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Building College-University Partnerships for Nanotechnology Workforce Development

Graphene and Other 2D Electronic Systems

June 17, 2015

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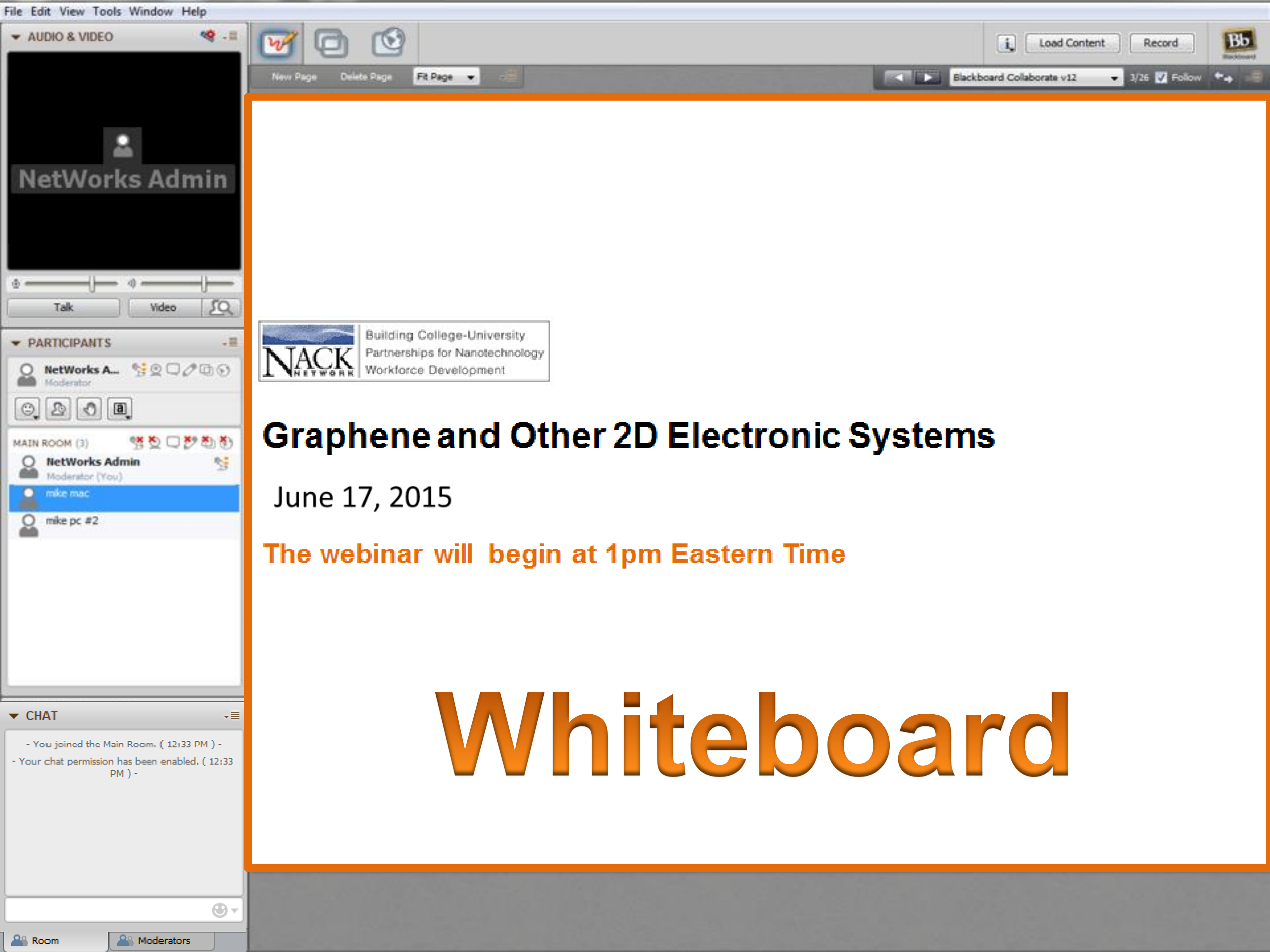
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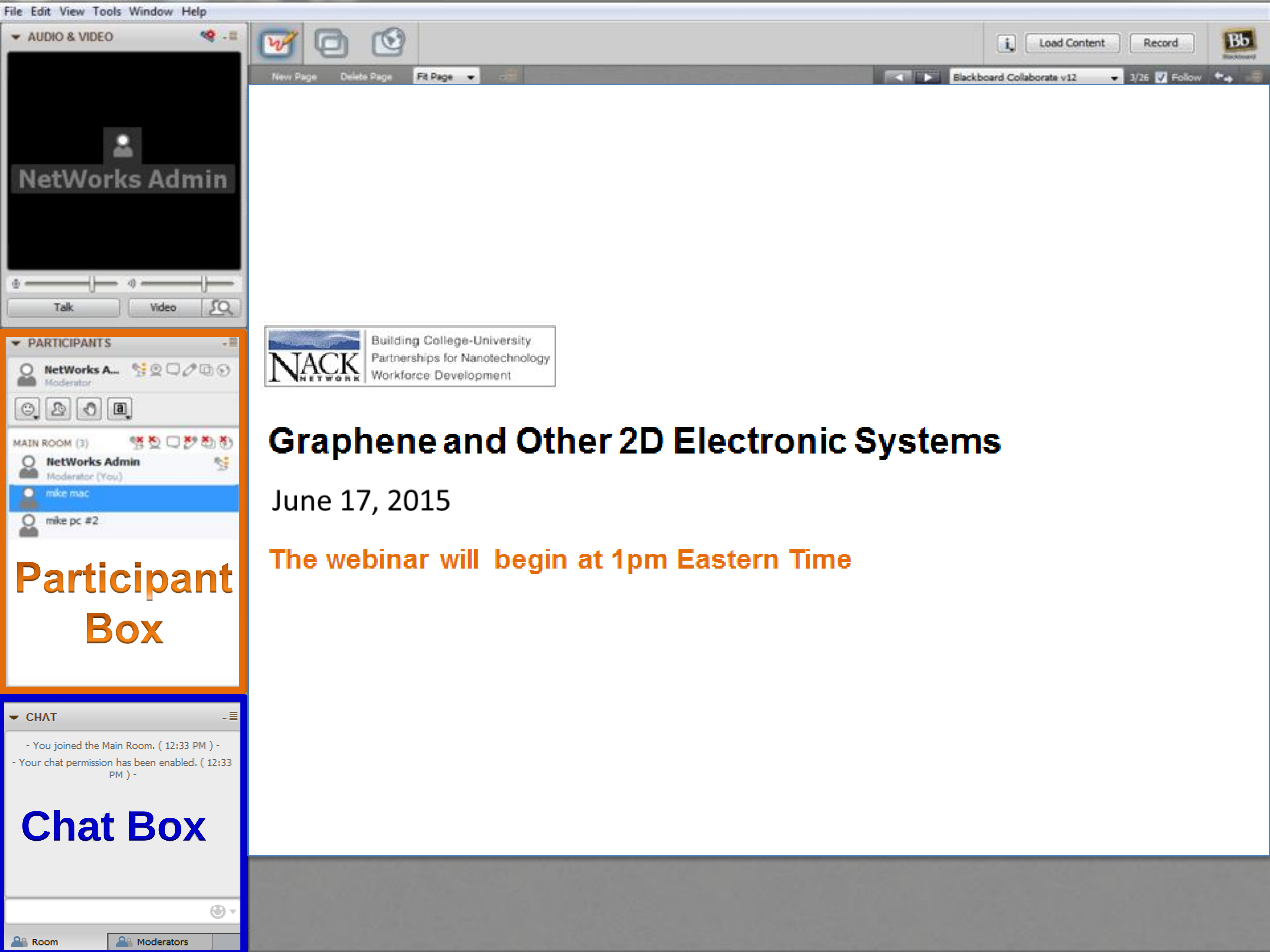
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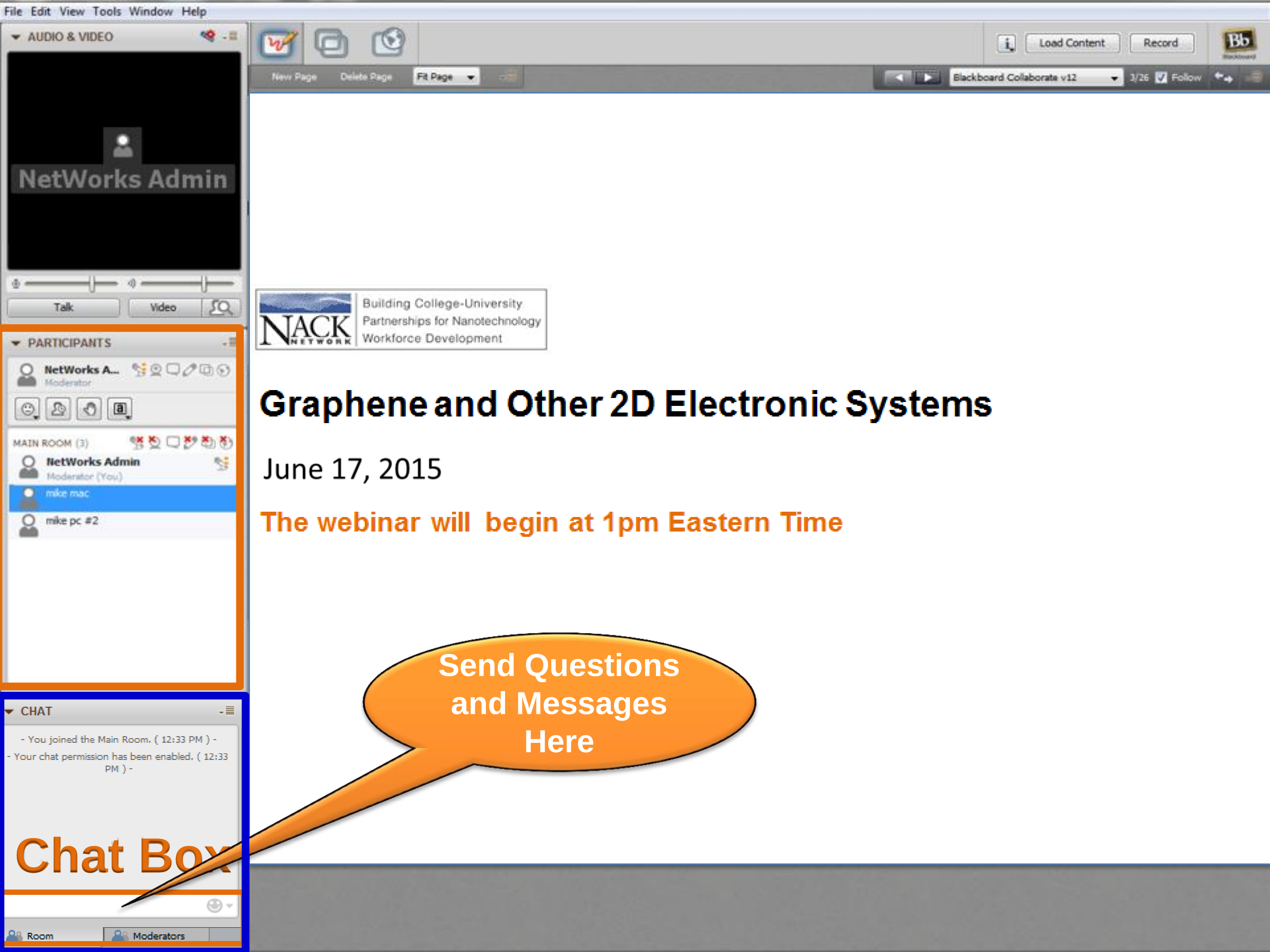

