Fundamentals of the condensed state: Where are the electrons? How do they determine the properties?

Start with a single atom and build up solid in real space as a huge molecule by considering interactions between atoms (more intuitive -> amorphous, defective materials)

Traditional momentum-space ($k$-space) approach exploits periodicity (less intuitive -> works well for crystals, some properties).
Class research?

- Graphene
- Carbon nanotubes
- Your research here …
Graphene

- No defects
- Very high conductivity, mobility
- Highest thermal conductivity
- Quantum hall effect
Carbon nanotubes

- Rolled-up graphene
- Stronger than steel
- High mobility

Why does the I-V characteristic look like this?
Organic Electronics

- Organic FETs
- Polymer solar cells
- Organic LEDs

Why does the I-V characteristic look like this?
Silicon

• Most perfect material we’ve ever made in production
• Underlies current technological era
• Prototypical semiconductor
• GaAs (III-V), ZnTe (II-VI) ….
Quantum-confined systems

- Quantum well lasers
- Quantum dots

![Image of quantum-confined systems](http://www.aist.go.jp/aist_e/aist_today/2006_21/hot_line/hot_line_22.html)

1nm → → → → → 5nm

GaInP/AlInP Quantum Well Laser Diode

http://www.optics.rochester.edu/workgroups/wicks/research.html
Cu(In,Ga)Se$_2$ (CIGS)

- Solar cell materials

http://www.hmi.de/people/daniel.abou-ras/SEM.htm
Ga$_{0.95}$Mn$_{0.05}$As

- Spintronics
- Dilute magnetic semiconductor - new electronics by control of spin?
YBa$_2$Cu$_3$O$_7$

- 90-K high-temperature superconductor
- We still don’t really know why it works
La[O\(_{1-x}\)F\(_x\)]FeAs

- Hosono et al., 2008
- 26-K HTSC with Fe in it!
Giant Magnetoresistance (GMR)

• Read heads
\( \text{In}_2\text{O}_3: \text{Sn} \)

- Representative of transparent conductors, transparent semiconductors
- \( \text{ZnO:Al, SnO}_2: \text{F, IGZO, IZO} \)
Thermoelectrics

- $\text{Na}_x\text{CoO}_2$
- $\text{Bi}_2\text{Te}_3$
- $zT = \alpha^2 \sigma T/\kappa$
Ferroelectrics

- $\text{BaTiO}_3$ PZT (lead zirconate titanate)
- Tunable capacitors, ferroelectric memory (like ferromagnetic)
Multiferroics

• Some combination of ferromagnetism (or antiferromagnetism), ferroelectricity, or ferroelasticity in same material.

• HoMnO$_3$
Metamaterials

- Photonic crystals
  (semiconductors with light)
- Negative index materials
  (sub-wavelength focusing, …)
Topological insulators

Symmetry-protected conducting surface states

2008: Sb/Bi, Sb, Bi$_2$Se$_3$, Bi$_2$Te$_3$, Sb$_2$Te$_3$

Majorana particles can occur at the interface between a TI and a superconductor. QC applications?

Qubits & quantum computing

- Quantum computing on a chip?

magnetic-based

Graphene-based
The future

- Solid state lighting
- Solid state batteries
- Solid state heating/cooling
- Solar cells
- Catalysts
- Spintronics
- Quantum computing
- Metamaterials
- Liquid Crystals