Graphene devices and integration: A primer on challenges

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Acknowledgments:

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UT Dallas and UT Austin

Outline

- Where we are
- Issues
    - Contact resistance
    - Graphene type
    - Mobility
- Summary

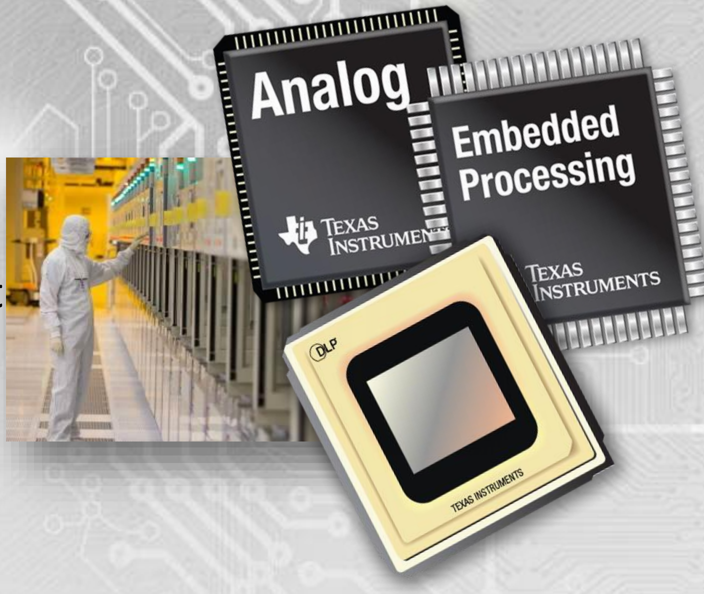
TI at a glance

Designs, manufactures and sells semiconductors

- Founded in 1930
- Nearly100,000 products
- More than 100,000 customers
- #1 in analog - 18% market share
- #2 in embedded processing - 15% market share

Invests in the future

- Nearly $9 billion invested over last 5 years in product development, R&D labs, manufacturing development & university partnerships
- $1.4 billion in R&D in 2014
- $385 million in Cap Ex in 2014



Focuses on innovation

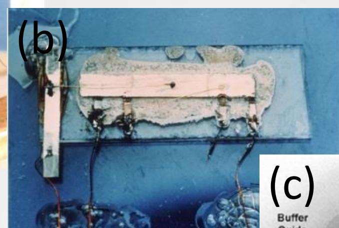
- TI patents issued worldwide
    - More than 40,000 cumulatively
    - More than 1,000 in 2013