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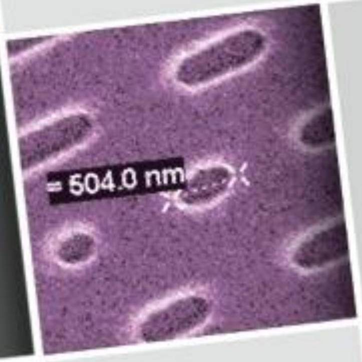

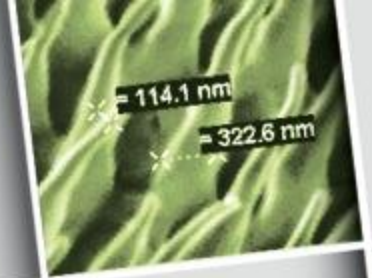

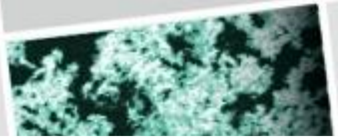

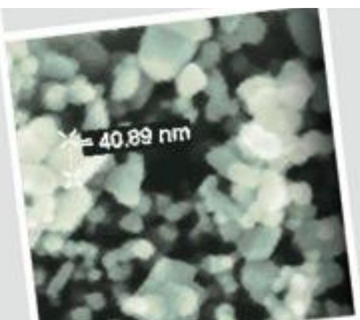

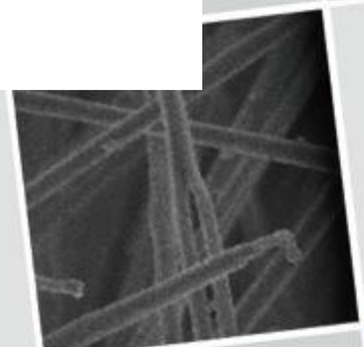

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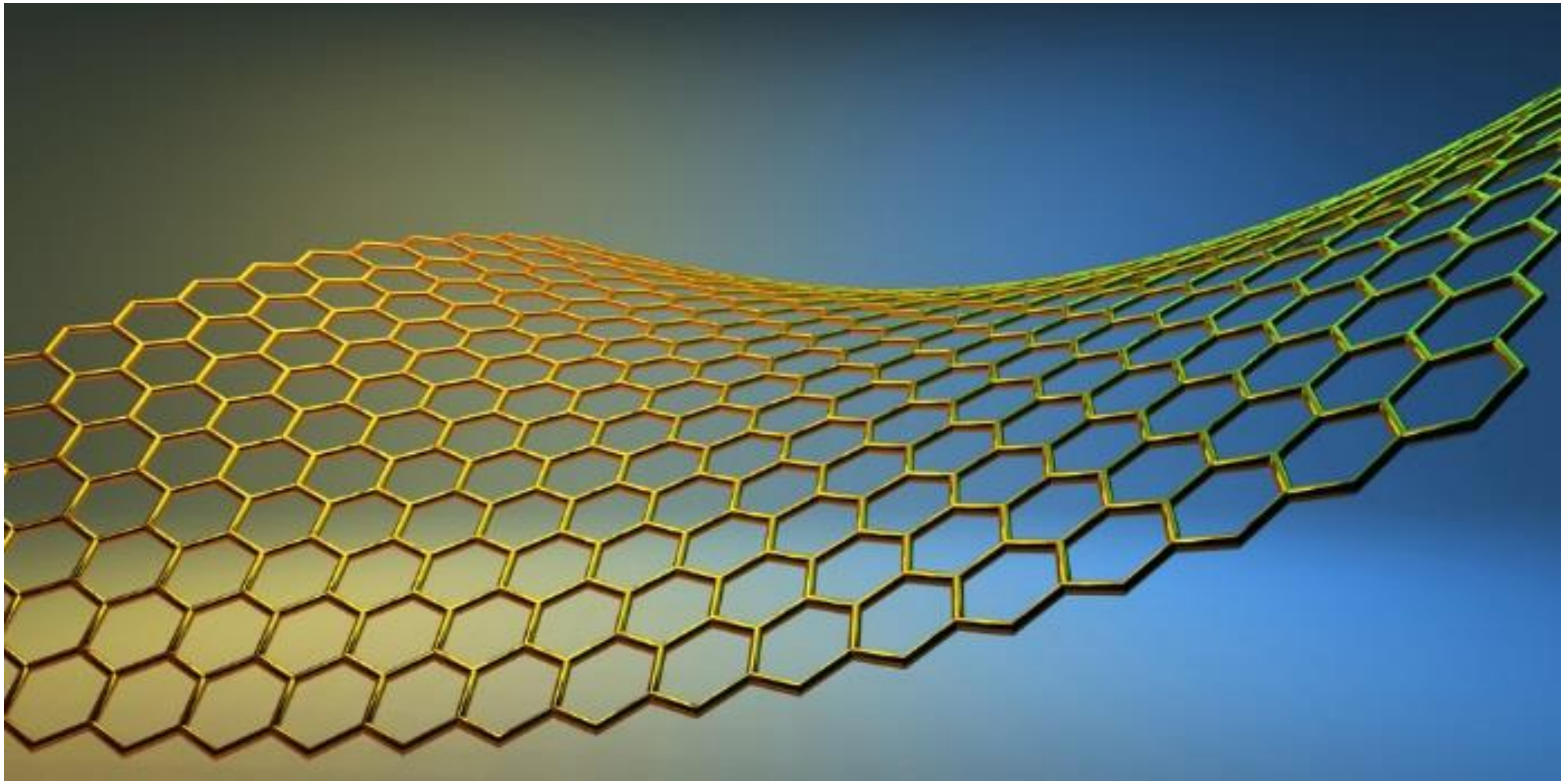
Welcome to NACK's Webinar

Today's presenter:
Trevor Thornton, PhD
Professor of Electrical Engineering
Arizona State University
Tempe, AZ

Moderator: Mike Lesiecki

Graphene and Other 2D Electronic Systems



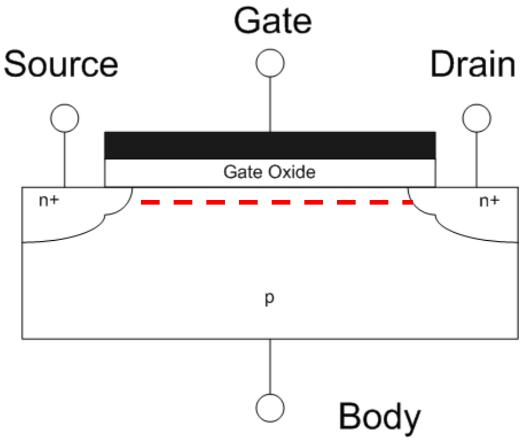
(credit: University of Bath)

So why the interest in 2D electronic systems?

We already depend upon 3D electronic systems!

Metallic conductors carry current due to the motion of electrons in three dimensions

We also depend upon 2D electronic systems!



The CMOS switches in computer chips carry current due to electrons that are restricted to flow in a 2D sheet of charge

If we can make a better 2D electronic system we can make faster computer chips.

How do we make a better 2D electronic system?

Increase the conductivity!

<u>electron sheet density</u>, n, i.e. the number of electrons per cm^2
e.g. ~10^{13} cm^{-2} in a CMOS transistor

<u>electron mobility</u>, μ
i.e. the average electron velocity in an electric field of 1V/cm
e.g. ~500cm^2/Vs in CMOS

Conductivity, $\sigma = n\, e\, \mu$

electron charge, e
1.6x10^{-19} Coulombs

To increase σ we need to increase both n and μ $\Rightarrow$ new materials

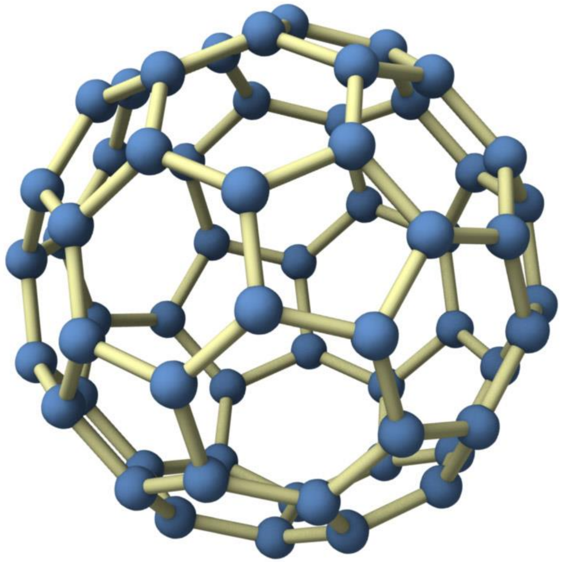
Before introducing graphene lets look at the history of carbon materials.

