How Small Can We Go? The Physics Behind Nanoelectronics

Nadya Mason
Dept. of Physics
University of Illinois at Urbana-Champaign
Making existing stuff smaller

Using new nano-scale materials

Understanding basic physics of small structures

Using behavior beyond conventional electronics (e.g., quantum)

Outline
(Nano)Electronics are Everywhere!
The Big Electronics are run by little electronics:

- microprocessor
- motherboard

Much research focuses on improving this basic element.

Trillions of Transistors! The “on/off” of the computer bit.
How do we Study “Electronics”?

We study how electrons flow through materials

Experiments can determine how well materials conduct electrons and their resistance to electron flow

Often determined via Ohm’s Law: Resistance = Applied voltage/Measured current

How do different elements (inductors, capacitors, switches) affect current?
How do we Study “Electronics”?  

From a research point of view: understanding and utilizing changes in conductance/resistance

Add molecules

A sensor!

Add electric potential (“gate”)

A transistor!
Why Nano?
Because everything is getting smaller!

We want smaller sensors, smaller computers, etc
Let’s start with example of small computers …
The first computer... Prototype created in 1832 by Professor Charles Babbage at Trinity College, Cambridge

- Works by hand crank
- 8,000 parts, 5 tons, 11 feet long
- Computes polynomials functions, logarithms, trigonometry
- Adds differences between columns of numbers to calculate
- Accurate to 31 digits.

http://www.computerhistory.org/babbage/howitworks/
The “first” electronic computer…

1946 ENIAC – Electronic Numerical Integrator and Computer

Uses electronic charges, rather than mechanical registers, to store numbers

ENIAC statistics

- 17,468 vacuum tubes ("bit" = vacuum tube current on/off)
- Weighed 30 tons
- 8’ x 3’ x 80’
- Consumed 150 kW of power
- Crashed every 2 days

- Could hold a 10 digit decimal number in memory
- Performs 5000 operations per second (5 kHz)
Bardeen changes everything!

The first transistor, 1947

Transistors:
- Are switches
- Use small currents to switch on much larger currents
- Can do logic: “on” = 1, “off” = 0
- Can be made tiny

UIUC Professor (1951-1991)

Nobel Prize 1956 - Transistor
Nobel Prize 1972 - Theory of Superconductivity
Shockley, Brattain, Bardeen at Bell Labs, 1947

“+” is lack of electrons → no current flow
Small white current removes “+” → big current flow
Smaller devices means smaller transistors

Integrated circuit

Cross section of integrated circuit

Single transistor device

Voltage to “Base”, current flows “Emitter” to “Collector”
Moore’s Law: transistor size halves every 18 months

2017: 14-nm size, 30 Billion on processor (Intel Stratix 10)
But we are reaching fundamental physical limits to shrinking conventional electronics

**WHY?** Because Quantum Mechanics prevents us from fully turning off a transistor that is too small.

Let’s look at an example of how we turn “on” and “off” a transistor with a voltage ...

But what if region of zero voltage is so narrow that “long” electrons extend through, even in off state?
A long electron??? But electrons are tiny particles.

And they are also WAVES.

De Broglie: All matter has a wave-like nature (1924)

Confirmed by electron interference & diffraction experiments.
So, even if we turn “off” a transistor, an electron wave can continue on through the other side of a thin enough barrier.

This is called quantum mechanical “tunneling”

It happens for thin barriers, typically $< 5$ nm
Quantum mechanics gives us a fundamental physical limit to shrinking conventional electronics.

- Quantum tunneling: a current flows without a voltage.
- Can’t turn current “off” at low power because of thin gate insulator.
- Can’t run at high power without over-heating.
What are the current ideas to fix the problem?

Some Solutions

No Known Solutions

Research

Development

Manufacturing

SiGe

Uniaxial Strain
(higher mobility electrons)

SiGe

Strain

50 nm

2003

65 nm

2005

45 nm

2007

32 nm

2009

2011

5 nm

Carbon Nanotube

Semiconductor Nanowire

3.0 nm High-k

Silicon substrate

Gate

Source

Drain

Si nano fins

Gate

S D S

III-V

5 nm

graphene
Need new nanomaterials having better properties –

e.g., Ultrasmall, Low power dissipation, High sensitivity to gate voltage, Novel effects

→ Nanotubes, Nanowires, and Graphene
Graphene: a Single Atomic Layer of Carbon

Producing Graphene

C atoms


exfoliate with tape

5 μm
Graphene is a wonder material with many superlatives to its name. It is the thinnest known material in the universe and the strongest ever measured. Its charge carriers exhibit giant intrinsic mobility, have zero effective mass, and can travel for micrometers without scattering at room temperature. Graphene can sustain current densities six orders of magnitude higher than that of copper, shows record thermal conductivity and stiffness, is impermeable to gases, and reconciles such conflicting qualities as brittleness and ductility. Electron transport in graphene is described by a Dirac-like equation, which allows the investigation of relativistic quantum phenomena in a benchtop experiment.”

