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

Lincoln J. Lauhon
Department of Materials Science & Engineering

NORTHWESTERN UNIVERSITY

12th U.S.-Korea Forum on Nanotechnology

October 5, 2015
2-D Geometry Produces New Functions


Degrees of Freedom to Explore

Explore, Understand, Control

Electrical
Optical
Spin
Mechanical
Interfaces
Defects
Grain boundaries lead to memristive behavior


- Hysteretic I-V curve with low and high resistance states $\rightarrow$ memristor.
- Switching ratio (ON/OFF) $\sim 10^3$
- 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.

SPCM modeling extracts band profiles

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

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

Explore, Understand, Control
Atom Probe Tomography of a 2D Material: Ag doped \((\text{PbSe})_5(\text{Bi}_2\text{Se}_3)_{3m}\)

- 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Ren, Lauhon et al, *unpublished.*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

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

Electrical
Optical
Spin
Mechanical
Interfaces
Defects

Explore, Understand, Control
Mechanical Properties of MoS$_2$ Membranes

Sensitive to small forces

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

Piezoelectric Monolayer

Membrane-like below \( \sim 6\)L

Nonlinear force vs. displacement
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.

Liu and Lauhon, *Nano Lett* ASAP.
Normal-mode splitting is observed

- Peak splitting $\rightarrow$ coupling rate $g$.
- $g$ is 10X the decay rate $\gamma$.

\textit{Strong coupling enables coherent energy exchange.}

Liu and Lauhon, \textit{Nano Lett} \textit{ASAP}.
Degrees of Freedom to Explore

Explore, Understand, Control
Degrees of Freedom to Explore

Explore, Understand, Control
Challenges in 2-D Materials & Devices

- Nanostructural Analysis
- Functional Imaging
- Integration of Quantum & Continuum Models
- Heterogeneity at Multiple Lengthscales
- Reproducible Processes & Interfaces
- Device Modeling
- Synthesis of New Materials
- Doping & Defects

*Integrated approach to 2D MSE*
Lauhon Research Group

Group:
Sarah Howell (G-4)
Nari Jeon (G-4)
Spencer Park (UG)
Ryan Paull (G-1)
Xiaocheng Ren (G-3)
Zhiyuan Sun (G-2)
KunHo Yoon (G-5)

Deep Jariwala (Hersam, Marks)

Collaborators:
Mark Hersam Northwestern
Tobin Marks Northwestern
Teri Odom Northwestern
M. Kanatzidis Northwestern
Gregor Koblmuller TU Munich
Yossi Rosenwaks Tel Aviv University
Arunima Singh NIST
Francesca Tavazza NIST

Cited Alumni:
Chung-Chiang Wu (PD)
Vinod Sangwan (PD)
In Soo Kim (PhD)

NUCAPT, NUANCE

NSF

BSF

NIST

United States – Israel Binational Science Foundation