Coal, diamond and graphite have been known for centuries.

But then in 1985 C^{60} was discovered by Robert Curl, Harold Kroto and Richard Smalley

Buckminsterfullerene (or bucky-balls for short) occur naturally in soot and have a molecular structure resembling that of a soccer ball.

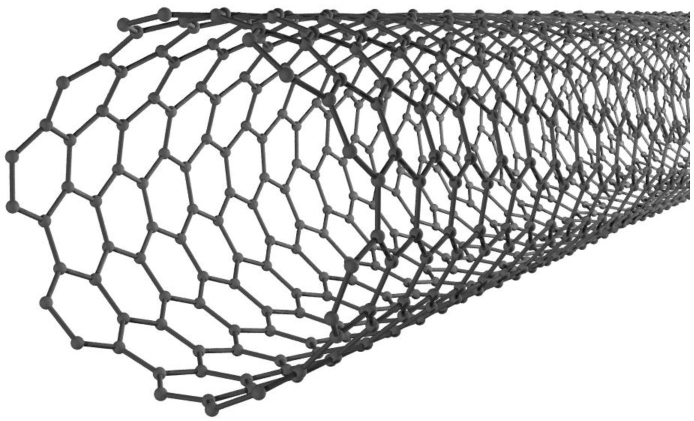
http://en.wikipedia.org/wiki/Buckminsterfullerene



http://nanotechnologyuniverse.com/wp-content/uploads/2011/10/buckyball.jpg

Then came carbon nanotubes….

In 1991 Sumio Iijima reported the discovery of hollow tubes of graphitic carbon with diameters of just a few nanometers. The carbon nanotubes (CNT) were found in the residue generated by forming an electric arc between graphite electrodes.



www.motoroids.com

Carbon nanotubes can support current densities of up to 4×10^9 A/cm^2 which is more than 1,000 times greater than typical metals such as copper can conduct.

CNT are 1D conductors

http://en.wikipedia.org/wiki/Carbon_nanotube#Discovery

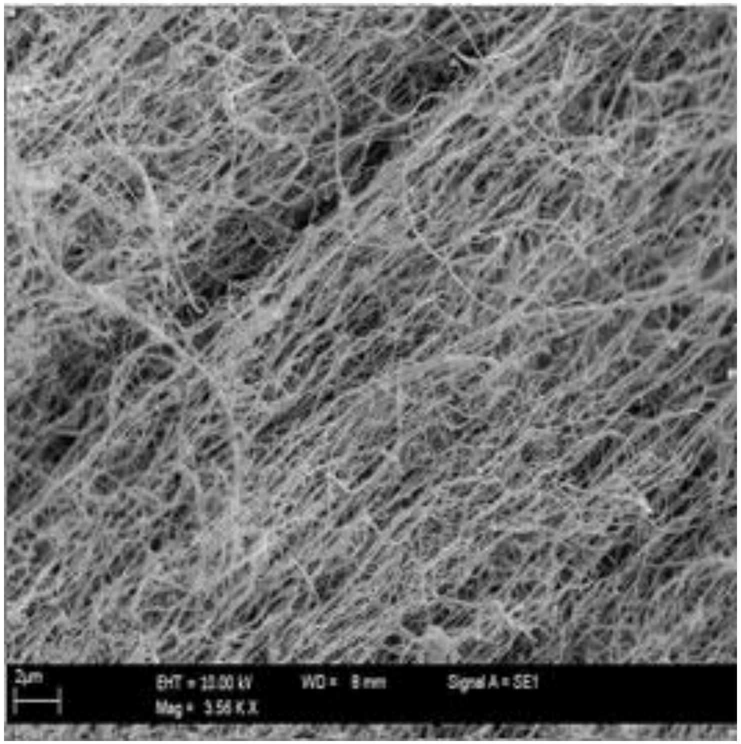
Then came carbon nanotubes….

The nanotubes are typically formed as bundles of interwoven threads.

CNTs are still the focus of much R&D for applications such as:

- interconnects for computer chips
- energy storage and generation
- biomedical systems

but the first widespread applications are likely those which exploit the mechanical strength of CNTs….



www.azonano.com

http://en.wikipedia.org

Then came carbon nanotubes….

Comparison of mechanical properties[46][47][48][49]			
Material	Young's modulus (TPa)	Tensile strength (GPa)	Elongation at break (%)
SWNT^E	~1 (from 1 to 5)	13–53	16
Armchair SWNT^T	0.94	126.2	23.1
Zigzag SWNT^T	0.94	94.5	15.6–17.5
Chiral SWNT	0.92		
MWNT^E	0.2[41]–0.8[50]–0.95[41]	11[41]–63[41]–150[50]	
Stainless steel^E	0.186[51]–0.214[52]	0.38[51]–1.55[52]	15–50
Kevlar–29&149^E	0.06–0.18[53]	3.6–3.8[53]	~2

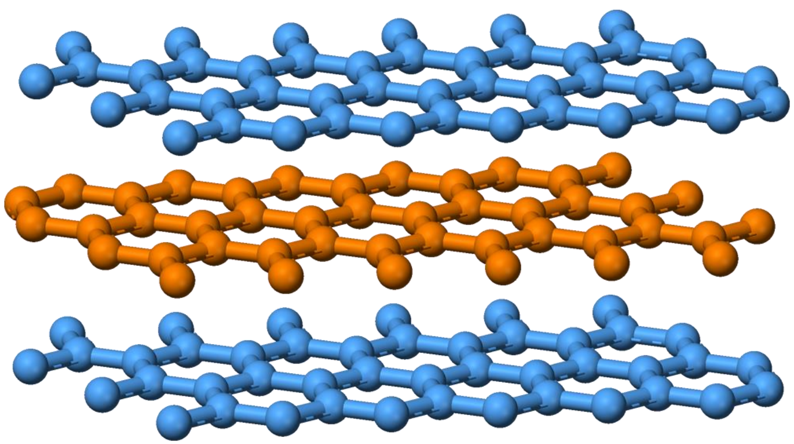
http://en.wikipedia.org/wiki/Carbon_nanotube#Discovery

And in 2004 Andre Geim and Kostya Novoselov isolated single sheets of carbon graphene from graphite.

