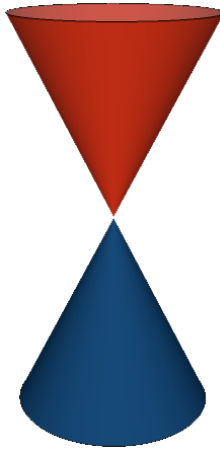
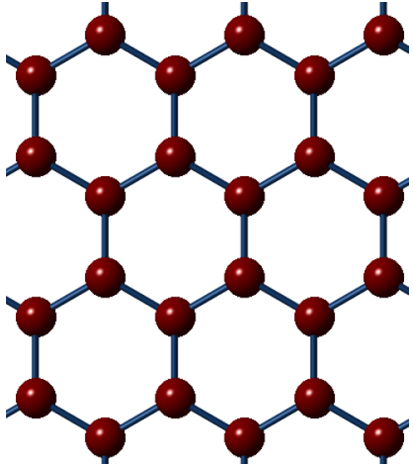


Exceptional service in the national interest

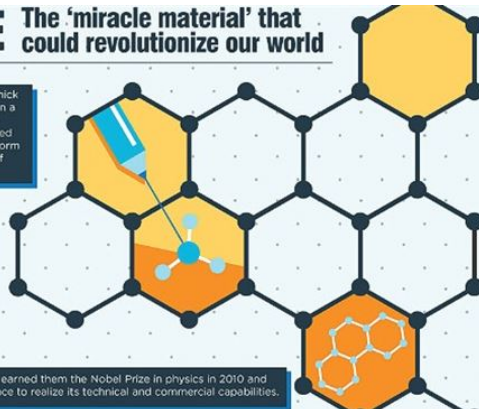


GRAPHENE The 'miracle material' that could revolutionize our world

What is it? Graphene is a one-atom thick layer of carbon arranged in a honeycomb lattice. When millions of these are stacked one on top of another they form graphite - a mineral consisting of carbon which is found in pencils.

Graphene was discovered in 2004 at the UK's University of Manchester by physicists Andre Geim and Konstantin Novoselov when they isolated a single-layer of graphene using Scotch Tape before going on to demonstrate its remarkable conductive and resilient properties.

Geim and Novoselov's work earned them the Nobel Prize in physics in 2010 and today researchers are in a race to realize its technical and commercial capabilities.

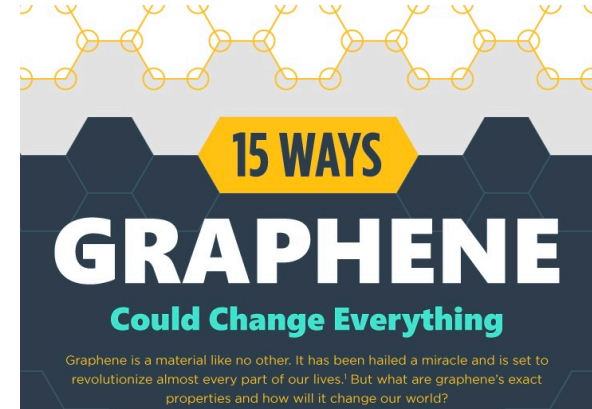


15 WAYS

GRAPHENE

Could Change Everything

Graphene is a material like no other. It has been hailed a miracle and is set to revolutionize almost every part of our lives. But what are graphene's exact properties and how will it change our world?



Graphene: the “Wonder” Material?

Hype vs. Realism: Using Materials Understanding to Filter BS

Straw Poll

My familiarity with graphene is.....

- 1. Geim and Novoselov call me for advice**
- 2. I use it**
- 3. I've read about it**
- 4. Is that the stuff that they make with Scotch tape?**
- 5. Is it a new plotting app?**

Text Questions: 505-933-1028



I want you to understand...

- 1. what graphene is and why everybody's excited**
- 2. the origin of graphene's electrical, thermal, and optical properties**
- 3. how to sift hype from reality for graphene and other wonder materials**

Hype Train

Iron Man

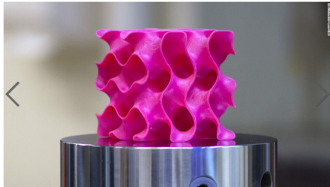
Why Iron man ditched iron for graphene

WIRED



Are we one step closer to being able to use the world's strongest material?

By Nicola D'Amico, CNN
Updated 8:53 AM ET, Fri January 13, 2017



Recommended for you
Chicago judge killed outside home
Co-MB-E player Otto Neom found safe

Photos: Incredible innovations: These materials could change the world
Graphene-gryllid - Researchers at the Massachusetts Institute of Technology have designed a new material that is 30 times stronger than steel.

The Washington Post

Innovations
Why the graphene light bulb could switch on a new era of innovation

By Dominic Basulto April 2



Physics Graphene - the new wonder material

Scientific interest rolls in for a material that is more solid than steel and a better conductor than copper



The molecule is priceless but it is not a matter of cost - a few hundred dollars per kilo. The value lies in its potential. The molecule in question is called graphene and the EU is prepared to devote €1bn (\$1.3bn) to it between 2013 and 2023 to find out if it can transform a range of sectors such as electronics, energy, health and construction. According to Scopus, the bibliographic database, more than 8,000 papers have been written about graphene since 2005.

- Most popular in US
- British spies were first to spot Trump team's links with Russia
 - Arizona Sky Village's residents have one rule: 'Turn off your goddamned lights'
 - United States' first female Muslim judge, Sheila Abdus-Salam, found dead in New York

Graphene Could Usher in Flexible, Ultra-Slim Gadgets

By NICK BILTON OCTOBER 12, 2012 5:54 PM 24

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You've probably never heard of [graphene](#), a carbon-based material, but it might be stuffed into your pocket or wrapped around your wrist in the not-too-distant future.

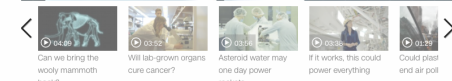
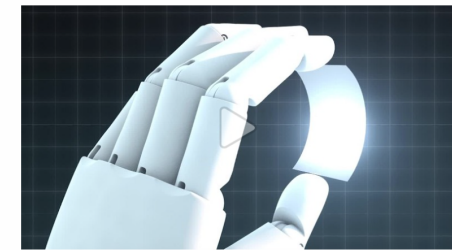


Graphene is a fully flexible material. Ji Hye Hong

According to the

Wonder material could harvest energy from thin air

By Peter Shadbolt, video produced by Curtis Brown and Jackson Loo, CNN
Updated 9:59 AM ET, Tue November 3, 2015



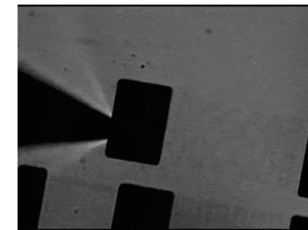
Story highlights

Researchers in the UK say a discovery involving wonder material graphene could revolutionize batteries
Graphene is 200 times stronger than steel and a million times thinner than a human hair
The material, which has the same atomic structure as the lead in pencils, is impermeable to atoms and molecules
Scientists found that positively charged hydrogen atoms could pass through it with implications for fuel cell efficiency

Editor's Note: Originally published December 2, 2014, updated November 2, 2015.

(CNN) — Bold claims for new battery technology have been around since the invention of the lead-acid battery more than 150 years ago.
But researchers at Manchester University in the UK say their latest discovery involving the new wonder material graphene could be the most revolutionary advance in battery technology yet.

According to a study published in the journal Nature.



Graphene can be folded and cut into a microscopic kirigami spring. Cornell University/McEuen Group

The New York Times

JULY 30, 2015

Graphene Origami

Graphene is a thin material with tremendous potential. Measuring only an atom-thick, it is harder than diamond, a better electrical conductor than copper, and 200 times as strong as steel.

Graphene is so strong that a sheet of it stretched across a coffee-cup should be able to support the weight of a truck bearing down on a pencil point. Some researchers call it a "wonder material" that could be used in everything from batteries and biosensors to computers and condoms.

Now researchers have discovered another one of graphene's feats: It's as flexible as paper. Not only can graphene be crumpled and then perfectly flattened, but it can also be folded like origami, according to a report published Wednesday in Nature.

Using a style of origami that involves cuts and folds called kirigami, the researchers fashioned a sheet of graphene into a tiny spring. According to Nature, researchers may one day use kirigami to craft graphene sheets into microscopic weighing scales or nets small enough to wrap around living cells.

—NICHOLAS ST. FLEUR

Wonder Material Properties

GRAPHENE: THE CARBON-BASED 'WONDER MATERIAL'

Since its discovery in 2003, graphene has been a hot topic in chemistry and materials science research. It's been linked with water purification, electronics, and biomedical applications. However, how close are we really to using graphene in our day-to-day lives? This graphic looks at its properties, uses, and future.

WHAT IS GRAPHENE?



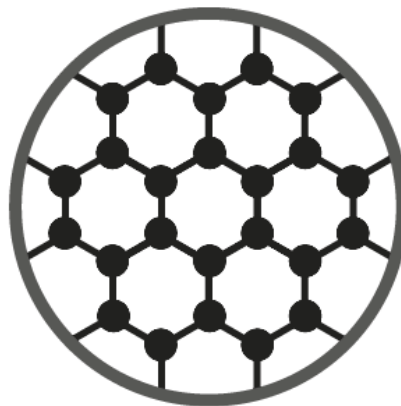
SINGLE LAYER OF CARBON ATOMS

HONEYCOMB-LIKE STRUCTURE

GRAPHITE IS LAYERS OF GRAPHENE

ISOLATED IN 2003 IN MANCHESTER

Graphene is a single layer of graphite, the carbon-based material found in pencil leads. Graphite has been known for centuries, but graphene was only isolated in 2003, by shearing layers off of graphite using sellotape. It's a single atom-thick layer of carbon atoms, that are arranged in a flat, hexagonal lattice structure.



POTENTIAL USES OF GRAPHENE



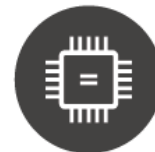
TOUCH SCREENS IN DEVICES

Graphene's transparency and conductivity means that it can be used in displays and touchscreens. However, currently these are more expensive to produce than the currently used material, indium tin oxide.



WATER FILTRATION SYSTEMS

Graphene allows water to pass through it, but not other liquids and gases, so it can be used in water purification. Researchers are working on a device that could be capable of filtering salt from sea water.



IN ELECTRONIC DEVICES

Graphene has been touted as silicon's successor, and has been used to make very fast transistors. However, its conductivity cannot be 'switched off' as silicon's can. Other 2D materials seem more promising.



MEDICAL SENSORS & DRUG DELIVERY

Several biomedical applications are being explored for graphene, including drug delivery, cancer therapy, and its use as a sensor. However, its toxicity profile must be investigated before any clinical uses.



ENERGY STORAGE & COMPOSITES

Graphene-based energy storage devices are possible. It can also substitute for graphite in normal batteries, improving efficiency. Additionally, it can be added to materials to make them stronger and more lightweight.

THE PROPERTIES OF GRAPHENE



HIGH ELECTRICAL
CONDUCTIVITY



200X STRONGER
THAN STEEL



THIN AND
LIGHTWEIGHT



HIGH THERMAL
CONDUCTIVITY



VERY HIGH
TRANSPARENCY

Graphene's 'wonder material' reputation stems from its superlative properties. It is a million times thinner than a piece of paper, yet stronger than diamond, and 200 times stronger than steel, due to the strong carbon-carbon bonds. It's also a flexible material, and conducts heat and electricity better than copper. Being only one atom thick, almost 98% of visible light passes through graphene, making it transparent.

