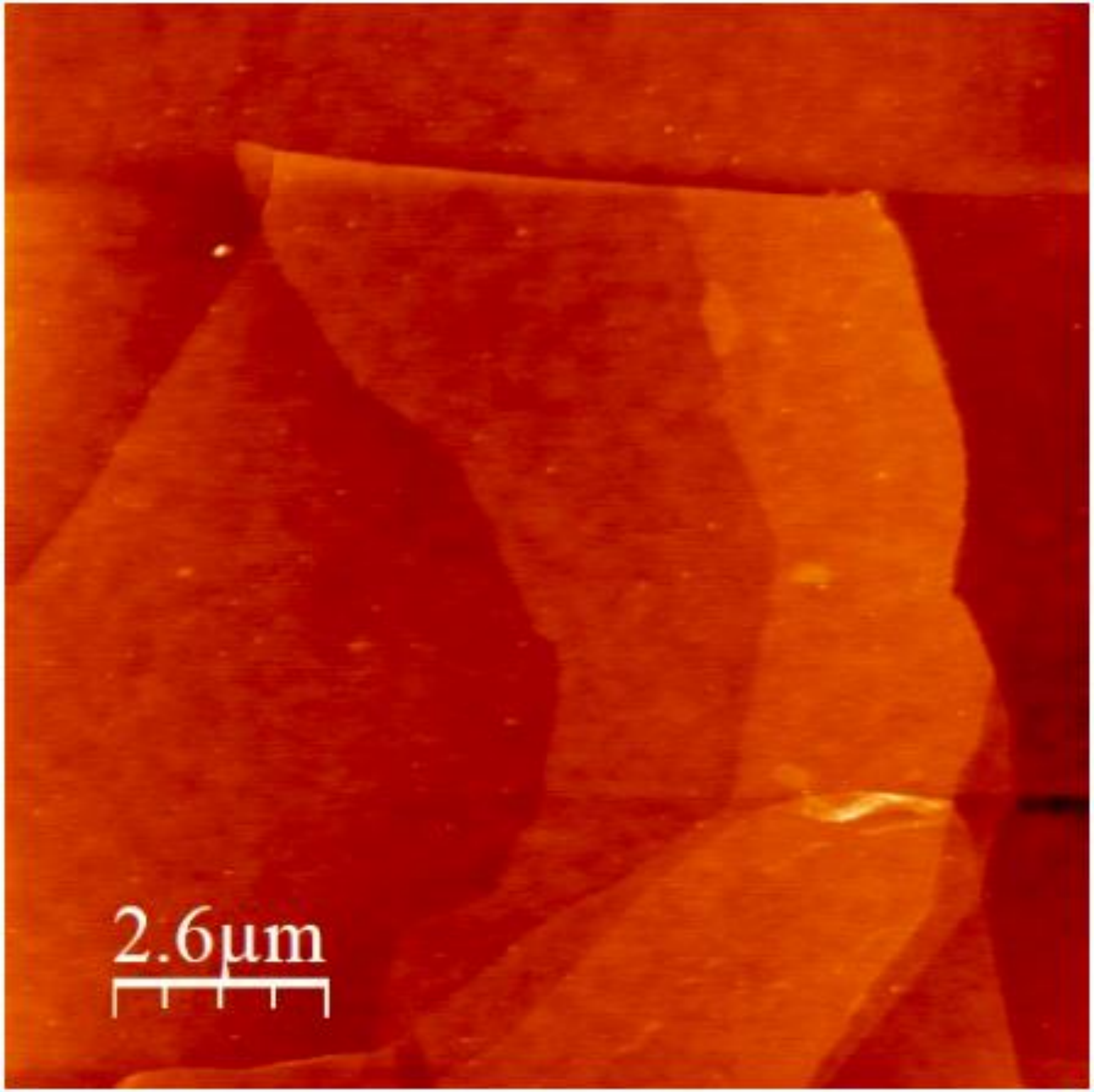
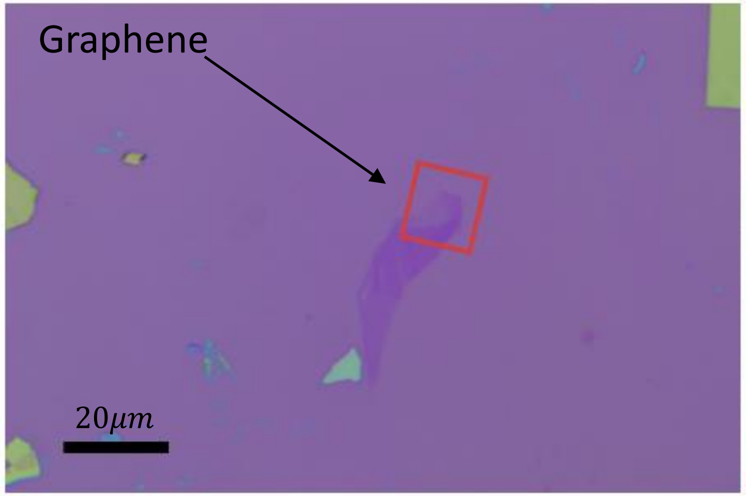
Nanoscale Imaging with Atomic Force Microscopy

