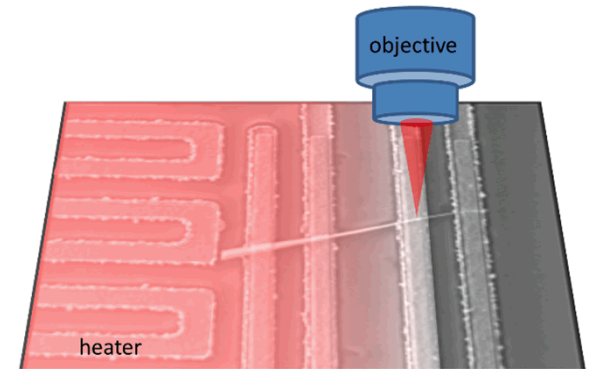
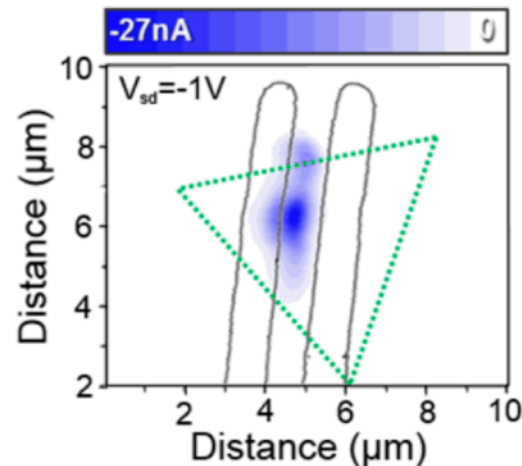
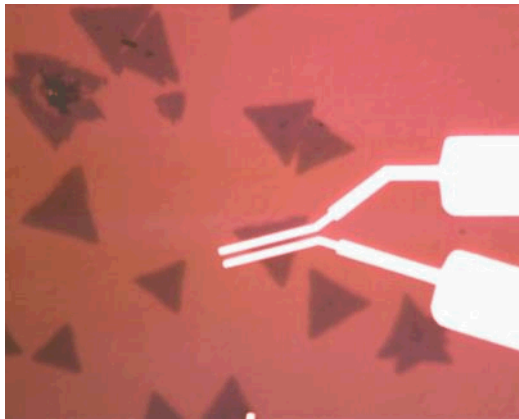
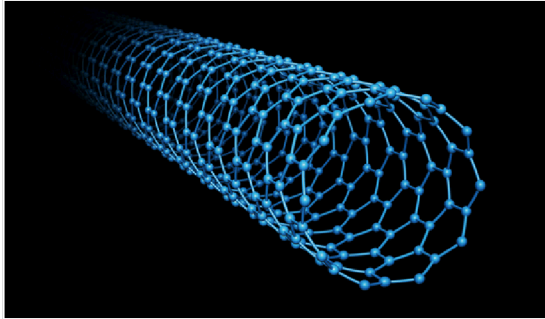


Optoelectronics in 1D and 2D Materials

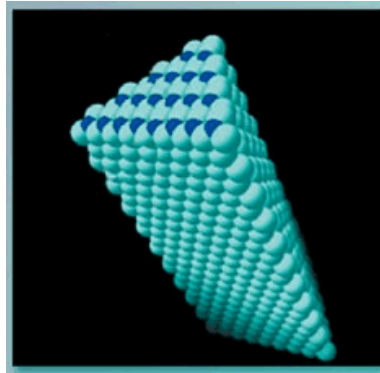
François Léonard
Sandia National Laboratories



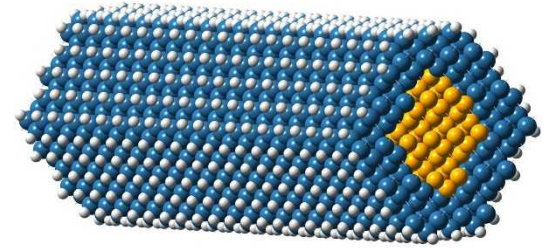
1D and 2D materials



(TASC)

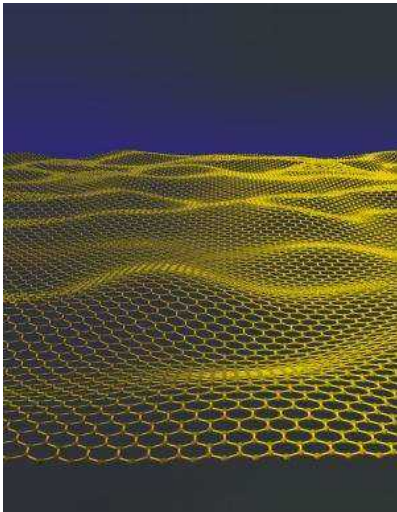


(Kuykendall et al, Nat. Mater. (2004))



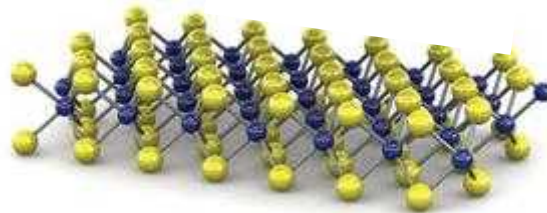
(X. Peng, ASU)

graphene



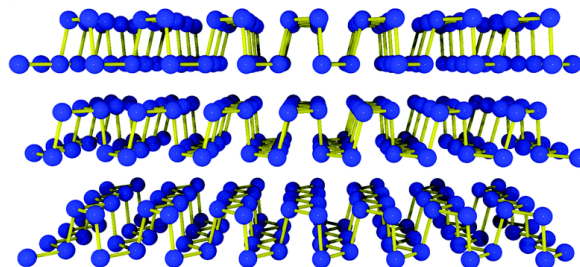
(U. Manchester)

MoS_2 , MoSe_2 , WSe_2



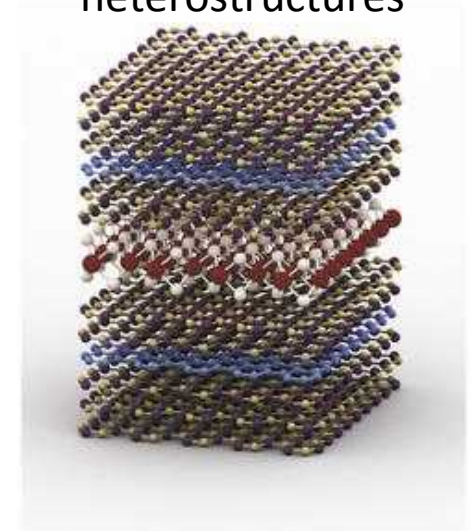
(Andras Kis)

black phosphorus



(Ye et al, Chem. Soc. Rev. (2015))

heterostructures



(Withers et al, Nat. Mater. (2015))

2D materials optoelectronics: TMDCs

Questions:

- *what are the photocurrent mechanisms?*
- *does the material matter?*
- *does the synthesis approach matter?*
- *novel non-equilibrium photophysics?*
- *can we make devices?*