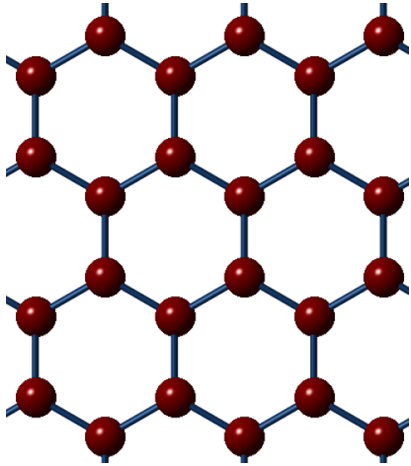


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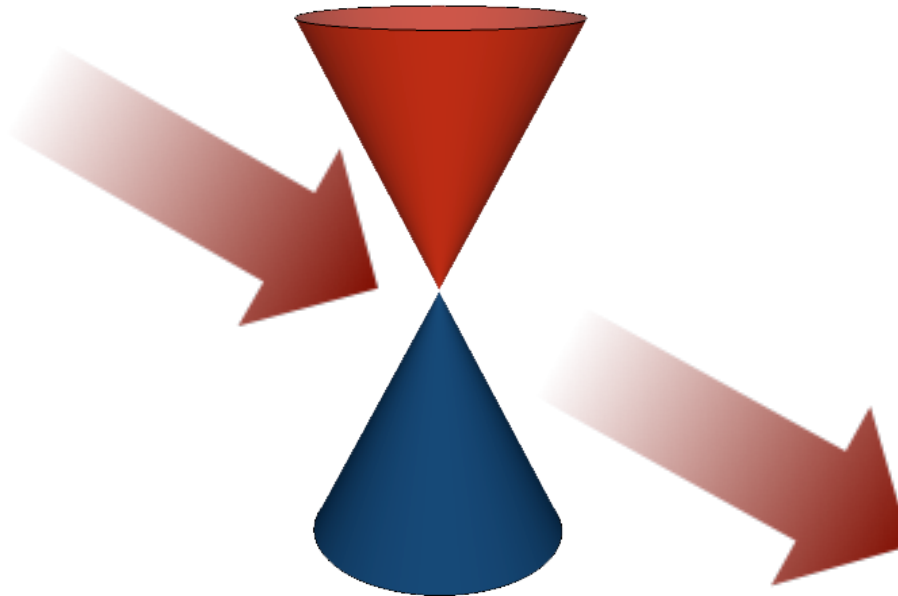


Origin: Properties

Periodicity



Bandstructure



Properties

Question:
What's so novel about
graphene's periodicity?

THE PROPERTIES OF GRAPHENE



HIGH ELECTRICAL
CONDUCTIVITY



200X STRONGER
THAN STEEL



THIN AND
LIGHTWEIGHT



HIGH THERMAL
CONDUCTIVITY

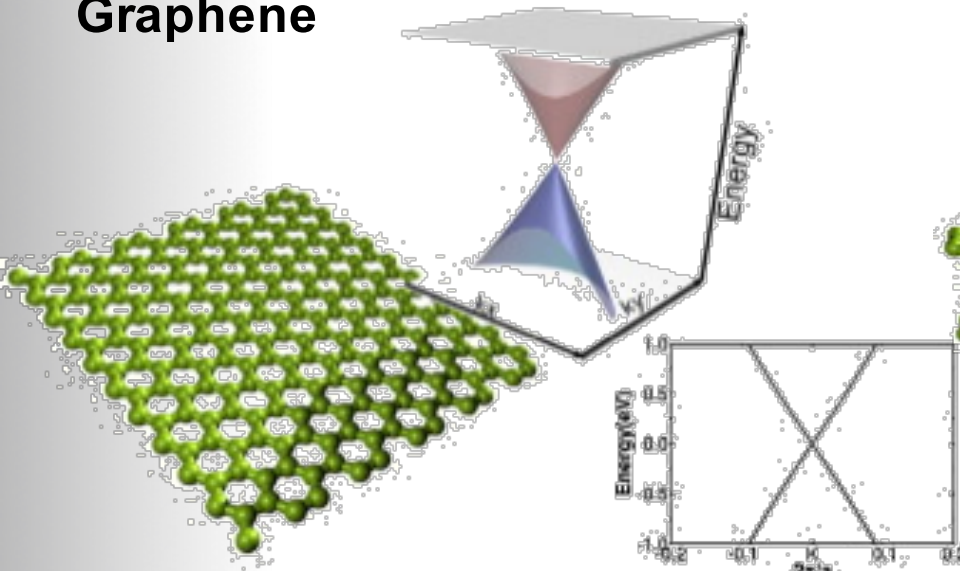


VERY HIGH
TRANSPARENCY

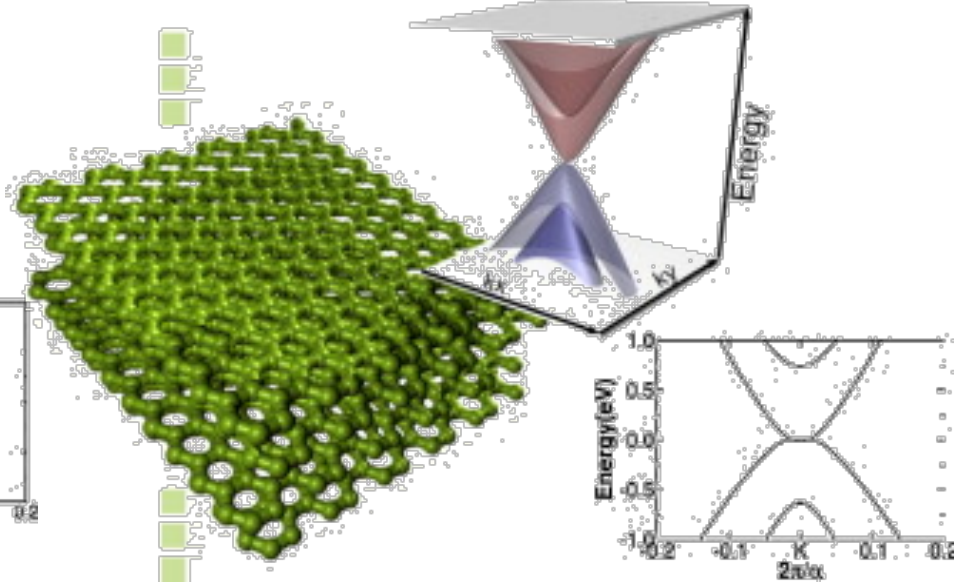
Electronic & Lattice Bandstructure

Electronic

Graphene

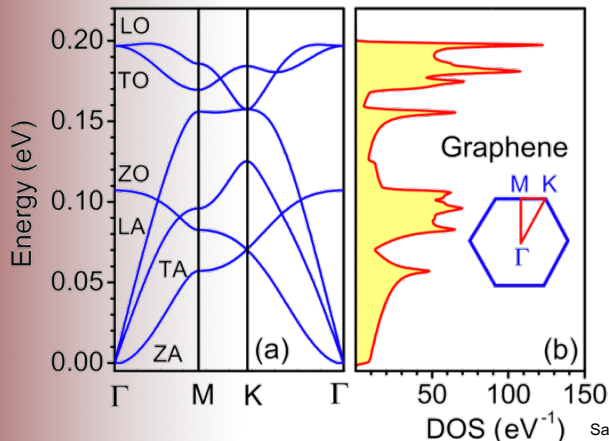


Graphite

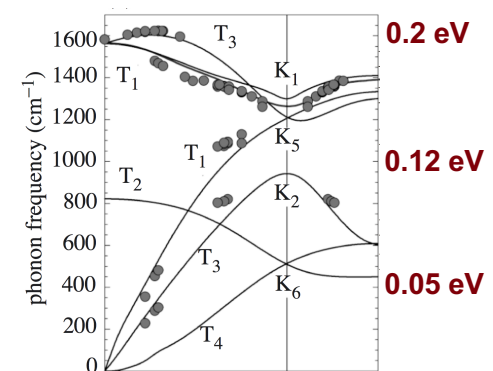


Terrones et al. nanotoday (5) 351, 2010.

Lattice



Sanders et al. J. Phys. Condens. Matter (25) 144201. 2013



Reich and Thomson. Phil. Trans. R. Soc. Lond. A (362) 2271. 2014

Question: When does "multilayer" graphene turn into graphite?

Counting Carriers

PREMISE: Amount of energy (electric, heat, optical) moved proportional to the number of energy carriers.

Question: How many carriers does graphene have?



Number of Charge Carriers

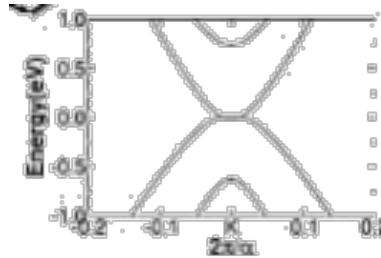
$$n = \int D(E) f_f(E) dE$$

3D

$$D(k) = 2 \frac{4\pi k^2 dk}{(2\pi/L)^3 V} = \frac{k^2 dk}{\pi^2}$$

Parabolic Dispersion

$$E - E_c = \frac{\hbar^2 k^2}{2m^*}$$



3D-DOS (Volumetric)

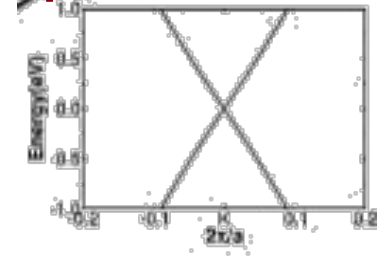
$$D(E) = \frac{1}{2\pi^2} \left(\frac{2m^*}{\hbar^2} \right)^{3/2} \sqrt{E - E_c}$$

2D

$$D(k) = 4 \frac{(2\pi k) dk}{(2\pi/L)^2 A} = \frac{2k dk}{\pi}$$

Linear Dispersion

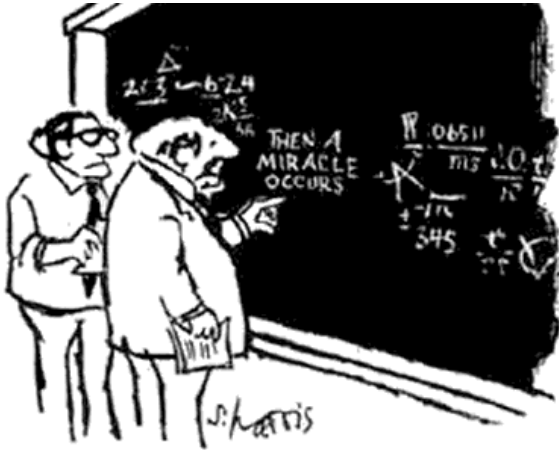
$$E - E_c = \hbar v_f k$$



2D-Linear-DOS (Areal)

$$D(E) = \frac{2(E - E_c) dE}{\pi(\hbar v_f)^2}$$

Number of Charge Carriers



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

$$n = \int D(E) f_f(E) dE$$

3D-Parabolic

$$n = N_c F_{1/2} \left(-\frac{E_c - E_f}{k_B T} \right)$$

2D-Linear

$$n = N_{c,g} F_1 \left(-\frac{E_c - E_f}{k_B T} \right)$$

$$N_c = 2 \left(\frac{m^* k_B T}{2\pi \hbar^2} \right)^{3/2}$$

$$N_{c,g} = \left(\frac{2^{1/2} k_B T}{\pi^{1/2} \hbar v_f} \right)^2$$

Challenge: How does the number of carriers compare in graphene vs. traditional semiconductors?