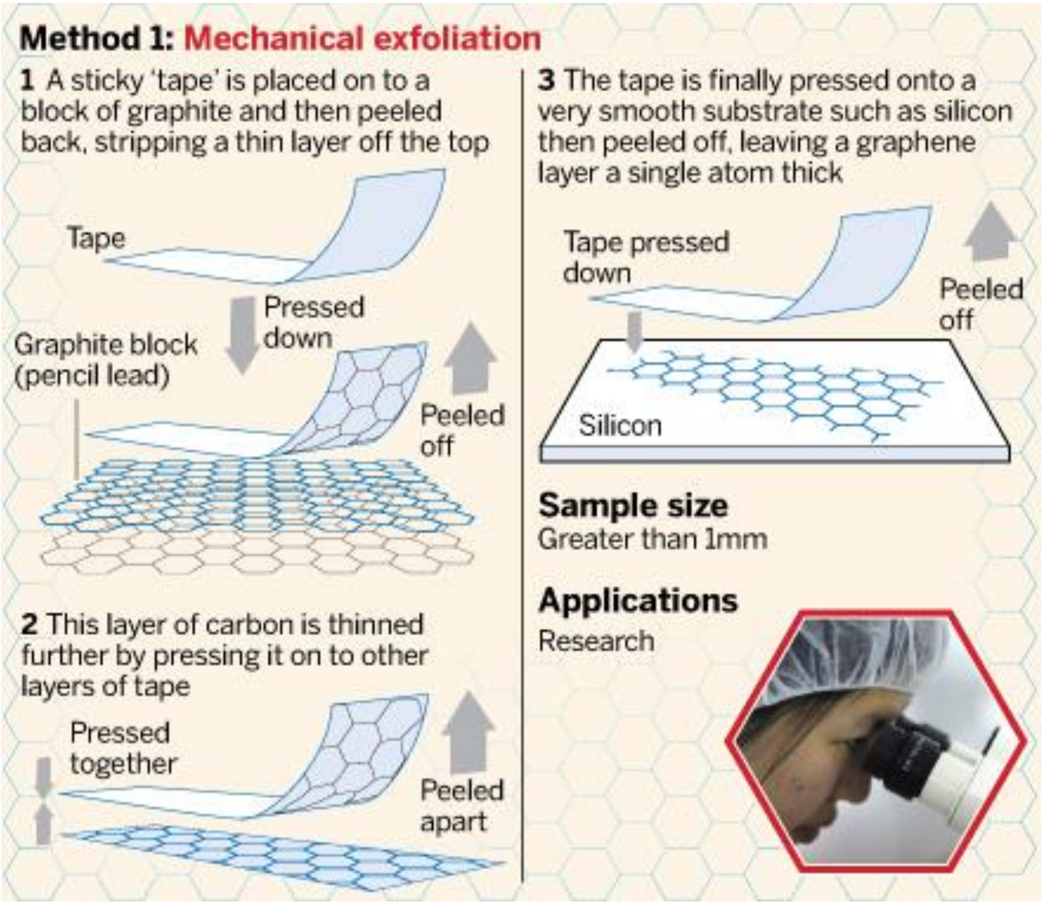
How did they do it?

http://en.wikipedia.org/wiki/Graphene

Graphite consists of sheets of carbon that are held together by relatively weak van-der-Waals forces



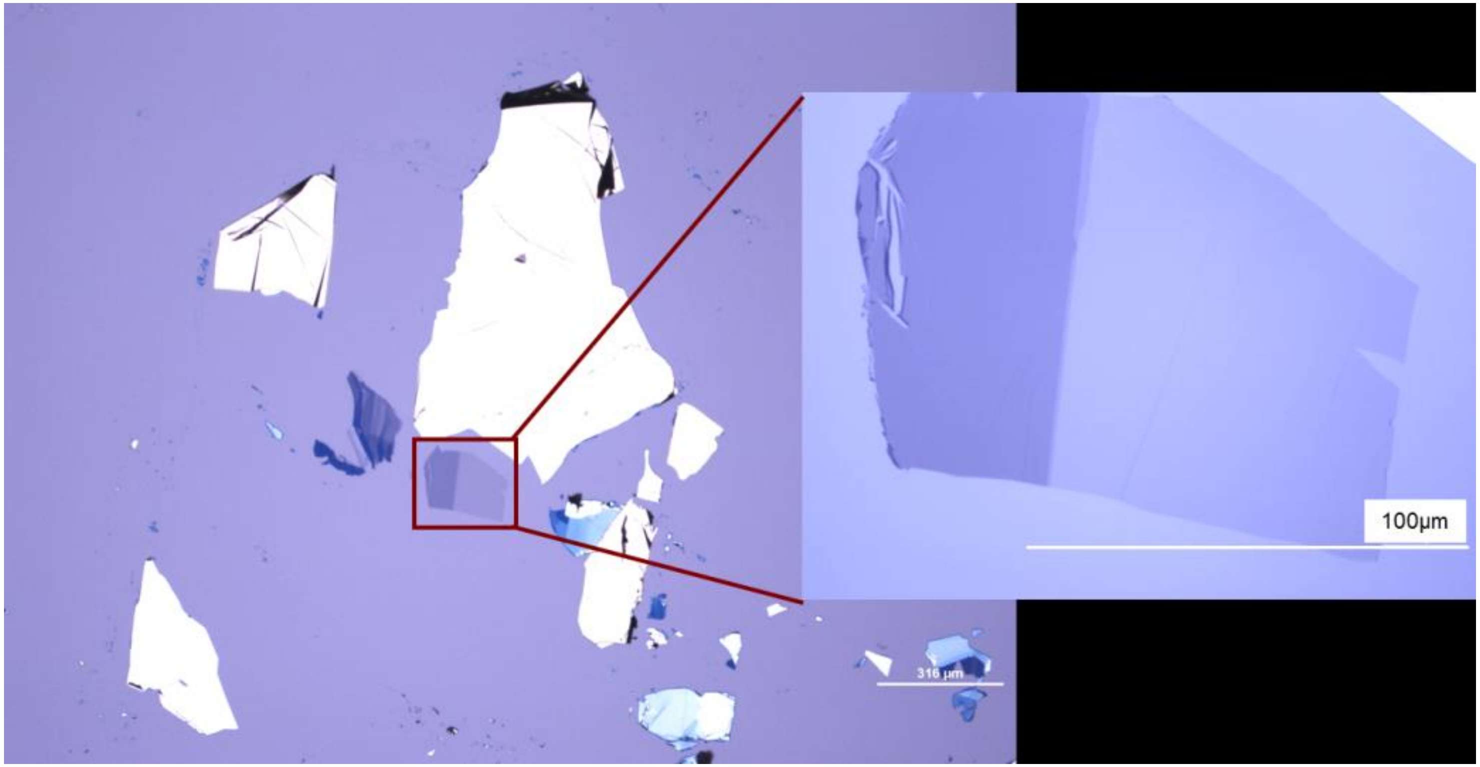
Scotch tape exfoliation of mono-layer graphene



www.ft.com

https://www.youtube.com/watch?v=waO020l25sU

When the final graphene monolayer is deposited on the oxidized surface of a silicon wafer it can, surprisingly, be seen by the naked eye because it absorbs green and red light.



