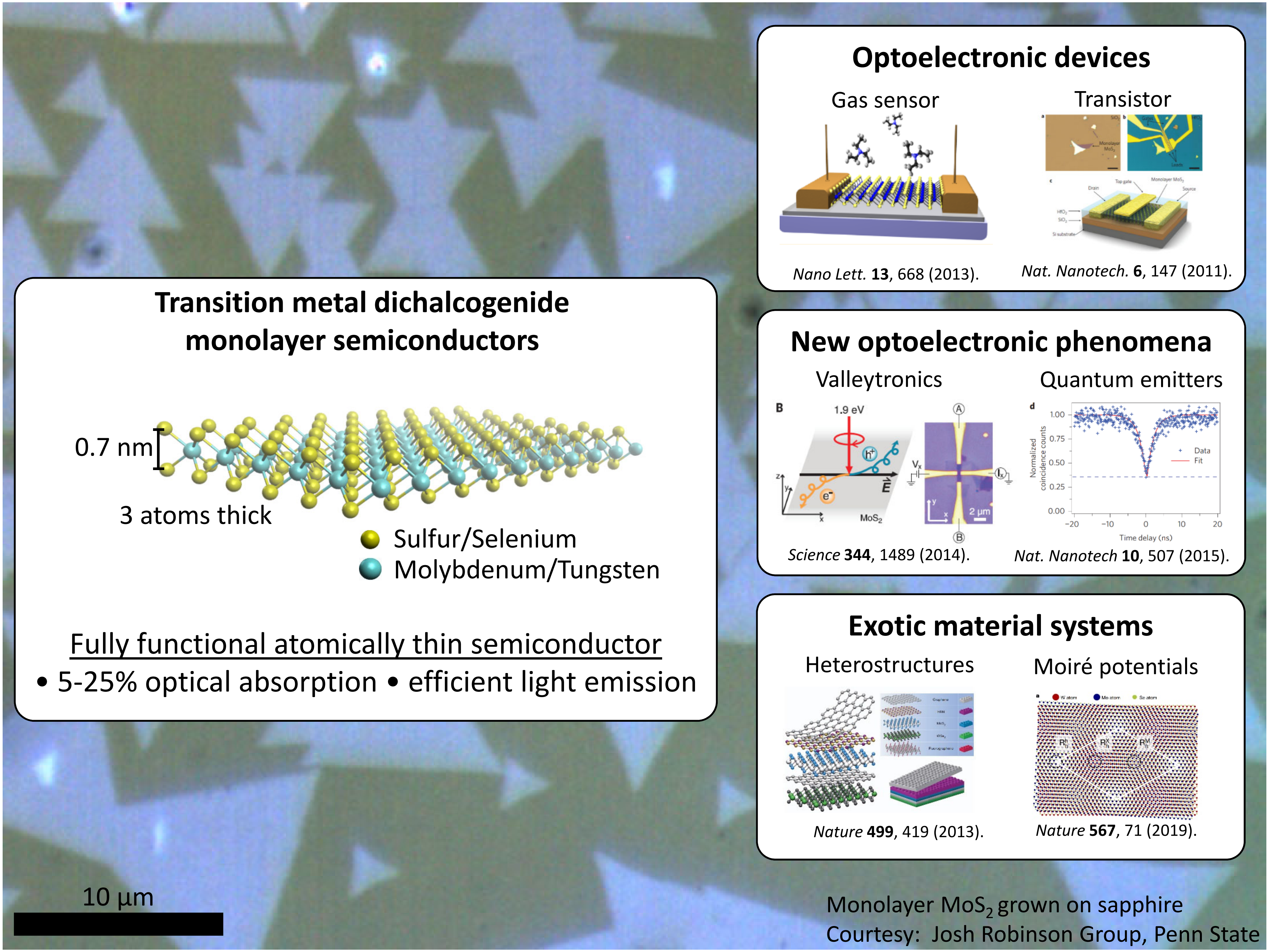


Exploration of novel nanoscale optoelectronic systems