Semiconductor timeline

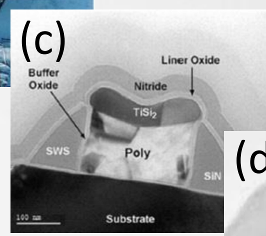
Vacuum Tube

1947 – Transistor Bell Labs

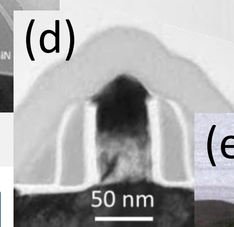
1958 –Texas Instruments



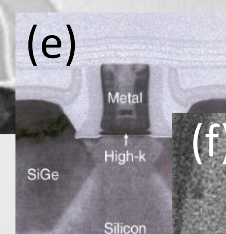
≈1995 – gate $TiSi_2$



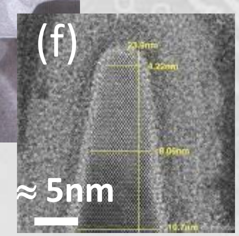
≈2000 – 50 nm



≈2007 – SiGe, metal gate, high-k - Intel



≈ 2010 – FinFET 3D - Intel



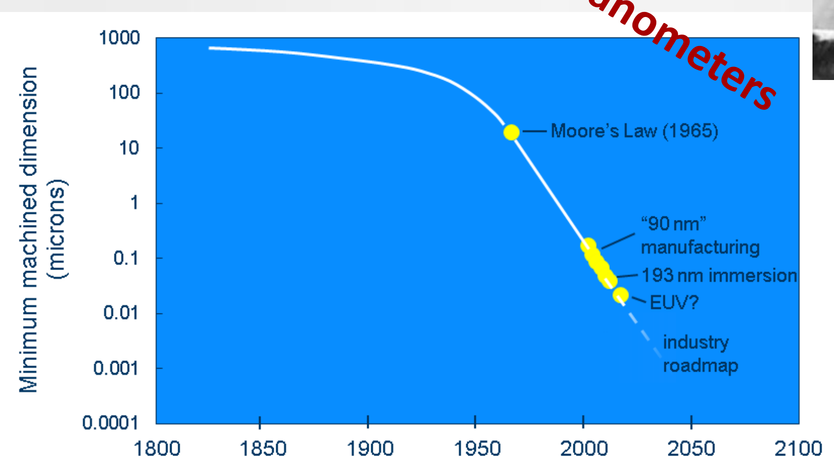
?

IT-using industry drives nearly 50% of US economic growth and accounts for about 25% of US GDP

Planar

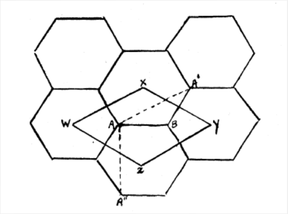
3-Dimensions (3D)