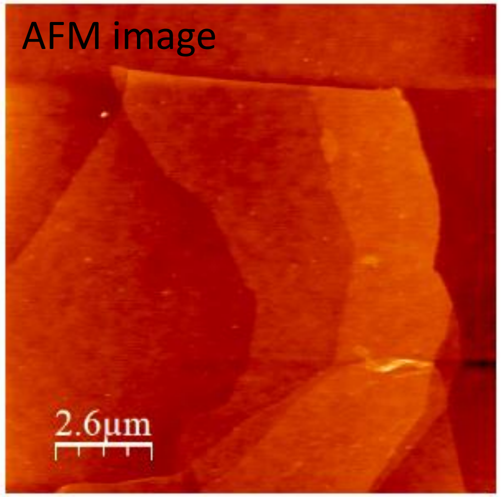
Alex Stram

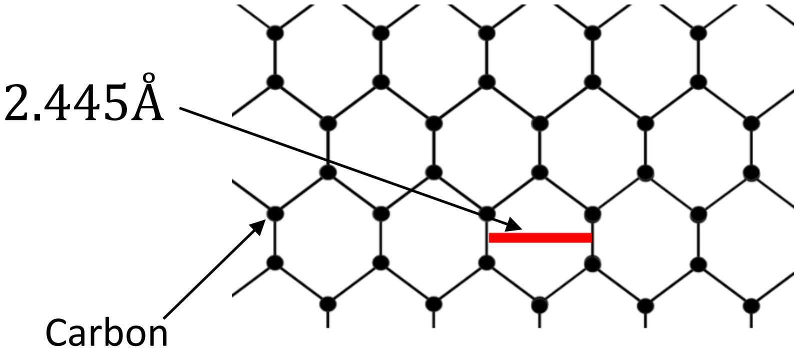


Outline

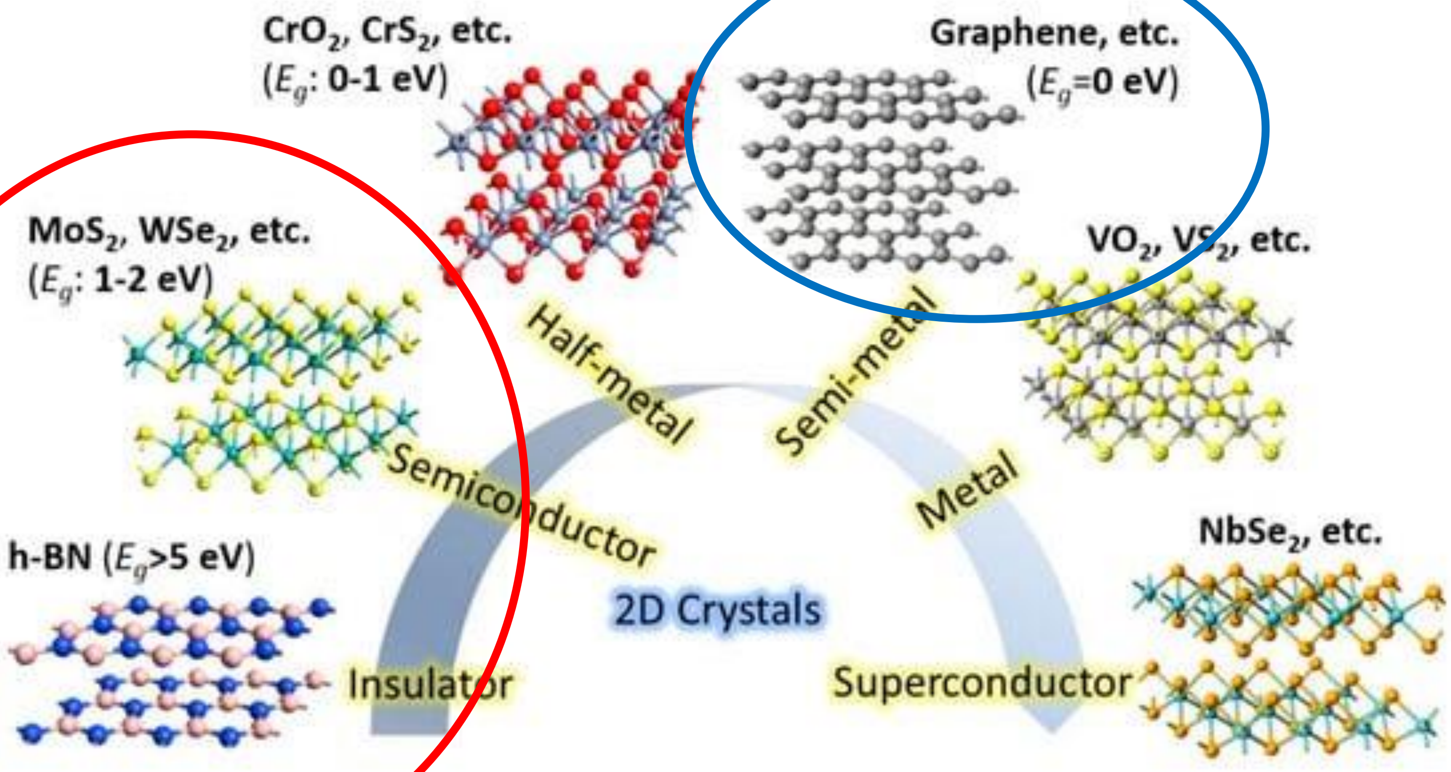
- Background
  - Two dimensional (2D) materials
  - Why Atomic Force Microscopy (AFM)?
- My work
  - Microwave Impedance Microscopy (MIM) of 2D materials
  - Photo-generated free electron physics







2D materials



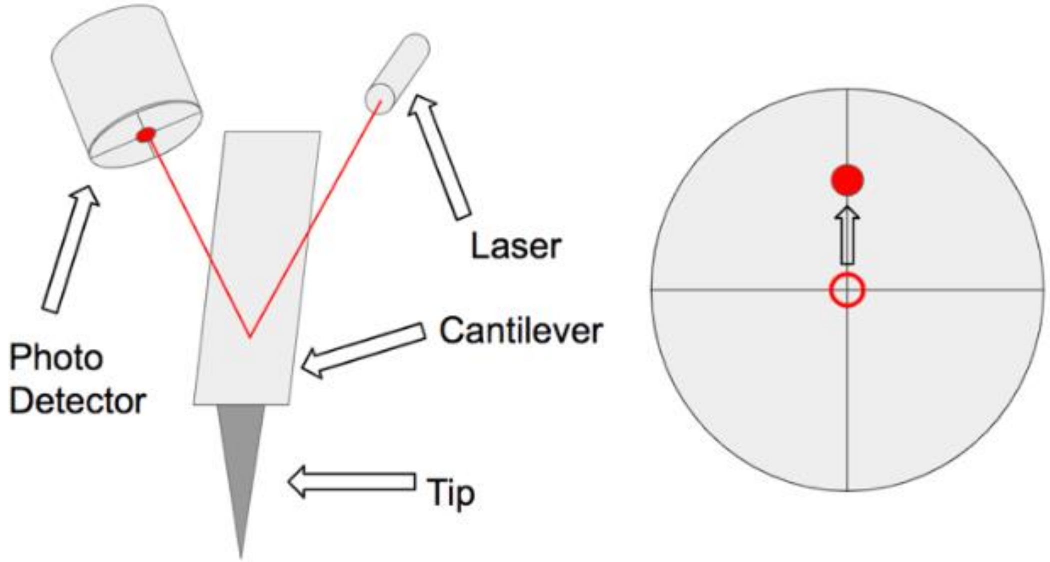
Title Slide

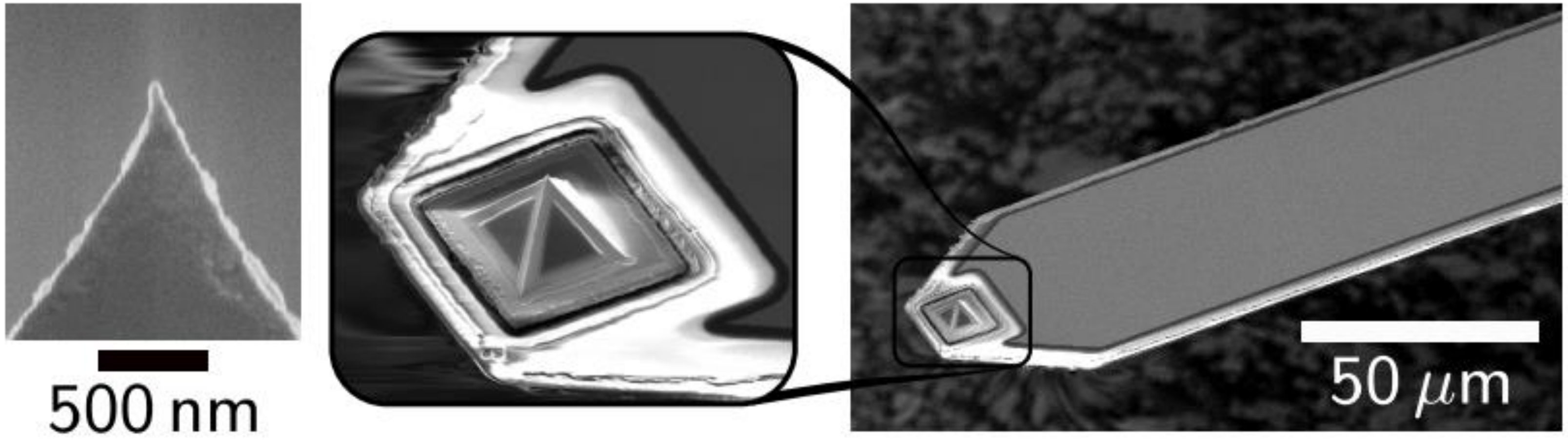
My current work

Two-Dimensional Electron Gas!
(2DEG)

Why Atomic Force Microscopy (AFM)?