Exfo

(Lopez

L

Monolay



SiO₂

Si substrate

Intrin



p

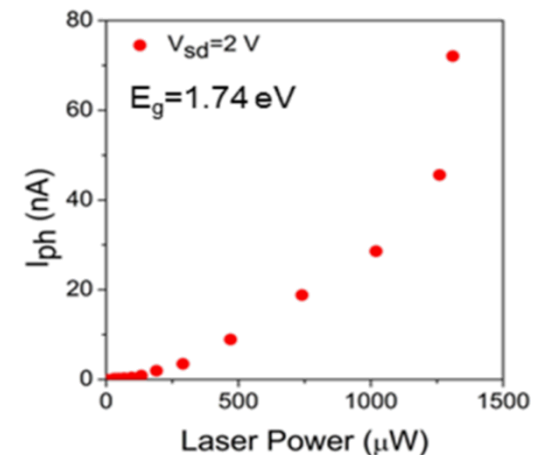
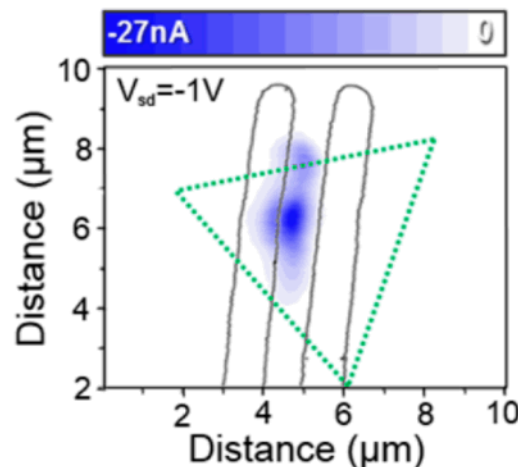
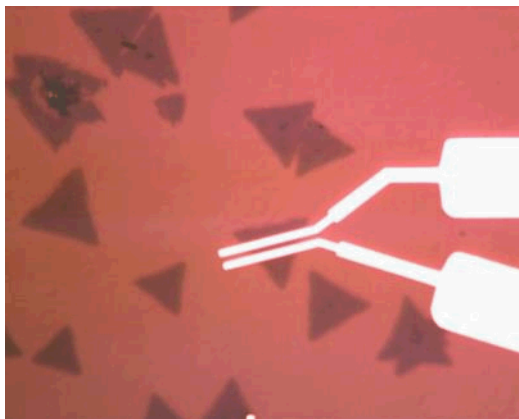
oS₂

013)

Superlinear Photocurrent in 2D alloys

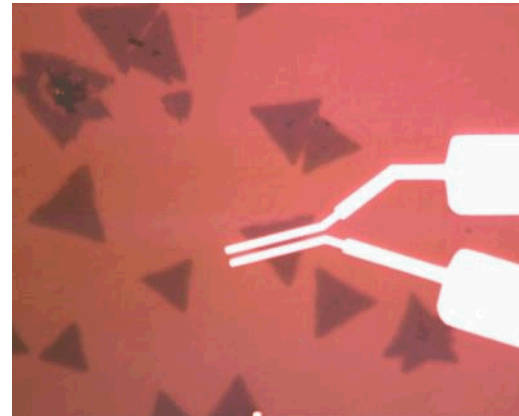
Velveth Klee, Edwin Preciado, David Barroso, Ariana E. Nguyen, Chris Lee, Brandon Davis, I-Hsi Lu, Sarah Bobek, Jessica McKinley, Joseph P. Martinez, John Mann, Ludwig Bartels
University of California Riverside

Kris Erickson, Mark Triplett, Alec Talin, François Léonard
Sandia National Laboratories

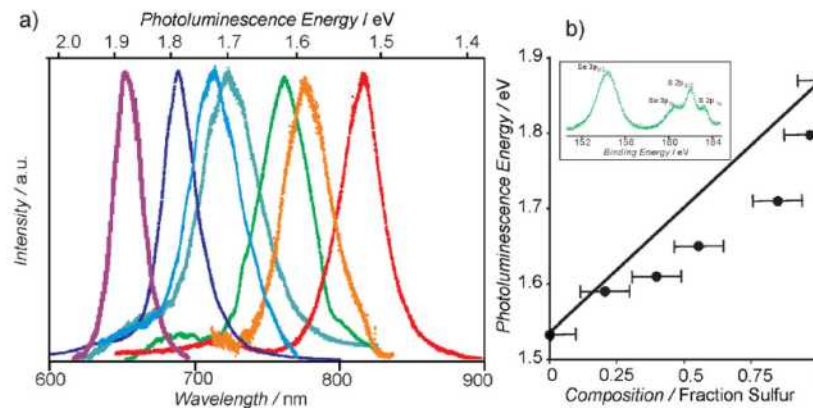


Devices with CVD-grown single-layer $\text{MoS}_{2(1-x)}\text{Se}_{2x}$

- Growth at 650C in a tube furnace
- Si/SiO₂ substrates
- Alloy compositions obtained by simultaneous flow of S and Se precursors
- E-beam lithography with PMMA
- Ti/Au electrodes (2nm/50nm)

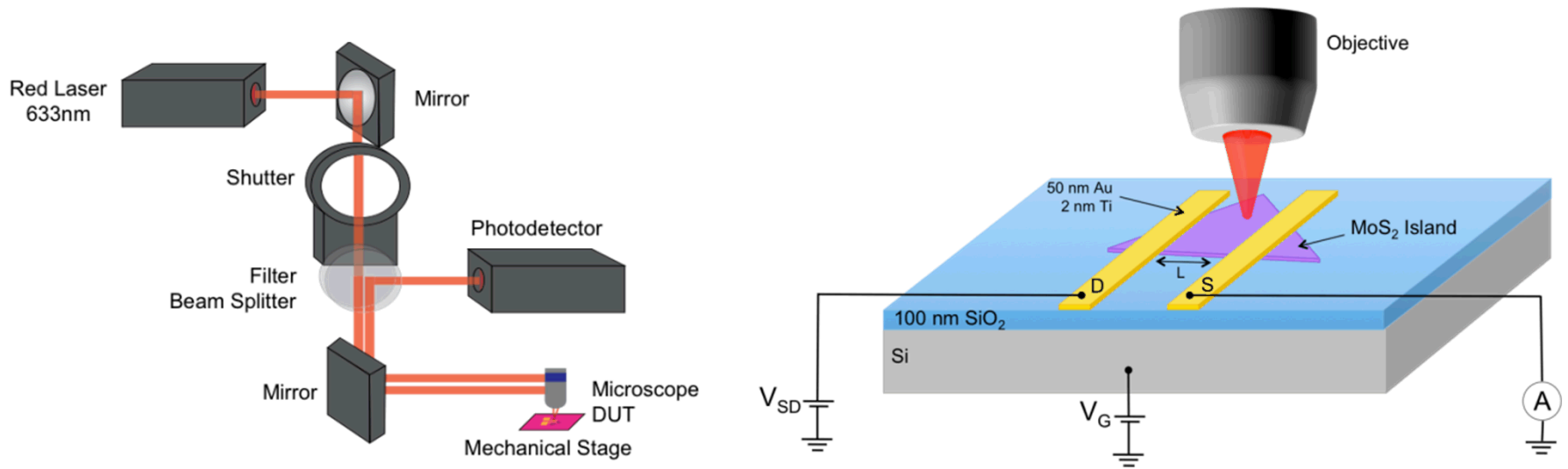


Bandgap:



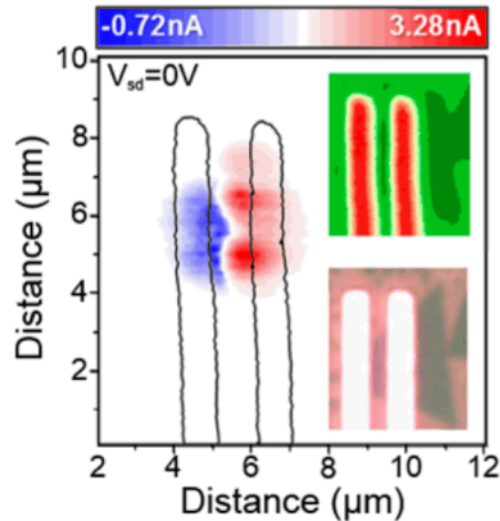
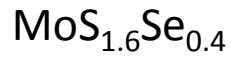
Mann et al, Adv. Mater. (2013).