Team Silicon

Bandgap= 1.1eV
Effective mass=1.08 m_0

Team Graphite

Bandgap= 0 eV
Effective mass=0.043 m_0

Team Graphene

Bandgap= 0 eV
Effective mass=0 m_0

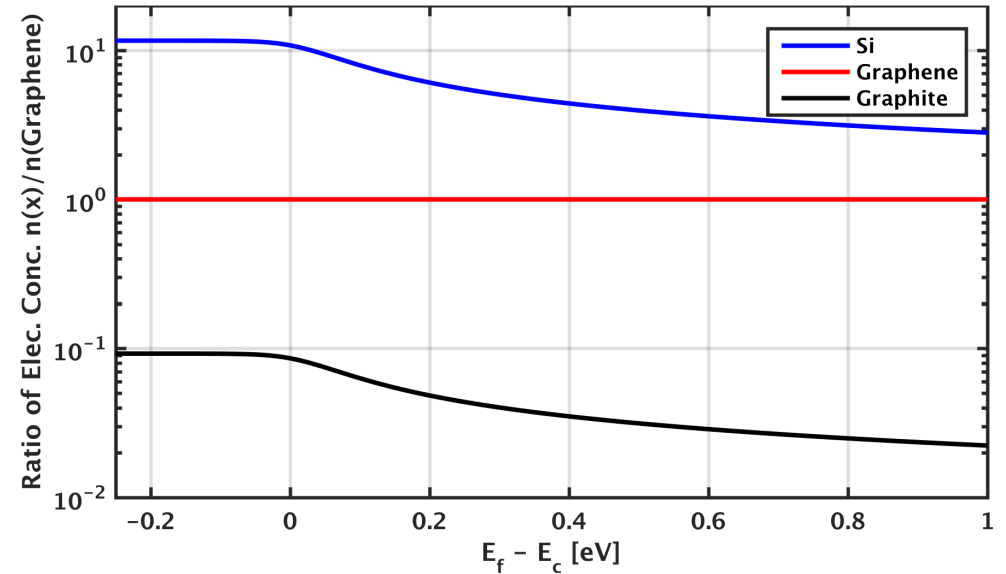
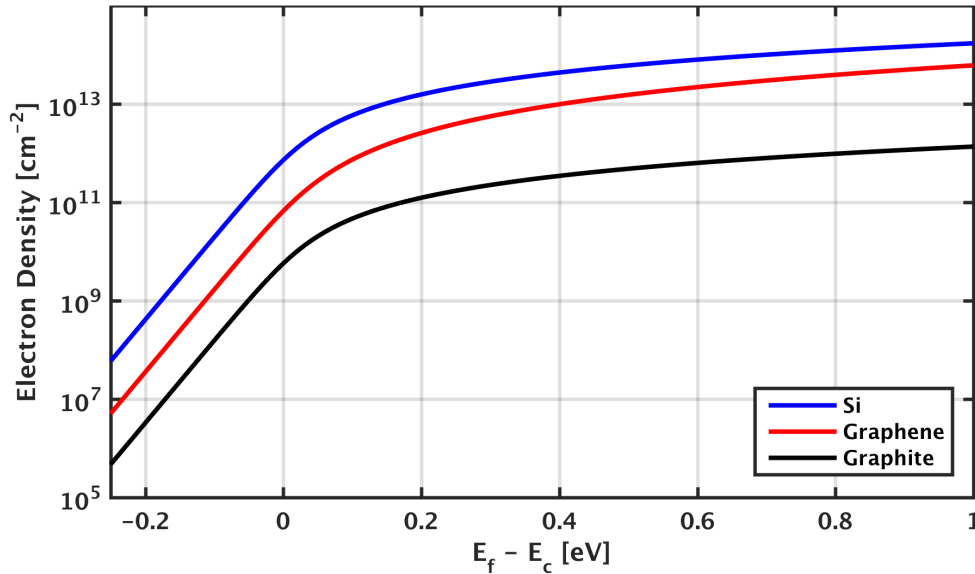
Dora's Backpack

Thickness of Si and Graphite is 0.335 nm

Assume Fermi-level starts at -0.2 eV below E_c and goes to 0.75 eV

Temperature= 4, 77, and 300K

Number of Charge Carriers

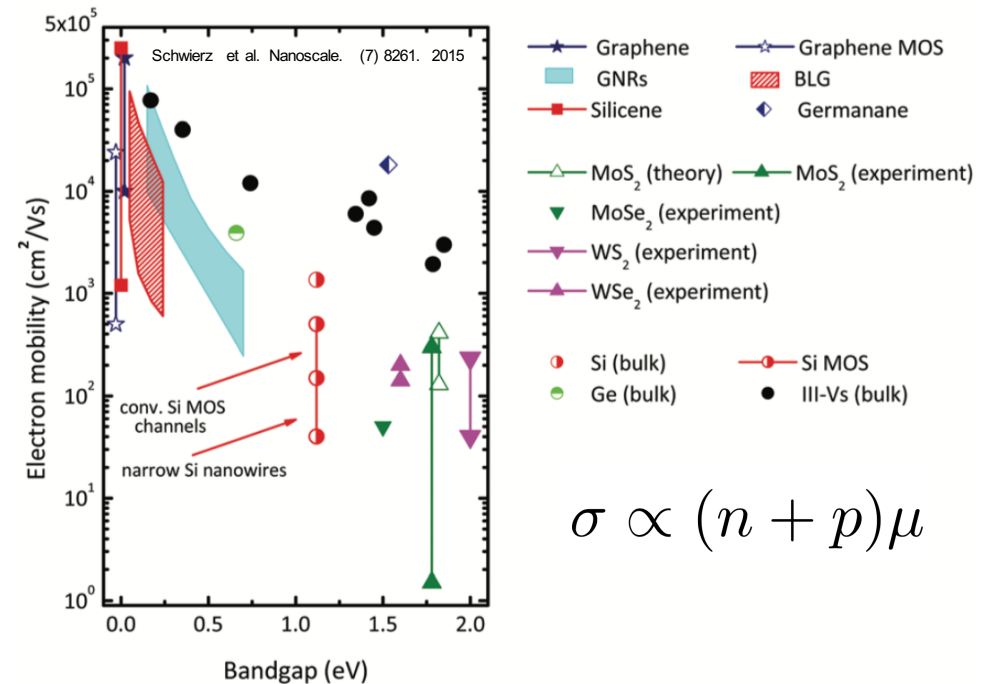


Good News

- Lower electron concentration
- High electron mobility
- High hole mobility

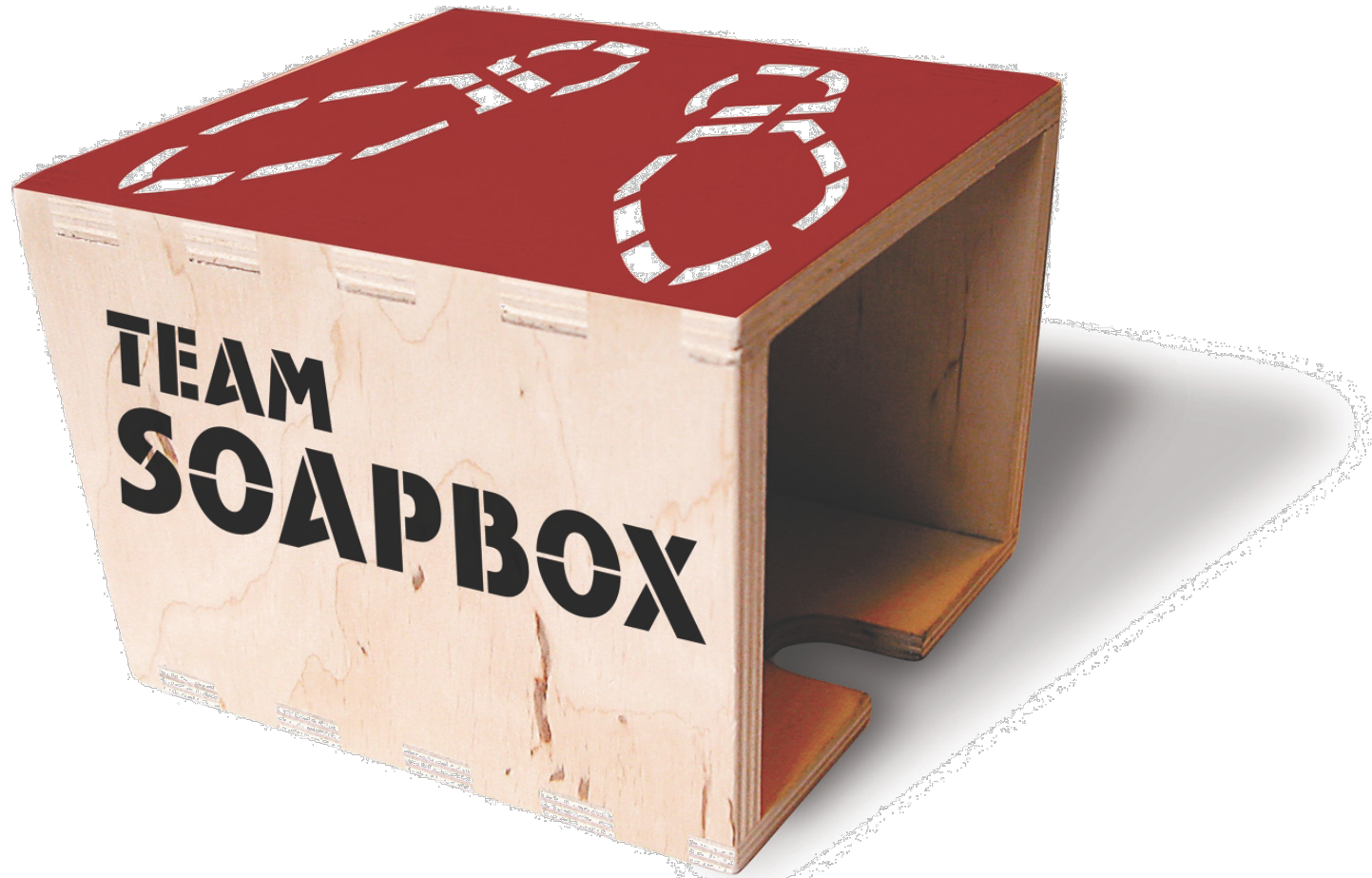
Bad News

- Lower electron concentration
- High mobility **SOMETIMES**
- See above



$$\sigma \propto (n + p)\mu$$

Electrical: Is graphene good for this?



Critical Questions


1. What mobility do I need for it to work?
2. Is it an **intensive** or **extensive** application?
3. Does graphene offer something "else" that I can't get otherwise?

Learning Objectives

I want you to understand...

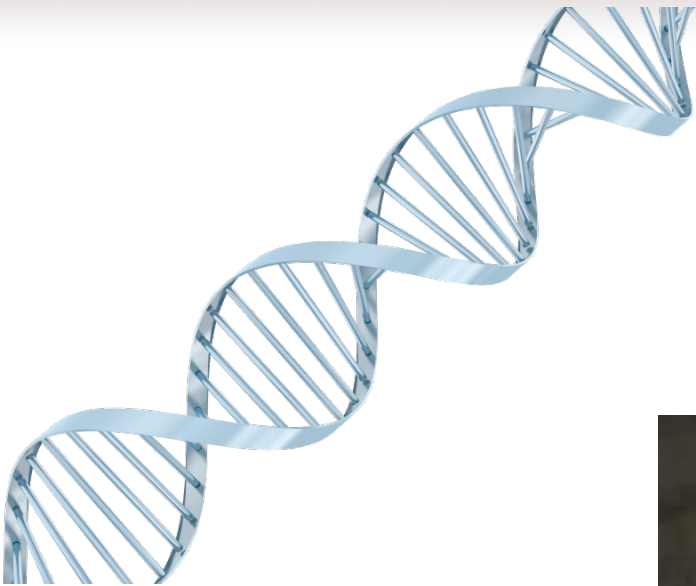
1. what graphene is and why everybody's excited
2. the origin of graphene's electrical, thermal, and optical properties
3. how to sift hype from reality for graphene and other wonder materials

Key Takeaways thus far

1. Periodicity, Bandstructure Property
 2. Difference between graphene and graphite
 3. Graphene Bandstructure: 2D-DOS & Linear Bands
-
- 

What makes me, me?

Genetic, Intrinsic

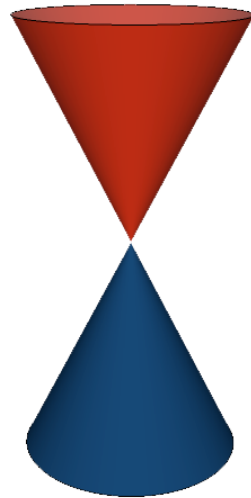
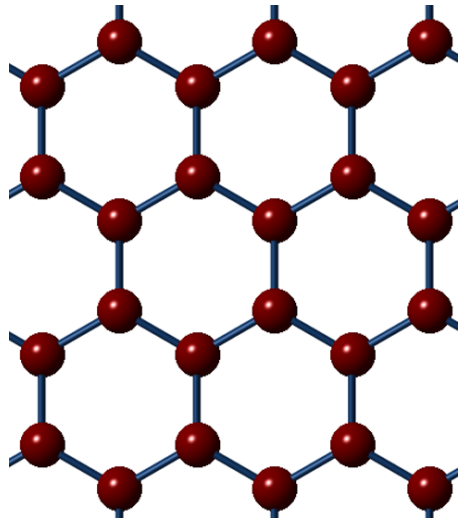


