Science & Technology Center for Integrated Quantum Materials

http://CIQM.Harvard.edu    http://CIQM.org

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Massachusetts Institute of Technology – co-PI Ray Ashoori
Museum of Science, Boston – co-PI Carol Lynn Alpert
Semiconductor Technology


QUANTUM MATERIALS
Topological Insulators
Graphene
NV Center Diamond
Mission

Transform electronics and photonics to 2D atomic layers, electron surface states and single-atom devices:

**Quantum Materials**

Atomic Layers: Graphene, BN, MoS$_2$ - *ultrafast devices*

Topological Insulators – *protected data*

Nitrogen Vacancy Center Diamond – *atomic memory*

**Broader Impact**

Attract young students to careers in science & engineering.

Engage public audiences in the quest for new frontiers.

Commercialize sciences - new technologies & products
Quantum Materials Research

Atomic Layer Materials

Topological Insulators

NV Diamond
Bringing public and school audiences face-to-face with leading scientists and engineers...
Award winning Current Science & Technology (CS&T) Center developed by CIQM Co-PI
Carol Lynn Alpert

Gary Harris on CS&T Stage

Headquarters:
National Center for Technological Literacy
Nanoscale Informal Science Education Network
Intel Computer Clubhouse Network
Commercializing Science
Fawwaz Habbal – SEAS Exec Dean
Joe Lassiter – Faculty Chair
ilab.harvard.edu
Graphene and other Atomically-Thin Layered Materials
The World of Atomically-thin 2D-Layered Materials

Graphene (G)

Hexagonal Boron Nitride (hBN)

Molybdenum Disulphide (MoS$_2$)

Tabletop Relativistic Physics

Thinnest Insulator & tunnel barrier

Electronic properties dramatically change with number of layers

< 1 nm!
New Concept:
Atomically Thin Layered Materials

From the Nobel Museum
Graphene for THz Electronics

THz emitter
- Long electron mean free path in graphene + magnetic field steering of electron trajectory
  → Potential for solid state magnetron

THz detector
- p-n interface magnetoplasmons.
- THz detection at room temperature
CVD Growth of Graphene, hBN, MoS$_2$ heterostructures
Single-layer MoS$_2$ for Wireless Sensors

MoS$_2$ Integrated Circuits

New, flexible wireless sensors

CVD Growth of Graphene for Large Area Flexible Electronics (Samsung Electronics)

Topological Insulators

Nuh Gedik
Can quantum Hall physics occur without a magnetic field?

Spin-orbit coupling

Nuclear E-field

Electron spin

Stationary observer

Moving observer

\[ E \rightarrow \begin{cases} +B \\ -B \end{cases} \]

Largest effect in heavy elements
The 2D quantum spin Hall insulator

Theoretical prediction (Kane and Mele 2005)

First realistic materials proposal
HgTe/CdTe (Bernevig, Hughes, Zhang 2006)

Experimental confirmation
(Konig, Molenkamp et al. 2007)
The 3D topological insulator

First genuinely 3D topological phase, zero magnetic field

Theoretical prediction

- Fu & Kane (2006)
- Roy (2006)

2D surface metal is immune to strong disorder

Intimate connection between charge and spin

The surface is a topological version of graphene

Liang Fu (MIT)
Novel Time-of-flight ARPES

3D band and spin mapping!

Gedik (MIT)

Diamond Nitrogen-Vacancy Centers
Its color centers make diamond excellent

Quantum Material

Nitrogen => Yellow & Orange    Boron => Blue    Hydrogen => Violet    Defects => Red    Radiation => Green
Nitrogen-Vacancy (NV) Color Center in Diamond

Negatively charged Nitrogen-Vacancy (NV-) color center:
- a carbon vacancy next to a nitrogen atom + additional electron;

Stable source of photons at room temperature:
- emits red (637-750nm) when excited with green (532nm)

$\text{NV}^-$: localized electronic spin state ($S=1$) with $T_2 > 1\text{ms}$ at room temperature!!!

Atom-like energy levels coupled by optical and microwave transitions
Diamond Nanowire Single Photon Source:

NV-Center Diamond Magnetic Imager

- Scanning NV fluorescence: 150 nm
- Optical Image:
  - Monolayer
  - Many-layers
  - Bilayer

- Image of magnetic domains magnetic disk

- NV at the diamond nanowire tip

Substrate

Amir Yacoby
The Dream: Scalable Quantum Networks
Wrap Up
Graphene & Atomic Layer Materials

Quantum Confinement

THz emitter

Graphene plasmonics
Topological Insulators

Create magnetic monopole!

Qi et al, Science 323, 1184 (2009)

Majorana fermions
Topological quantum computing

TI crystal growth
NV Centers in Diamond

single crystal diamond growth

1 bit on 1 spin at RT

Diamond nanowires

NV diamond magnetic imager

12/6/13
Low Dimensional Materials for 21st Century

**Graphene:** High mobility, transparent Flexible Displays, RFID Tags

**MoS$_2$ family:** Thinnest semiconductors Ultra-Low-power Flexible (Opto-Electronics)

**Topological Insulators:** Protected metallic surface state. Manipulate the spin, no heat generation in the device

**Nitrogen-vacancy Diamond:** Transduction and Spintronics
Challenges

- Stacked atomic layers – assembly and growth
- Atomic layer devices – sensors, ultrasmall, ultrafast
- Topological insulator (TI) surface probes
- TI material growth – low internal conductivity
- NV center memory arrays in diamond
- Ultra-sensitive, ultra-sharp NV magnetometers
- Integrated atomic layer / TI / diamond systems
  - atomic layers – ultrafast devices
  - TI materials – topologically protected data
  - NV diamond – atomic scale memory