Graphene

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Materials 265
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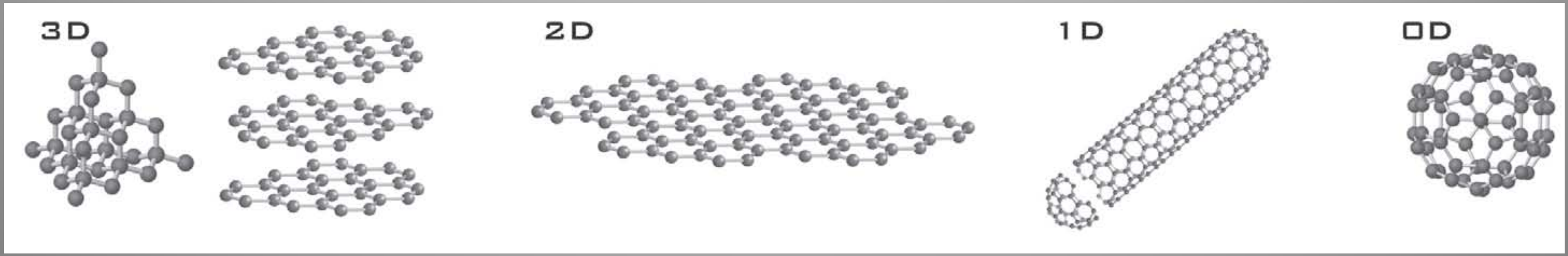
History

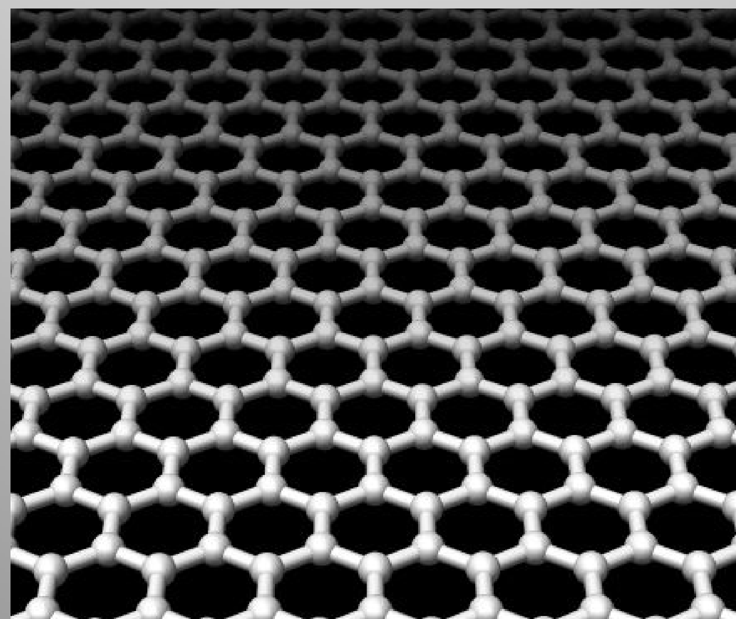
- Diamond and Graphite
- Buckminster Fullerine (C_{60})
  - 1985: Kroto, Curl, Smalley
  - 1996 Nobel Prize
- Carbon Nano-tube (CNT)
  - Sumio Iijima – 1991
  - Various prior works