from cm to nanometers



Graphene – a timeline

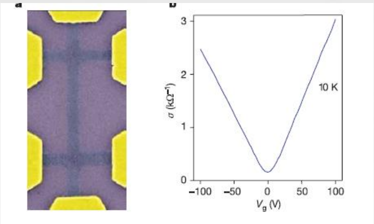
1947



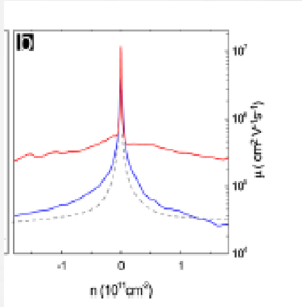
P.R. Wallace., Phys. Rev. 71, 622

2005

K.S.Novoselov et al., Nature 438, 197



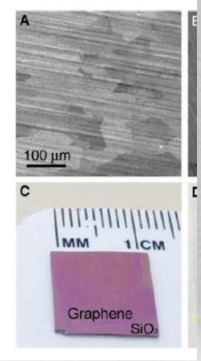
2008



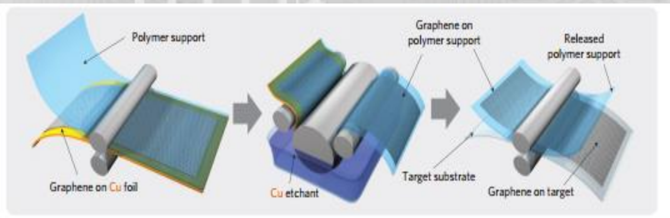
K.I. Bolotin et al., SSC,146,351

2009

X. Li et al., Science 324, 1312



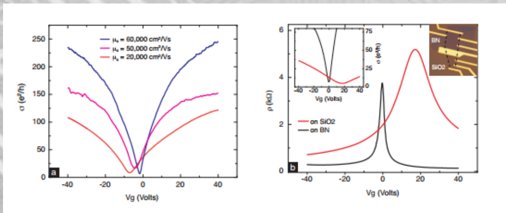
2010



S. Bae et al., Nature Nanotechnology 5, 574

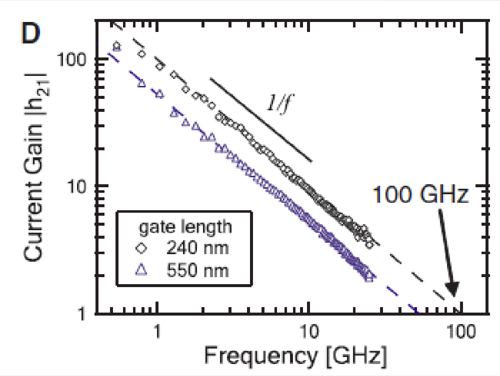
2010

C. R Dean et al., Nature Nanotechnology 5, 722–726



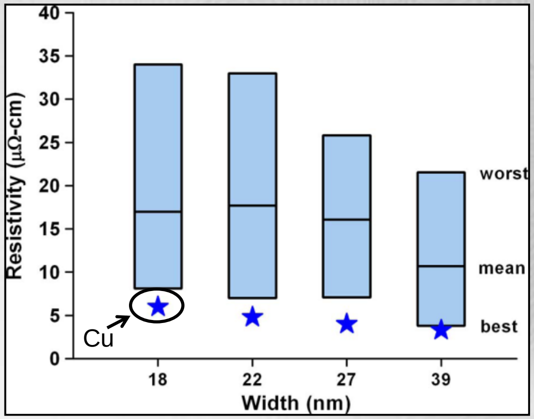
Graphene - applications

Y. M. Lin et al., Science, 327,662 (2010)



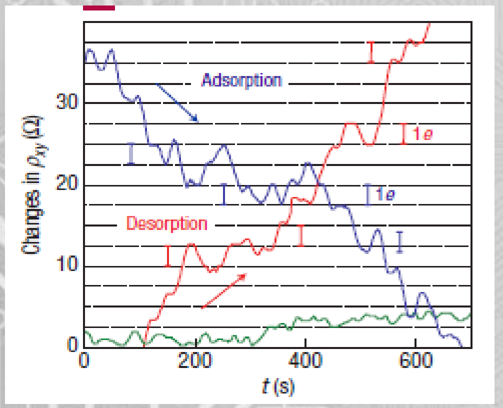
[***RF transistors with cutoff frequencies ~ 100 GHz***]

R. Murali et al., IEEE EDL, 30,611 (2009)



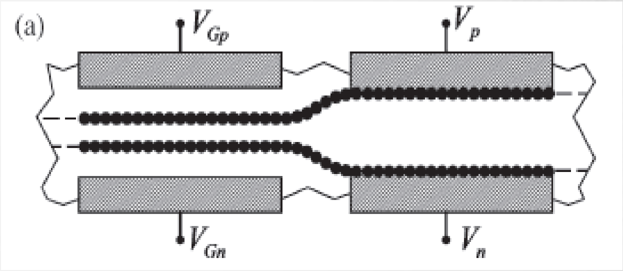
[***GNR interconnects with resistivities comparable to Cu***]

F. Schedin et al., Nature Mat. 6, 652 (2007)



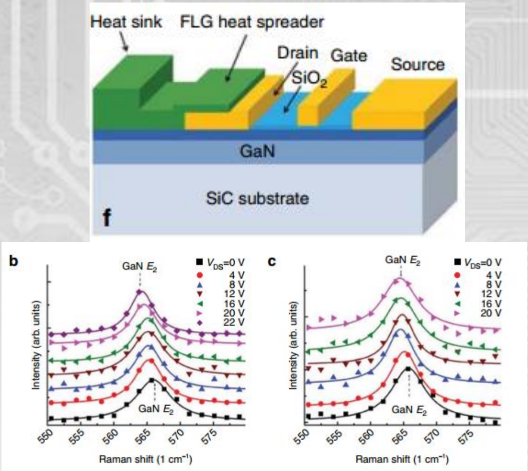
[***Gas sensors capable of single molecule detection***]

S. K . Banerjee et al., IEEE EDL 30,158(2009)



[***Bilayer pseudospin FET (BiSFET)***]

Z. Yan et al., Nature Comm., 3, 827 (2012)



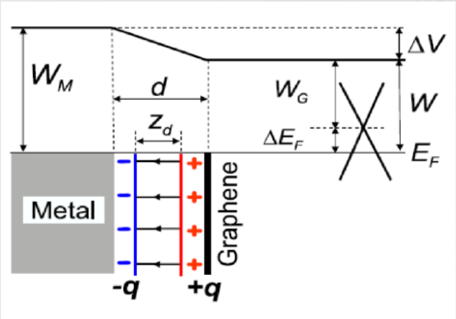
[***Thermal spreading***]

- **Should graphene be evaluated only as a switch ?**
- **What are the roadblocks to integration?**

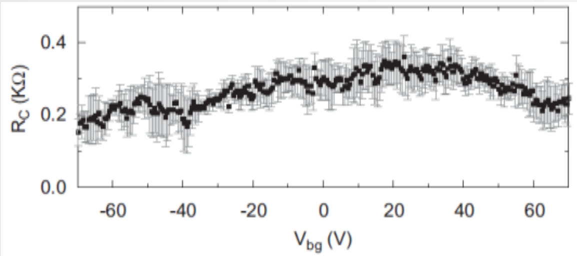
Outline

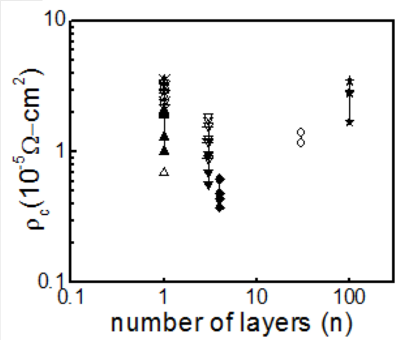
- Where we are
- Issues
  - Contact resistance
  - Graphene type
  - Mobility
- Adoption by industry