Environment

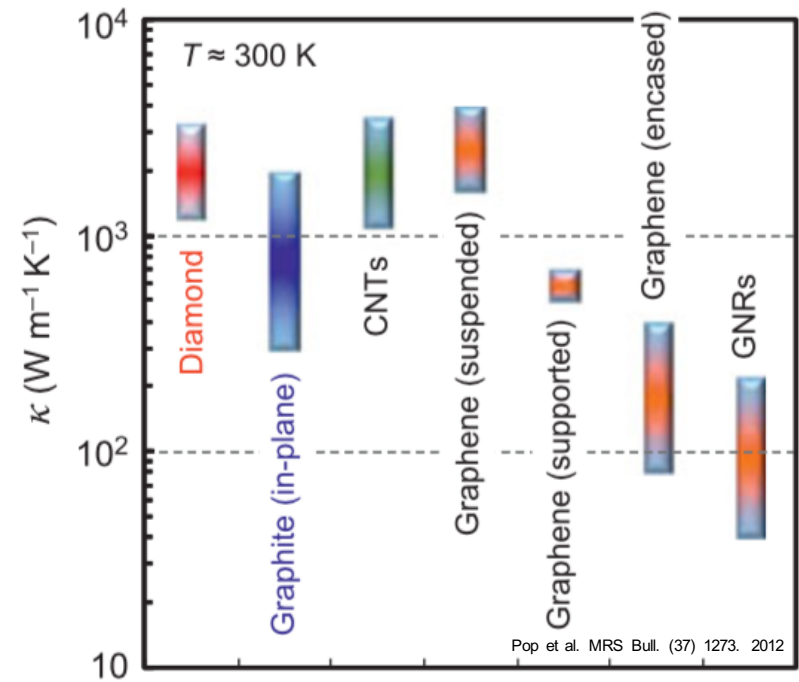
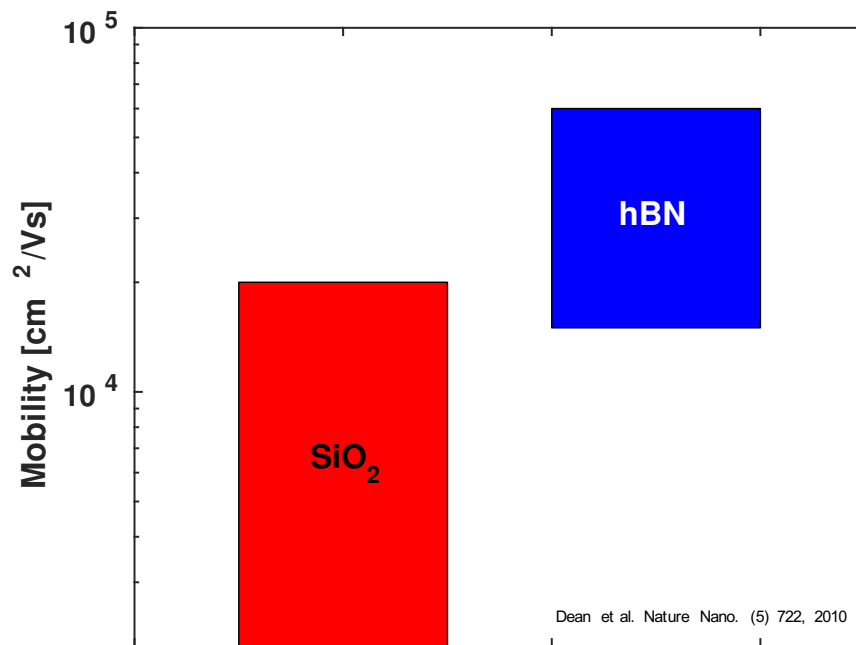


Takeaway: We are who we are **AND** what we're around.

Env.: Graphene & Peer Pressure

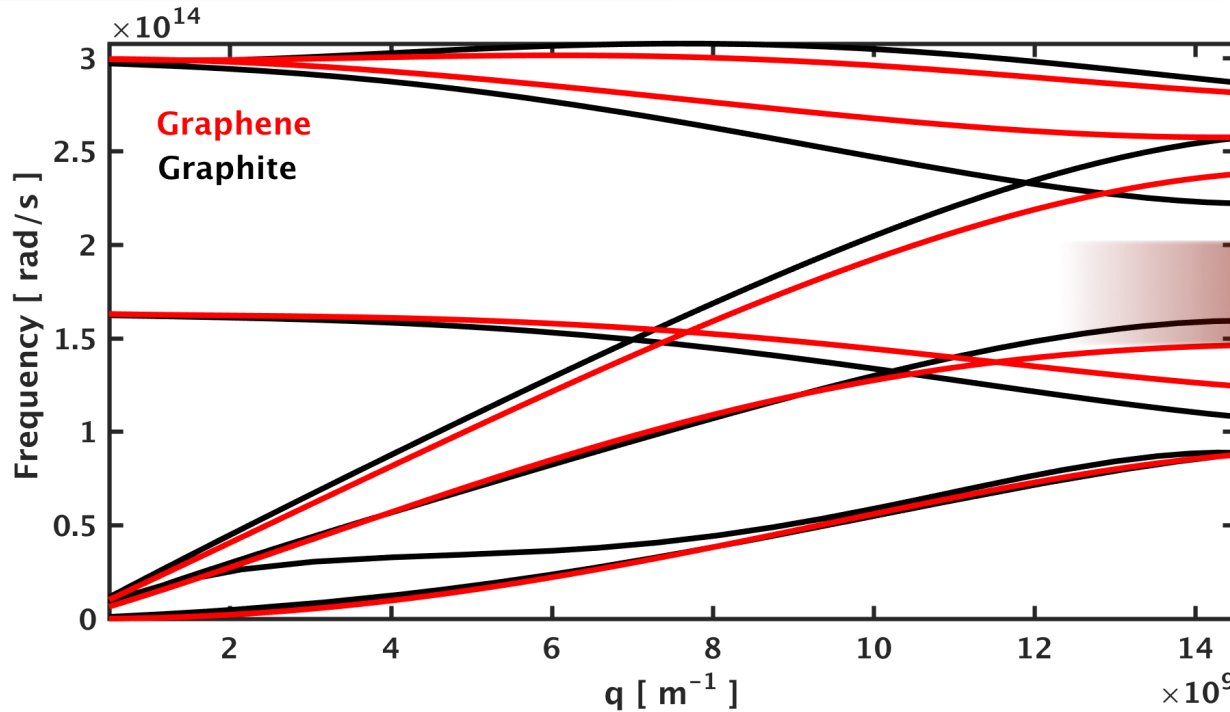
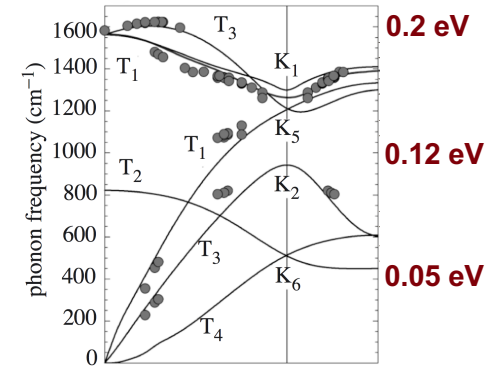
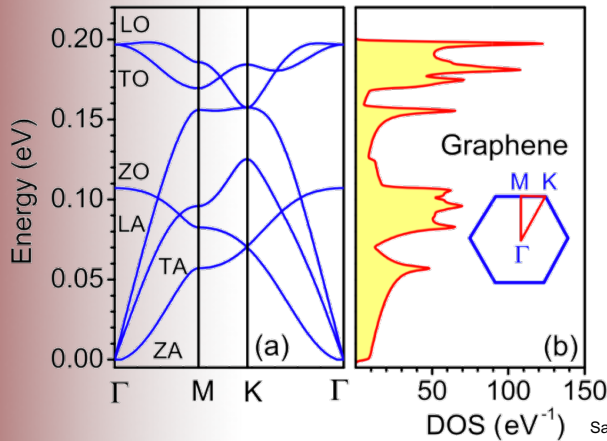


D.A.R.E.[®]



Lattice Bandstructure: Thermal

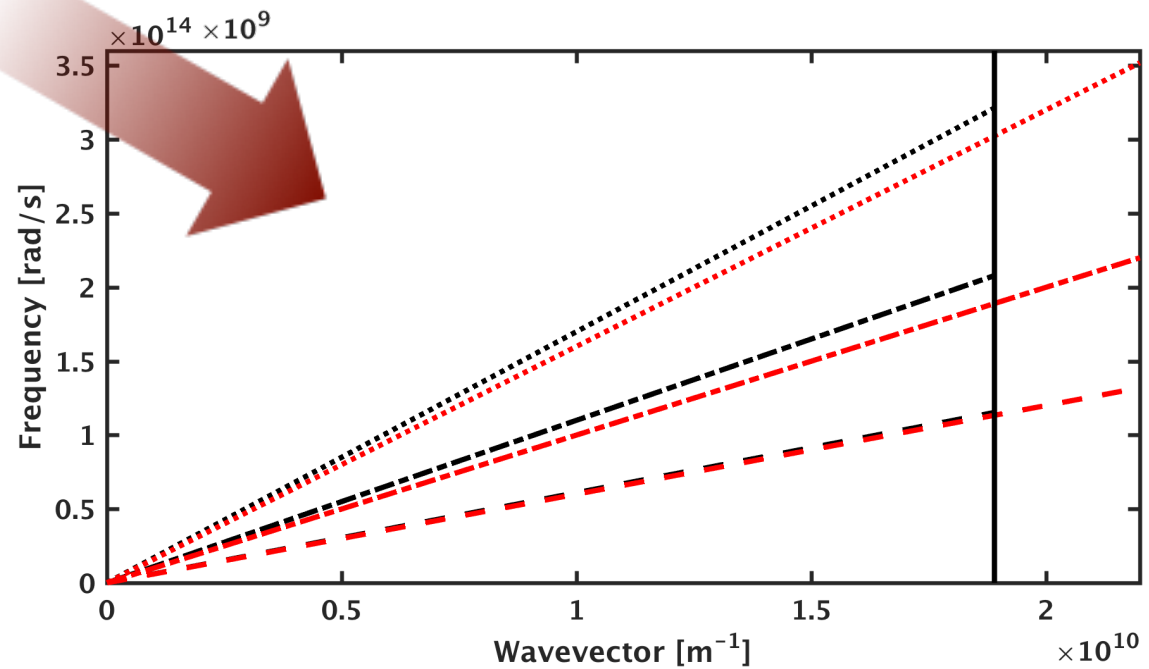
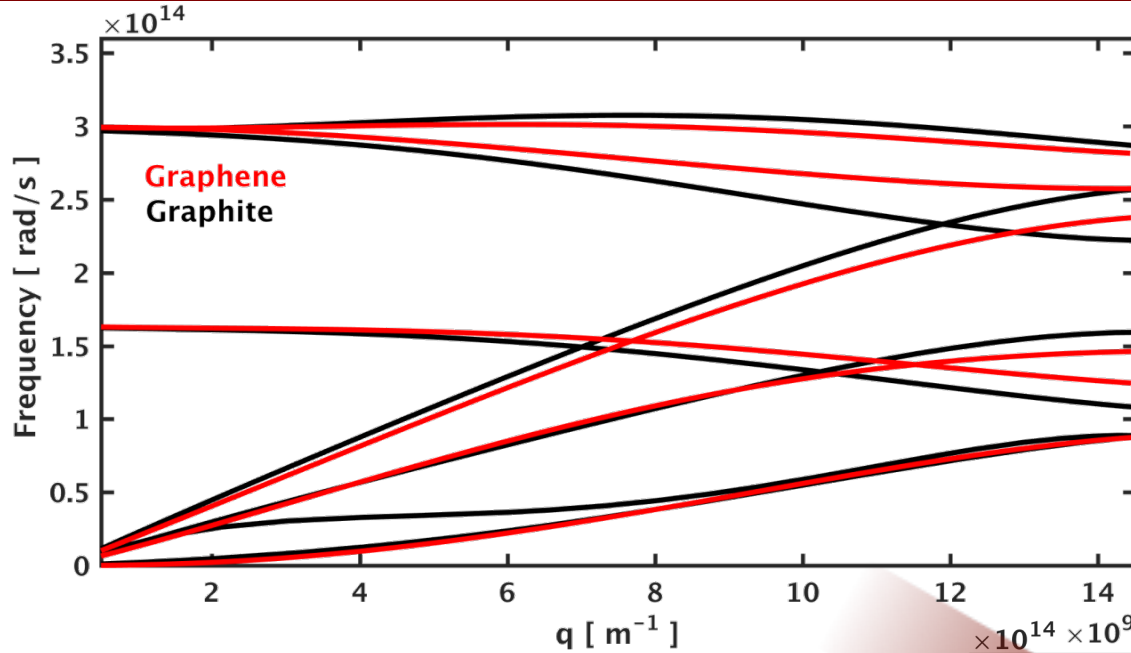
Lattice



$$k = \sum_i C_i v_i \Lambda_i$$

Question: Why is graphene's thermal conductivity sometimes more & sometimes less than graphite?