Scanning Photocurrent Microscopy

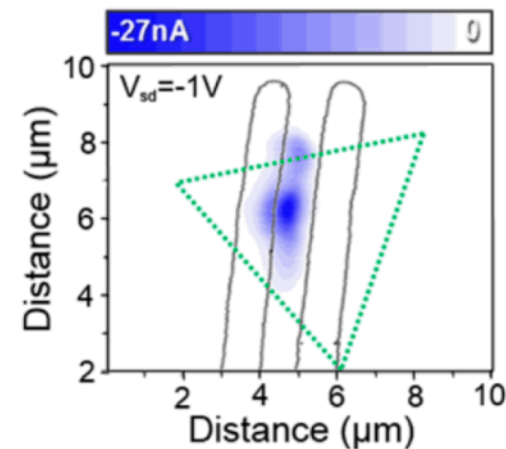
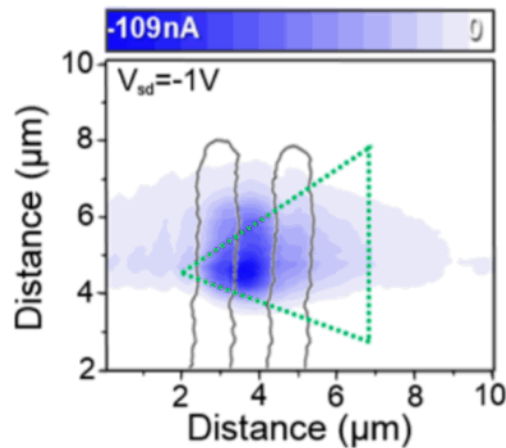
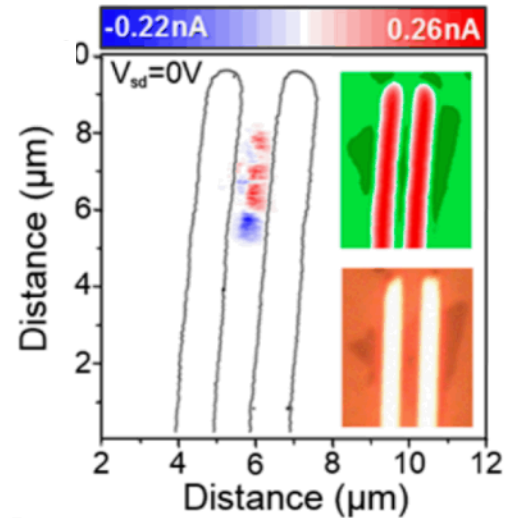
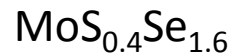


Scanning Photocurrent Microscopy

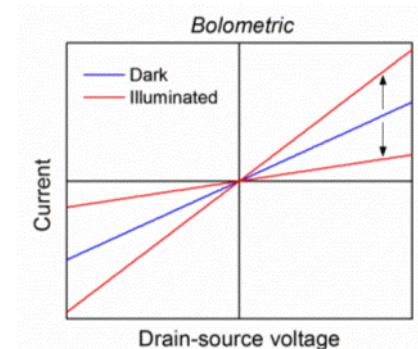
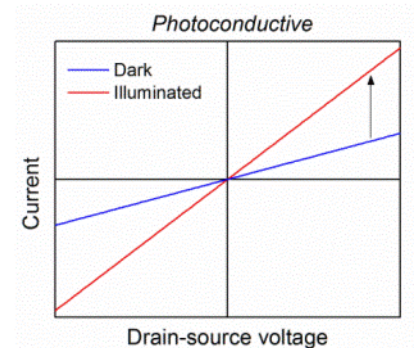
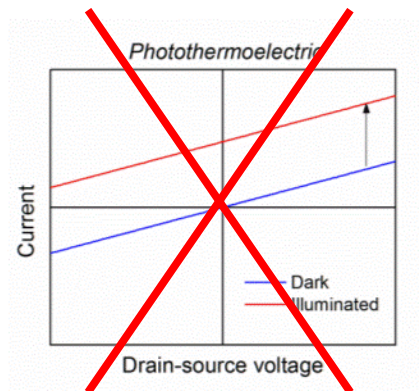
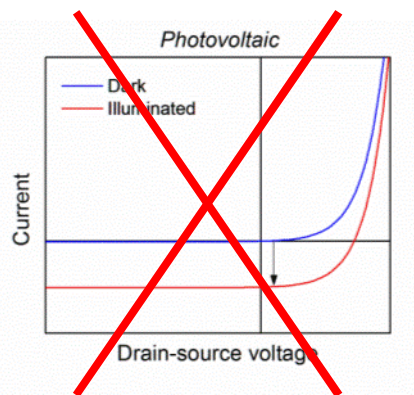
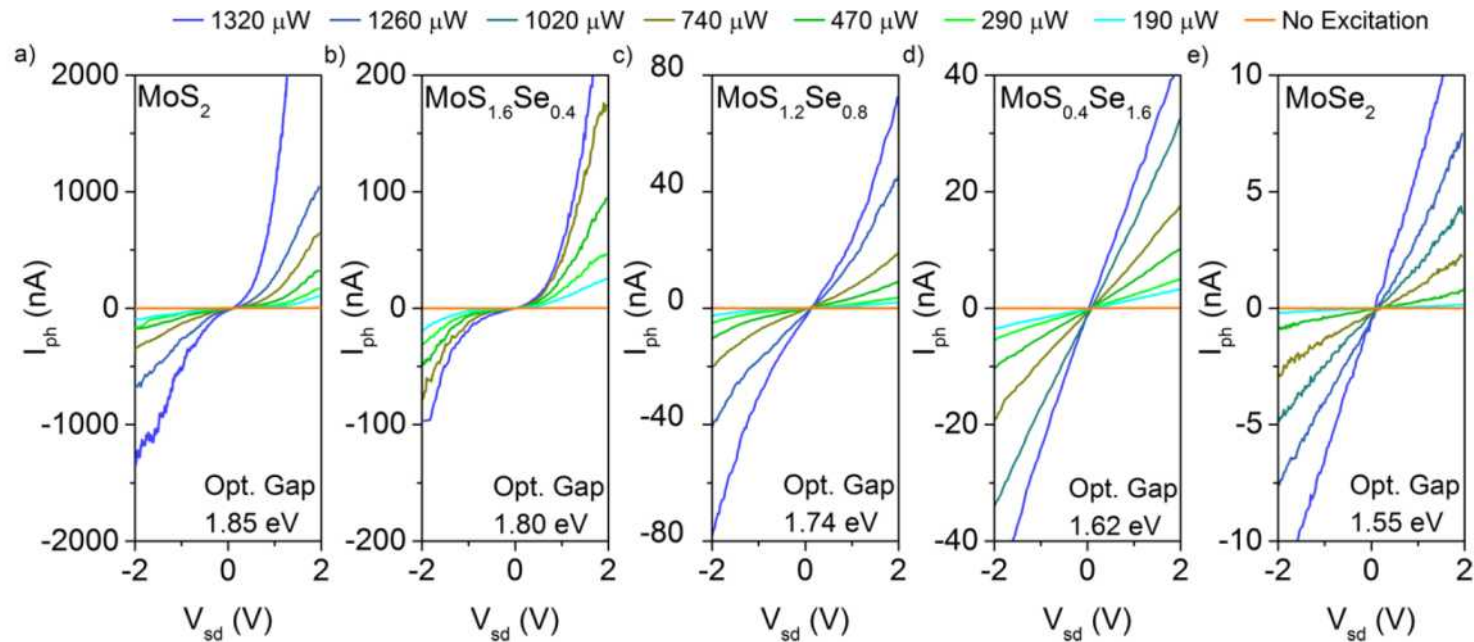
S-rich