Katsnelson Review in *Materials Today*

Introduction

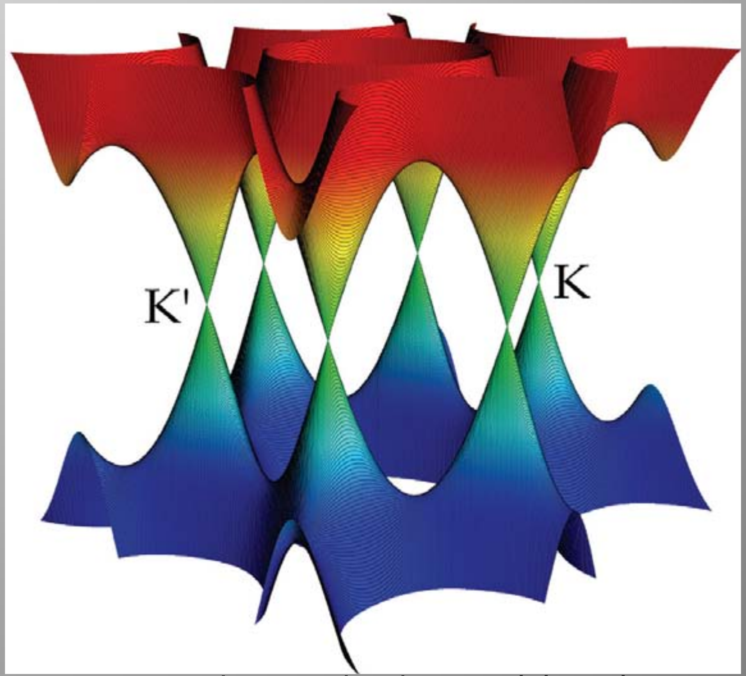
- Stable 2-D lattice exists!*
  - Landau and Peierl hypothesized against this
  - *Actually not exactly flat. Rippled.
- One monolayer of graphite structure
- sp^2 bonding and one unbound electron



Dr. Thomas Szkopek Website, McGill University

Electronic Structure

- Three localized hybridized electrons
- One unbound electron
  - Hybridized across entire sheet
  - Fourth electron behaves similarly to free electron
  - Interacts with periodic field to form Dirac fermions
  - Cone-like Energy bands
  - Massless fermions



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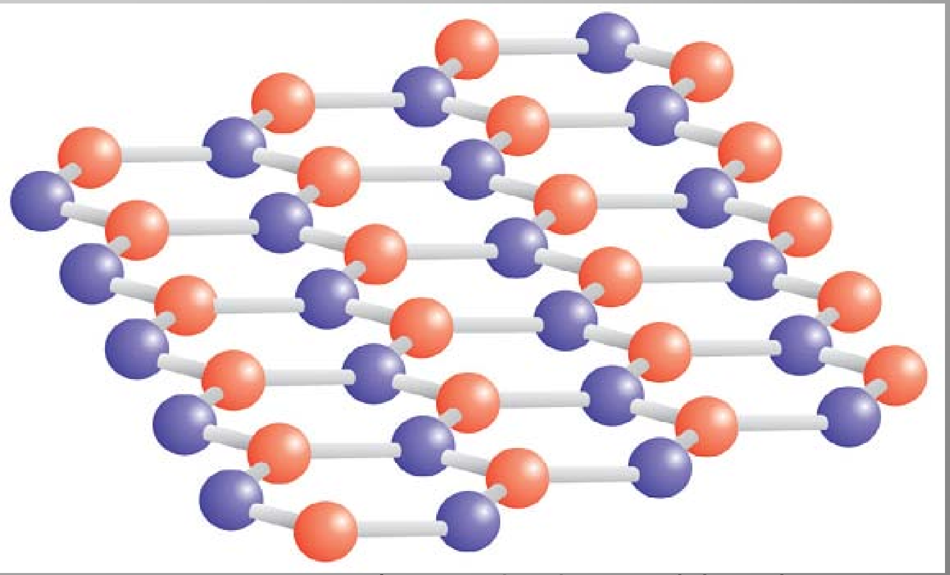
Quantum Sublattices

- Carriers follow Dirac, not Schrodinger Eqn.
- Two identical crystal sublattices
- Quantum-mechanical hopping btw. sublattices
  - Formation of two energy bands
  - Intersect at edges of Brillouin zone as a cone
  - Quasiparticles in graphene behave as massless relativistic particles