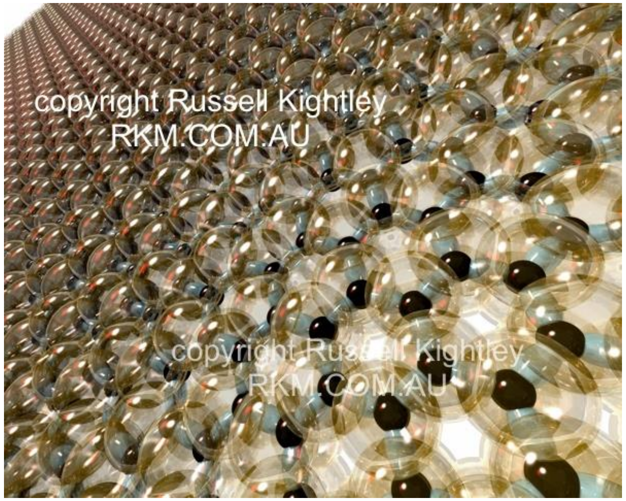
Atomic Structure of Graphene and h-BN Layers and Their Interactions with Metals

By Recep Zan, Quentin M. Ramasse, Rashid Jalil and Ursel Bangert

DOI: 10.5772/56640

Properties of Graphene

- Mobility of graphene can theoretically approach 200,000cm^2/Vs but it is commonly measured to be ~15,000 cm^2/Vs when deposited on silicon.
- High mobility and high carrier concentration lead to excellent electronic properties.



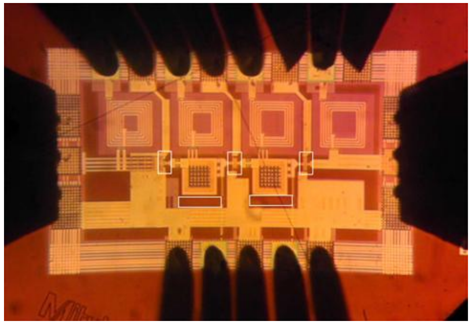
http://www.graphenea.com/pages/graphene-properties

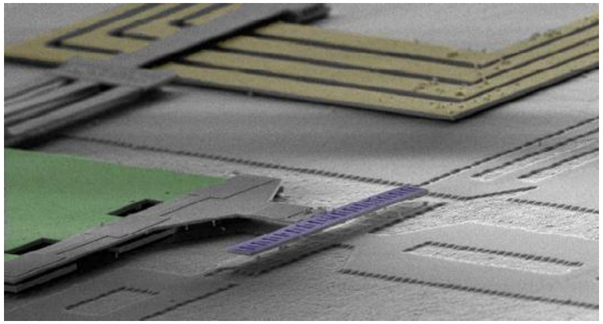
Electronic Applications of Graphene

Radio Frequency Integrated Circuits

4.3GHz radio frequency integrated circuit with three graphene transistors and CMOS passives.

- The passive components and FET T-gates were fabricated first in the back-end-of-line process of a standard CMOS flow
- graphene films grown last by CVD to preserve the high electron mobility.



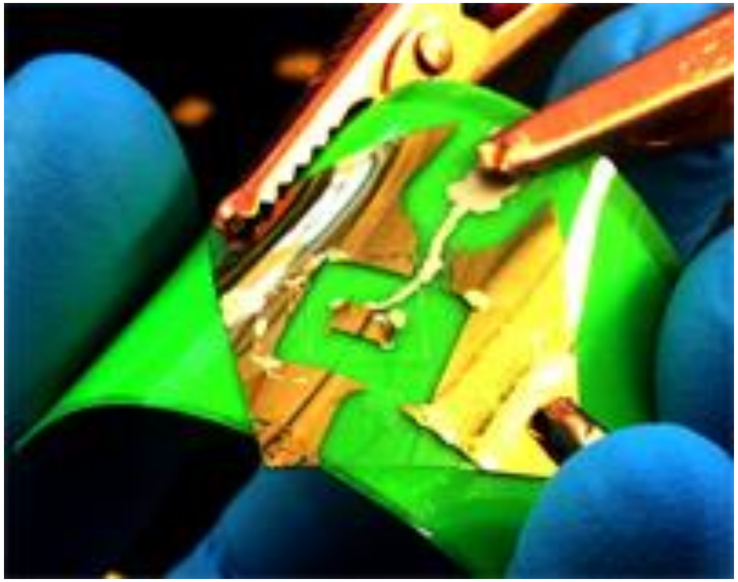


Han et al. Nature Communications, Jan 2014, DOI: 10.1038/ncomms4086

Electronic Applications of Graphene

<u>Flexible and Transparent Integrated Circuits</u>

The thin 2D nature of the graphene allows for extreme flexibility



http://www.condmat.physics.manchester.ac.uk/imagelibrary

Other Properties of Graphene

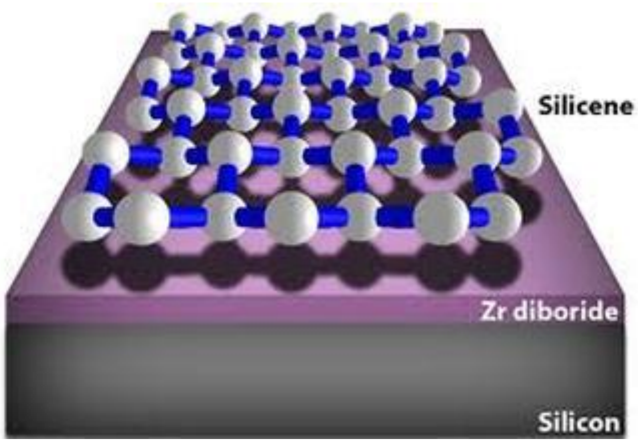
- The strong carbon-carbon bonds give graphene a tensile strength of 130 GPa, similar to CNT
- A graphene monolayer absorbs 2.3% of the white light shining through it.