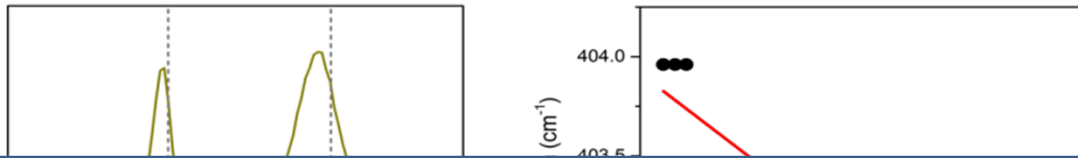
Se-rich



Photocurrent mechanism

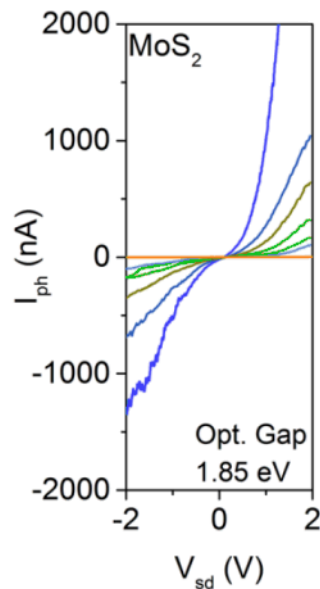
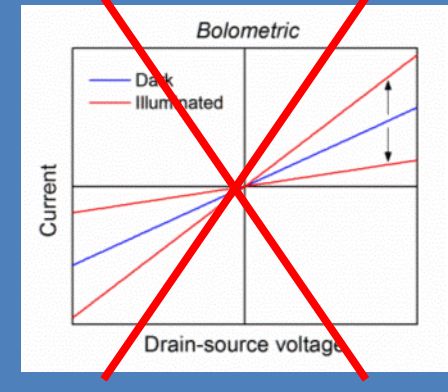
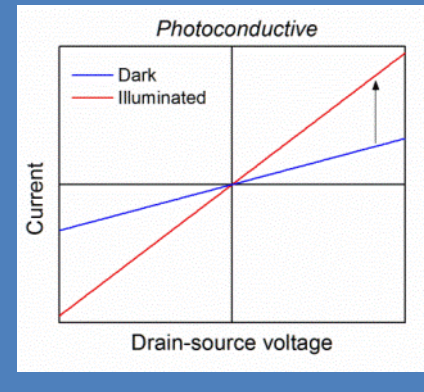
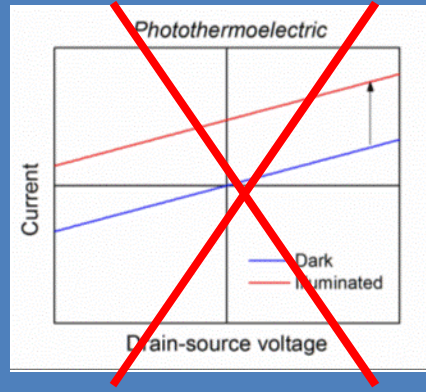
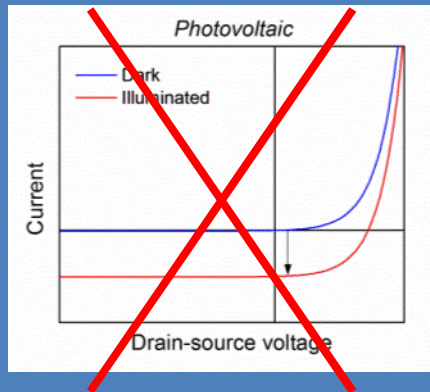


Raman thermometry

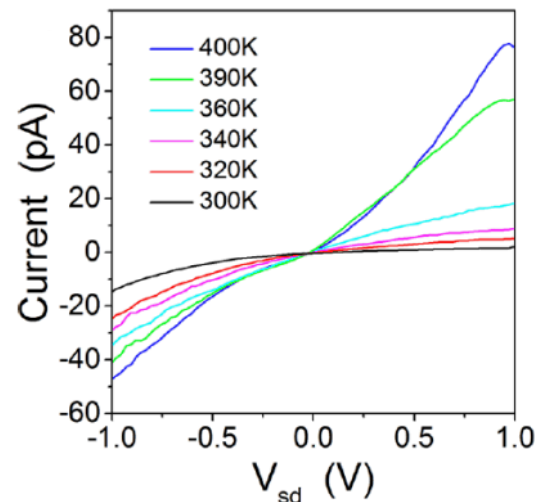


$$d\omega / dT = -0.016 \text{ cm}^{-1} / \text{K}$$

Lanzillo et al. APL (2012)



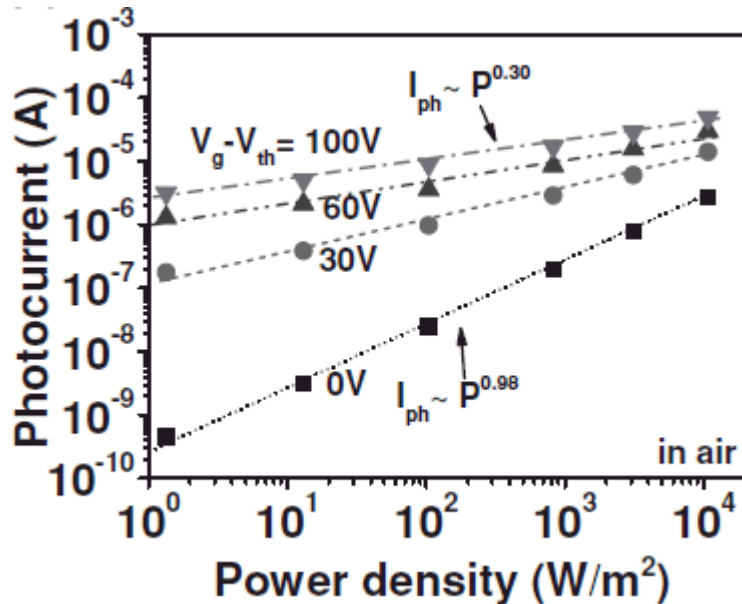
heating of MoS₂ device



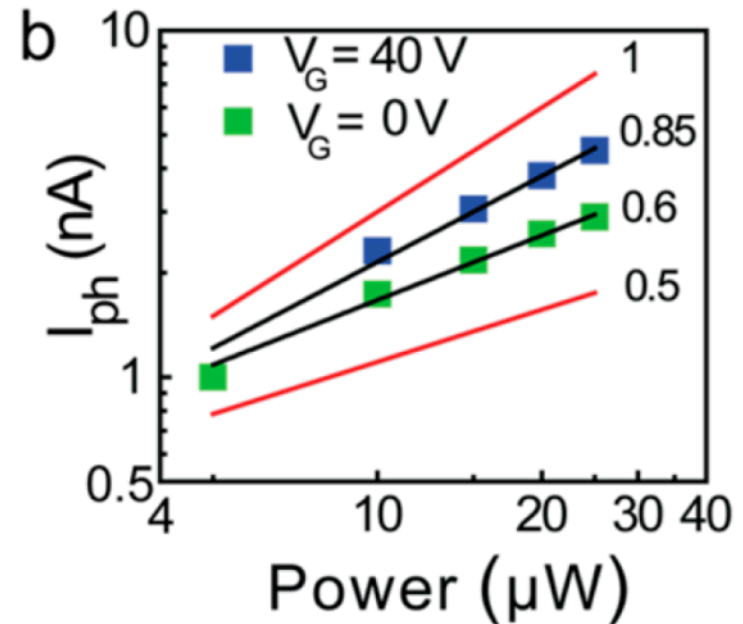
Power dependence of photocurrent

Typically, power dependence is sub-linear (linear at best)

