Novel Materials and Devices for Millimeter-wave and THz Applications

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DoD Basic Research Enterprise

Total FY12 = $2.12B
THz Gap

Introduction

- Compact, high-power and room-temperature THz source has been a dream for decades
- Three-terminal devices are needed for wideband modulation/tuning with low noise
- Transistors are compact and easy to integrate
- New devices usually come from new material and new physics
- This talk will focus on new materials
New Semiconductors

- **Conventional Covalent Semiconductors**
  - Si, GaAs, InP, GaN ...

- **Heterostructures of 2D Layers**
  - graphene, silicene, germanene, 2D boron nitride ...

- **Ionic Semiconductors**
  - Transparent Electronics: ZnO, MgO, InGa₃Zn₅O₅ ...
  - Heterojunctions: MgZnO/ZnO, LaAlO₃/SrTiO₃ ...
  - Multiferroics: BiFeO₃, EuO ...
  - Metal-Insulator Transition: VO₂, SmNiO₃, NdNiO₃ ...
  - Topological Insulators: Bi₂Se₃, Bi₂Te₃ ...
  - Chalcogenides: sulfides, selenides, tellurides ...

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THz Electronics

- Sub-millimeter-wave radar & imaging
- Space situation awareness
- Chemical/biological/nuclear sensing
- Ultra-wideband communications
- Ultra-high-speed on-board & front-end data processing

J. Albrecht (2009)
Intel’s High-k FinFETs

\[ I = Qv = Q\mu \frac{V}{\ell} \]

\[ C = \frac{\Delta Q}{\Delta V} = \frac{k\varepsilon_0}{d} \]
Covalent Semiconductors

3D $\rightarrow$ 2D heterostructures of graphene, silicene, germanene, boron nitride ...

NSF/AFOSR Workshop on 2D Materials and Devices Beyond Graphene, 30-31 May 2012

http://nsf2dworkshop.rice.edu/
Heterostructures of 2D Layers

- Graphene beautiful but difficult to deal with
- Best to mate graphene with other 2D layers through van der Waals force
- Graphene – conductor, 2D BN – insulator, 2D MoS\textsubscript{2} – semiconductor, 2D NbSe\textsubscript{2} – superconductor
- Bandgap of MoS\textsubscript{2} transitions from being indirect in bulk to direct in 2D
- Free of epitaxial strains, 2D heterostructures can do more wonders than 3D heterostructures

h-BN/Graphene/h-BN
Challenges for 2D Heterostructures

• While new 2D layers continue to be synthesized, 2D heterostructure is in infancy
• Only graphene grown on BN substrate have comparable properties to that of exfoliated graphene
• Limited success for growing 2D BN on graphene without metal catalyst
• Little theoretical understanding/prediction of properties of 2D heterostructures
Funded Projects


• A. Kiefer & B. Clafin, AFRL/Ry, “Strain-Induced Band-Gap Modification of α-Sn (Grey Tin),” 10/1/2012-9/30/2015.
Graphene-BN Superlattice
A. Geim & K. Novoselov (2012)
Van Der Waals Epitaxy

A. Koma (1984)

MBE

VDWE

VDWE on 3D Substrate
Fundamental Studies of 2D Material Synthesis/Modeling/Characterization/Prototype

- Innovative growth techniques for uniform and reproducible growth of 2D heterostructures with precise control of purity and stoichiometry
- Theoretical tools for predictive modeling/simulation of properties of 2D materials and their interactions with the environment and other 2D materials including edge effects
- Advanced characterization techniques and structure-property correlation for 2D materials and interfaces
- Demonstration of 2D heterostructure devices with unprecedented performance

2-3 interdisciplinary teams each at ~$1M/yr
Other Important Challenges

- Growth of 2D materials on top of graphene or other 2D materials with controlled doping/edge effects and without metal catalysts
- Understanding/demonstration of correlated transport in 2D heterostructures
- Understanding/demonstration of electrical/thermal contacts to 2D layers
- Nanocomposite properties of 2D materials

1-3 smaller teams each at ~$300K/yr
BAA-AFOSR-2013-0001 scheduled for Feb. 2013
Additional NSF funding to be announced later
**Ionic Semiconductors**

- **Transparent Electronics:** ZnO, MgO, InGaZnO
- **Heterojunctions:** MgZnO/ZnO, LaAlO$_3$/SrTiO$_3$
- **Multiferroics:** BiFeO$_3$, EuO,
- **Metal-Insulator Transition:** VO$_2$, SmNiO$_3$
- **Topological Insulators:** Bi$_2$Se$_3$, Bi$_2$Te$_3$
- **Sulfides, selenides, tellurides**

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BAA-AFOSR-2012-02
Merits of Ionic Semiconductors

- Less demanding on crystalline perfectness
- Deposition on almost any substrate at low temperature
- Radiation hard, fault tolerant, self healing
- High electron concentration with correlated transport
- Wide bandgap for high power and transparency
- Multiferroics, metal-insulator transition, topological effects
- SWAP-C and conforming

Challenges
- Composition and purity control
- Transport not well understood

Covalent Semiconductor

Oxygen 2p-orbital

Ionic Semiconductor

Metal ns-orbital
High-T Superconductors
A. Geim (2012)

Conductive CuO Planes
Insulating Spacers
Conductive Graphene Planes
Insulating BN Spacers

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Semiconductor Technologies

ITRS Roadmap (2009)

- Conventional Scaled CMOS
- Scaled CMOS
- Multicore
- Von Neumann
- Reconfigurable
- Quantum
- Analog
- Digital
- Patterns
- Qubit
- SETs
- Spintronics
- Quantum
- Molecular
- Ferromagnetic
- Carbon
- Complex metal oxides
- Macro molecules
- Nanostructured materials
- Spin orientation
- Strongly correlated electron state
- Electric charge
- Polarization
- Strongly correlated electron state
- Phase state
- New Information Process Technologies
- Correlated Transport
- Polarization Engineering
- Polarization Engineering
- Bandgap Engineering
- Bandgap Engineering
- Field Effect
- Field Effect
- Field Effect
- Field Effect
- Si
- GaAs, InP
- GaN
- Oxides

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Power Transistors Figure of Merit

S. Rajan & S. Stemmer (2010)
Challenges for Ionic Semiconductors

K. Takahashi (2007)
Funded Projects

Conclusion

• While the speed of conventional covalent semiconductor transistors are approaching THz, power capacity is likely limited.
• Ionic semiconductor devices may offer speed, power and robustness, especially with correlated transport, metal-Insulator transition, and/or topologically protected states.
• Future of heterostructure materials and devices of 2D layers is wide open.