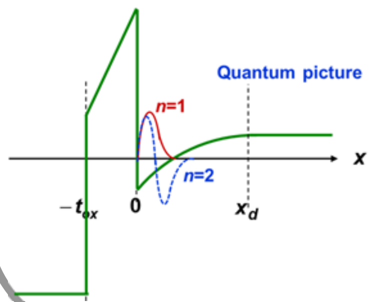
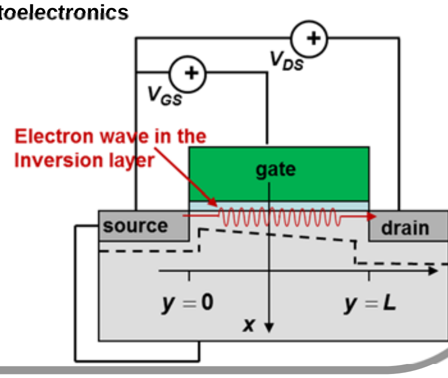
Lecture 27

New Materials and New Physics at the Nano-Scale

In this lecture you will learn:

- New physics at the nano-scale
- Quantum physics and the FETs
- New materials for electronics and optoelectronics



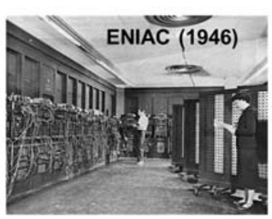


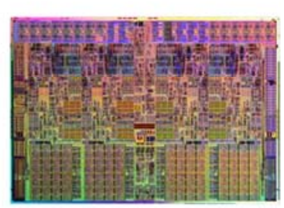
What is Nano-Technology?

Two ways to look at Nanotechnology:

1) Take what is large and make it very small in order to:

- increase number of components/transistors/functionality in a chip
- reduce cost
- increase revenues

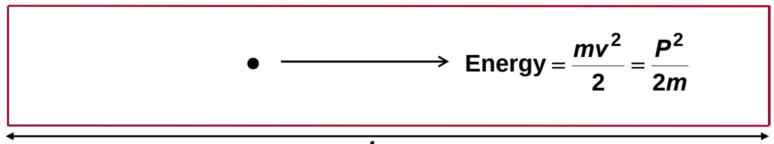




2) New science and new physics emerges at the very small scales.
This new science can be used to design novel devices and components with functionalities not available in larger scale models

Quantum Physics and Matter

Electron confined in Large box:



$$\text{Energy} = \frac{mv^2}{2} = \frac{P^2}{2m}$$

Quantum Physics:

Electron behaves like a wave

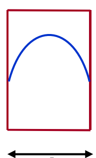
And the wavelength is related to its momentum *P* as:

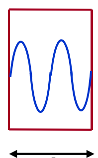
$$P = \hbar \frac{2\pi}{\lambda}$$

Plank's constant:

$$\hbar = 1.05458 \times 10^{-34} \ \text{Joule} - \text{Sec}$$

Electron confined in small box:





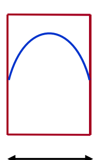
Electron wavelength must fit in the box

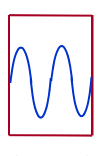
$$L = n\frac{\lambda}{2}$$

$$\{n = 1,2,3 \cdots\cdots$$

Quantum Physics and Matter

Electron confined in small box:





Electron wavelength must fit in the box:

$$L = n\frac{\lambda}{2}$$

$$\Rightarrow \lambda = \frac{2L}{n}$$

$$\{n = 1,2,3 \cdots\cdots$$

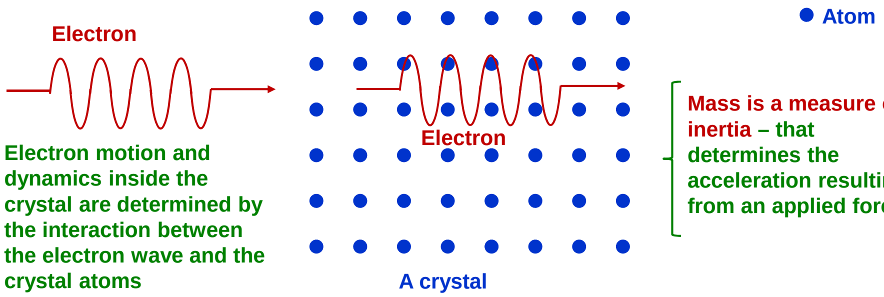
$$\text{Momentum} = P = \hbar \frac{2\pi}{\lambda}$$

$$\text{Energy} = \frac{P^2}{2m} = \frac{(\hbar)^2}{2m}\left(\frac{2\pi}{\lambda}\right)^2$$

$$= \frac{(\hbar)^2}{2m}\left(n\frac{\pi}{L}\right)^2$$

The momentum and the energy of the electron confined in a small box are "quantized" – they can only have discrete values