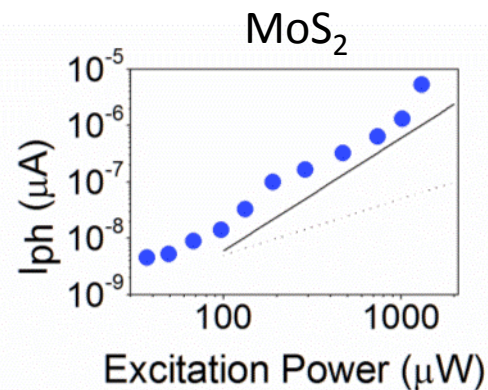
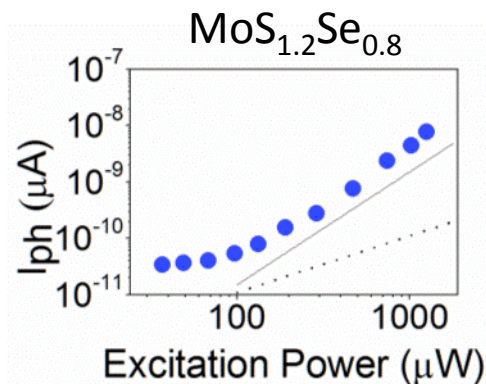
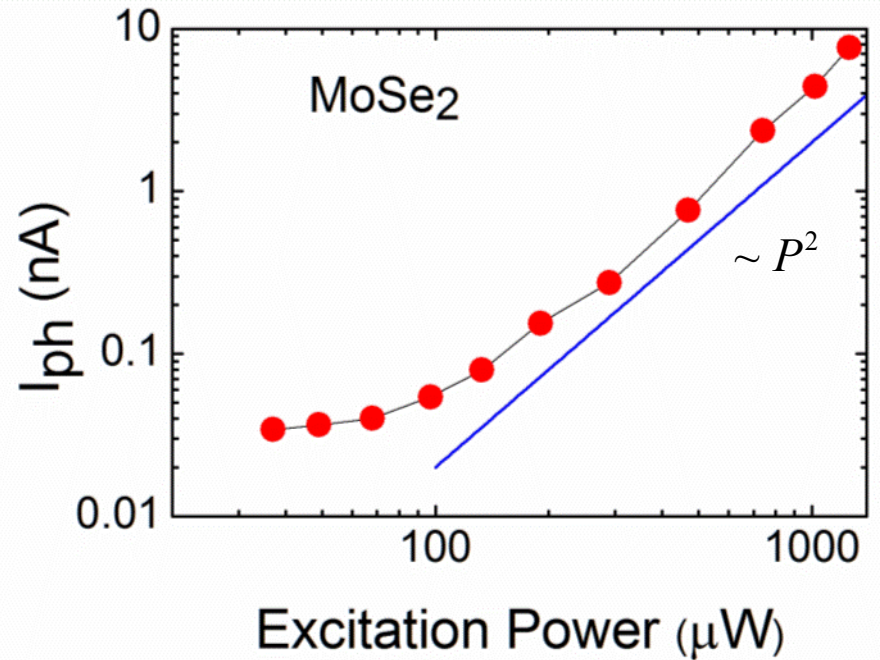
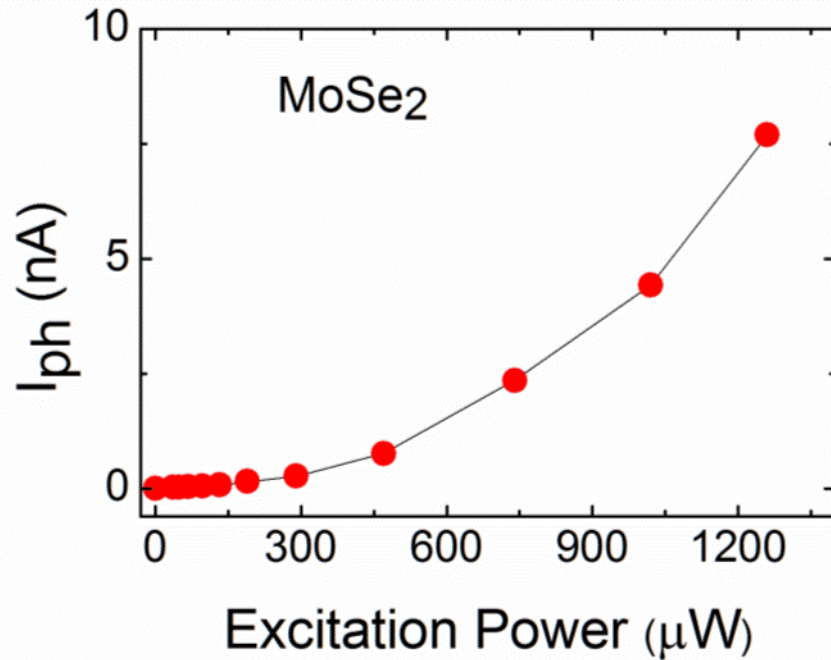
Zhang et al, Adv. Mater. (2013)



Wu et al, J. Phys. Chem. Lett. (2013)



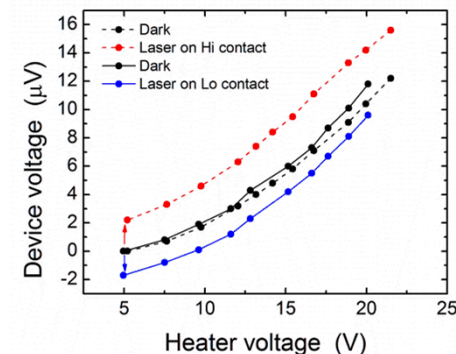
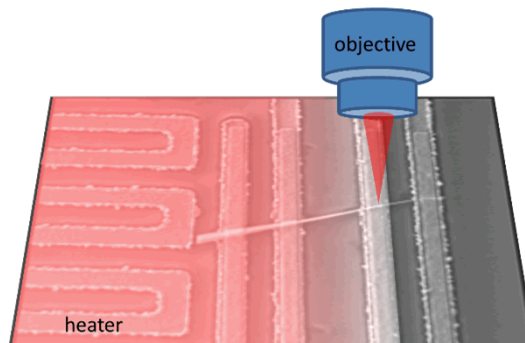
Superlinear photocurrent !



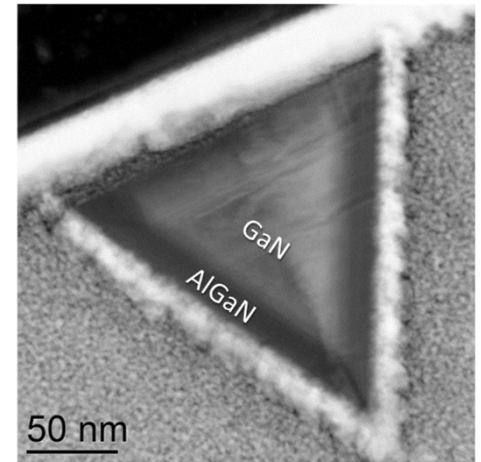
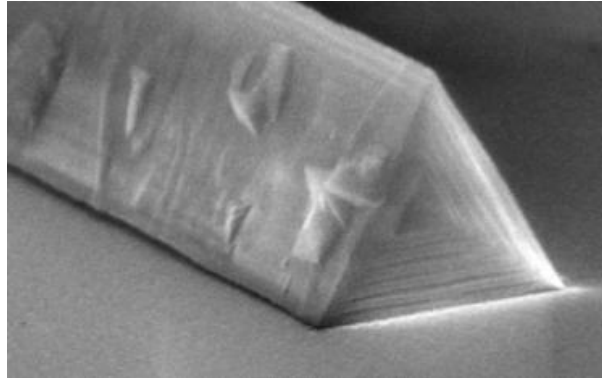
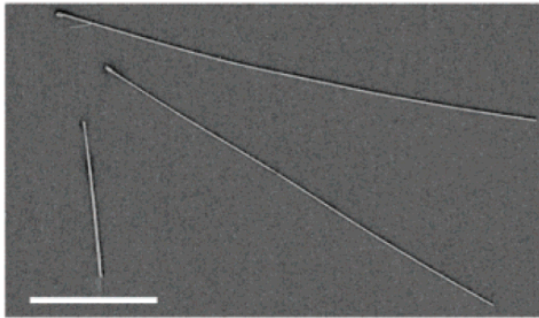
Simultaneous Thermoelectric and Optoelectronic Characterization of Individual Nanowires