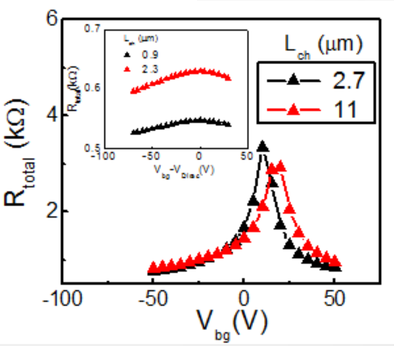
Contacts on graphene



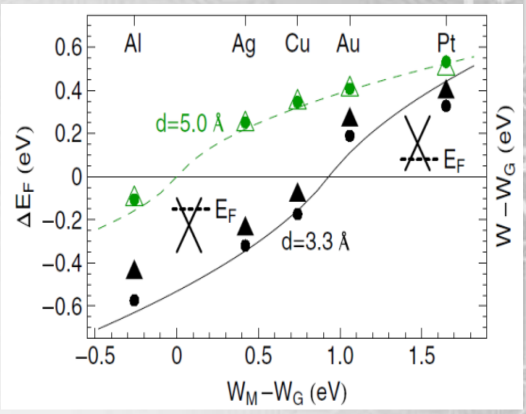
R_c contributes significantly to the total measured resistance

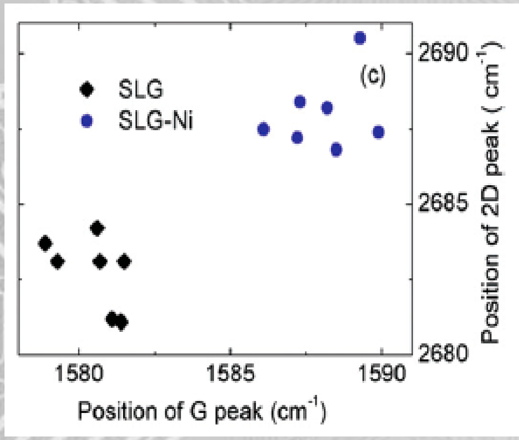






Metal – Graphene interface reactions : charge transfer and Fermi level shift





Giovannetti G. et al., Phys. Rev. Letters. 101, 026803(2008);
J.H. Lee et al., Nature Nano. 3 , 486(2008)
W. X. Wang et al., J. Appl. Phys. 109, 07C501 (2011)

S.Russo et al., Physica E. 42, 677 (2010),
A.Venugopal et al., Appl. Phys. Lett. 96, 013512 (2010),
Nagashio et al., APL 97, 143514 (2010)

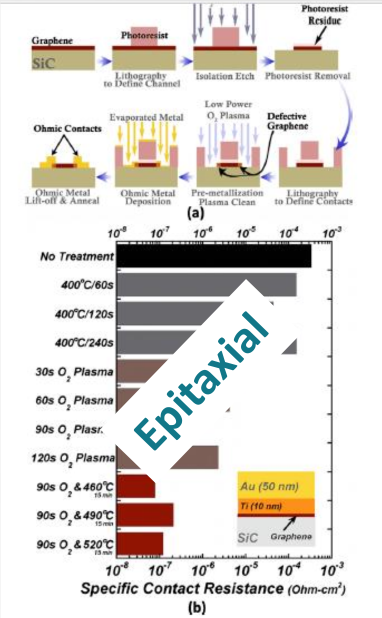
Issues:

- High R_c – not suitable for low bias operations; affects g_m
- R_c for graphene > 10^{-6} Ohm –cm^2; for Si – 10^{-8} Ohm – cm^2

Reported improvements

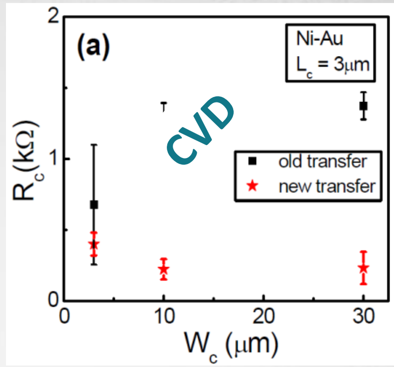
J. Robinson et al., APL 98, 053103 (2011)