$$E = \hbar k \upsilon_F$$



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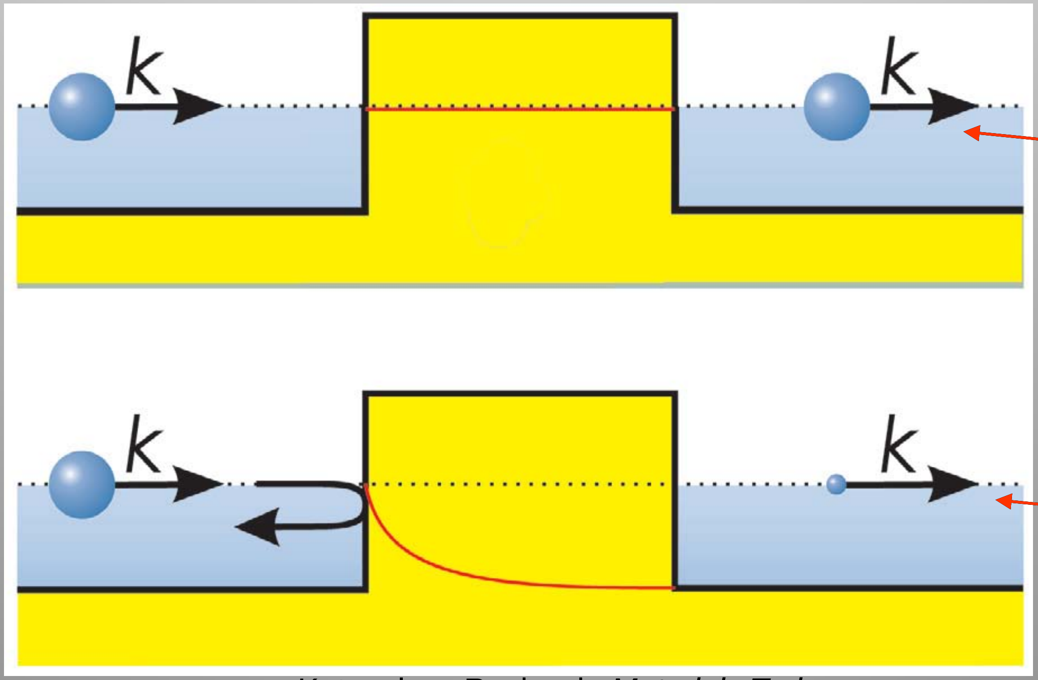
Electronic Properties

- Ultra-high mobility
  - Routinely achieving 20,000 $cm^2/V \cdot s$
  - Order of magnitude better than Si
  - Three times higher than GaAs
  - World record 200,000 $cm^2/V \cdot s$ set this January
- Ultra-low resistivity
  - Lower than silver (10^{-6} $Ohm \cdot cm$)
- Tunneling probability is always unity

Klein Paradox

- Exponential decay in finite well
- Graphene: tunneling probability is unity
  - Sufficiently strong potential barrier attracts positrons
- Positron wave functions in barrier align with electron wave function



Relativistic quantum mechanical particle (In Graphene)

Classical particle

Non-relativistic quantum mechanical particle

Katsnelson Review in *Materials Today*

Consequences of Klein Paradox

- Complete tunneling of electrons through potential barriers twice electron’s rest energy
- Single-layer graphene transistor will be “always-on”, not “normally-on”
- No applied bias will turn it off
- Must create a bilayer graphene transistor
  - Can strongly suppress normally-incident electron tunneling

Fabrication of Graphene

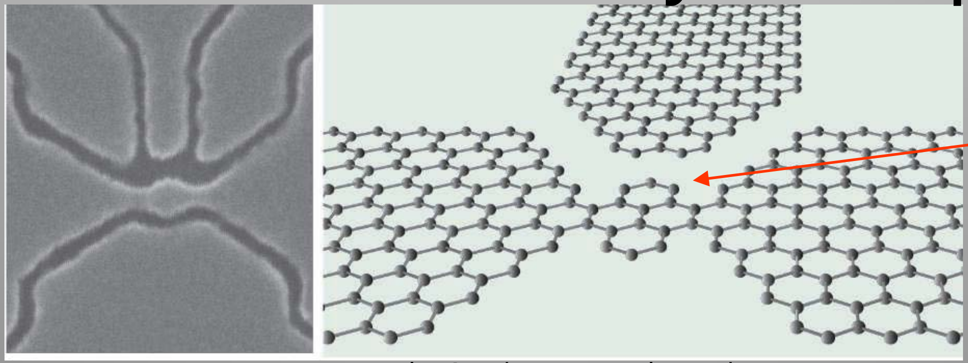
- Mechanical exfoliation of graphite
  - Method used by most people
  - By IBM and others to create first Graphene FET
- Heat up SiC to desorb Si
  - In UHV, heat up SiC to ~1300°C
  - Si atoms sublimate
  - Hexagonal carbon lattice (graphene) left behind

Processing of Graphene

- CNTs have well-defined edges
- Graphene has dangling bonds at edges
- Difficult to cut manually into ribbons
  - By confining electrons to narrow ribbon, open up small bandgap and make transistor possible
- Hope to get graphene nanoribbons (GNRs) 2 nm wide
- Silicon technology will die at around 20 nm