Number of Heat Carriers: Debye



Number of Heat Carriers

$$n = \sum_i^3 \int_0^{\omega_{i,max}} D(\omega) f_{BE}(\omega) d\omega$$

3D

$$D(k) = \frac{4\pi k^2 dk}{(2\pi/L)^3 V} = \frac{k^2 dk}{2\pi^2}$$

3D-Debye

$$\omega = v_i k$$

3D-DOS (Volumetric)

$$D(\omega) = \frac{\omega^2 d\omega}{v_i^3 \pi^2}$$

Max. Frequency

$$\omega_{i,max} = v_i k_{max}$$

Max. Wavevector

$$q_{max} = (6\pi^2 n_o)^{1/3}$$

2D

$$D(k) = \frac{2\pi k dk}{(2\pi/L)^2 A} = \frac{k dk}{2\pi}$$

2D-Debye

$$\omega = v_i k$$

2D-DOS (Areal)

$$D(\omega) = \frac{\omega d\omega}{v_i^2 2\pi}$$

Max. Frequency

$$\omega_{i,max} = v_i k_{max}$$

Max. Wavevector

$$q_{max} = (4\pi n_o^*)^{1/2}$$

Number of Heat Carriers

Challenge: How many phonons exist in each Debye branch for graphene and graphite

Parameter	Graphene	Graphite
n_0 [atoms/cm ²⁽³⁾]	3.85e15	1.14e23
v_1 [Km/s]	16	17
v_2 [Km/s]	10	11
v_3 [Km/s]	6	6

$$n = \sum_i^3 \int_0^{\omega_{i,max}} D(\omega) f_{BE}(\omega) d\omega$$

3D

$$D(k) = \frac{4\pi k^2 dk}{(2\pi/L)^3 V} = \frac{k^2 dk}{2\pi^2}$$

3D-Debye

$$\omega = v_i k$$

3D-DOS (Volumetric)

$$D(\omega) = \frac{\omega^2 d\omega}{v_i^3 \pi^2}$$

Max. Frequency

$$\omega_{i,max} = v_i k_{max}$$

Max. Wavevector

$$q_{max} = (6\pi^2 n_o)^{1/3}$$

2D

$$D(k) = \frac{2\pi k dk}{(2\pi/L)^2 A} = \frac{k dk}{2\pi}$$

2D-Debye

$$\omega = v_i k$$

2D-DOS (Areal)

$$D(\omega) = \frac{\omega d\omega}{v_i^2 2\pi}$$

Max. Frequency

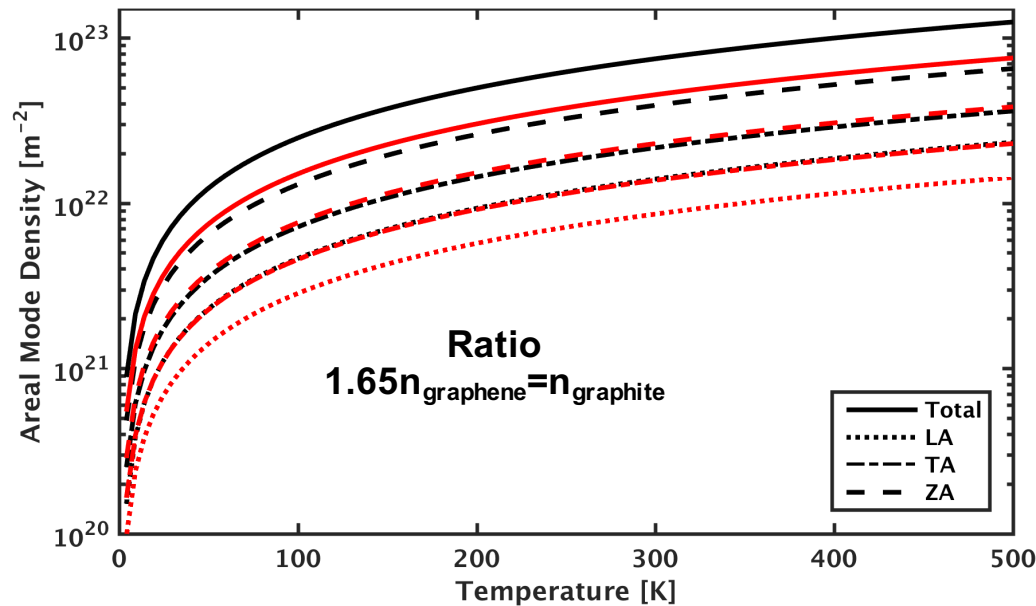
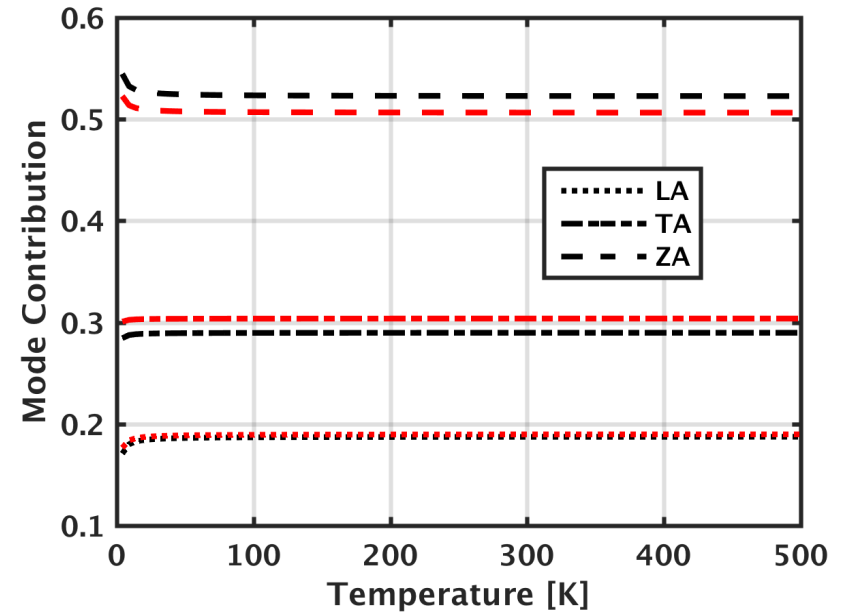
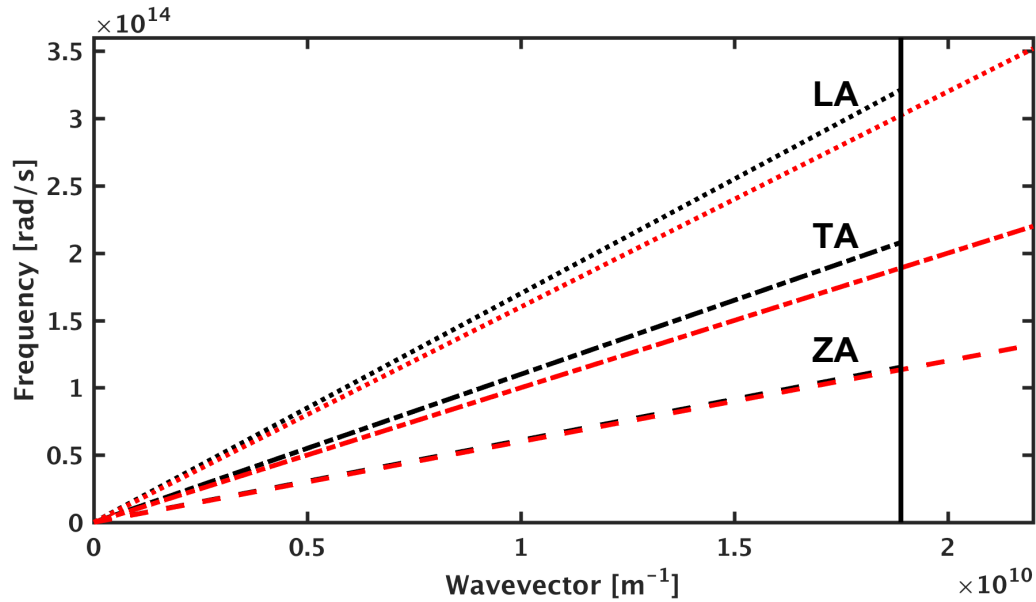
$$\omega_{i,max} = v_i k_{max}$$

Max. Wavevector

$$q_{max} = (4\pi n_o^*)^{1/2}$$

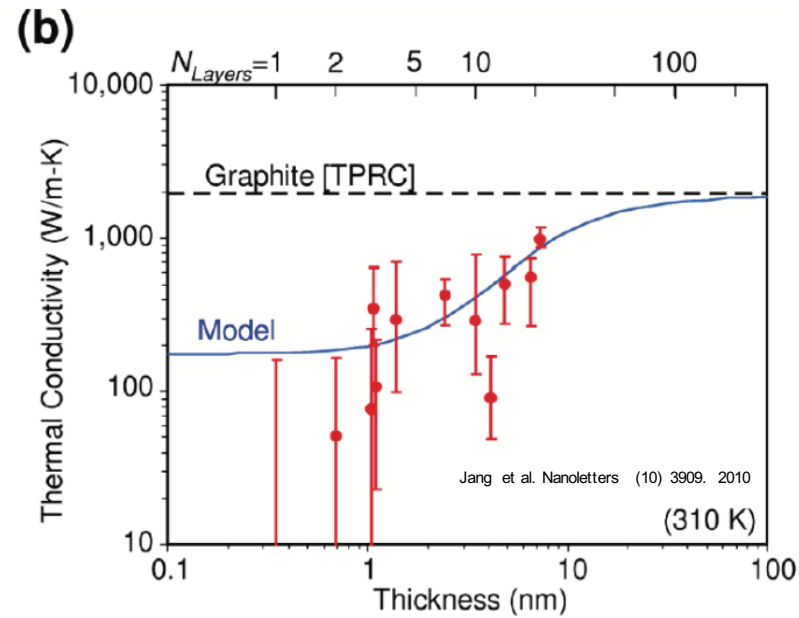
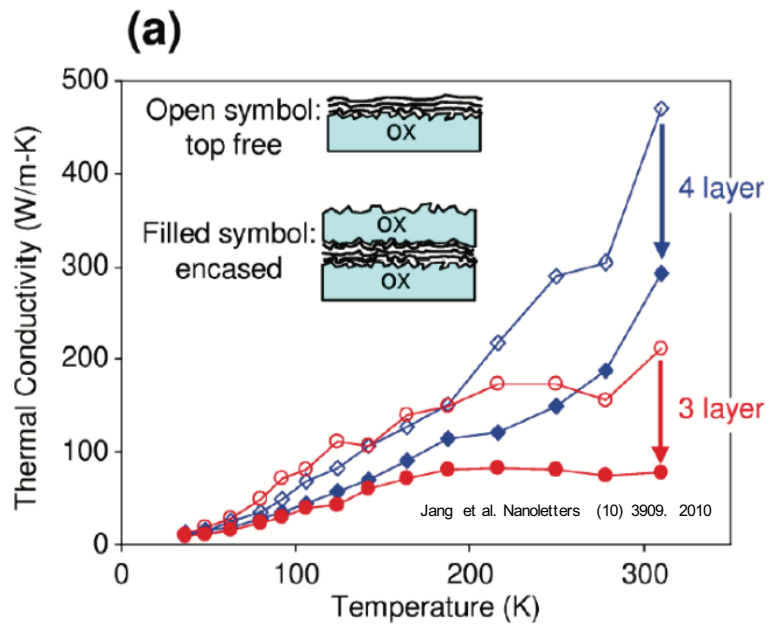
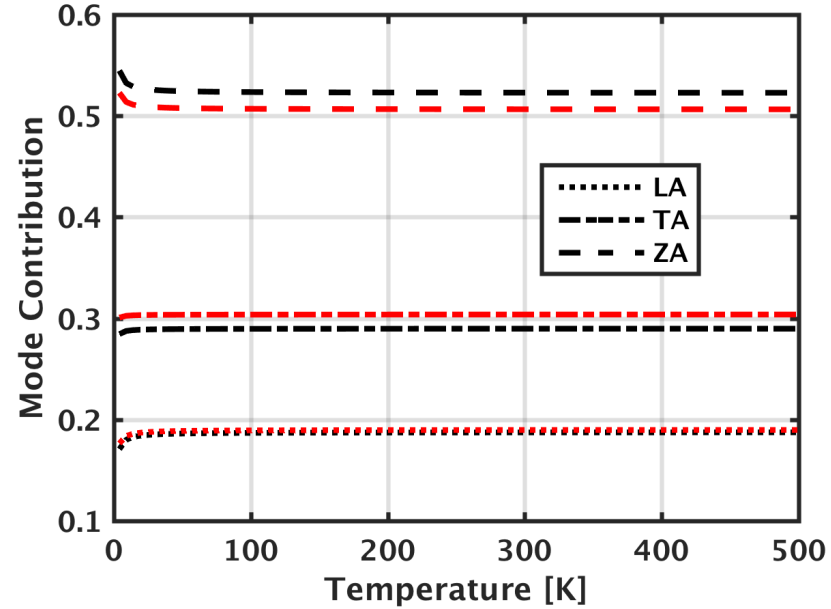
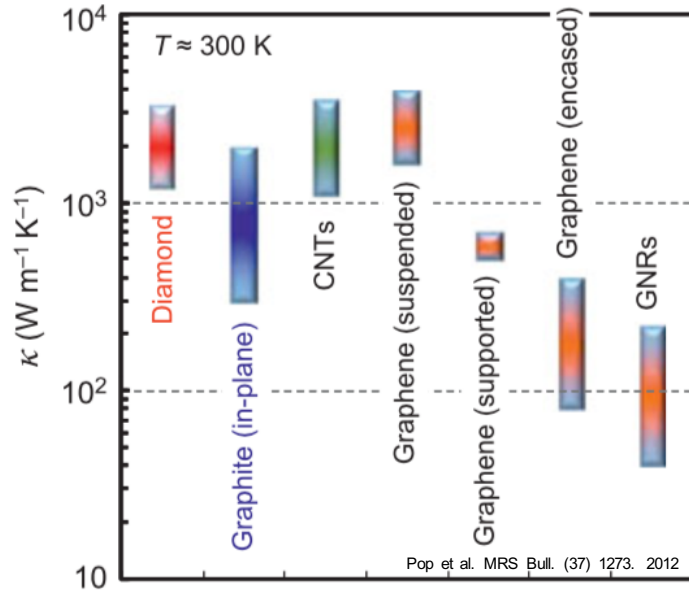
Challenge: What happens if you remove the v_3 branch in graphene?