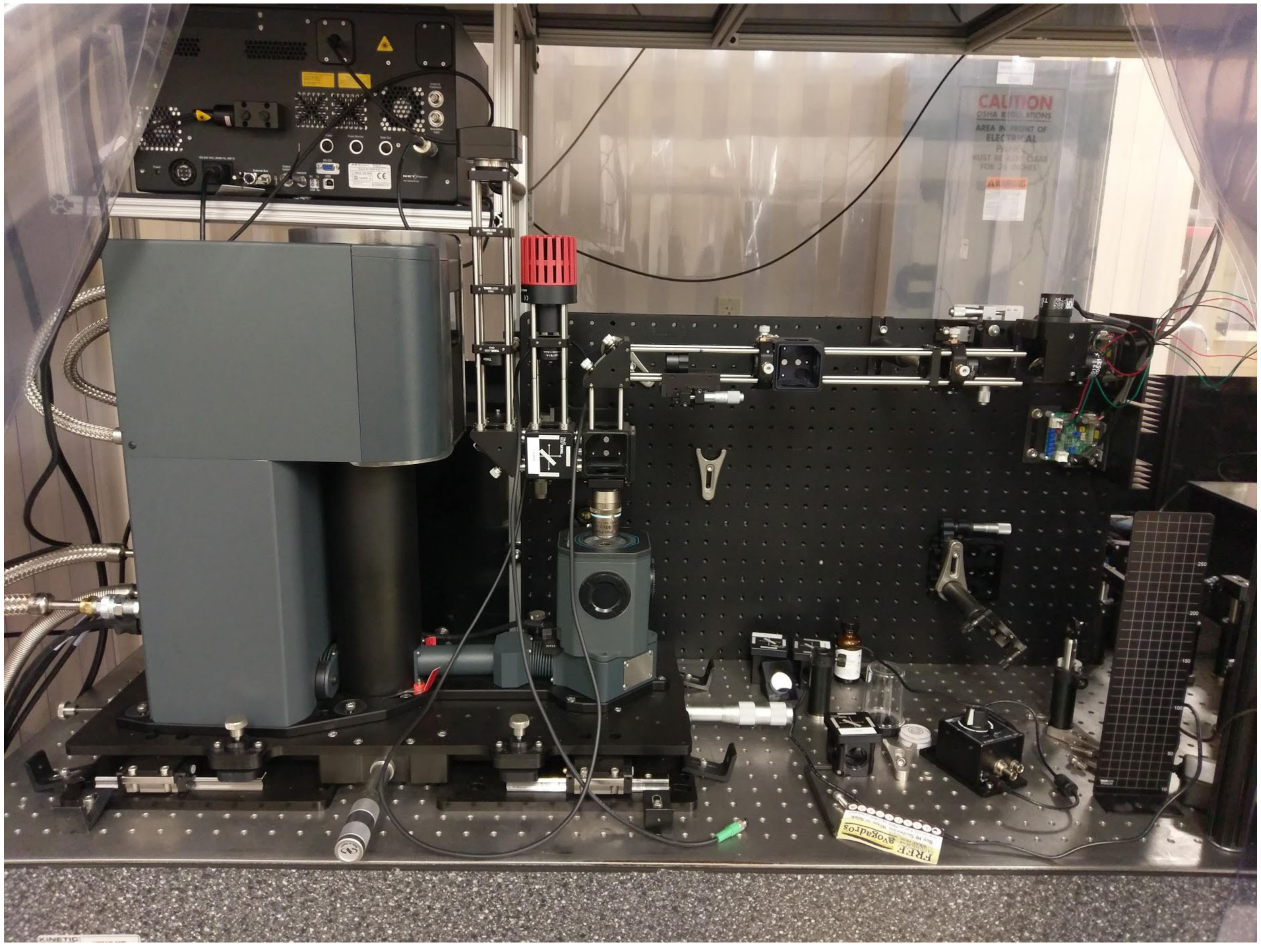




ACS Nano **13**, 5646 (2019). Nature Photonics **12**, 402 (2018).