Erdong Song, Julio Matrtinez
New Mexico State University

George Wang, Brian Swartzentruber, Qiming Li, François Léonard
Sandia National Laboratories



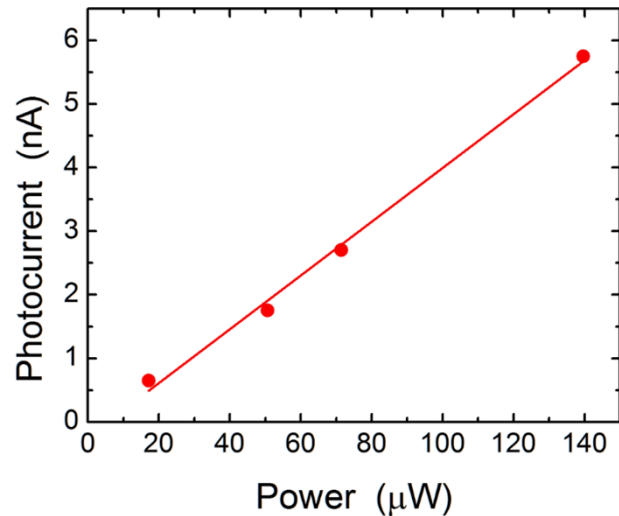
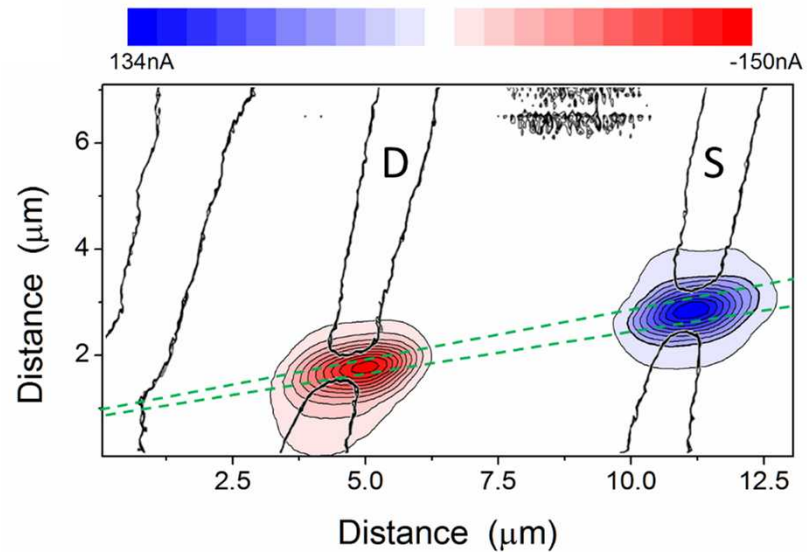
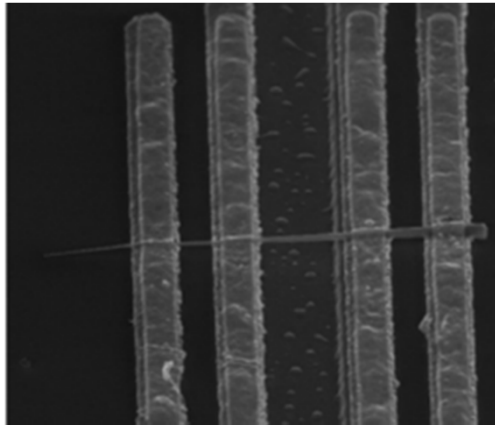
GaN/AlGaN core/shell nanowires



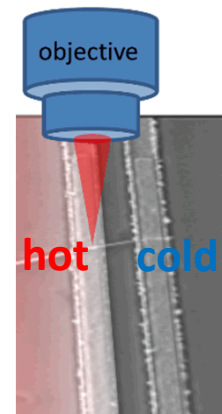
Of interest for:

- Light Emitting Diodes
- Electron gases

Scanning Photocurrent Microscopy

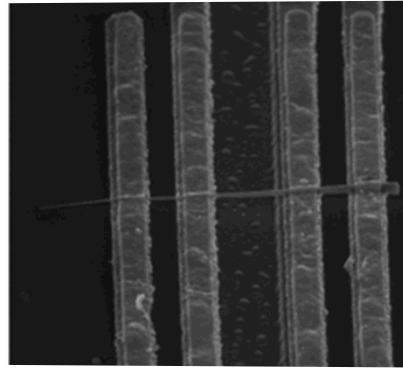


Likely candidate: photothermoelectric effect



$$\Delta V = -S\Delta T$$

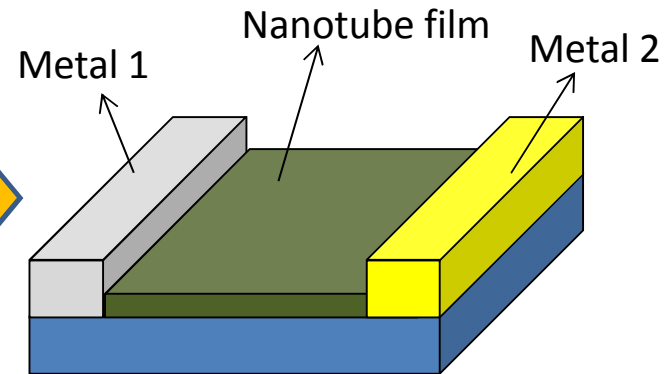
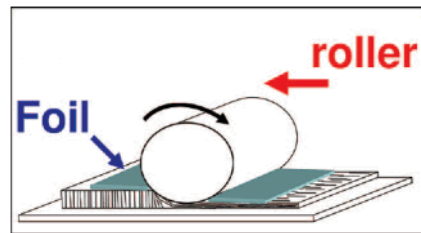
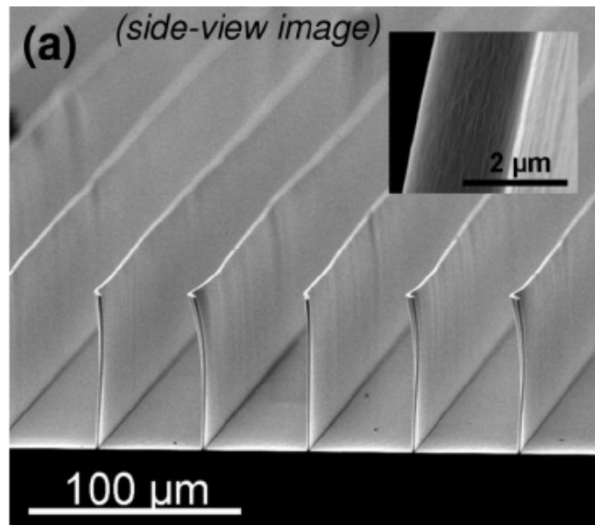
Thermoelectric + Optoelectronic