Number of Heat Carriers

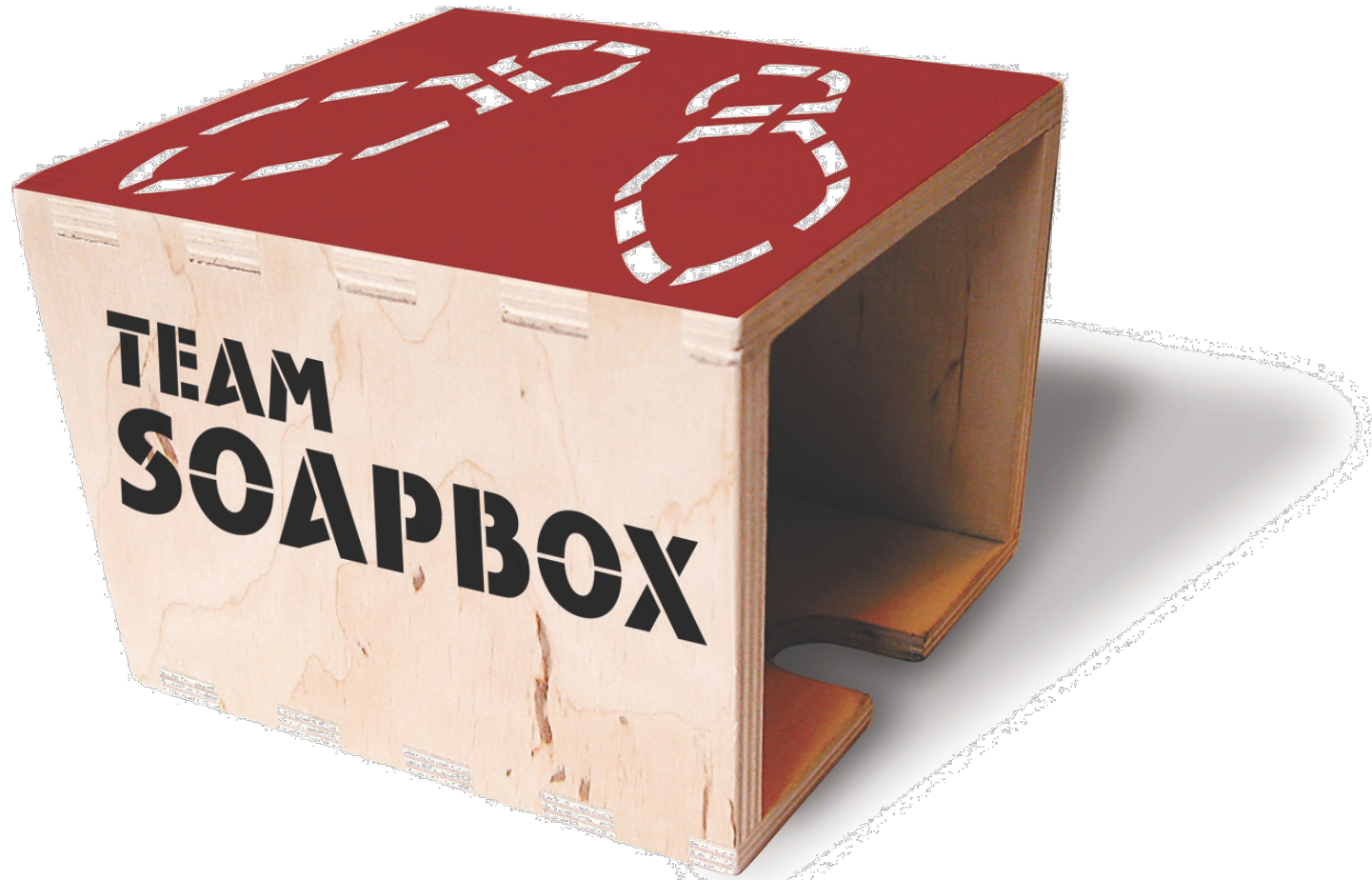


Question:
Out of plane mode is biggest contributor. Is that bad?

Thermal Properties



Thermal: Is graphene good for this?



Critical Questions


1. Is the graphene touching anything?
2. Is it an **intensive** or **extensive** application?
3. No...Just No...It's not a thermal solution.

Learning Objectives

I want you to understand...

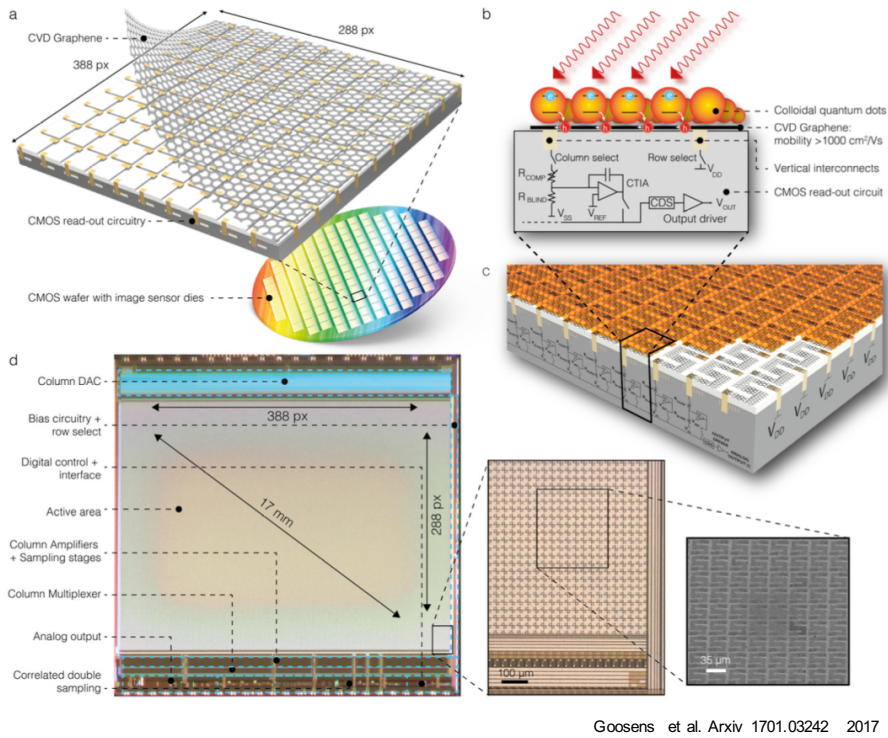
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2. the origin of graphene's electrical, thermal, and optical properties
3. how to sift hype from reality for graphene and other wonder materials

Key Takeaways thus far

1. Periodicity, Bandstructure Property
 2. Difference between graphene and graphite
 3. Bandstructure: 2D-DOS & Linear Bands
 4. Bandstructure: Debye Solid & the impact of ZA
 5. Impact of surroundings on properties
-
- 

Can Graphene See?

Graphene Digital Camera



Question: Why is graphene a promising optical material?

Optical: Controlling Transitions

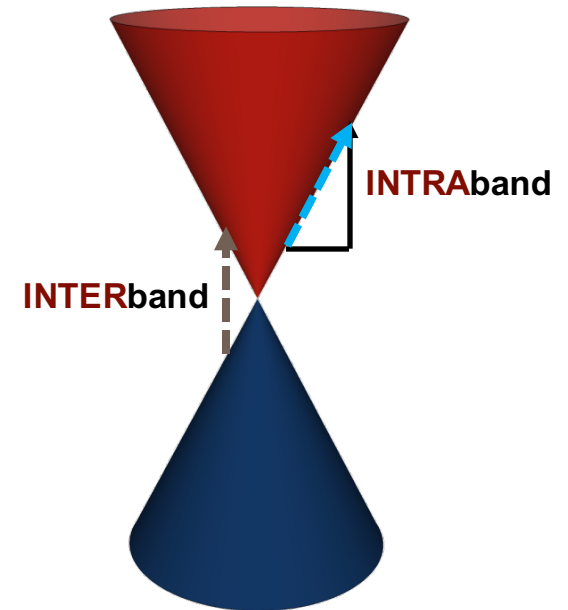
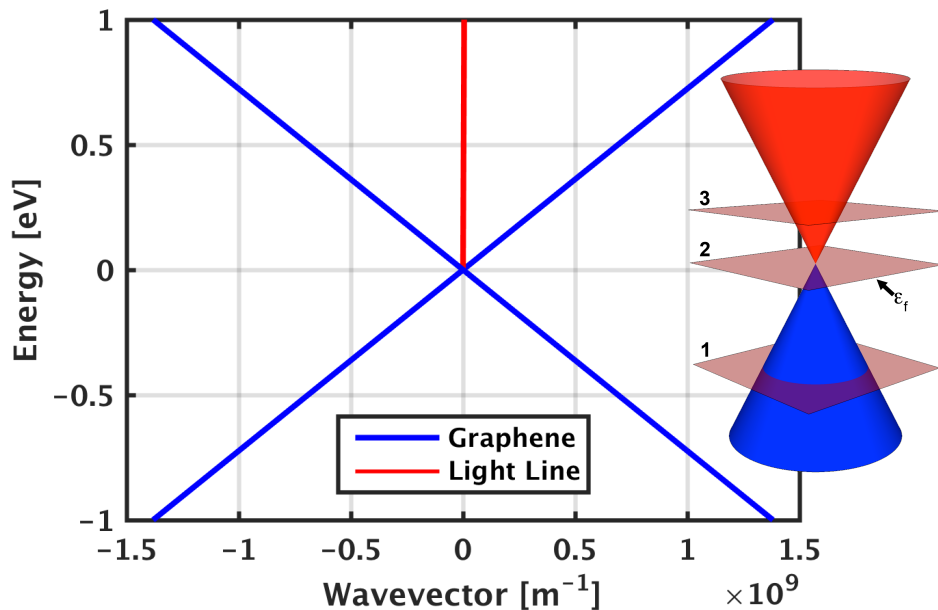
PREMISE: Must conserve energy and momentum to create an optical transition