Graphene: Properties and Applications

- ultra-thin (0.4 nm)
- strong
- impermeable to gas
- high thermal conductivity
- high stiffness (Young’s modulus ~ 1 Tpa)
- flexible

- high current density
- high charge carrier mobility
- low carrier density (but tunable with gate)
- Dirac-like transport (E ~ h\k)
- chirality (pseudospin)

Applications:
- transparent electrodes
- sensors
- solar cells
- biodevices
- ultra-capacitors
- transistors

- And lots of basic physics:
  What do electrons do in 2D,
  How is quantum mechanics relevant, Can we make novel devices?
Graphene electronics

Super-fast transistor!

IBM, 100-GHz graphene transistor (Science 327, 5966 (2010)) & (2012)

- little power dissipation (limited electron scattering)
- high frequencies for cell phone, radar, internet, etc.
Graphene electronics

Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures

L. Britnell,¹ R. V. Gorbachev,² R. Jalil,² B. D. Belle,² F. Schedin,² A. Mishchenko,¹ T. Georgiou,¹ M. I. Katsnelson,³ L. Eaves,⁴ S. V. Morozov,⁵ N. M. R. Peres,⁶,⊥ J. Leist,⁸ A. K. Geim,¹,⊥ K. S. Novoselov,³⊥ L. A. Ponomarenko¹⊥

An obstacle to the use of graphene as an alternative to silicon electronics has been the absence of an energy gap between its conduction and valence bands, which makes it difficult to achieve low power dissipation in the OFF state. We report a bipolar field-effect transistor that exploits the low density of states in graphene and its one-atomic-layer thickness. Our prototype devices are graphene heterostructures with atomically thin boron nitride or molybdenum disulfide acting as a vertical transport barrier. They exhibit room-temperature switching ratios of ≈50 and ≈10,000, respectively. Such devices have potential for high-frequency operation and large-scale integration.

Graphene is nanoscale in the **vertical** direction: best utilized in nanoelectronics via layering or applications utilizing unique properties (e.g., high frequency electronics, mechanical stability, high conductivity per unit volume).

Need to work on: creating large scale, defect-free graphene that is easily transferred
Most electronic materials are hard (semiconductors, metals) – How can they be flexible?

*Make them thin!*
Graphene *flexible* electronics

Graphene is highly conducting, ultra-thin
→ Flexible, transparent

But how do electronic properties of graphene change when it is bent or strained?
Graphene electronics: Strain Engineering

Applying mechanical strain affects electronics: introduces energy gaps, induces large pseudo-magnetic fields, enables novel flexible devices.

New & useful electronic behavior!

Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles


Actual magnets with this field would blow up after a second!
Graphene electronics: Strain Engineering

Few methods exist to control strain in graphene …

Our methods:

- Global strain via substrate stretching

We observe cracks reversibly opening and closing, and corresponding reversible resistance
Graphene electronics: Strain Engineering

Few methods exist to control strain in graphene ...

Our methods:

• Local strain via micro-patterned substrate features

Decreasing pyramid spacing increases strain: causes graphene to de-adhere from bottom, stay pinned & strained at apex.
Graphene electronics: Substrate Engineering

Strain engineering via nanoscale SiO$_2$ pyramids

---

Raman spectroscopy

Electrical resistance measurements

---

(A) [Image of nanoscale SiO$_2$ pyramids]
(B) [Image with higher magnification]
(C) [Image showing graphene structure]
(D) [Image with graphene and SiO$_2$ layers]
Graphene electronics: Substrate Engineering

Strain engineering via nanoparticles

- Kink in data due to electrons filling spaces between nanoparticles (as opposed to just filling lattice of graphene)
- Kink disappears when strain is relaxed
Lots of other possibilities for new transistors and electronic devices using nano-materials ...

Germanium nanowires (IEEE Spectrum, 2016)

MoS$_2$ transistor with 1-nm carbon nanotube gate (Phys Org, 2016)

Metal Nanoparticles (Science Advances, 2017)
Can we use quantum properties for anything? Can we improve computing beyond simply scaling down?

➔ Quantum Computers

Use quantum properties of quantum bits (qubits) to perform calculations more rapidly than a classical computer:

Specifically, quantum computers use wave superposition of two different particles (qubits can be electron charges, electron spins, electron-like particles in materials ...)

Quantum Computers

To operate on N bits, classical computer needs $2^N$ calculations (64 bits $\rightarrow 10^{19}$ calculations); quantum computer needs N calculations.

Can use superposition of spin states as qubits, for Parallel Processing

Useful for: factoring large numbers, sorting databases, & …

Requirements: well-defined qubits, scalability, coherence

→ Need to define and control spin or other qubits in small structures

Example: nanowire-based quantum computer based on a theoretical proposal by DiVincenzo et al. (Nature 2000).
Summary

1. Making existing stuff smaller

2. Using new nano-scale materials

3. Understanding basic physics of small structures

4. Using behavior beyond conventional electronics (e.g., quantum)
Questions?
How small is small?

- Human Hair
- Transistor: 50 nm
- Ebola Virus: 80 nm