Mass and Dynamics of Electrons in Solids



Electron motion and dynamics inside the crystal are determined by the interaction between the electron wave and the crystal atoms

Mass is a measure of inertia – that determines the acceleration resulting from an applied force

Outside the crystal, in free-space, electron has a mass m_o

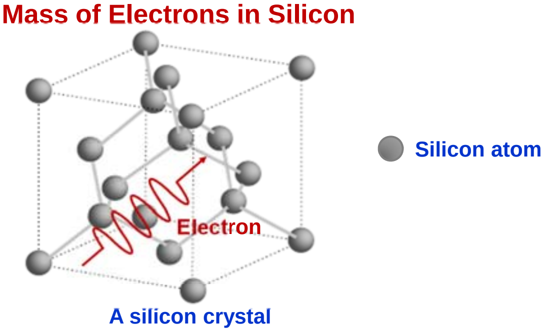
$$m_o = 9.1\times10^{-31}\ \text{kg} \longrightarrow \text{K.E} = \frac{1}{2}m_o v^2 = \frac{1}{2}m_o\left(v_x^2 + v_y^2 + v_z^2\right)$$

Inside the crystal, electrons can have different masses in different directions that are very different from the electron mass in free-space:

$$\text{K.E} = \frac{1}{2}\left(m_x v_x^2 + m_y v_y^2 + m_z v_z^2\right)$$

Electrons can "appear" heavier when moving in some directions and "lighter" when moving in other directions as a result of the interaction of the electron wave with the atoms

Mass of Electrons in Silicon



There are 6 different kinds of electrons in silicon:

1,2: $\text{K.E} = \frac{1}{2}\left(m_\ell v_x^2 + m_t v_y^2 + m_t v_z^2\right)$

3,4: $\text{K.E} = \frac{1}{2}\left(m_t v_x^2 + m_\ell v_y^2 + m_t v_z^2\right)$

5,6: $\text{K.E} = \frac{1}{2}\left(m_t v_x^2 + m_t v_y^2 + m_\ell v_z^2\right)$

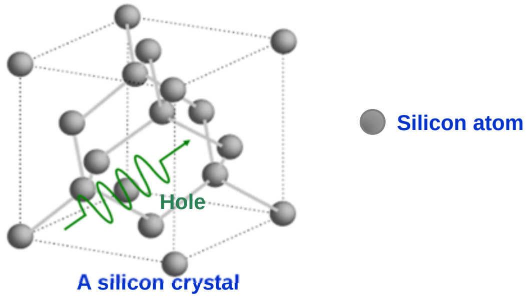
$m_\ell = 0.92\ m_o$

$m_t = 0.19\ m_o$

Small mass is better for higher mobility:

$$\mu_n = \frac{q\tau_n}{m_n}$$

Mass of Holes in Silicon



Inside the silicon crystal, holes can also have different masses

There are two different kinds of holes in silicon:

1: $$\text{K.E} = \frac{1}{2} m_{\ell h}\left(v_x^2 + v_y^2 + v_z^2\right)$$

2: $$\text{K.E} = \frac{1}{2} m_{hh}\left(v_x^2 + v_y^2 + v_z^2\right)$$

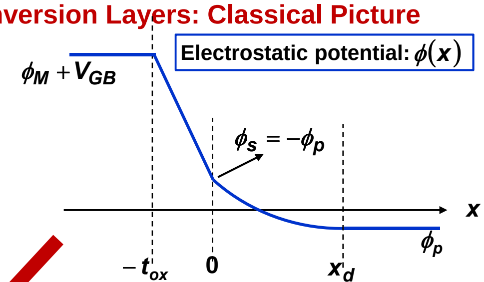
$$m_{\ell h} = 0.16\, m_o$$
$$m_{hh} = 0.49\, m_o$$

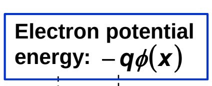
Small mass is better for higher mobility:

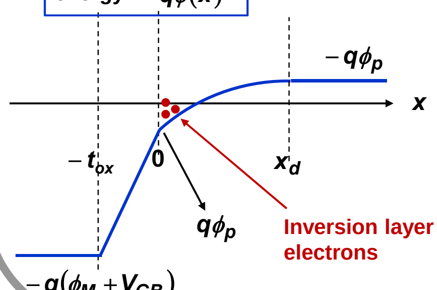
$$\mu_p = \frac{q\tau_p}{m_p}$$

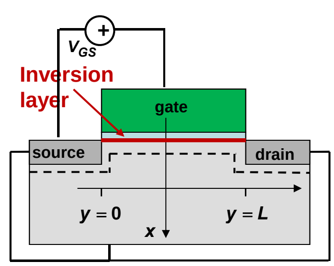
Electrons in FET Inversion Layers: Classical Picture