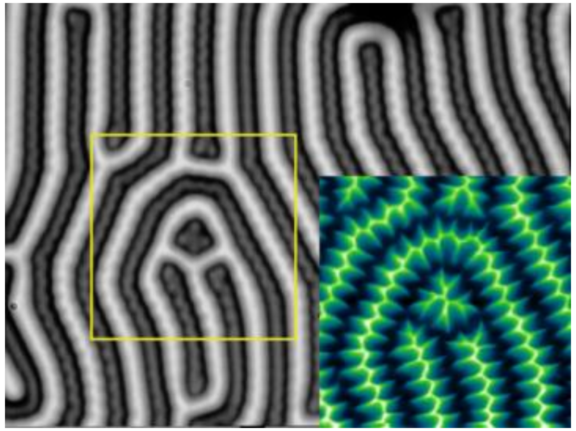
- Resolution >> light
- AFM enables new 2D material research



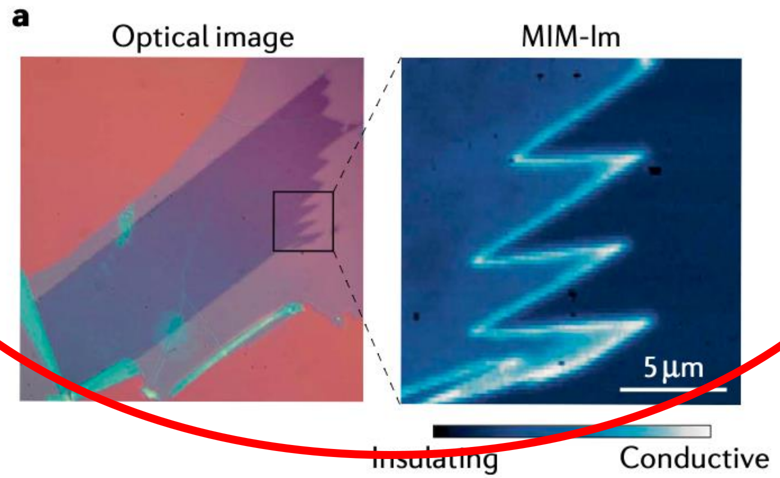


AFM

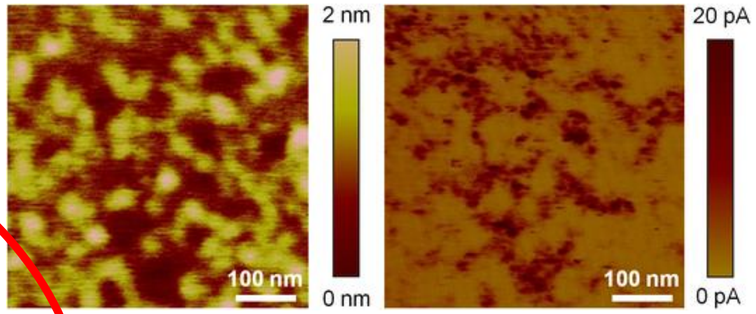
Magnetic Force Microscopy (MFM)



Microwave Impedance Microscopy (MIM)



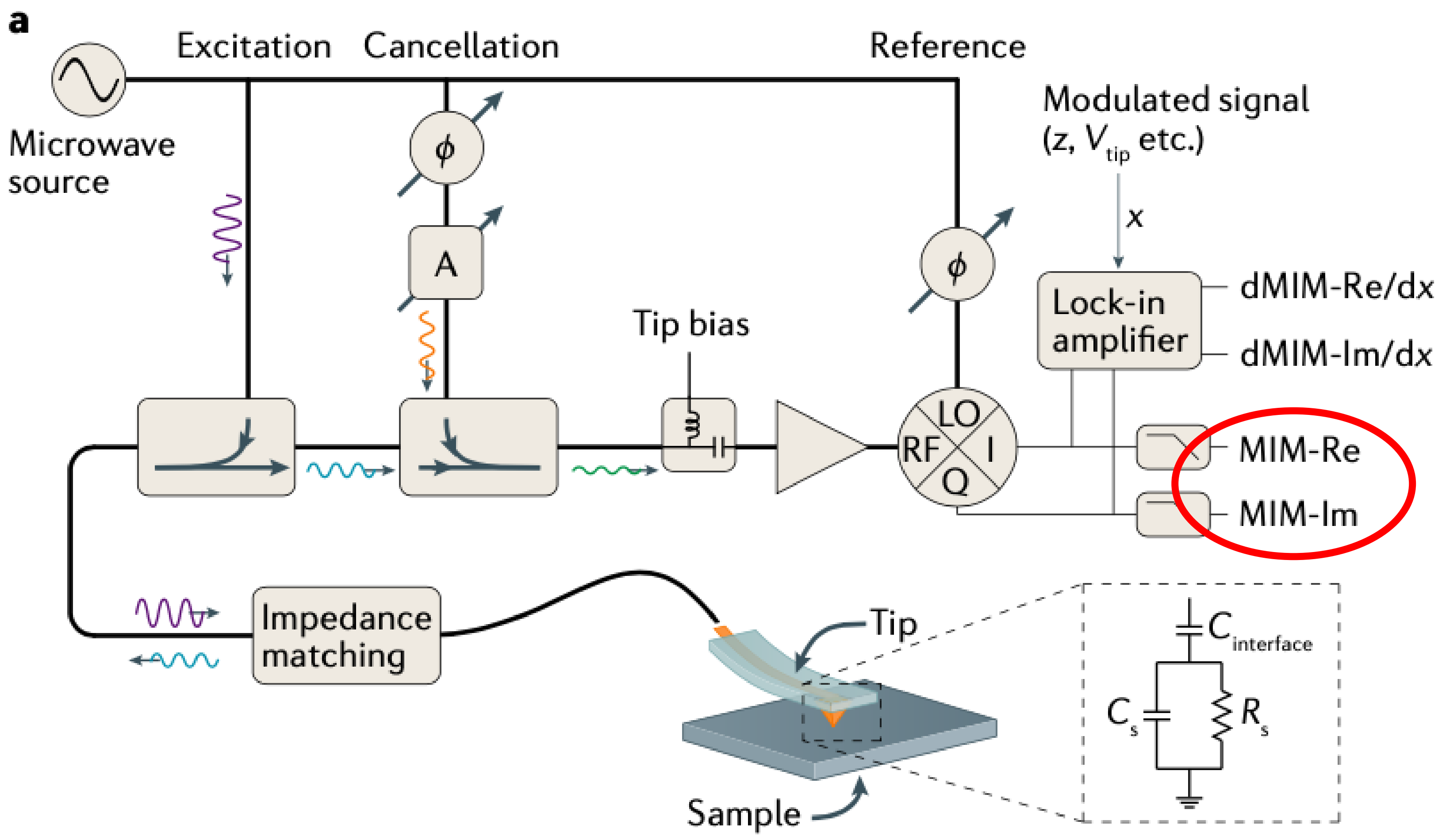
Electrostatic Force Microscopy (EFM)