Graphene Dispersion

$$E - E_c = \hbar v_f k$$

Photon Dispersion

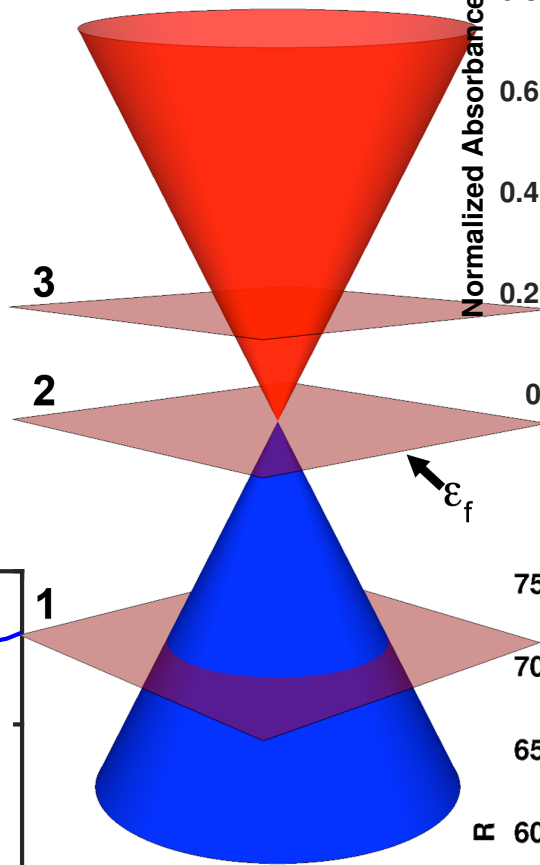
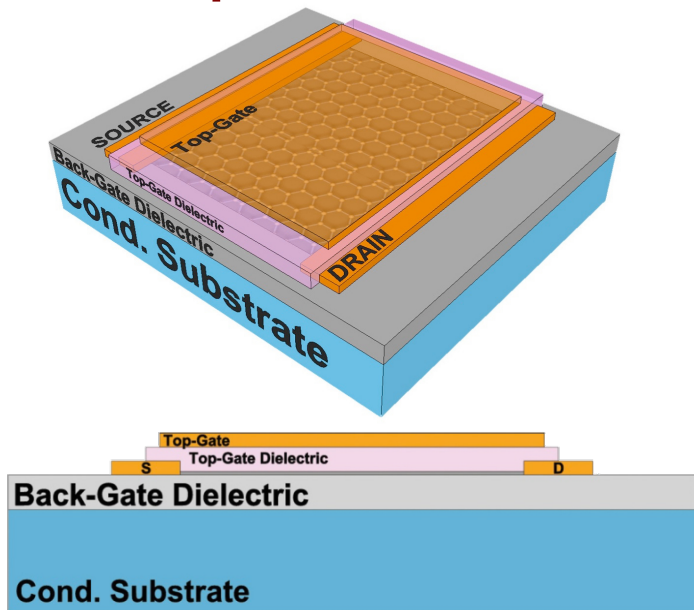
$$E = \hbar c k = \frac{hc}{\lambda}$$



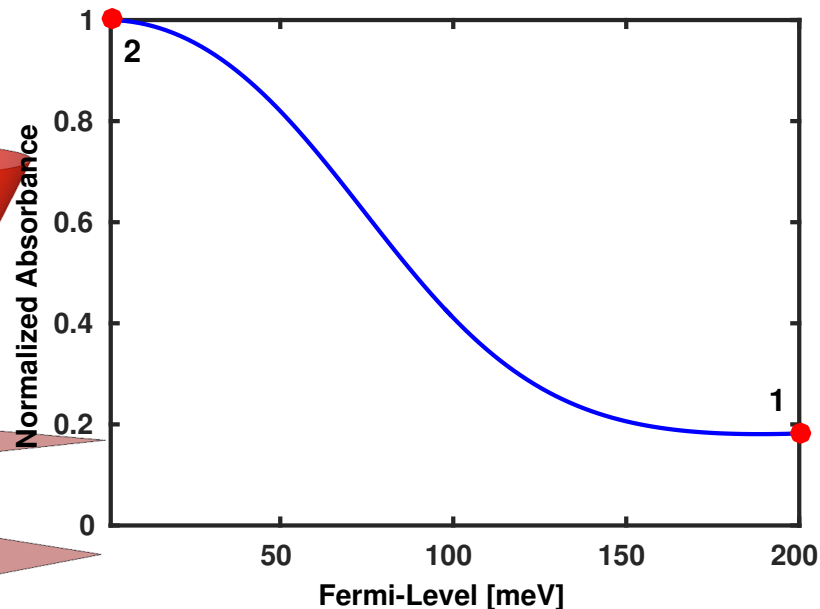
Question:
What happens when
Fermi-level changes?

Optical: Controlling Transitions

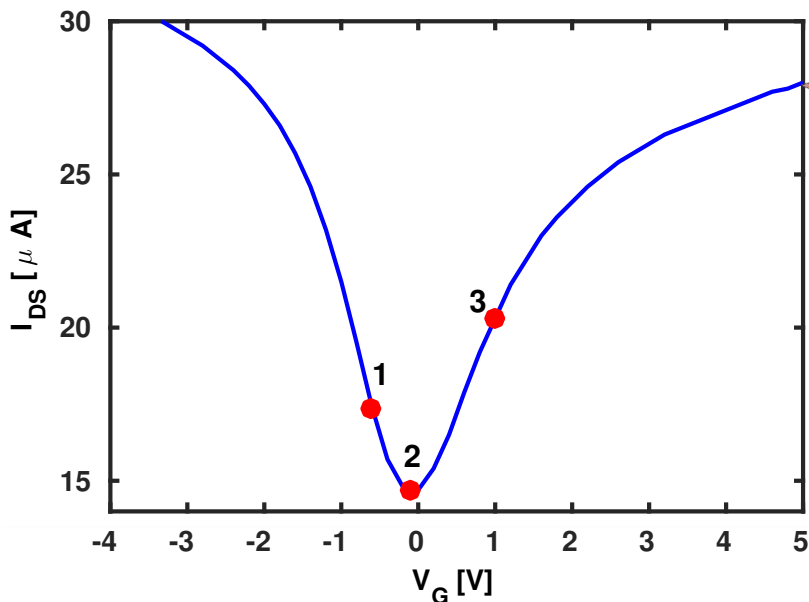
Graphene Transistor



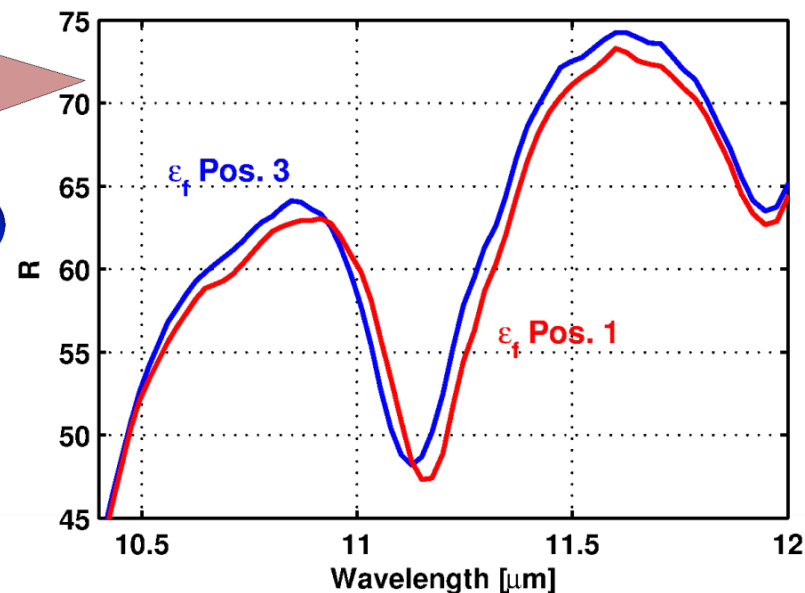
Tunable Absorber



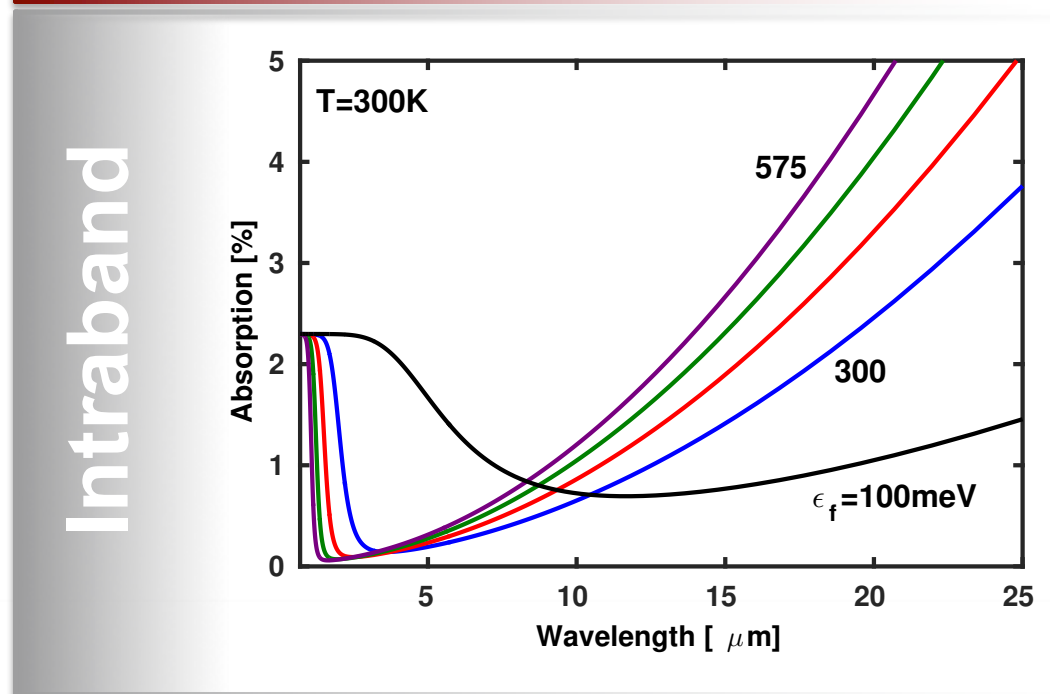
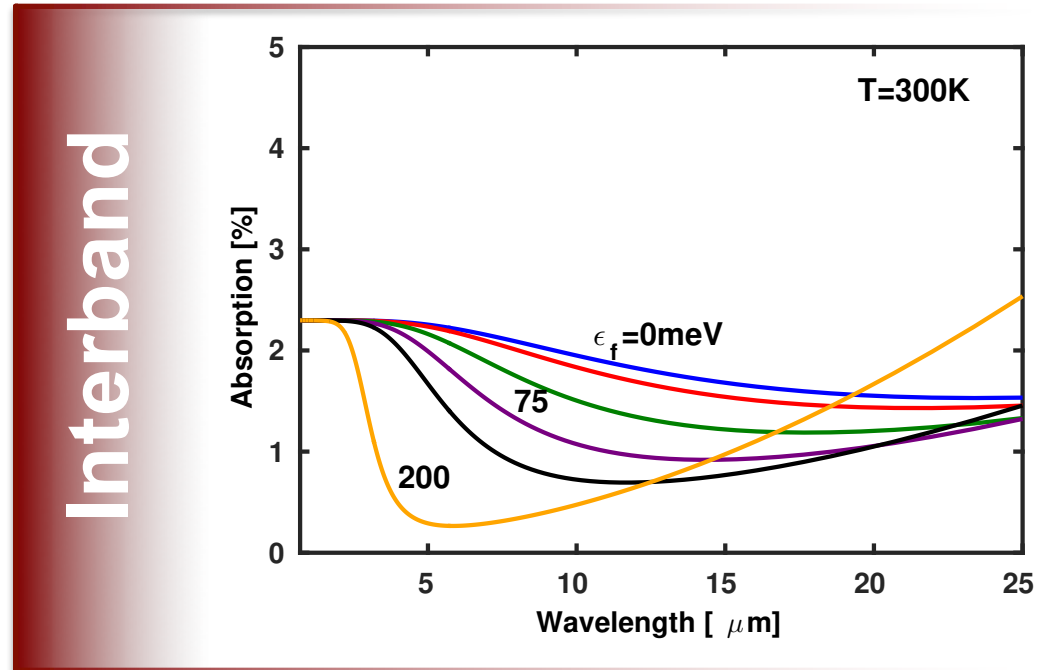
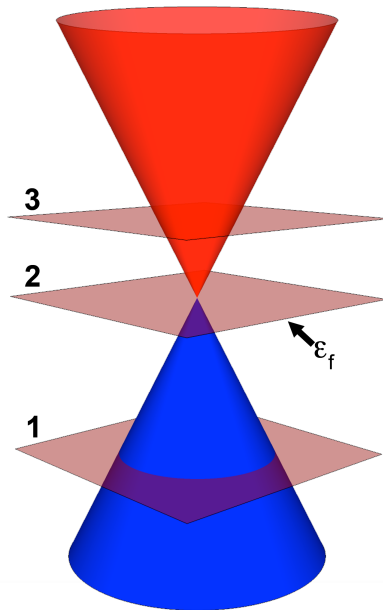
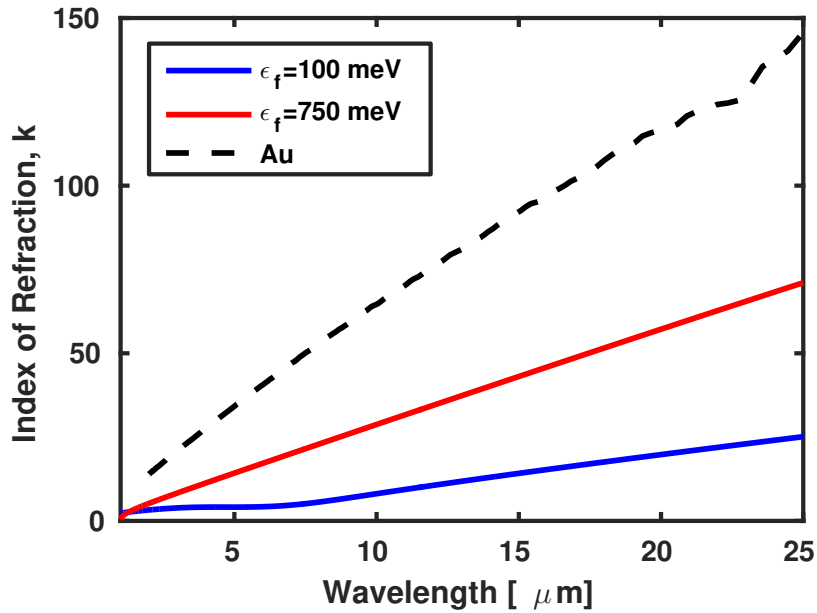
Tunable Resistance