The classical picture of electrons in an inversion layer

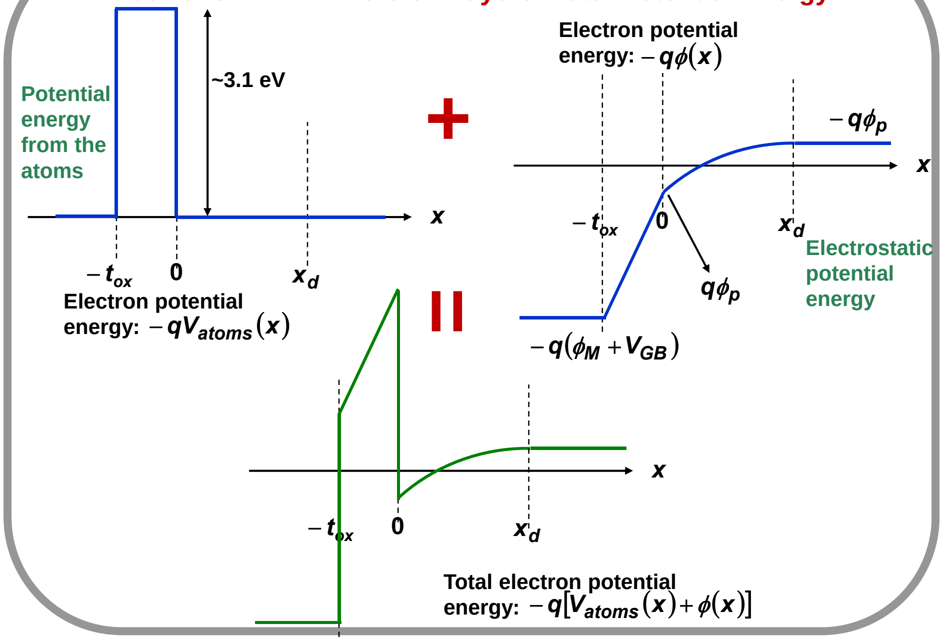






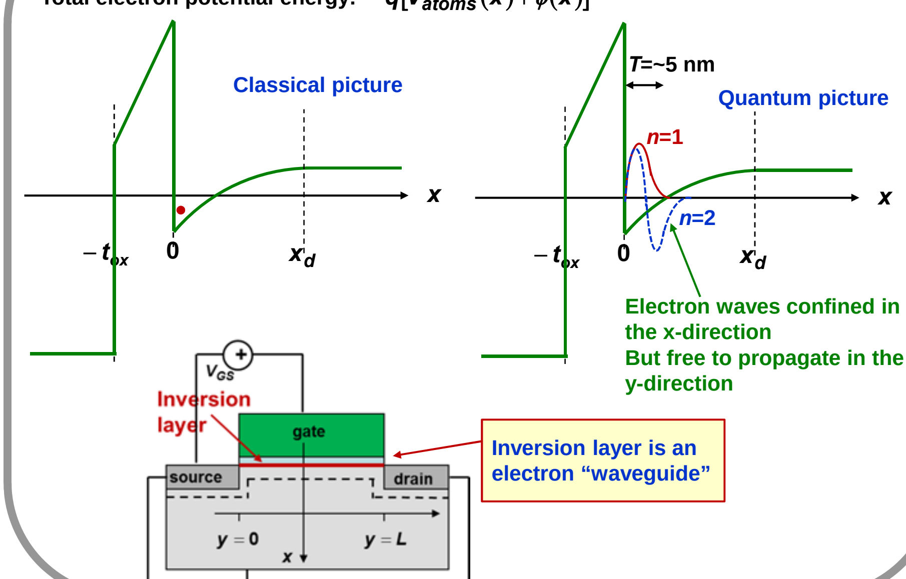


Electrons in FET Inversion Layers: Total Potential Energy

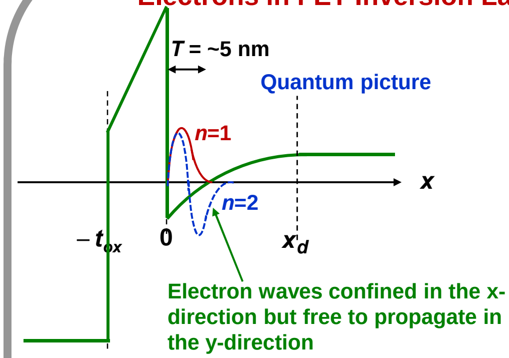


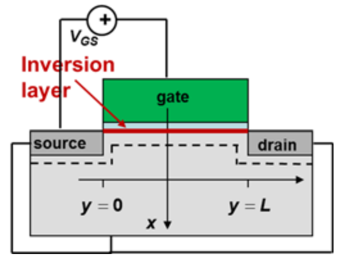
Electrons in FET Inversion Layers: Quantum Picture