http://www.graphenea.com/pages/graphene-properties

2D Electronic Systems Beyond Graphene

Other Group IV 2D systems

- 2D sheets of silicon – silicene
- 2D sheets of germanium - germanene

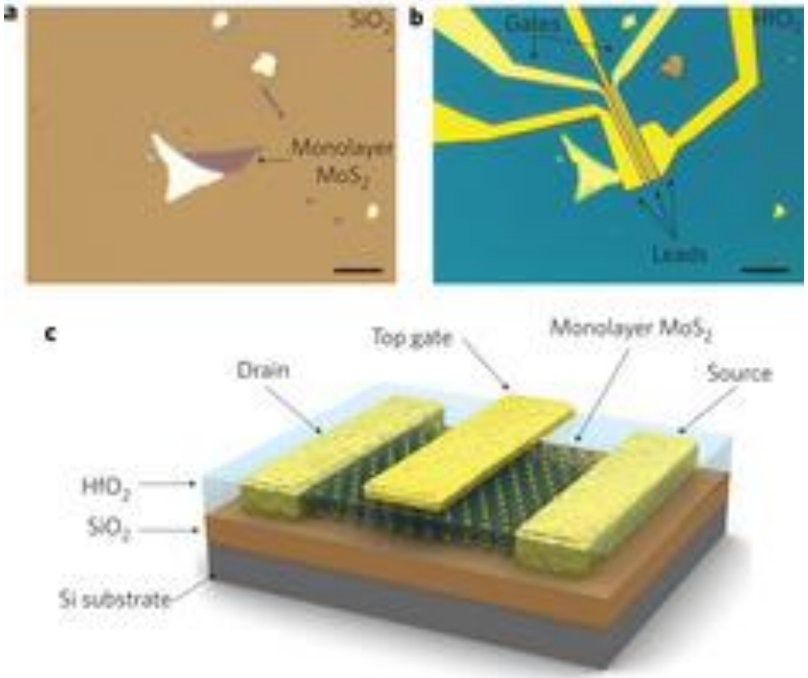


http://en.wikipedia.org/wiki/Germanene http://en.wikipedia.org/wiki/Silicene

2D Electronic Systems Beyond Graphene (cont)

Molybdenum Disulphide, MoS_2

- Graphene is intrinsically metallic and extra effort is required to convert it to a semiconductor.
- MoS_2 is intrinsically semi-conducting and lends itself more easily to transistor fabrication



http://www.nature.com/nnano/journal/v6/n3/full/nnano.2010.279.html

2D Electronic Systems Beyond Graphene (cont)

Topological Insulators

- These are materials that are insulators in the bulk but have good metallic conductivity on the surface.
- Early examples include layers of mercury telluride sandwiched between cadmium telluride and now there are numerous examples.

2D Electronic Systems Beyond Graphene (cont)

Topological Insulators

Table I. Summary of topological insulator materials that have bee experimentally addressed. The definition of (1;111) *etc.* is introduced in Sec. 3.7. (In this table, S.S., P.T., and SM stand for surface state, phase transition, and semimetal, respectively.)

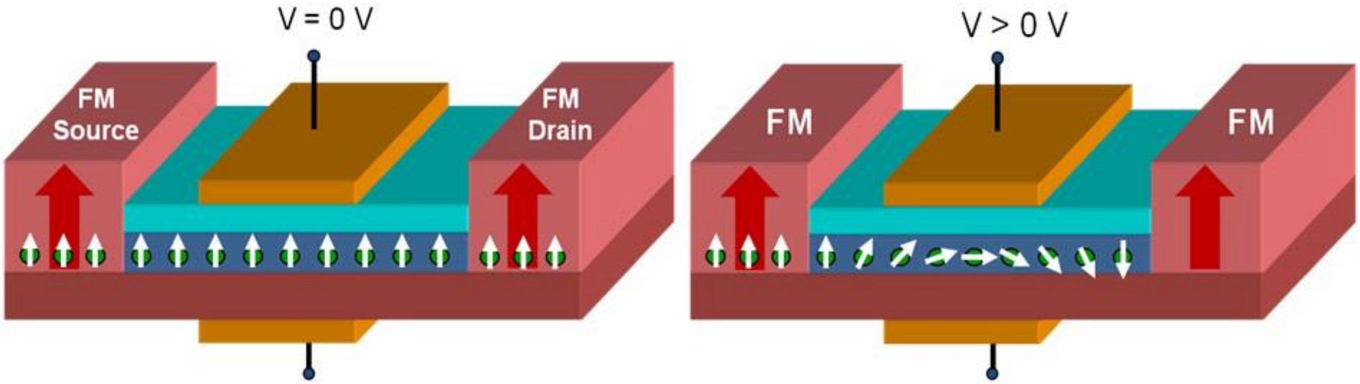
Type	Material	Band gap	Bulk transport	Remark	Reference
2D, $\nu = 1$	CdTe/HgTe/CdTe	< 10 meV	insulating	high mobility	31)
2D, $\nu = 1$	AlSb/InAs/GaSb/AlSb	~4 meV	weakly insulating	gap is too small	73)
3D (1;111)	$Bi_{1-x}Sb_x$	< 30 meV	weakly insulating	complex S.S.	36, 40)
3D (1;111)	Sb	semimetal	metallic	complex S.S.	39)
3D (1;000)	Bi_2Se_3	0.3 eV	metallic	simple S.S.	94)
3D (1;000)	Bi_2Te_3	0.17 eV	metallic	distorted S.S.	95, 96)
3D (1;000)	Sb_2Te_3	0.3 eV	metallic	heavily *p*-type	97)
3D (1;000)	Bi_2Te_2Se	~0.2 eV	reasonably insulating	ρ_{xx} up to 6 Ωcm	102, 103, 105)
3D (1;000)	$(Bi,Sb)_2Te_3$	< 0.2 eV	moderately insulating	mostly thin films	193)
3D (1;000)	$Bi_{2-x}Sb_xTe_{3-y}Se_y$	< 0.3 eV	reasonably insulating	Dirac-cone engineering	107, 108, 212)
3D (1;000)	$Bi_2Te_{1.6}S_{1.4}$	0.2 eV	metallic	*n*-type	210)
3D (1;000)	$Bi_{1.1}Sb_{0.9}Te_2S$	0.2 eV	moderately insulating	ρ_{xx} up to 0.1 Ωcm	210)
3D (1;000)	Sb_2Te_2Se	?	metallic	heavily *p*-type	102)
3D (1;000)	$Bi_2(Te,Se)_2(Se,S)$	0.3 eV	semi-metallic	natural Kawazulite	211)
3D (1;000)	$TlBiSe_2$	~0.35 eV	metallic	simple S.S., large gap	110–112)
3D (1;000)	$TlBiTe_2$	~0.2 eV	metallic	distorted S.S.	112)
3D (1;000)	$TlBi(S,Se)_2$	< 0.35 eV	metallic	topological P.T.	116, 117)
3D (1;000)	$PbBi_2Te_4$	~0.2 eV	metallic	S.S. nearly parabolic	121, 124)
3D (1;000)	$PbSb_2Te_4$	?	metallic	*p*-type	121)
3D (1;000)	$GeBi_2Te_4$	0.18 eV	metallic	*n*-type	102, 119, 120)
3D (1;000)	$PbBi_4Te_7$	0.2 eV	metallic	heavily *n*-type	125)
3D (1;000)	$GeBi_{4-x}Sb_xTe_7$	0.1–0.2 eV	metallic	*n* (*p*) type at $x = 0$ (1)	126)
3D (1;000)	$(PbSe)_5(Bi_2Se_3)_6$	0.5 eV	metallic	natural heterostructure	130)
3D (1;000)	$(Bi_2)(Bi_2Se_{2.6}S_{0.4})$	semimetal	metallic	$(Bi_2)_n(Bi_2Se_3)_m$ series	127)
3D (1;000)	$(Bi_2)(Bi_2Te_3)_2$	?	?	no data published yet	128)
3D TCI	SnTe	0.3 eV (4.2 K)	metallic	Mirror TCI, $n_M = -2$	62)
3D TCI	$Pb_{1-x}Sn_xTe$	< 0.3 eV	metallic	Mirror TCI, $n_M = -2$	164)
3D TCI	$Pb_{0.77}Sn_{0.23}Se$	invert with *T*	metallic	Mirror TCI, $n_M = -2$	162)
2D, $\nu = 1$?	Bi bilayer	~0.1 eV	?	not stable by itself	82, 83)
3D (1;000)?	Ag_2Te	?	metallic	famous for linear MR	134, 135)
3D (1;111)?	SmB_6	20 meV	insulating	possible Kondo TI	140–143)
3D (0;001)?	$Bi_{14}Rh_3I_9$	0.27 eV	metallic	possible weak 3D TI	145)
3D (1;000)?	*R*BiPt (*R* = Lu, Dy, Gd)	zero gap	metallic	evidence negative	152)
Weyl SM?	$Nd_2(Ir_{1-x}Rh_x)_2O_7$	zero gap	metallic	too preliminary	158)