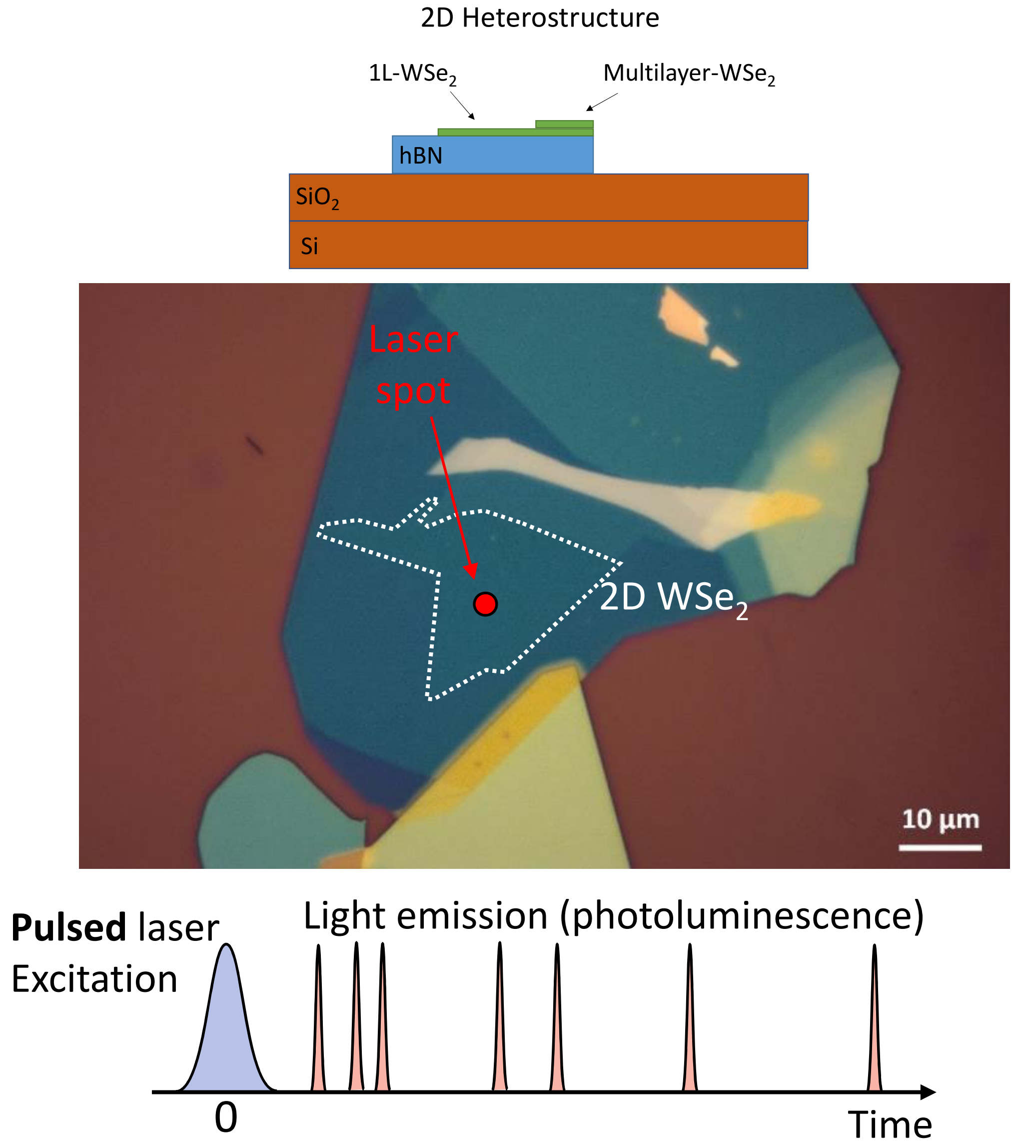

Transition metal dichalcogenide
monolayer semiconductors
0.7 nm
3 atoms thick
Sulfur/Selenium
Molybdenum/Tungsten
Fully functional atomically thin semiconductor
• 5-25% optical absorption • efficient light emission
Optoelectronic devices
Gas sensor
Transistor
Nano Lett. 13, 668 (2013).
Nat. Nanotech. 6, 147 (2011).
New optoelectronic phenomena
Valleytronics
Quantum emitters
1.9 eV
MoS2
2 μm
Data
Fit
Time delay (ns)
Science 344, 1489 (2014).
Nat. Nanotech 10, 507 (2015).
Exotic material systems
Heterostructures
Moiré potentials
Nature 499, 419 (2013).
Nature 567, 71 (2019).
10 μm
Monolayer MoS2 grown on sapphire
Courtesy: Josh Robinson Group, Penn State