Microwave Impedance Microscopy (MIM)

Incident wave:
$e^{i(kx-\omega t)}$ with $f\sim 1GHz$

Reflected wave:
$e^{i(k'x-\omega t)}$



Microwave Impedance Microscopy (MIM)

Continuity Equation

$$\nabla \cdot \left(J_\mathrm{f} + \frac{\partial D}{\partial t} \right) = 0\,.$$

$$J_\mathrm{f} = \sigma E \quad D = \varepsilon E$$

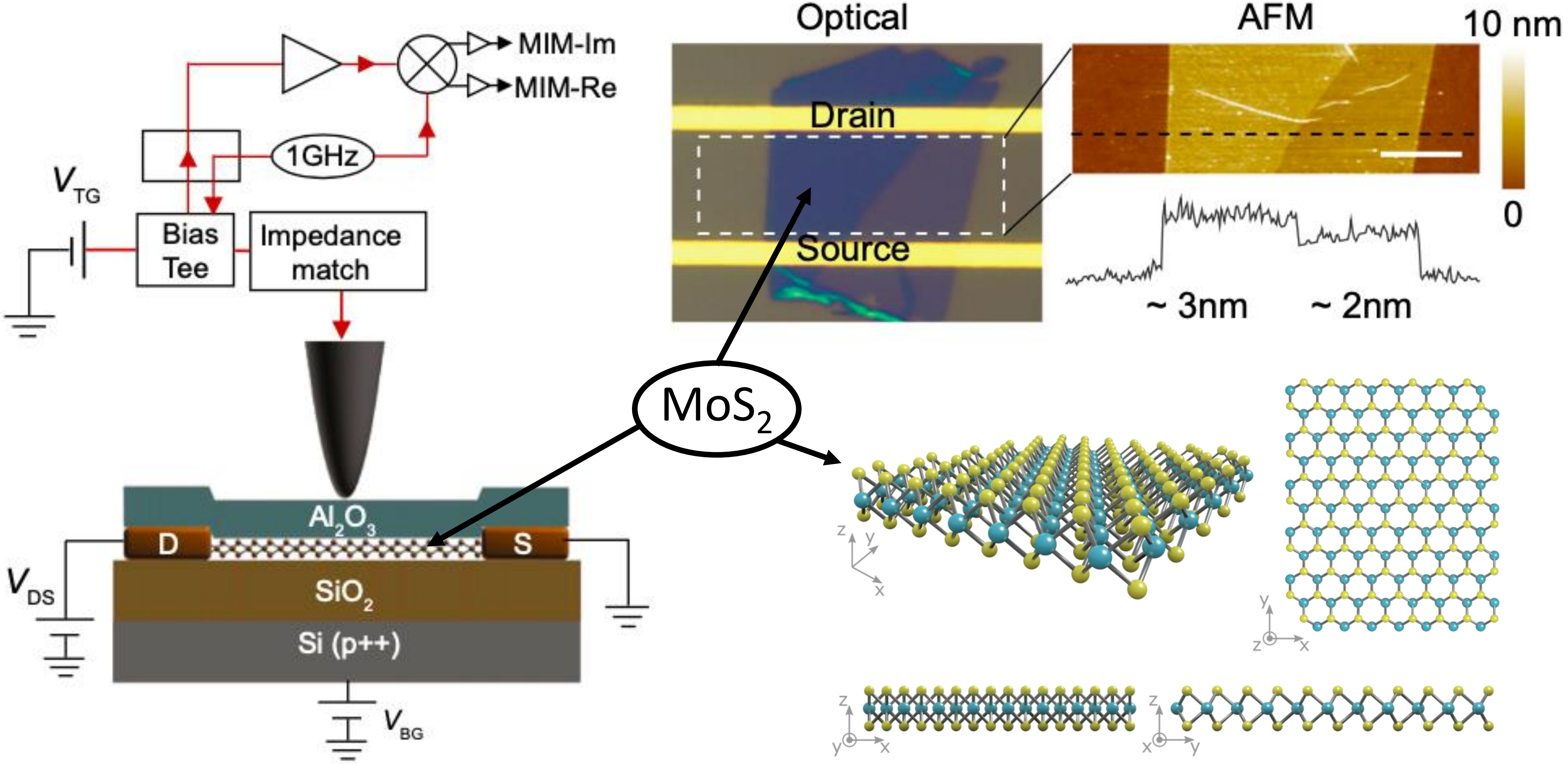
$$-\nabla \cdot \left(\sigma \nabla V + \frac{\partial (\varepsilon \nabla V)}{\partial t} \right) = 0\,.$$

Simulation

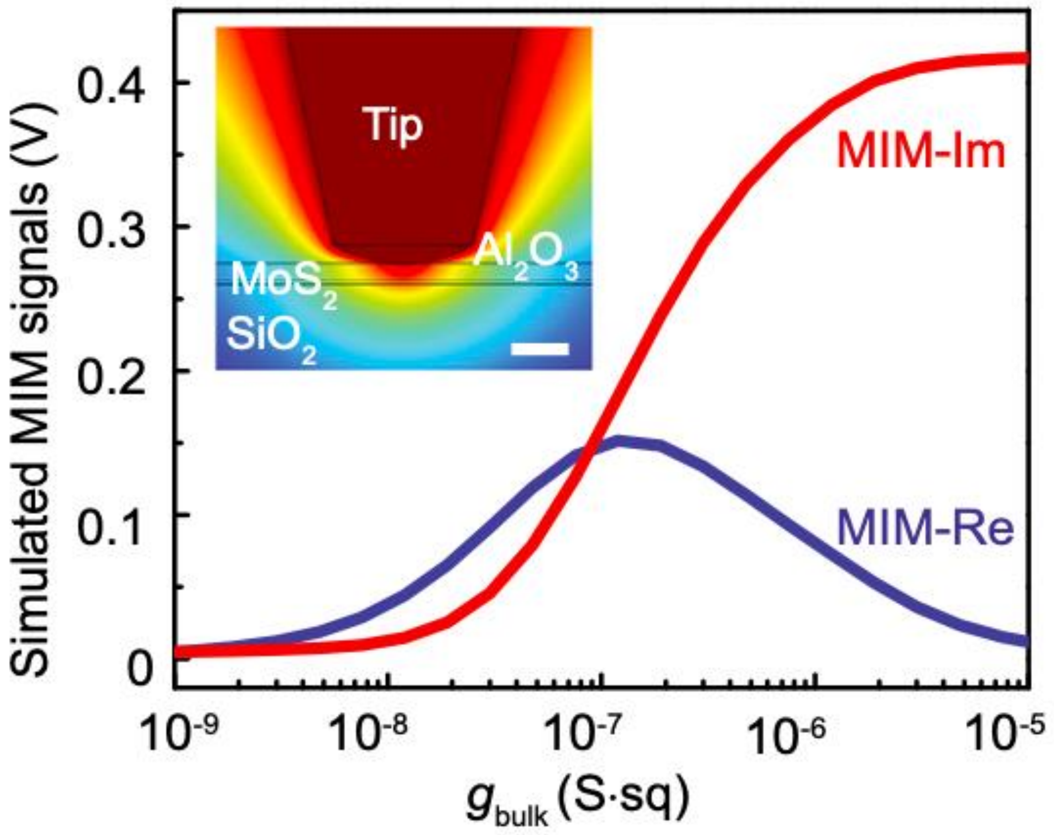
$$-\nabla \cdot [(\sigma - i\omega\varepsilon)\nabla V] = 0\,.$$