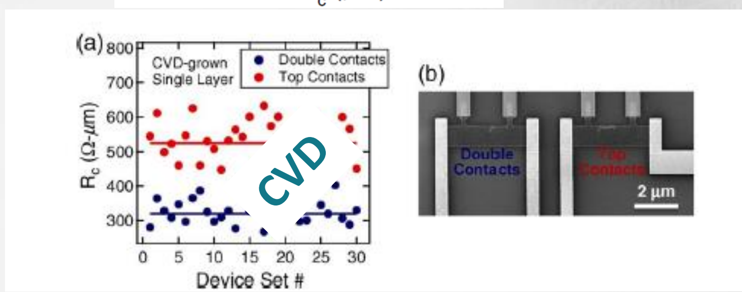
Oxygen plasma clean



Venugopal, A. (2012). PhD thesis, UT, Dallas

Thinner PMMA for transfer



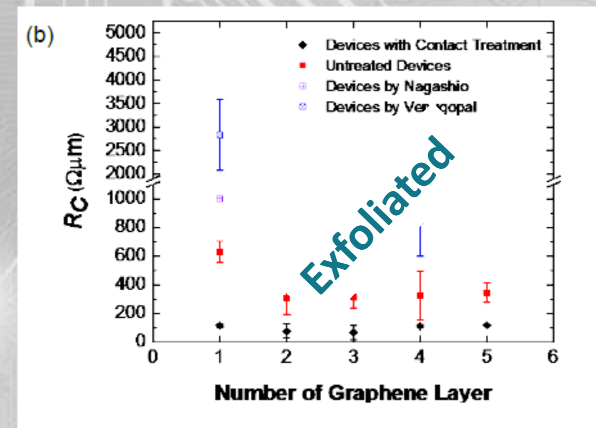


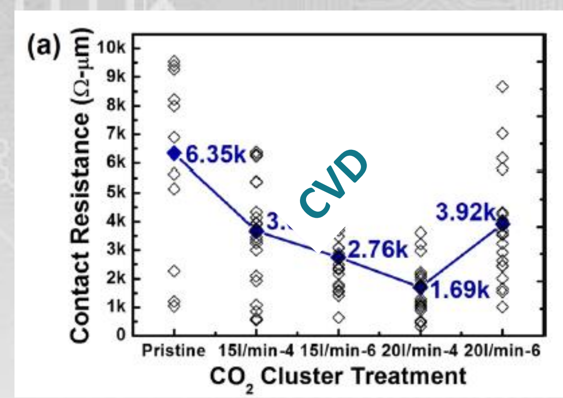
A.D. Franklin et al., IEEE EDL 33, 17(2012)

Double contacts

W.S. Leong et al., ACS Nano, 8, 994 (2014)

End contacts





S. Gahng et al., APL 104, 223110 (2014)

CO_2 cluster cleans

Issues:

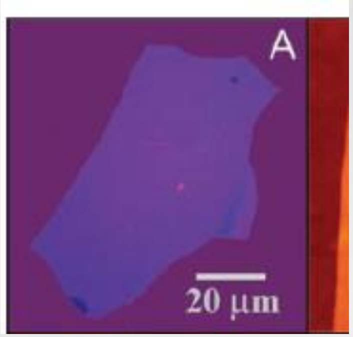
- **Absence of a standardized pre clean baseline flow**
- **Different graphene sources**

Outline

- Where we are
- Issues
  - Contact resistance
  - Graphene type
  - Mobility
- Adoption by industry

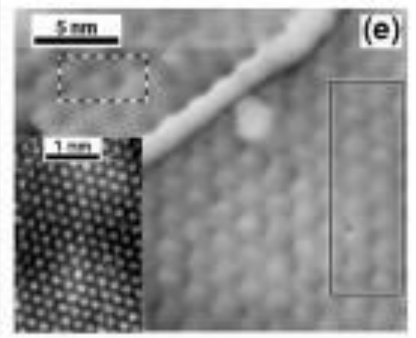
Graphene types

K.S. Novoselov et al., Science 306, 666 (2004)