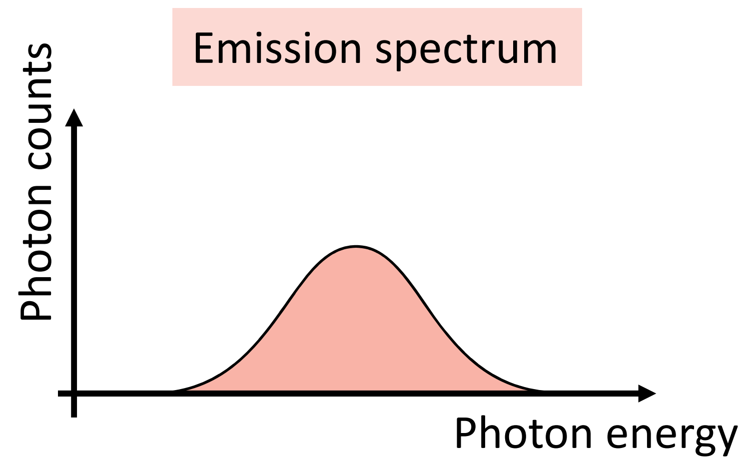
A versatile quantum-optical spectroscopy setup

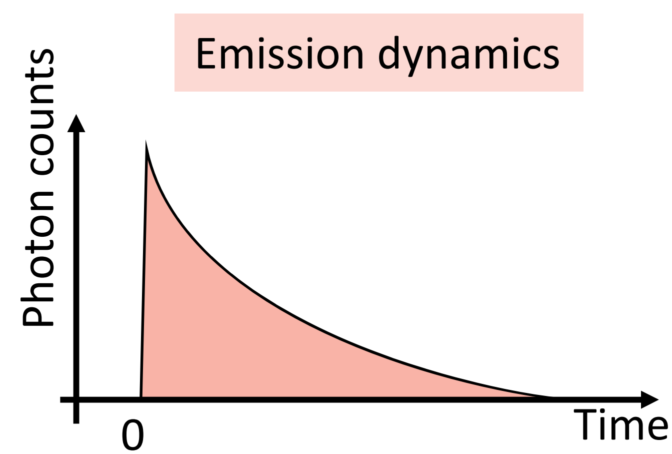


- μPL, μRaman, μAbsorption, μPolarization spectroscopy & imaging.
- Temp: 3.5 K – 350 K.
- Spatial resolutions: >300 nm.
- Time resolution: 30 ps.
- Detection wavelengths: 400 nm – 1100 nm
- Laser wavelengths: 400 nm – 2000 nm