$$J = J_\mathrm{f} + \frac{\partial D}{\partial t} = -(\sigma - i\omega\varepsilon)\nabla V$$

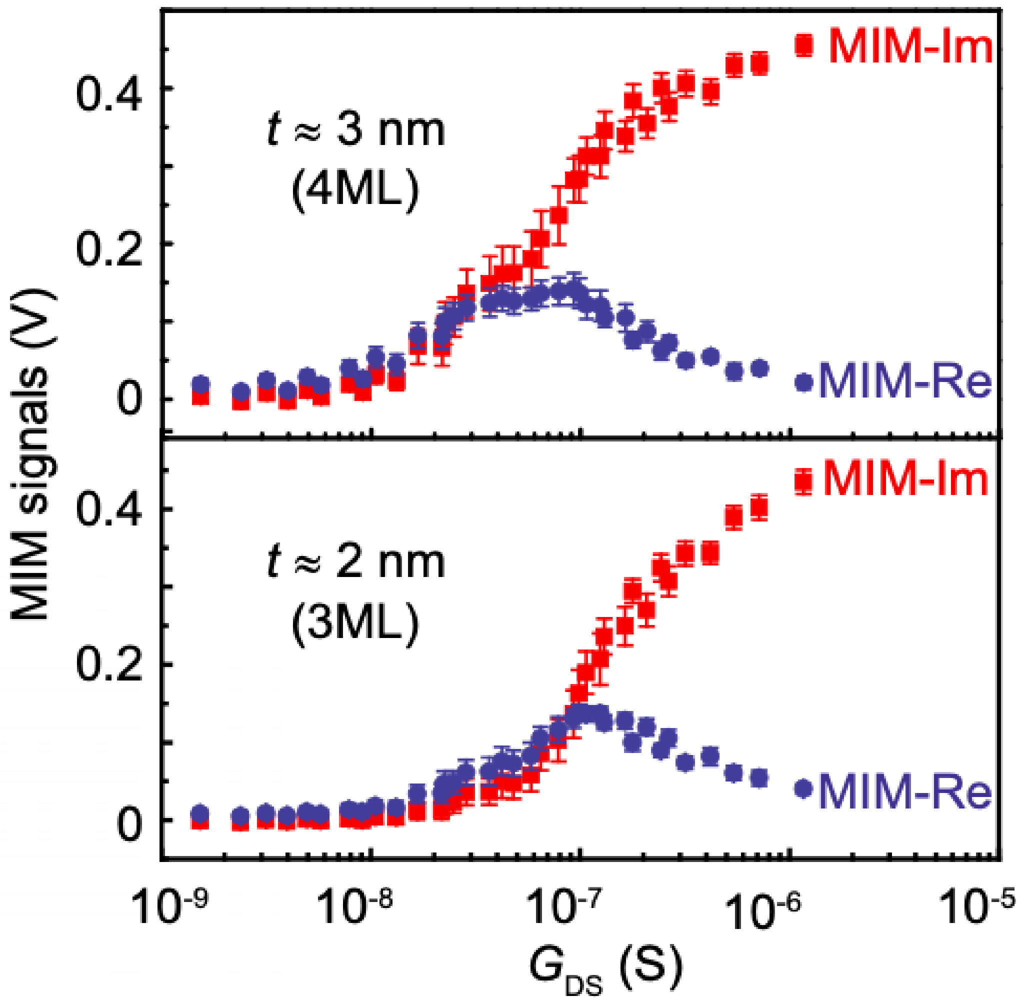
2D material research



Simulation



Experiment



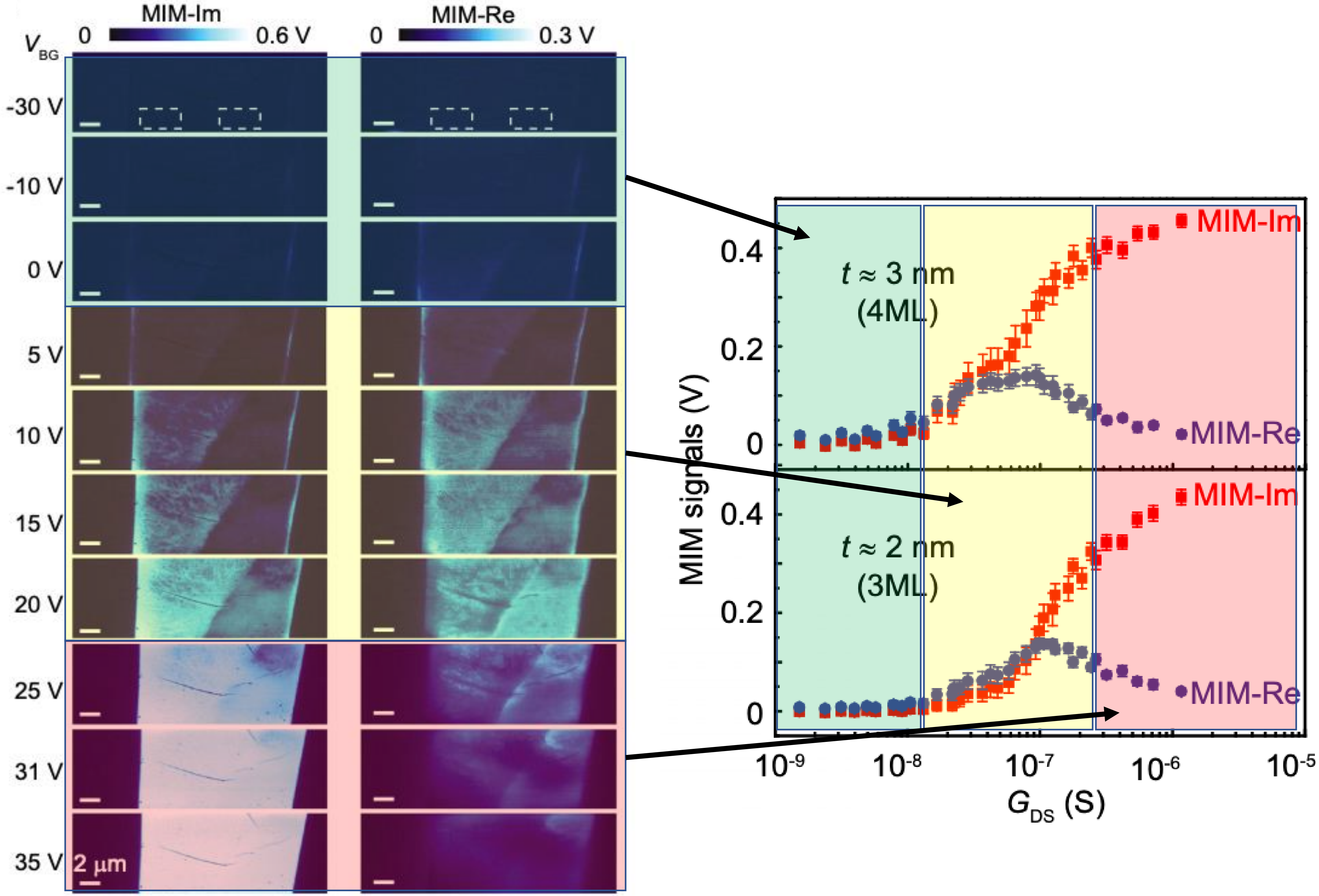
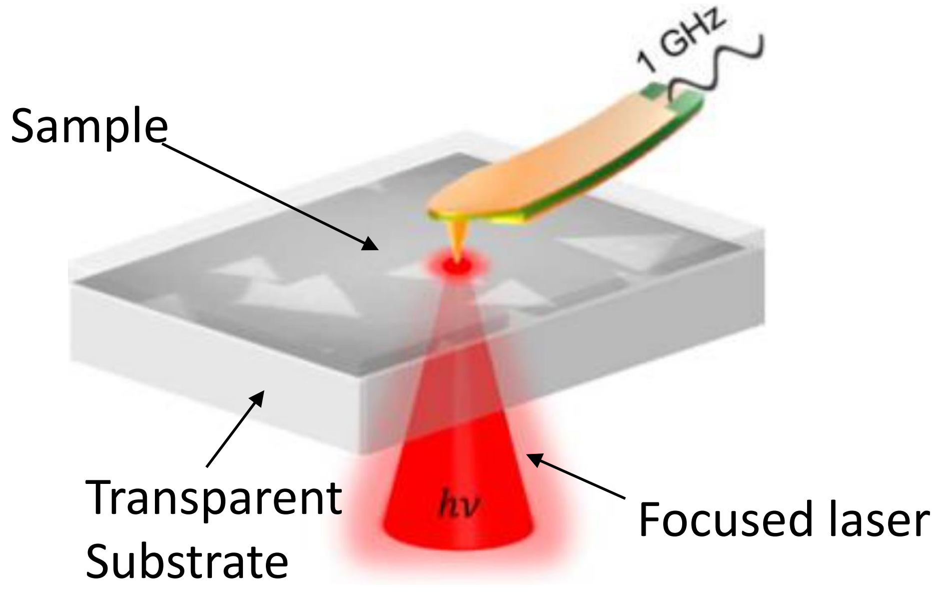

MIM-Im
0
0.6 V
MIM-Re
0
0.3 V
V_{BG}
-30 V
-10 V
0 V
5 V
10 V
15 V
20 V
25 V
31 V
35 V
2 μm
MIM signals (V)