Tunable Nanoantenna



Myth: Graphene Absorbs 2.3%



Optical Counting Transitions

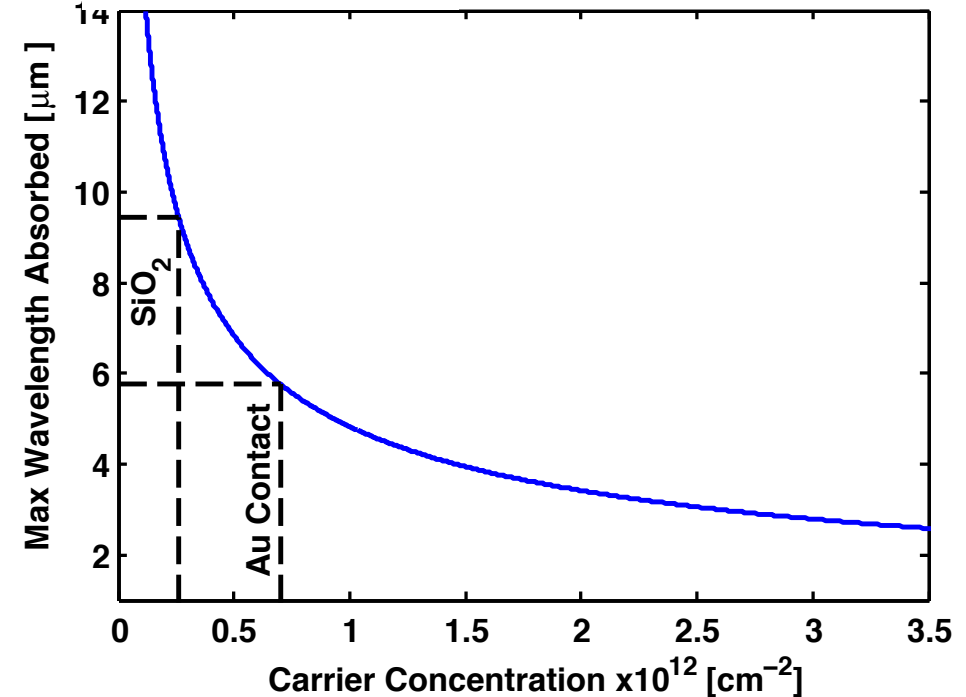
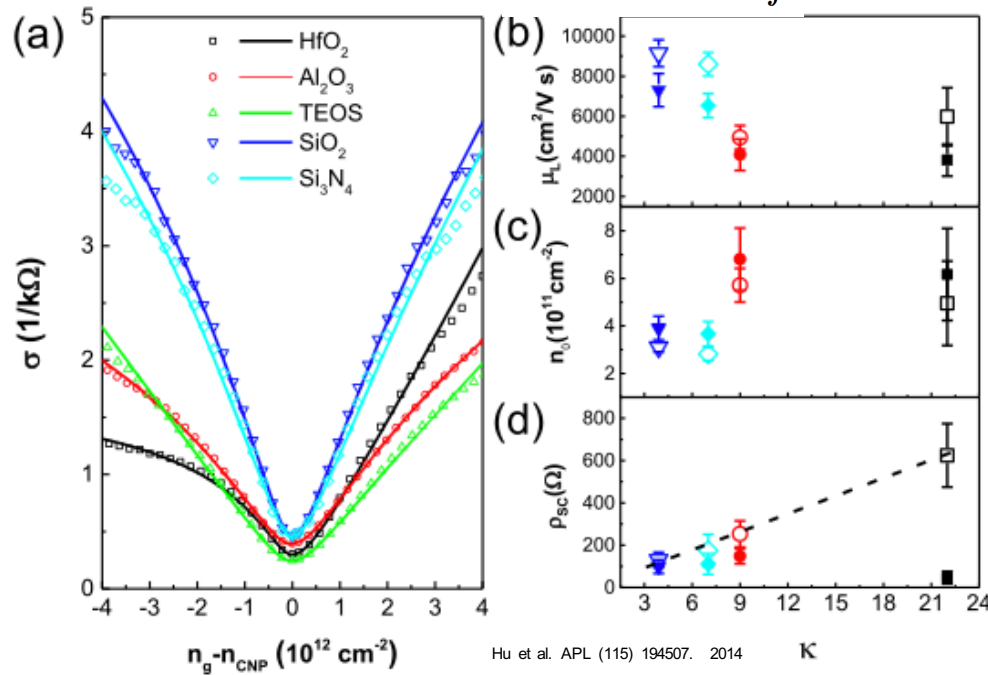
Challenge: How much charge can I have & still absorb 500 nm, 1 μm, 10 μm?

"Absorbable" Light

$$\lambda_{max} = \frac{hc}{2\epsilon_f}$$

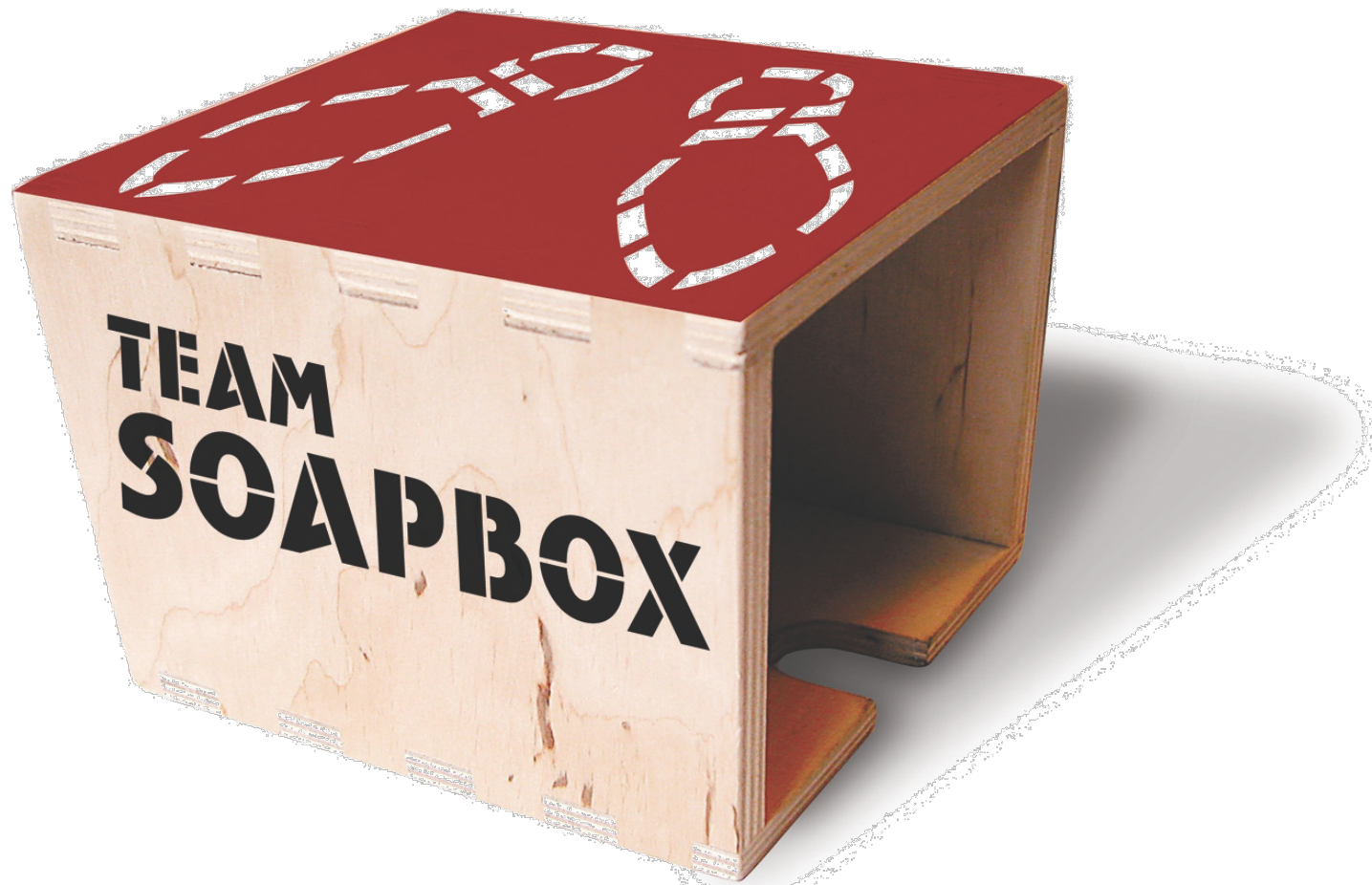
Fermi-Level & Charge

$$\epsilon_f = \frac{h\nu_f}{2\pi} \sqrt{\pi n}$$



Takeaway: You don't get all your Fermi-levels in real life.

Optical: Is graphene good for this?



Critical Questions


1. Does the wavelength match my Fermi-levels?
2. How much absorption do I really need?
3. Can another material do the same thing?

Learning Objectives

I want you to understand...

- 1. what graphene is and why everybody's excited**
- 2. the origin of graphene's electrical, thermal, and optical properties**
- 3. how to sift hype from reality for graphene and other wonder materials**

Key Takeaways

- 1. Periodicity, Bandstructure Property**
 - 2. Difference between graphene and graphite**
 - 3. Bandstructure: 2D-DOS & Linear Bands**
 - 4. Bandstructure: Debye Solid & the impact of ZA**
 - 5. Impact of surroundings on properties**
 - 6. Differentiation from other materials**
-
- 

“Brands” of Graphene

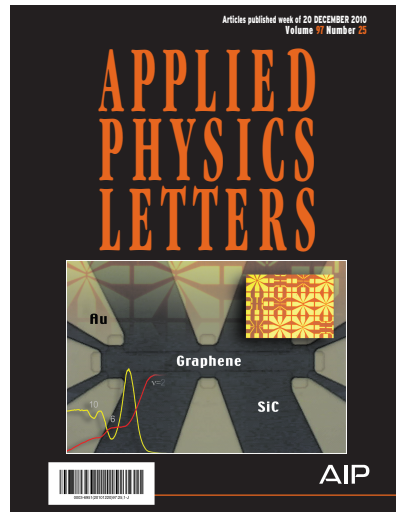
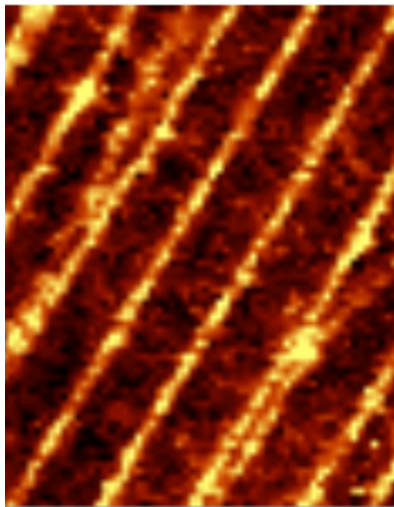
Exfoliated



Copper Based CVD



Epitaxial on SiC



Twisted Bilayer Graphene