Probing materials by analyzing their interactions with light

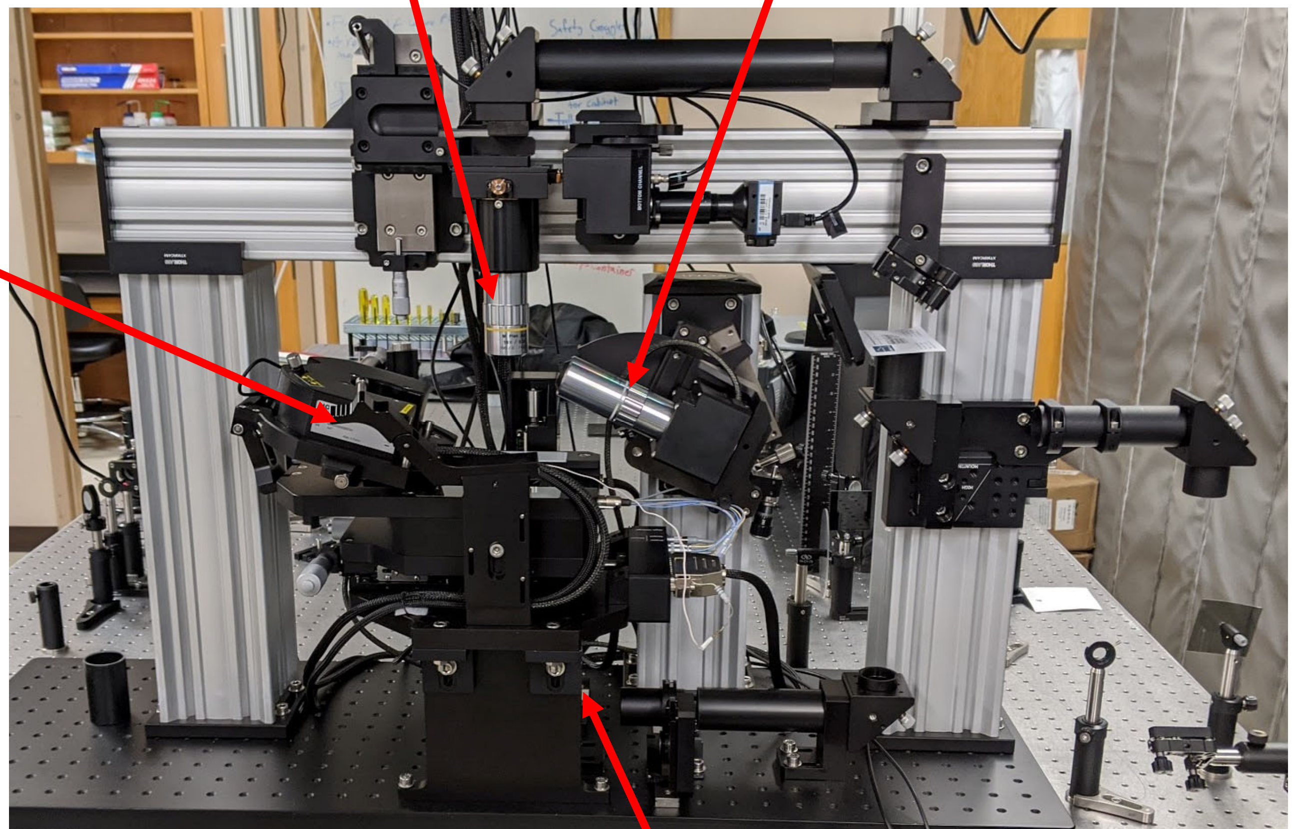






Sample courtesy of the Jim Hone Group at Columbia University

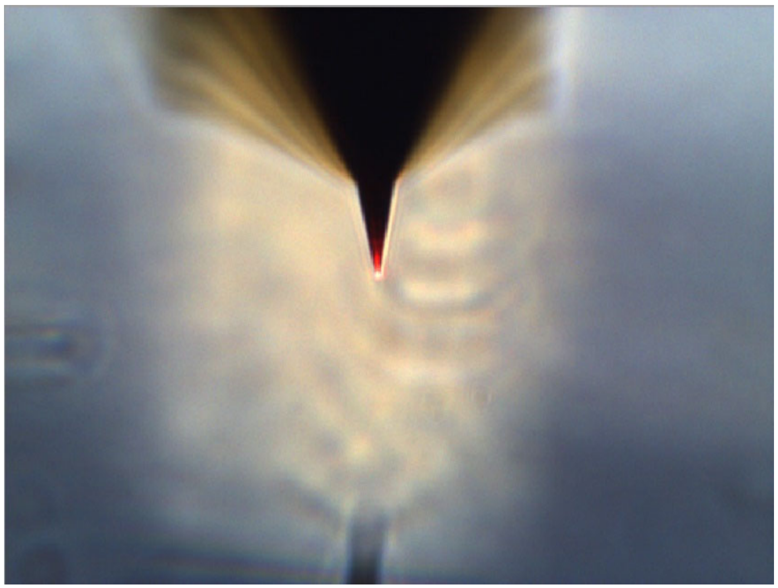
Nano-optical system: 4 microscopes in 1!



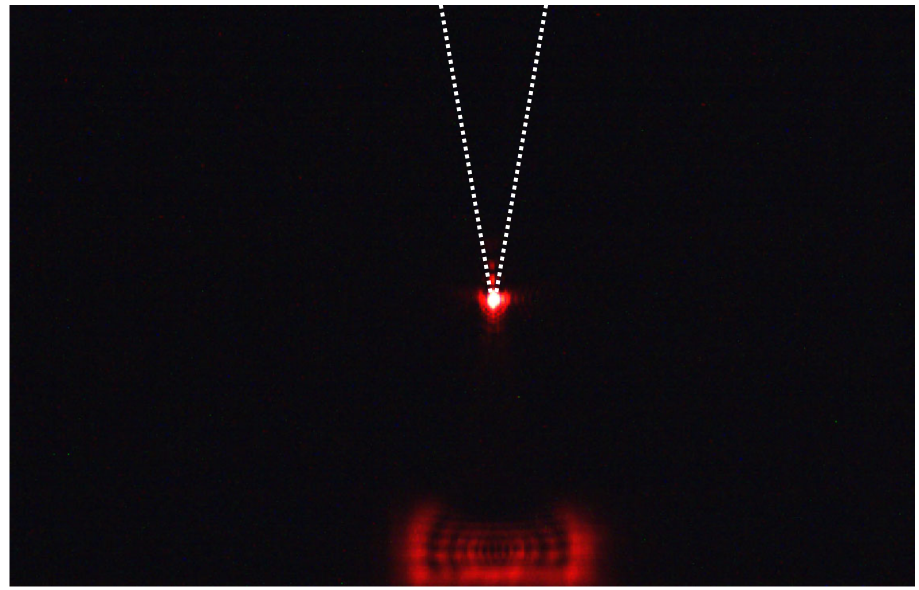
- Optical nano-imaging.
- AFM nano-imaging
- Spatial resolutions: <20 nm.
- Temp: 300K.