Total electron potential energy: $-q[V_{atoms}(x)+\phi(x)]$



Electrons in FET Inversion Layers: Quantum Picture





$$\text{K.E} = \frac{1}{2}\left(m_x v_x^2 + m_y v_y^2 + m_z v_z^2\right) = \frac{P_x^2}{2m_x} + \frac{P_y^2}{2m_y} + \frac{P_z^2}{2m_z}$$

$$T = n\frac{\lambda_x}{2}$$

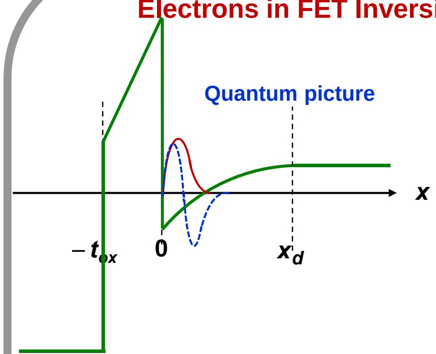
$$\Rightarrow \lambda_x = \frac{2T}{n}$$

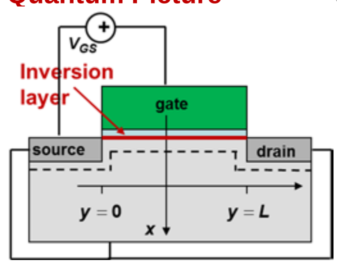
$$\{n = 1,2,3\cdots\cdots$$

$$\text{Momentum} = P_x = \hbar\frac{2\pi}{\lambda_x}$$ → Momentum in the x-direction can have only discrete ("quantized") values

$$\text{K.E} = \frac{(\hbar)^2}{2m_x}\left(n\frac{\pi}{T}\right)^2 + \frac{P_y^2}{2m_y} + \frac{P_z^2}{2m_z}$$ → *n*=1 energy state contains majority of the electrons (but not all)

Electrons in FET Inversion Layers: Quantum Picture





1,2: $$\text{K.E} = \frac{1}{2}\left(m_\ell v_x^2 + m_t v_y^2 + m_t v_z^2\right)$$

3,4: $$\text{K.E} = \frac{1}{2}\left(m_t v_x^2 + m_\ell v_y^2 + m_t v_z^2\right)$$

5,6: $$\text{K.E} = \frac{1}{2}\left(m_t v_x^2 + m_t v_y^2 + m_\ell v_z^2\right)$$

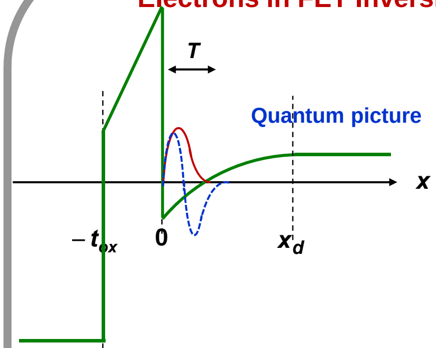
IDEA:

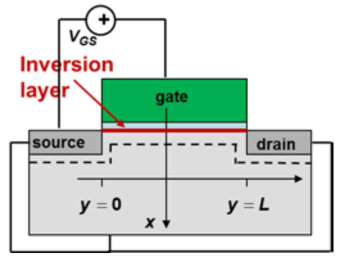
What if one could only have electrons of kinds 1,2 and 5,6 and eliminate electrons of kind 3,4?

Then the mass of the electrons in the direction of current transport (y-direction) would be only the lighter mass and the electron mobility would be very high!!

This elimination automatically happens because of quantization!!

Electrons in FET Inversion Layers: Quantum Picture





1,2: $$K.E = \frac{1}{2}\left(m_\ell v_x^2 + m_t v_y^2 + m_t v_z^2\right)$$

3,4: $$K.E = \frac{1}{2}\left(m_t v_x^2 + m_\ell v_y^2 + m_t v_z^2\right)$$

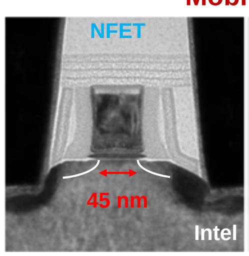
5,6: $$K.E = \frac{1}{2}\left(m_t v_x^2 + m_t v_y^2 + m_\ell v_z^2\right)$$

The lowest quantized energy levels correspond to the heaviest mass m_ℓ in the x-direction (quantization direction):

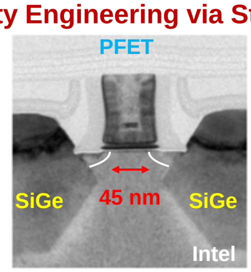
$$K.E = \frac{(\hbar)^2}{2m_\ell}\left(\frac{\pi}{T}\right)^2 + \frac{P_y^2}{2m_t} + \frac{P_z^2}{2m_t}$$