Graphene Devices

- World record mobility
  - 1-2 orders of magnitude better than Si
  - Over 1 order of magnitude better than GaAs
- Ballistic conduction at submicron distances
- FETs based on QDs
  - Mechanically carve QDs out of graphene sheet
- P-n junction FETs on bilayer Graphene



Schematic of Quantum Dot carved into graphene

R. M. Westervelt, "Graphene Nanoelectronics"

Problems/Future Work

- Difficult to make and process
  - Can’t make large uniform wafers
  - Difficult to cut uniformly
  - Dangling bonds after cutting cause background electrons to scatter
- Switching speed too slow in prototype graphene transistors

Other Applications

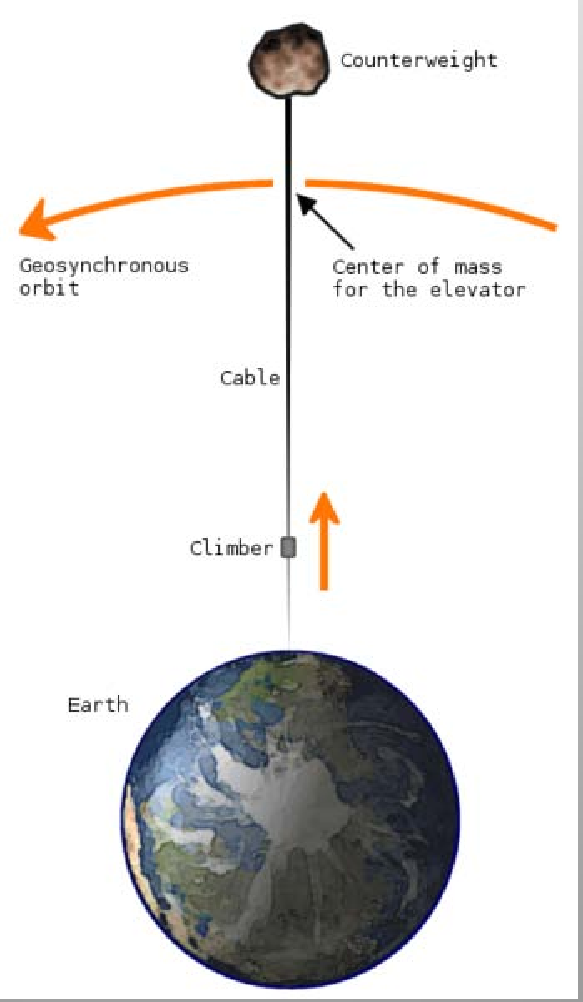
- Gas Sensors
  - Absorption of gas molecules dopes graphene
  - Measure change in resistivity
- THz Light Emitters
  - Human body invisible in THz frequency regime
- Superconductivity (proximity effect)
- Magnetic/spintronics applications
  - Low spin-orbit coupling
- Graphene Oxide Paper
  - Oxidize, float in water, dry as paper

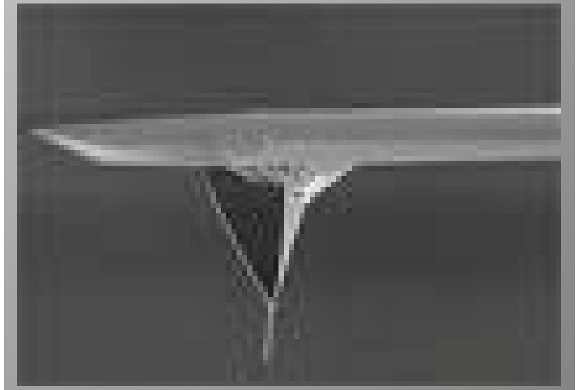
Dimitriy Dikin, Northwestern. *MIT Technology Review*

MATERIALS UC Santa Barbara

Space Elevator

- Random drawings of space elevator





Carbon Nanotube AFM tip

Conclusions

- Extremely new material system
  - Production issues
  - Processing issues
- Excellent electrical and structural properties
- Potential for small nano-scale (2 nm) devices
- Many potential applications
- Will never replace Si, but has plenty of potential niche markets

References

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Questions?