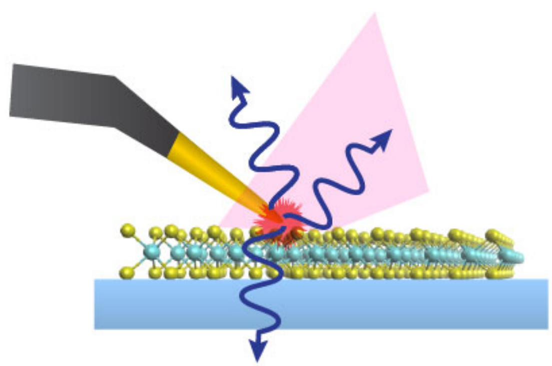
AFM probe illuminated with an excitation laser

Top optical microscope (lights on)



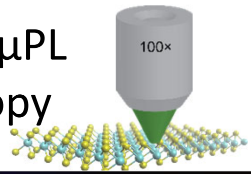
Side optical microscope (lights off)

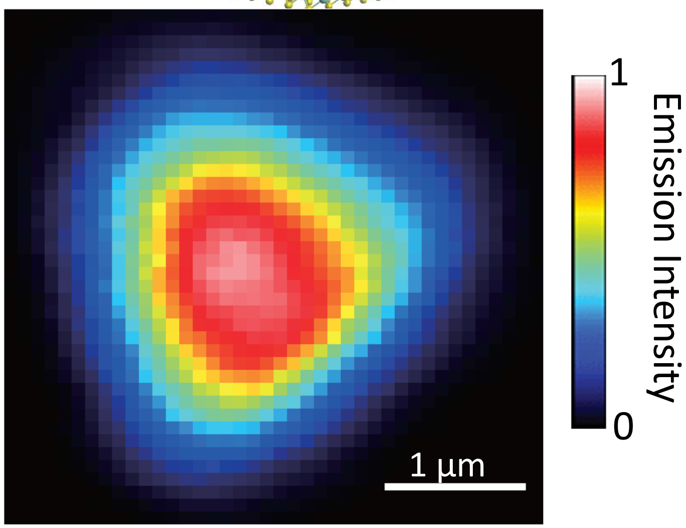




Significant nanoscale heterogeneity resolved with nano-PL

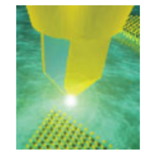
Confocal μPL microscopy

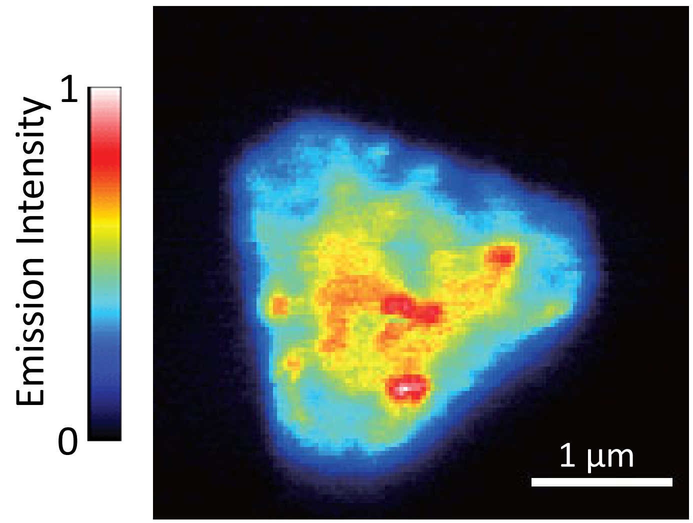




Resolution: ~380 nm

Campanile near-field nano-PL microscopy





Resolution: ~50 nm

Nat. Commun. **6**, 7993 (2015).
Front. Phys. **11**, 117804 (2016).
2D Mater. **4**, 021024 (2017).