The higher energy levels are much less occupied by electrons at room temperature

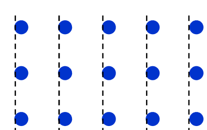
Mobility Engineering via Strain in FETs



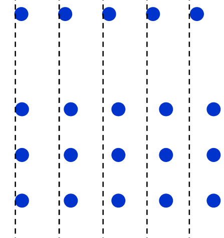
Channel under uniaxial tensile strain



Channel under uniaxial tensile strain



Normal silicon crystal



Uniaxial tensile strained silicon crystal

Strain completely eliminates the unwanted electrons

Strain also reduces the electron and hole masses

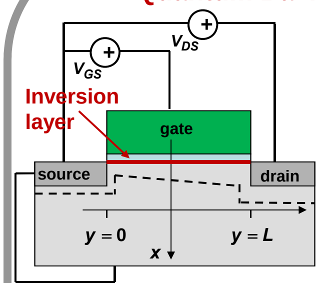
1,2: $$K.E = \frac{1}{2}\left(m_\ell v_x^2 + m_t v_y^2 + m_t v_z^2\right)$$

3,4: $$K.E = \frac{1}{2}\left(m_t v_x^2 + m_\ell v_y^2 + m_t v_z^2\right)$$

5,6: $$K.E = \frac{1}{2}\left(m_t v_x^2 + m_t v_y^2 + m_\ell v_z^2\right)$$

Strain changes the distance between the atoms and, thereby, modifies the electronic energy levels in the crystal

Quantum Ballistic Transport in Electron Waveguides



The electron drift current density is:

$$J_n^{drift} = qn\mu_n E$$

Where:

$$\mu_n = \frac{q\tau_n}{m_n}$$

Mean time between electron collisions

Mean distance between electron collisions (also called "mean free path") is:

$$\lambda_n = \langle v_n \rangle \tau_n$$

~20-30 nm in silicon

Mean velocity of electrons

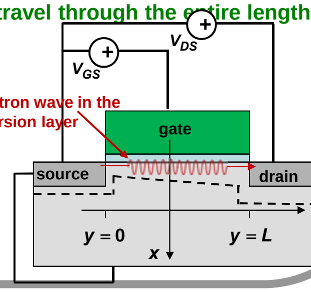
What is the device is so short that the electron can travel through the entire length of the device without a collision? $\tau_n \rightarrow \infty$ or $L < \lambda_n$

The classical expression for current via drift does not work:

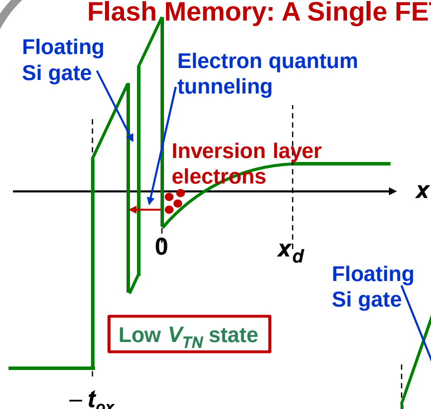
$$J_n^{drift} = qn\mu_n E$$

Concepts like mobility and conductivity don't make sense anymore

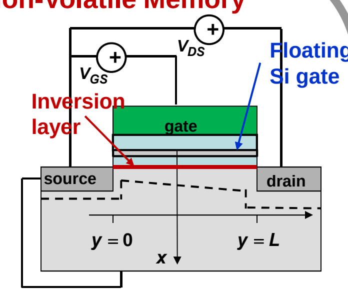
Electron transport is described as a the propagation of a wave from the source end to the drain end