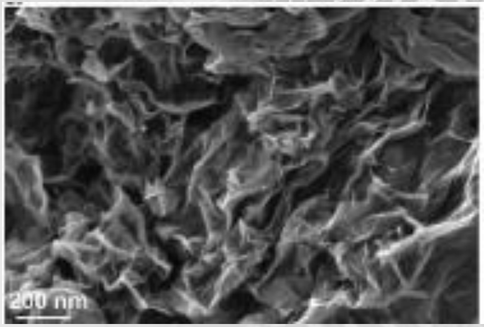
Exfoliated

C. Berger et al., J. Phys. Chem. B 108, 19912 (2004)



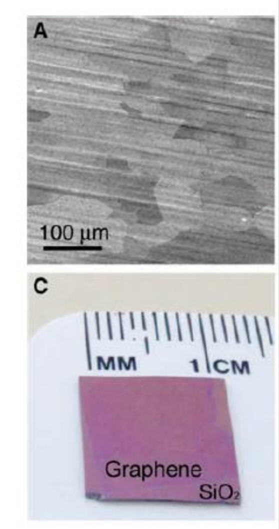
Epitaxial

S. Stankovich et al., Carbon 45, 7 (2007)



Chemically reduced

CVD grown



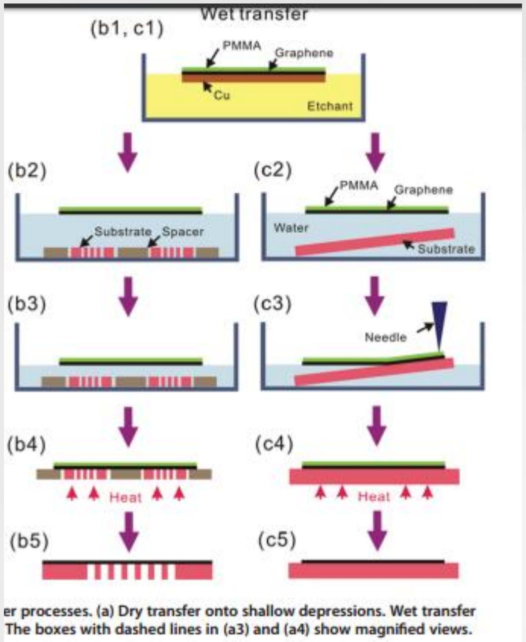
X. Li et al., Science 324, 1312 (2009)

Issue:

- **Only CVD process yields large area monolayer graphene**
  - **Typical growth temperature > 1000C**
  - **Typical substrate – Cu**
  - **Involves transfer to substrate of choice post growth**

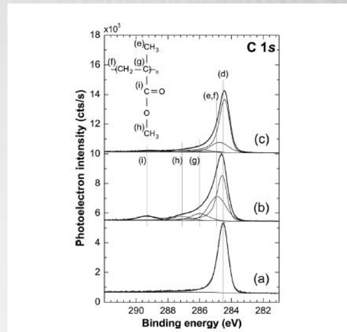
Transfer and cleaning

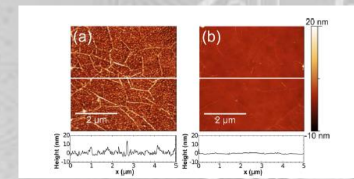
Wet transfer



J.W. Suk et al., ACS Nano, 5 , 6916(2011)

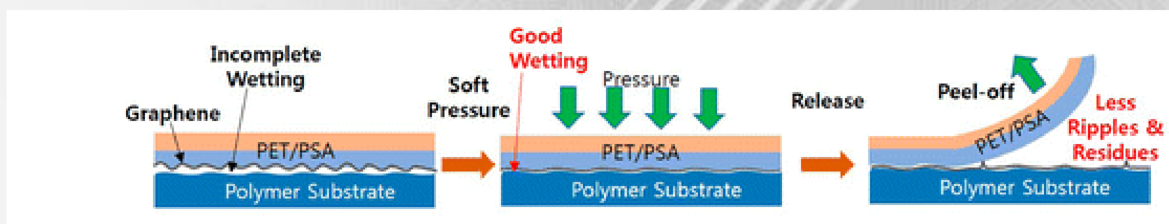
UHV anneal





A. Pirkle et al., Appl. Phys. Lett. 99, 122108 (2011)

Non PMMA based transfer



S.J. Kim et al., Nano Lett, 15,3236 (2015)