0.4
0.2
0
$t \approx 3$ nm
(4ML)
$t \approx 2$ nm
(3ML)
MIM-Im
MIM-Re
MIM-Im
MIM-Re
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
G_{DS} (S)

Photo-generated free electrons

<u>Experimental Parameters</u>

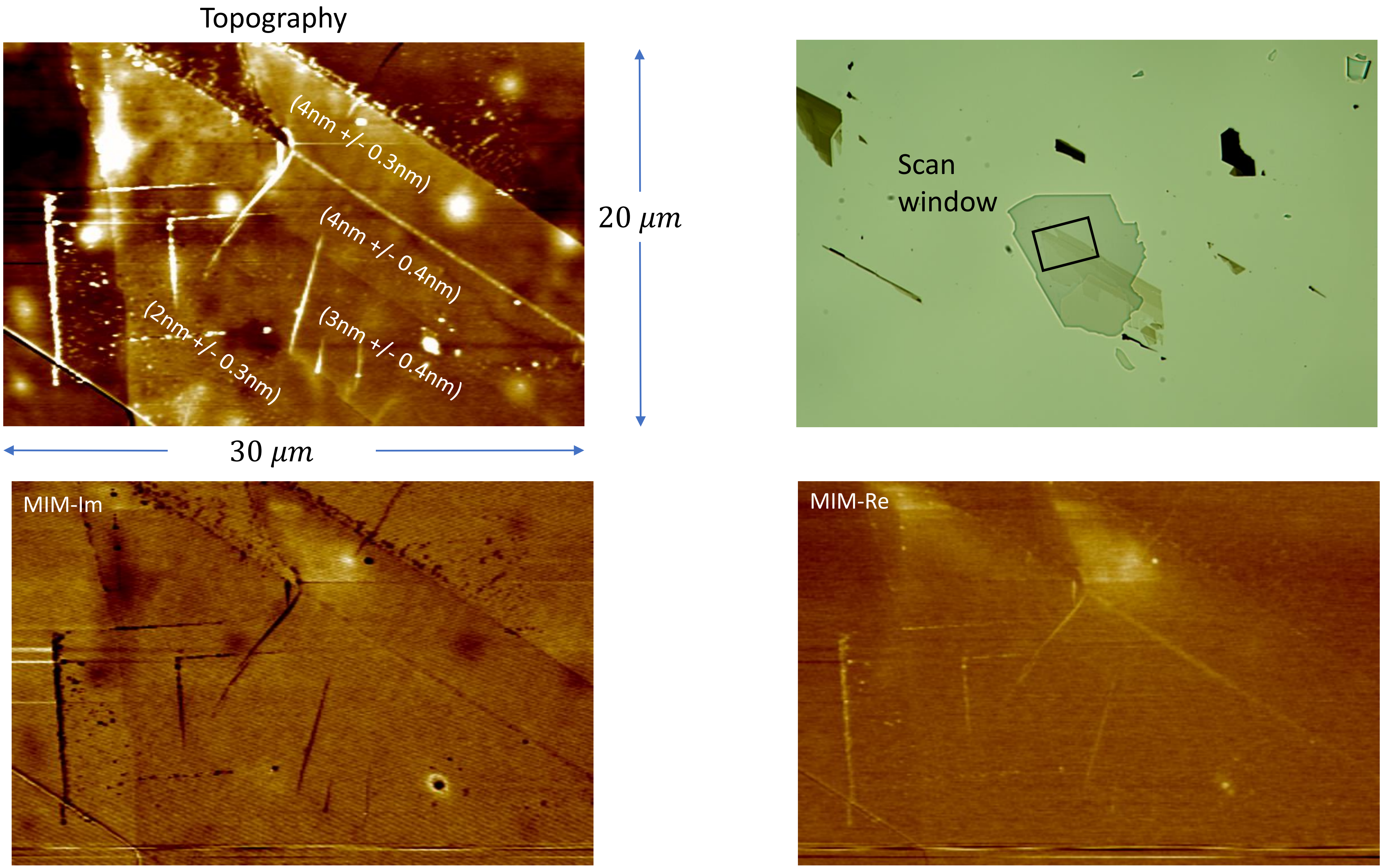
- Laser wavelength
  - $\hbar\omega > E_g$
- Laser intensity → # of photons → # of free electrons → conductivity