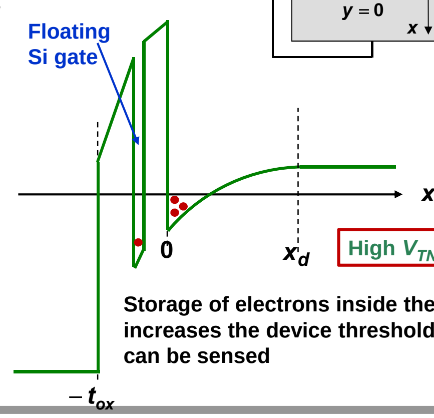


Flash Memory: A Single FET based Non-Volatile Memory



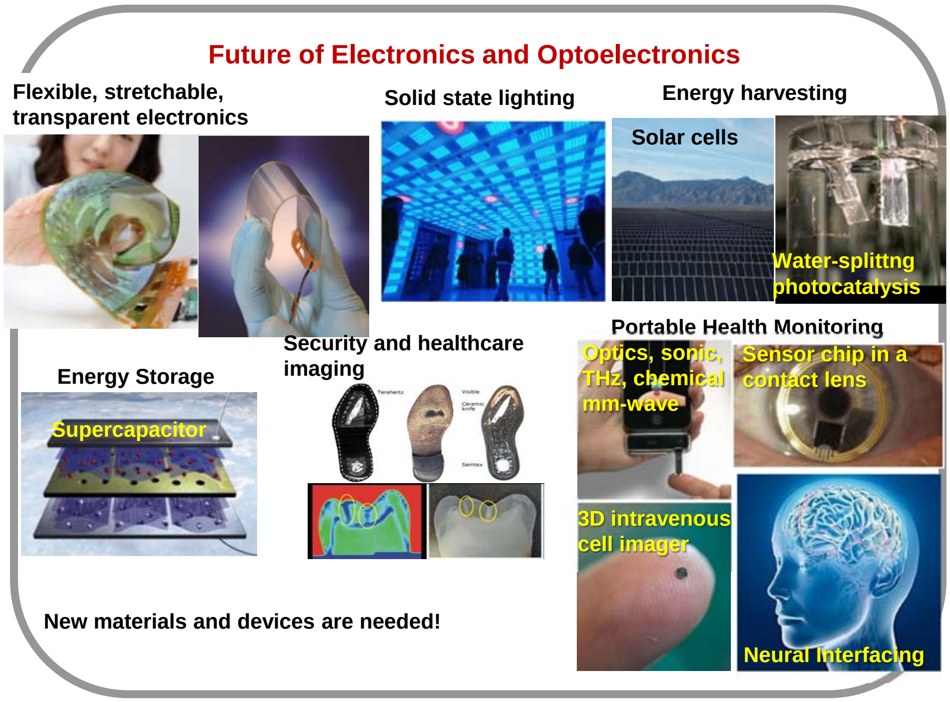
Low V_{TN} state

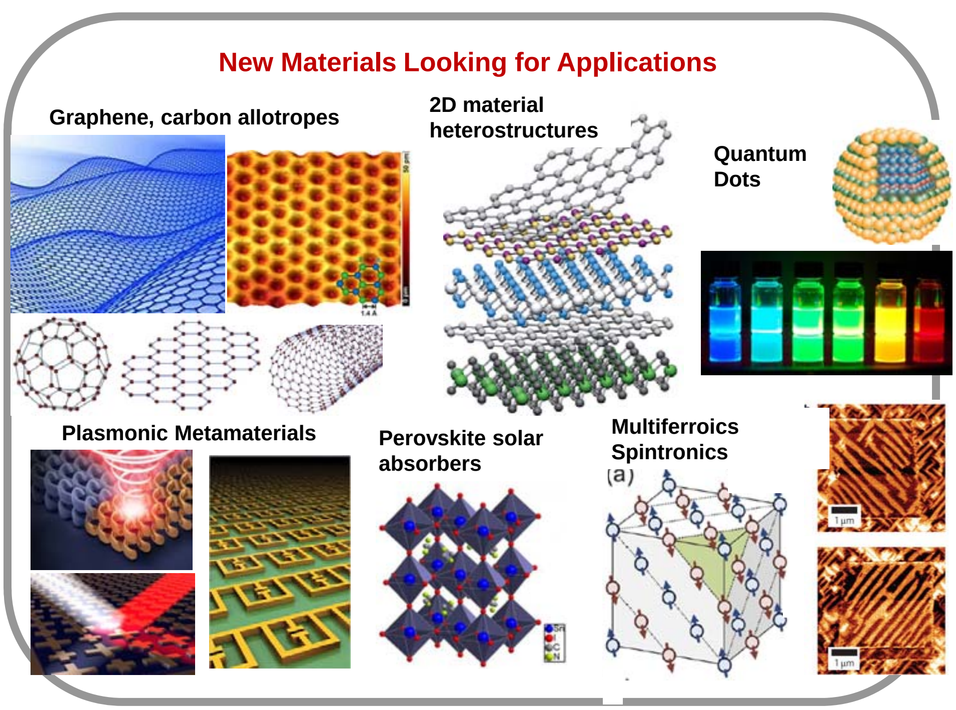




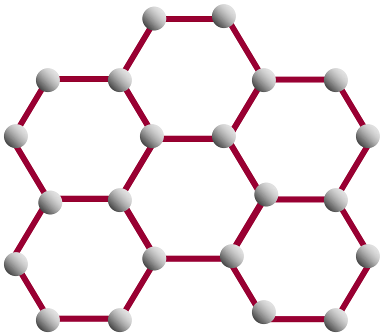
High V_{TN} state

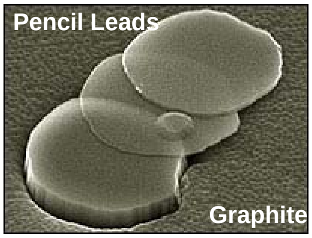
Storage of electrons inside the floating gate increases the device threshold voltage which can be sensed

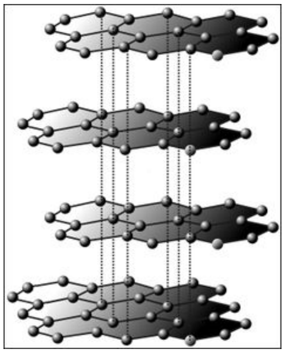

Future of Electronics and Optoelectronics
Flexible, stretchable, transparent electronics
Solid state lighting
Energy harvesting
Solar cells
Water-splittng photocatalysis
Portable Health Monitoring
Optics, sonic, THz, chemical mm-wave
Sensor chip in a contact lens
Security and healthcare imaging
Energy Storage
Supercapacitor
3D intravenous cell imager
Neural Interfacing
New materials and devices are needed!