Nano-optics of quantum materials at Montana State

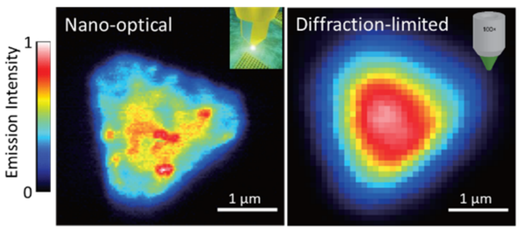
New materials to harness quantum phenomena on ultra-small length scales and ultrashort timescales.

quantum sensing • quantum information science • next-generation optoelectronics
fundamental many-body physics • non-equilibrium systems

Borys Lab – www.boryslab.com – nicholas.borys@montana.edu

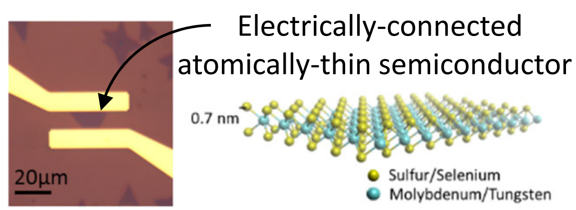
Research Highlights

Optical microscopy & spectroscopy beyond the diffraction-limit



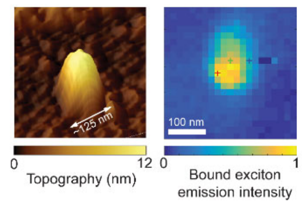
Nat. Commun. **6**, 7993 (2015) • *2D Mater.* **4**, 021024 (2017)
Nature Nano. **15**, 854 (2020)

Nanoscale & ultrafast many-body physics in 2D materials



PRL **119**, 087401 (2017) • *ACS Nano* **11**, 2115 (2017)
Nature Commun. **11**, 1156 (2020) + 1 new sub.

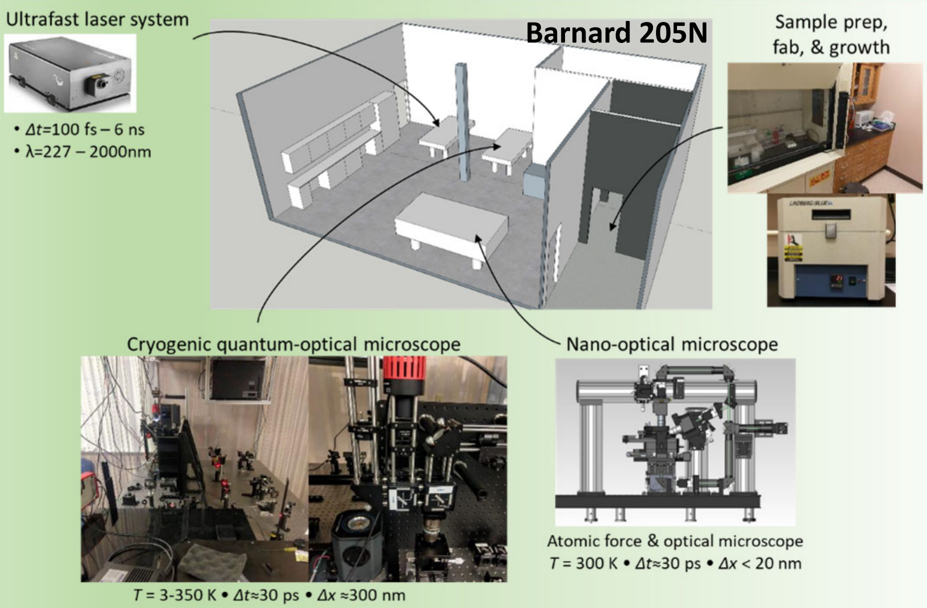
2D material engineering for on-chip quantum photonics



Strain-engineered non-classical light source in a 2D semiconductor!

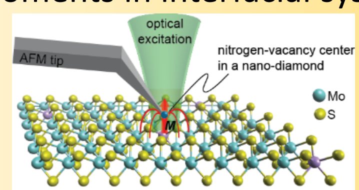
ACS Nano **13**, 1284 (2019) • *ACS Nano* **13**, 10520 (2019)
J. Phys. Chem C. **124**, 8000 (2020) + 1 new sub.

Experimental facilities



Example Potential Projects

- Nano-optical quantum sensing of nanoscale magnetic moments in interfacial systems.



- Low-temperature and nano-optical investigations of laterally-confined 2D materials (i.e., graphene and hexagonal boron nitride nanoribbons).