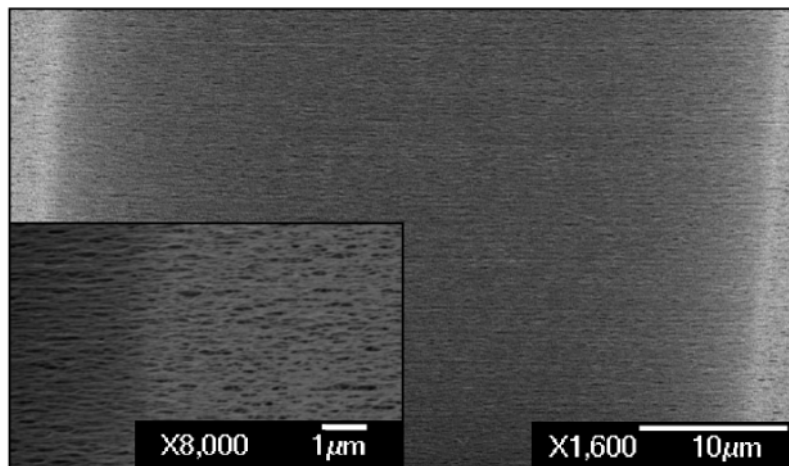
$$\Delta V = -S\Delta T$$

- Seebeck coefficient directly measured: -78 $\mu\text{V/K}$
- Sign of Seebeck agrees with sign of photocurrent
- Allows extraction of temperature increase
- Can extract materials properties (e.g. heat transfer coefficient)

From individual nanostructures to collections of nanostructures

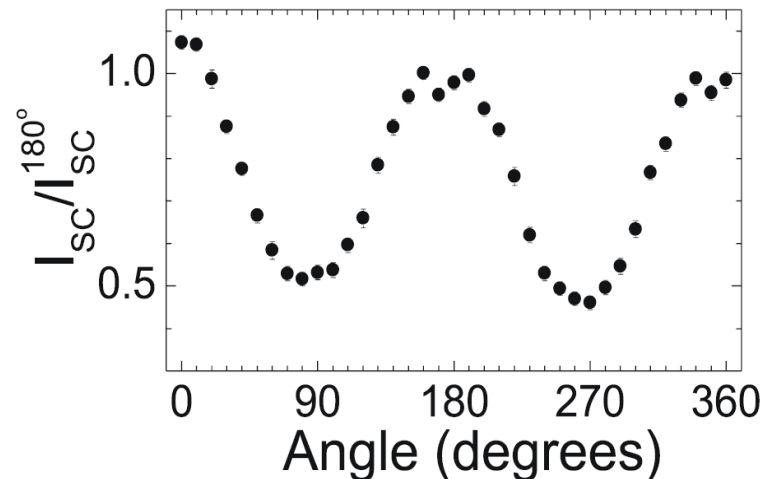
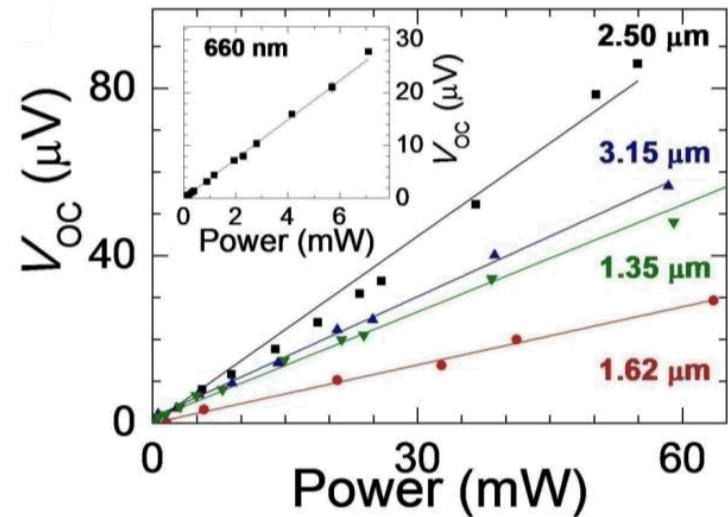
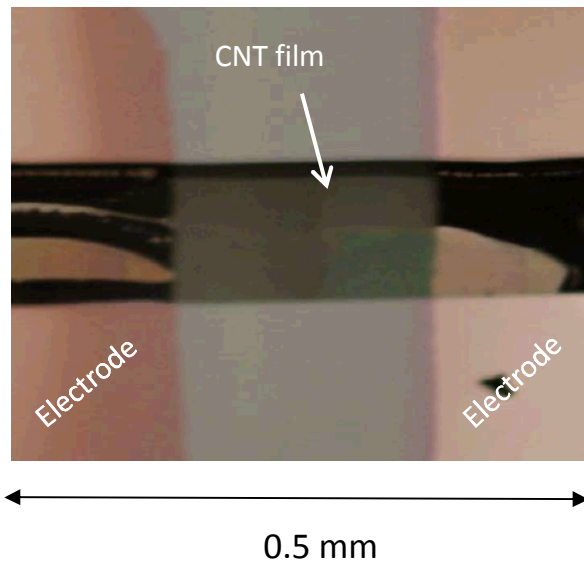


C. Pint *et al.*, *ACS Nano*. **2**(9), 1871 (2008)

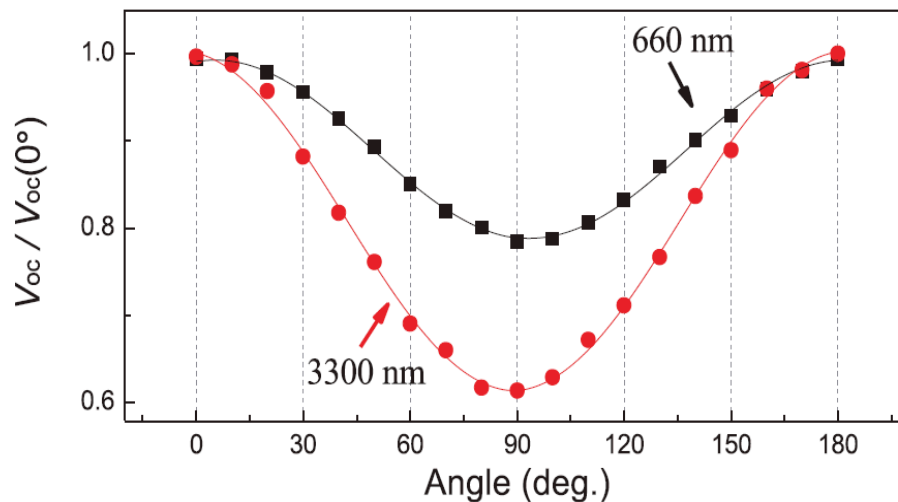
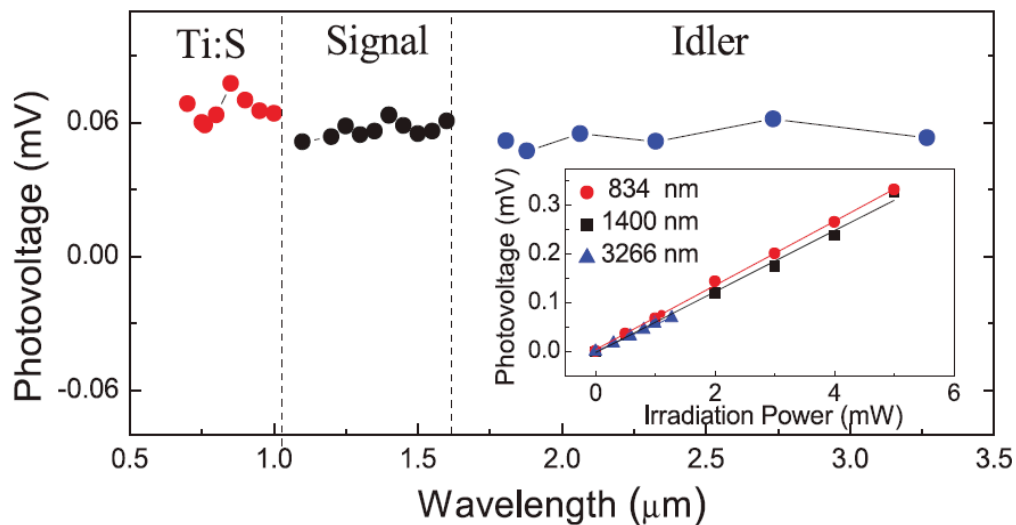
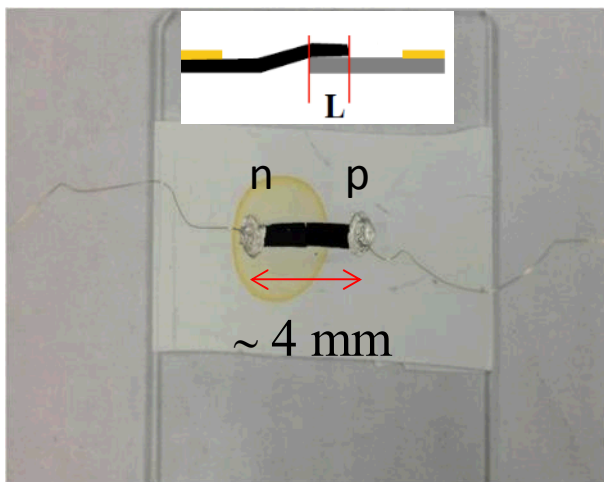