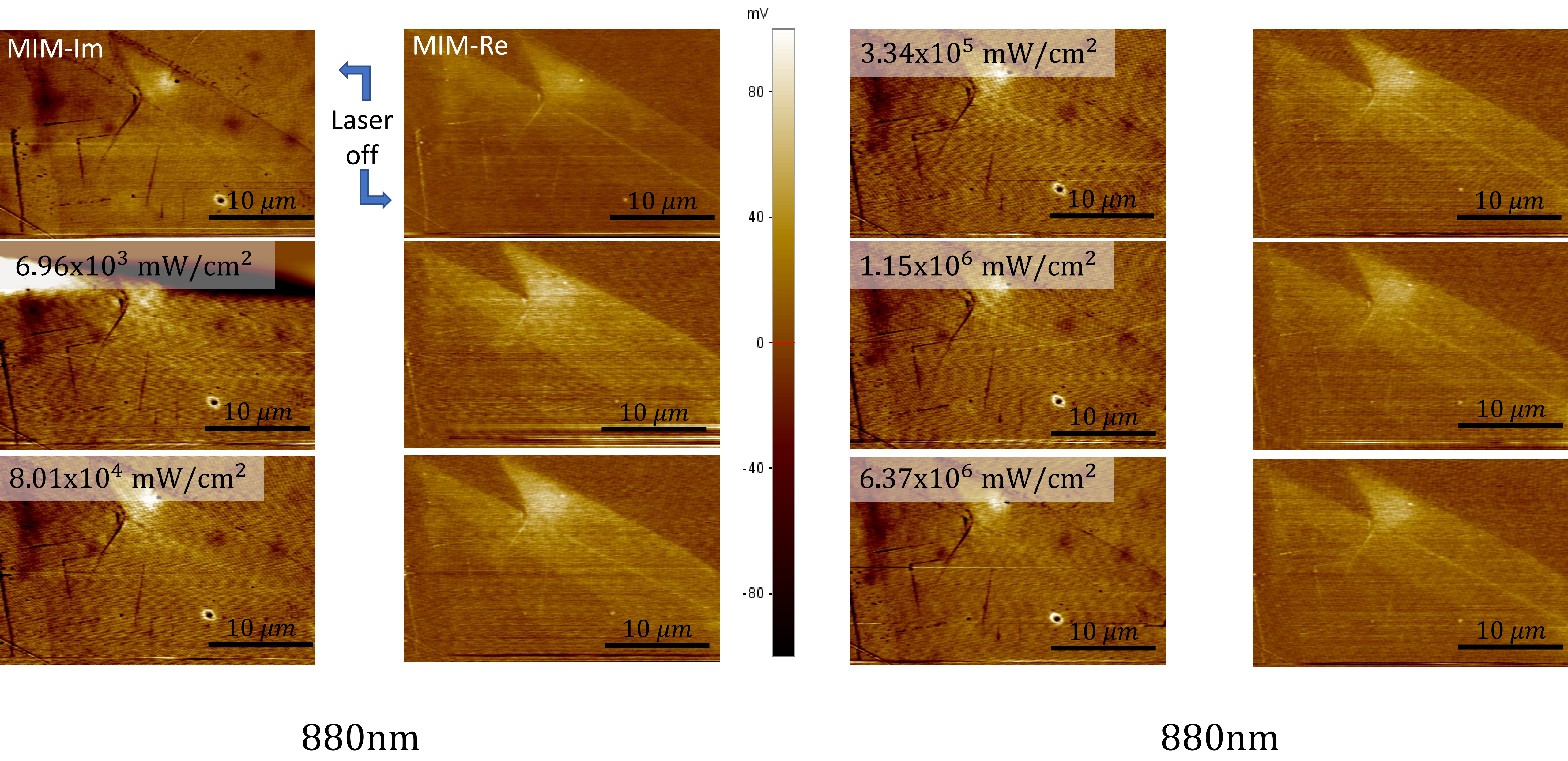
Solar Cells

Photon Detectors

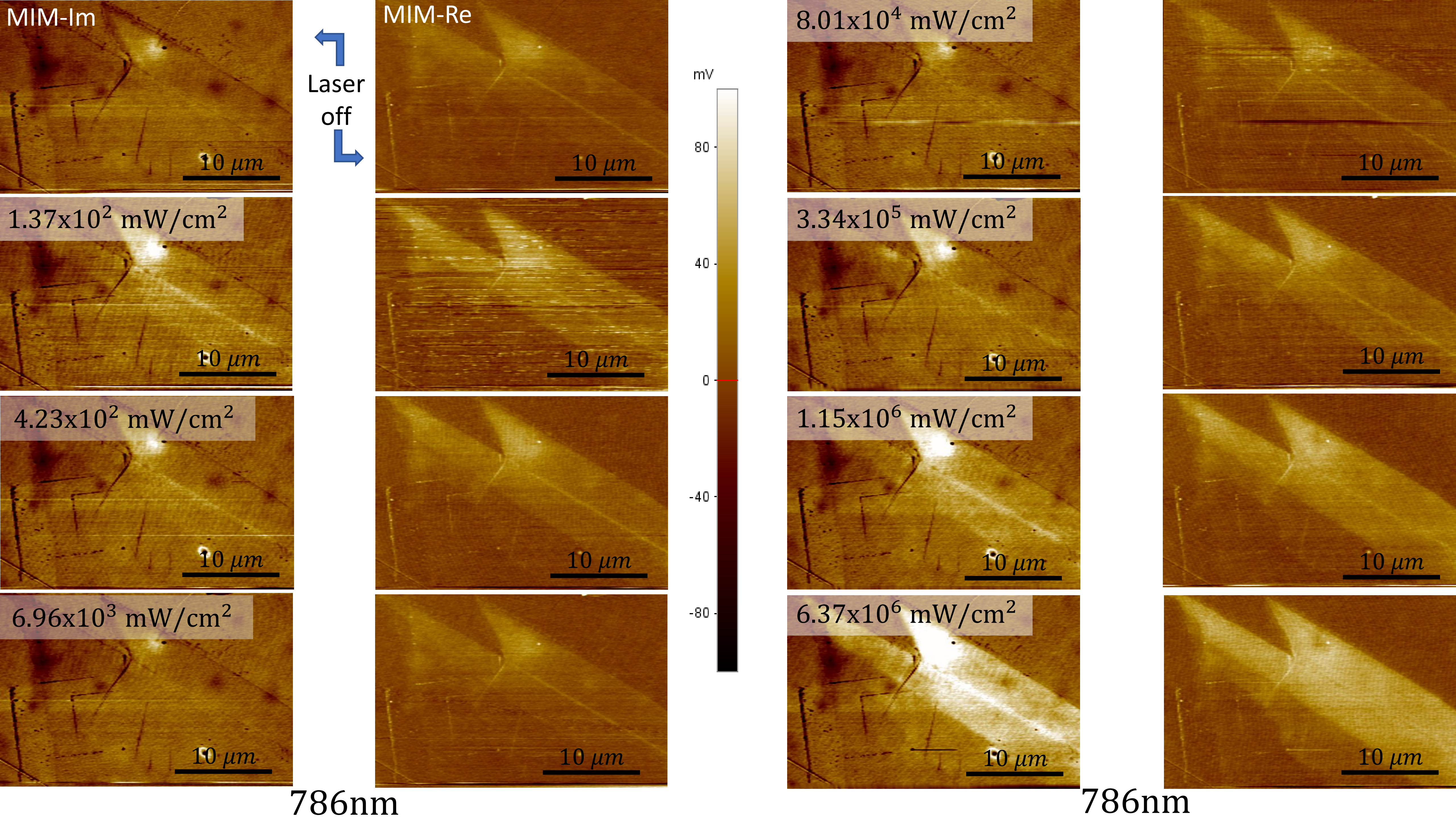
Rhenium Disulfide (ReS_2, Semiconductor) hexagonal Boron Nitride(hBN, Insulator)

