Integration Challenges and Opportunities for Two-Dimensional Materials

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Lessons from One-Dimensional Materials

http://www.nanointegris.com/

Transitioning from the research laboratory to the marketplace for carbon nanotubes required:

- Focus on homogeneity, reproducibility, and reliability (as opposed to chasing exceptional, champion performance)
- Alternative manufacturing and fabrication approaches (e.g., printing to avoid competition with established methods)
- Unique applications (as opposed to attempting to supplant an incumbent technology)

• NanoIntegris founded in 2007
• ~700 customers in 40+ countries
• Acquired by Raymor in 2012
Outline

• Monodisperse materials
• Additive manufacturing
• New device concepts

Review Articles:
ACS Nano, 8, 1102 (2014).
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ACS Nano, 8, 1102 (2014).
Density Gradient Ultracentrifugation of Graphene

Nano Letters, 9, 4931 (2009).

- Exfoliate graphite powder via sonication in aqueous solution with the planar surfactant sodium cholate.
- DGU enables sorting by the number of graphene layers.
DGU enables sorting of transition metal dichalcogenides by thickness including MoS$_2$, MoSe$_2$, WS$_2$, and WSe$_2$.
Solution-processed BP is comparable to mechanically exfoliated BP in field-effect transistors (mobility $\sim$50 cm$^2$/Vs; on/off ratio $\sim$10$^4$)
2D Black Phosphorus in Ambient on SiO₂

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)

Nano Letters, 14, 6964 (2014).

- AFM images of unencapsulated black phosphorus (BP) in ambient conditions
- Samples are stored in the dark in ambient (relative humidity: 30-40%) between AFM images
- Apparent bubble or droplet formation and coalescence with increasing ambient exposure
- Scale bars = 1 µm
Atomic Layer Deposition $\text{AlO}_x$ Passivation of BP

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)

*Nano Letters, 14, 6964 (2014).*

$\text{AlO}_x$ passivated surface shows no BP degradation, even after 34 days (now up to ~6 months) in ambient conditions.
Improved BP FET Stability After Encapsulation

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)

*Nano Letters, 14, 6964 (2014).*

- Unencapsulated devices rapidly degrade in ambient conditions
- $I_{ON}/I_{OFF}$ ratios and mobilities nearly constant for encapsulated devices
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Review Articles:
ACS Nano, 8, 1102 (2014).
• Use of a stabilizing polymer (ethyl cellulose) increases the concentration of graphene in ethanol by ~100-fold.

• Iterative solvent exchange with terpineol and water increases the graphene concentration by another factor of 10 (~1 mg/mL) without centrifugation.
Inkjet Printable Graphene for Flexible Interconnects

*Journal of Physical Chemistry Letters, 4, 1347 (2013).*

Available from Sigma-Aldrich: Catalog # 793663

- Inkjet printable graphene based on ethyl cellulose stabilizer in terpineol.
- Low resistivity of 4 mΩ-cm maintained following repeated flexing and even folding.
Large-Area Gravure Printable Graphene

*Advanced Materials, 26, 4533 (2014).*

Collaboration with Lorraine Francis and Dan Frisbie (University of Minnesota)

Ethyl cellulose stabilizer allows viscosity tuning over multiple orders of magnitude, enabling compatibility with a diverse range of printing methods.
Screen printable graphene is compatible with other materials that are commonly employed in printed/flexible electronics.
3D Printable Graphene as Conductive Bioscaffolds

High-content (60 vol%) graphene inks can be 3D printed into self-supporting, electrically conductive, and mechanically resilient structures (e.g., implantable tubular nerve conduits)

Collaboration with Ramille Shah (Northwestern University Medical School)
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Review Articles:
ACS Nano, 8, 1102 (2014).
SWCNT/MoS$_2$ p-n Heterojunction Diode

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)

*Proceedings of the National Academy of Sciences USA, 110, 18076 (2013).*
Gate bias tunes the diode rectification ratio by 5 orders of magnitude.

As a three-terminal device, it shows ‘anti-ambipolar’ transfer curves.

Proceedings of the National Academy of Sciences USA, 110, 18076 (2013).

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)
Wafer-Scale SWCNT/IGZO p-n Heterojunctions
Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)

*Nano Letters, 15, 416 (2015).*

- Wafer-scale p-n heterojunctions can be fabricated via photolithography using p-type SWCNTs and n-type indium gallium zinc oxide (IGZO).
- ALD deposited 15 nm thick hafnia enables low voltage operation.
Anti-Ambipolar SWCNT/IGZO Heterojunctions
Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)


- Anti-ambipolarity results from p-type SWCNT and n-type IGZO being fully depleted at positive and negative $V_G$, respectively.
- Low voltage operation with on/off ratio in excess of $10^4$. 
Anti-Ambipolar Phase/Frequency Shift Keying

Collaboration with Chris Kim (University of Minnesota)


→ Anti-ambipolarity enables efficient realization of communications circuits such as binary phase and frequency shift keying

→ Anti-ambipolar heterojunctions present opportunities for next-generation WiFi technology
CVD MoS$_2$ Grain Boundary Memristors

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)


- Hysteretic I-V curve with low and high resistance states → memristor
- Switching ratio (ON/OFF) ~ $10^3$
- Observed in devices with grain boundaries
Gate Tunability in MoS$_2$ Memristors

Collaboration with Lincoln Lauhon and Tobin Marks (Northwestern University)


- 90% of the EFM phase shift at GB
- GB dominates charge transport
- Gate-tunable set voltage in memristor
Summary

- Centrifugal solution processing allows the scalable production of highly monodisperse 2D materials

- Tunable solution rheology enables a suite of additive manufacturing options for 2D materials

- Atomically thin materials can serve as the basis of new device concepts:
  - Anti-ambipolar heterojunctions for communications circuits
  - Gate-tunable memristors for non-volatile memory and/or neuromorphic computing
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