- Optically-thick film (1 micron)
- Aligned CNTs
- Long channel (several hundred microns realized)
- Dense CNTs (average spacing 10 nm)

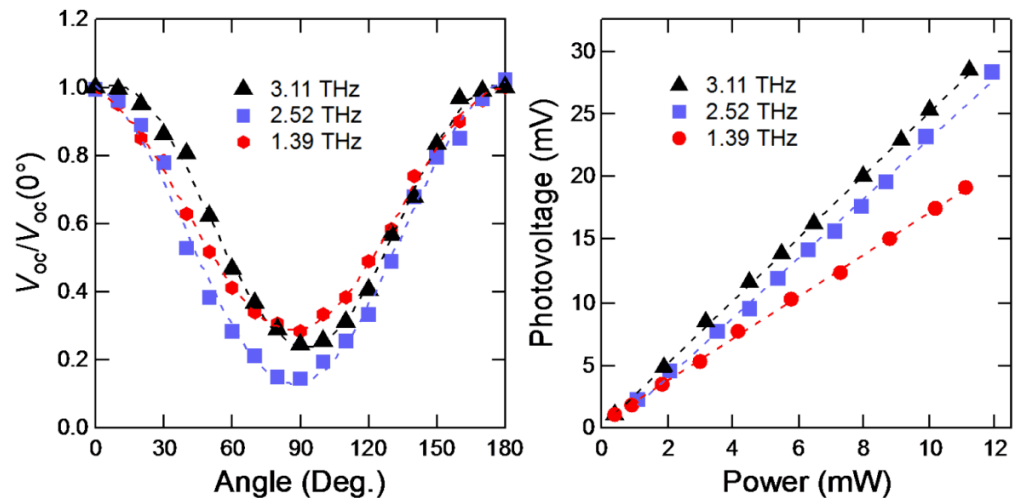
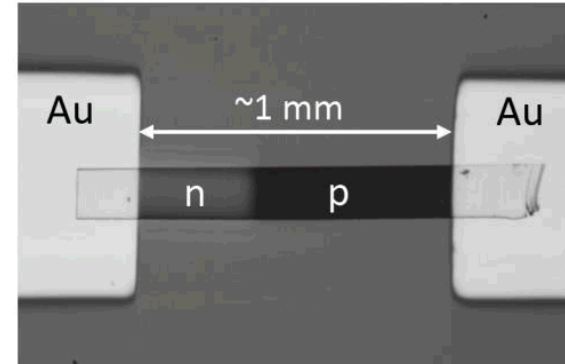
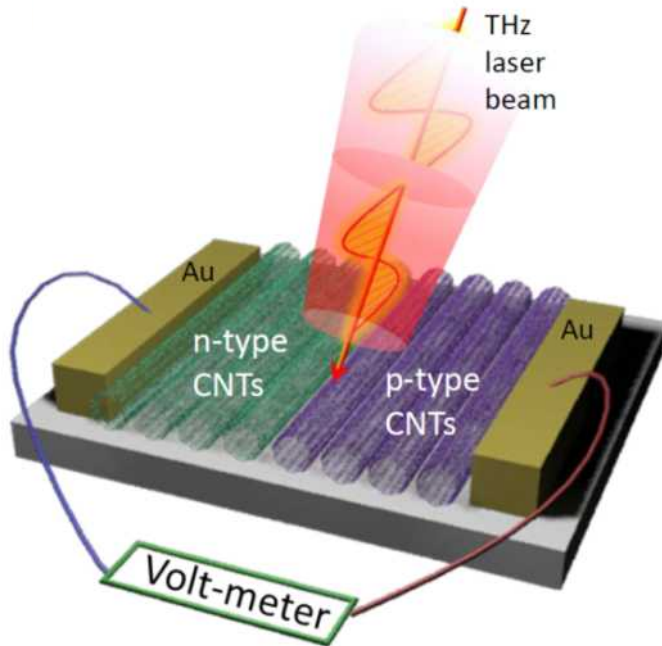
Macroscopic CNT thin film photodetector



CNT p-n Junction Detectors



CNT Terahertz Photodetector

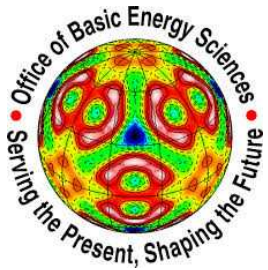


➤ Photocurrent observed at zero bias, no antenna needed

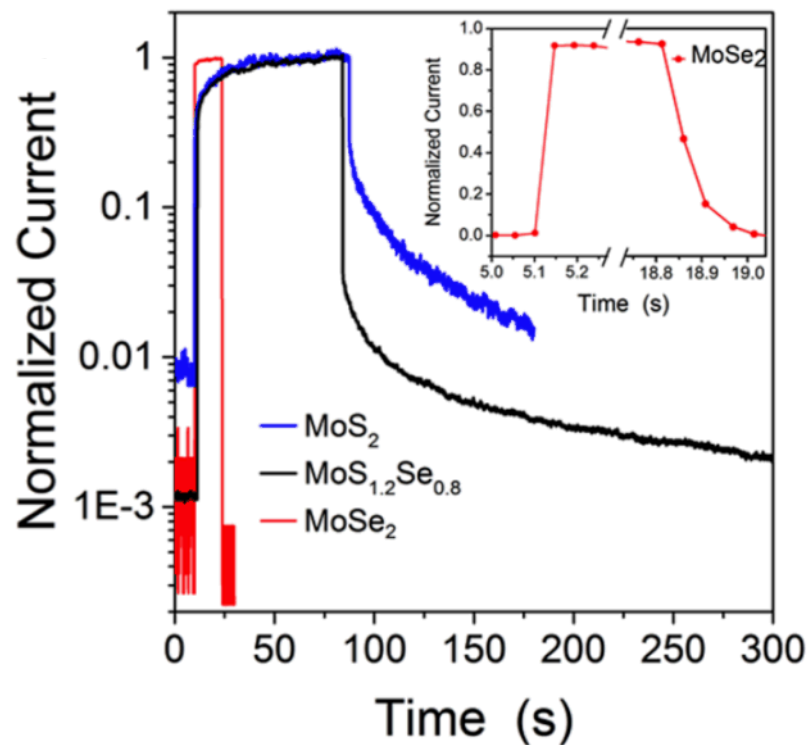
X. He *et al.*, *Nano Letters* **14**, 3953 (2014).

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Composition-dependent dynamics



Non-equilibrium recombination