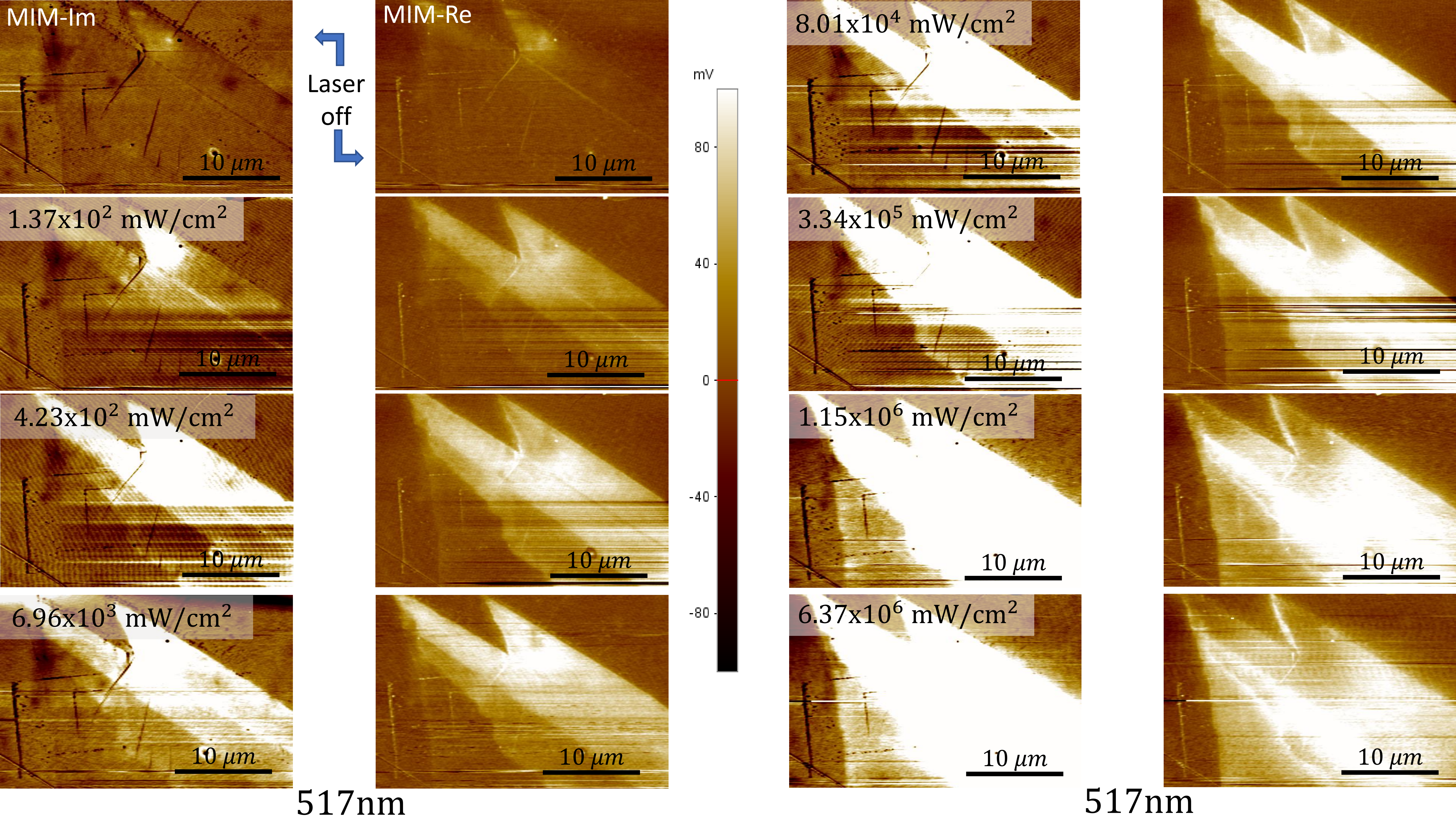


Topography
(4nm +/- 0.3nm)
(4nm +/- 0.4nm)
(3nm +/- 0.4nm)
(2nm +/- 0.3nm)
20 μm
30 μm
Scan
window
MIM-Im
MIM-Re

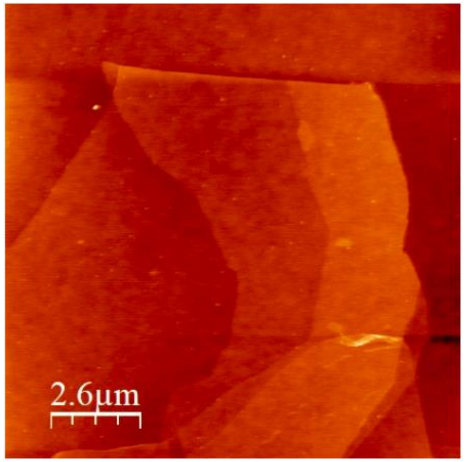


MIM-Im
Laser
off
MIM-Re
mV
80
40
0
-40
-80
3.34x10^5 mW/cm^2
6.96x10^3 mW/cm^2
1.15x10^6 mW/cm^2
8.01x10^4 mW/cm^2
6.37x10^6 mW/cm^2
10 μm
880nm
880nm


MIM-Im
Laser off
MIM-Re
mV
80
40
0
-40
-80
8.01x10^4 mW/cm^2
1.37x10^2 mW/cm^2
3.34x10^5 mW/cm^2
4.23x10^2 mW/cm^2
1.15x10^6 mW/cm^2
6.96x10^3 mW/cm^2
6.37x10^6 mW/cm^2
10 μm
786nm
786nm


MIM-Im
Laser off
MIM-Re
mV
80
40
0
-40
-80
1.37x10^2 mW/cm^2
4.23x10^2 mW/cm^2
6.96x10^3 mW/cm^2
8.01x10^4 mW/cm^2
3.34x10^5 mW/cm^2
1.15x10^6 mW/cm^2
6.37x10^6 mW/cm^2
10 μm
517nm
517nm

Conclusion



- AFM allows nanoscale observation
  - New data collection techniques
- MIM is a unique conductivity measurement
  - No electrodes required
  - Nanoscale resolution
- Novel Light-Matter interactions (QM)