New Materials Looking for Applications
Graphene, carbon allotropes
2D material heterostructures
Quantum Dots
Plasmonic Metamaterials
Perovskite solar absorbers
Multiferroics Spintronics
(a)
1 μm
1 μm

Graphene: A 2D Semiconductor

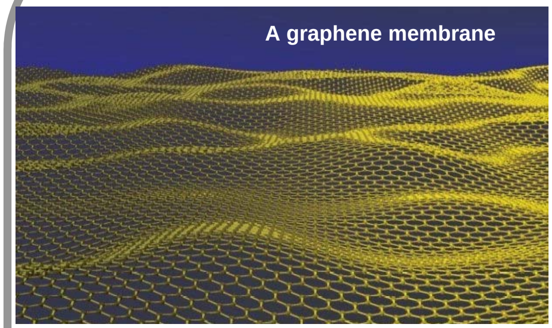


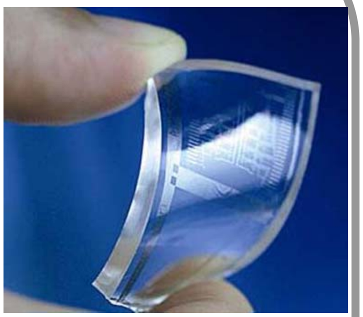




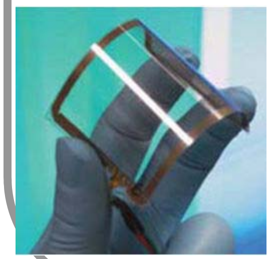
Graphene is a two dimensional single atomic layer of Carbon atoms arranged in a honeycomb lattice

Graphene Atomic Membranes

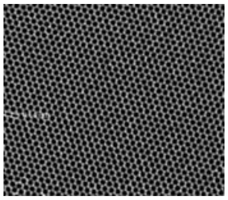




A flexible transparent electronic chip made from graphene



A flexible transparent touch-screen for displays made of graphene (Samsung)

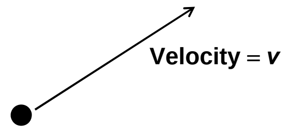


Grpahene atoms (STEM)

Massive and Massless Particles

Energy of a massive particle (e.g. electron):

$$\text{Energy} = \frac{1}{2}mv^2 = \frac{P^2}{2m}$$



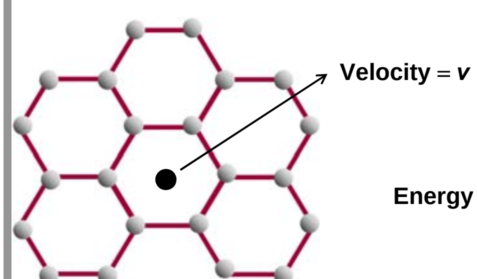
Energy of a massless particle (e.g. photon):

$$\text{Energy} = Pc$$

c = speed of light = 3×10^8 m/s

Massive and Massless Particles

Electrons in graphene behave like light (or photons):



$$\text{Energy} = Pv$$

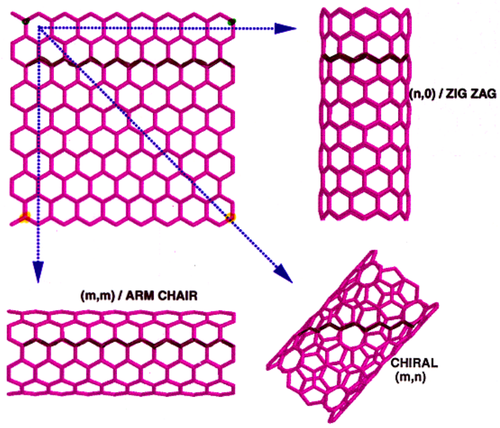
v = speed of electrons = 10^6 m/s

Electrons move faster in graphene than in any other known semiconductor at room temperature (~100 times faster than in Silicon)!!