http://arxiv.org/pdf/1304.5693v3.pdf

2D Electronic Systems Beyond Graphene (cont)

Applications of Topological Insulators

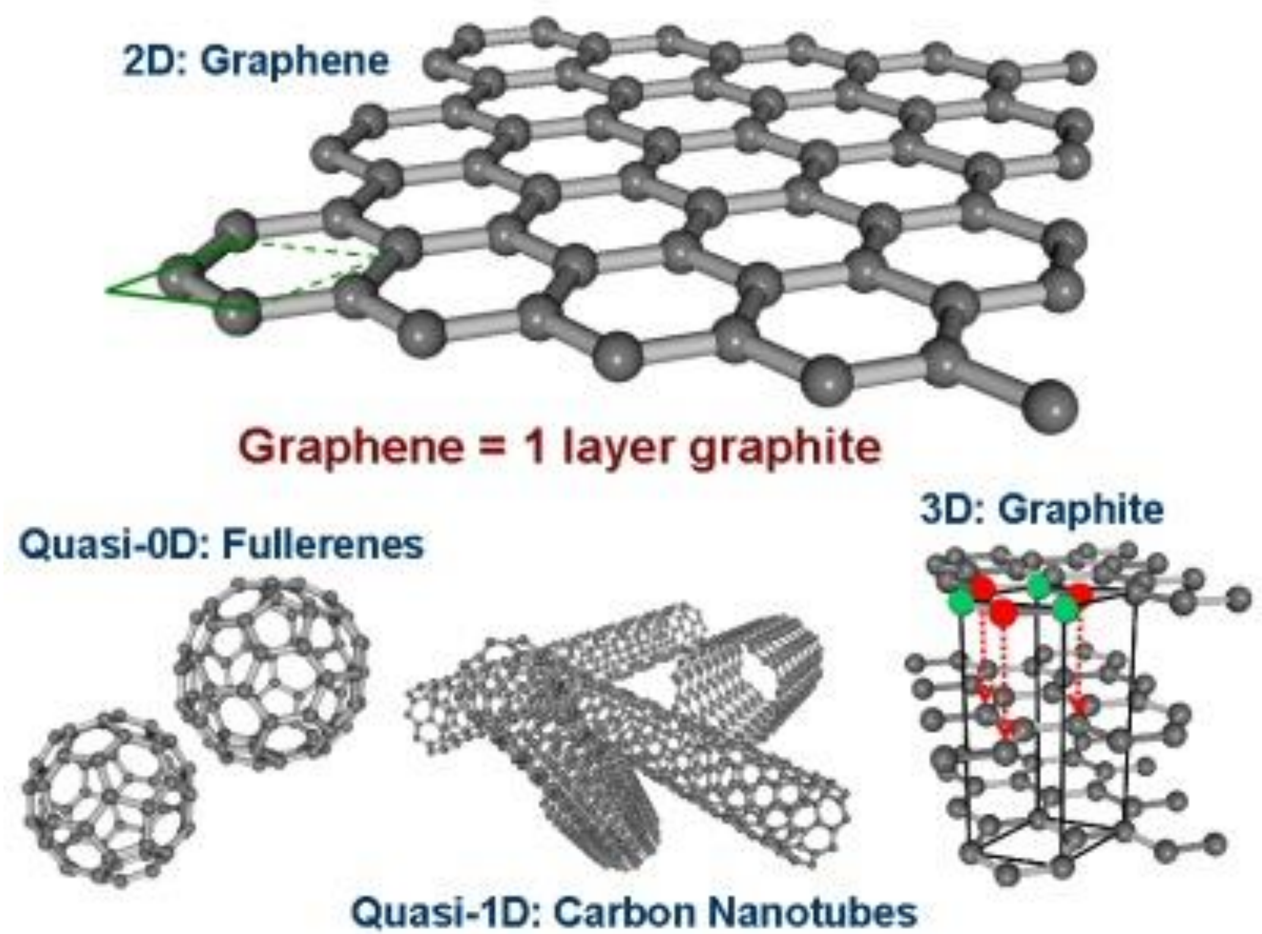
- Interest for spintronic applications.
- Information is processed using the electron spin (up or down) compared to the electron charge.
- Offers the potential for much lower power dissipation



Summary

- 2D electronic systems have been around for decades
- Only growing in importance
- Look for future developments not only in electronics but in textiles, biological and health systems, energy generation and storage

Final Questions



http://www.graphene.nat.uni-erlangen.de/grapheneng.htm

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August 10 - 13, 2015 *Nanotechnology Course Resources II: Patterning, Characterization, and Applications Workshop*

November 17- 19, 2015 *Hands-on Introduction to Nanotechnology for Educators, Workshop*

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