(2010 Nobel Prize in Physics for Graphene)

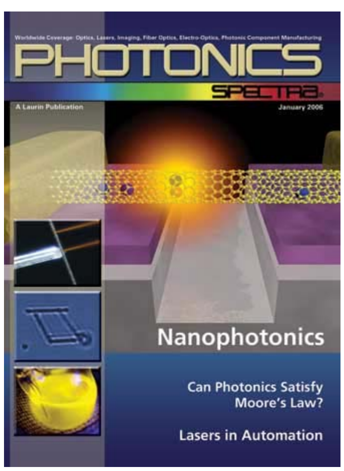
Folded Graphene: Carbon Nanotubes

Nanotube: A carbon nanotube is a folded sheet of graphene:

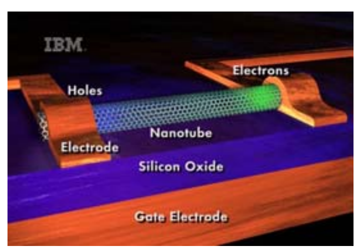


A long carbon nanotube is a one-dimensional (1D) conductor (or semi-conductor)

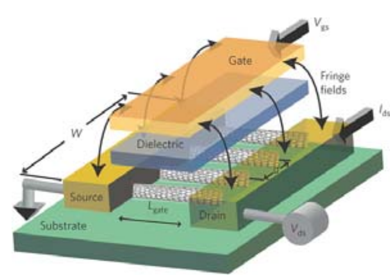
Carbon Nanotubes: A 1D Material



Carbon Nanotube LEDs (IBM)

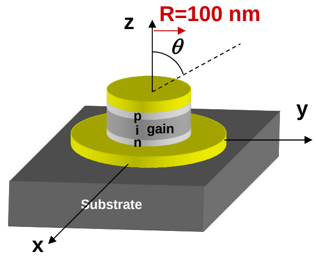


Carbon Nanotube FET (IBM)

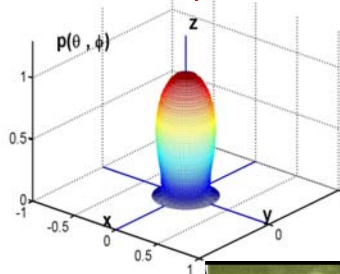


Semiconductor Plasmon Lasers: The Nanopatch Laser

Circular Nanopatch Laser
(Size of a FET)



Circular Nanopatch Laser: Radiation Pattern

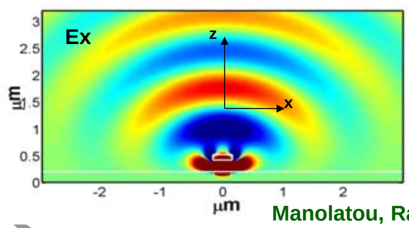


SNLs are optical versions of microwave patch antennas

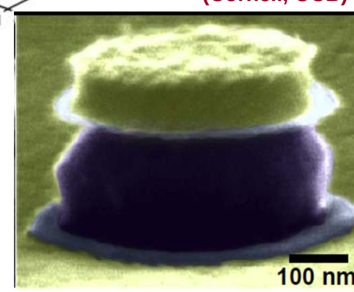
Lasers on chip are becoming much smaller than the size of a photon!!

(Cornell, UCB)

Surface-normal emission

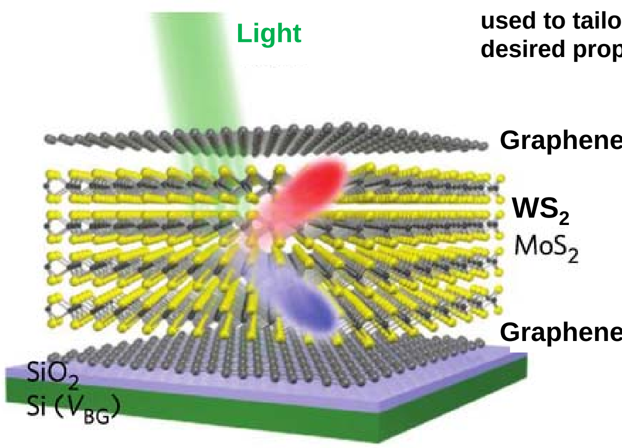


Manolatou, Rana (2009)

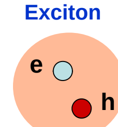


Tailoring and Designing Complex 3D Materials and Devices with 2D Materials

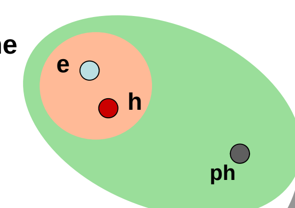
Stacks of 2D materials can be used to tailor 3D materials with desired properties….!!



Exciton



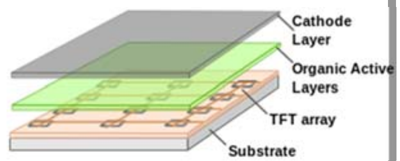
A "hydrogen atom" of an electron and a hole

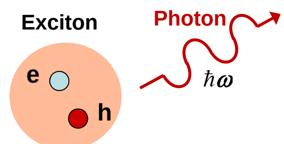


A solar cell made using 2D material stacks

Polariton

AMOLED Displays (Samsung Galaxy)





A “hydrogen atom” of an electron and a hole

Visions of the Future (From Samsung)

https://youtu.be/RTp8kEuZ1eY

The Last Slide

ECE Courses after 3150 to Match your Interests