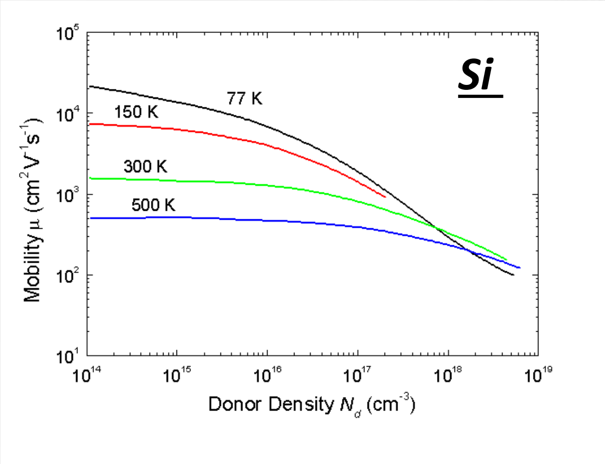
Issues:

- **Transfer**
- **Using mobility as a gauging parameter for quality**

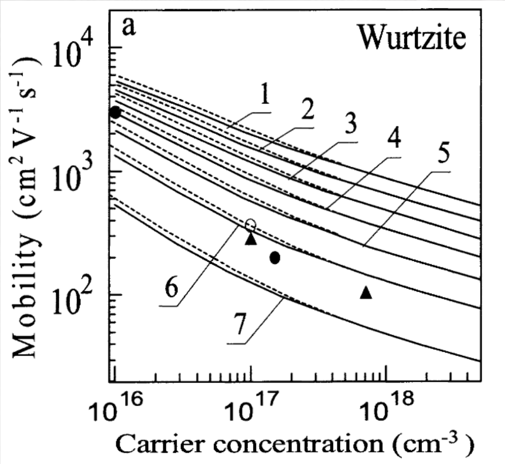
Outline

- Where we are
- Issues
  - Contact resistance
  - Graphene type
  - Mobility
- Adoption by industry

Mobility in Si, III- Vs and graphene

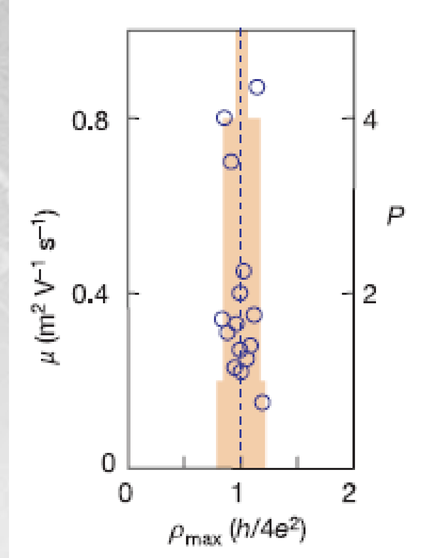


S.S. Li et al., Volume 20, Issue 7, July 1977



V. W. L. Chin et al., J. Appl. Phys. 75, 7365 (1994)

K.S.Novoselov et al., Nature 438, 197 (2005)

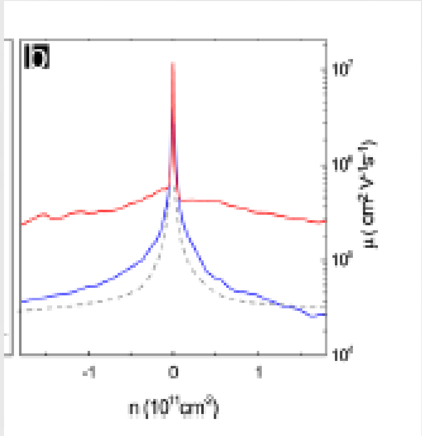


Mobility is typically used as a gauging parameter in the semiconductor industry

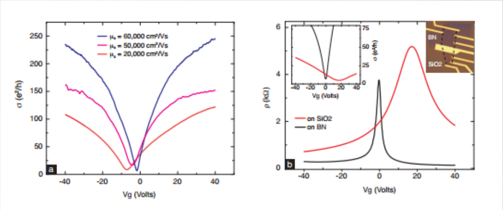
- **Dependent only on material properties and independent of geometry**

Gauging quality with mobility

Substrate effect

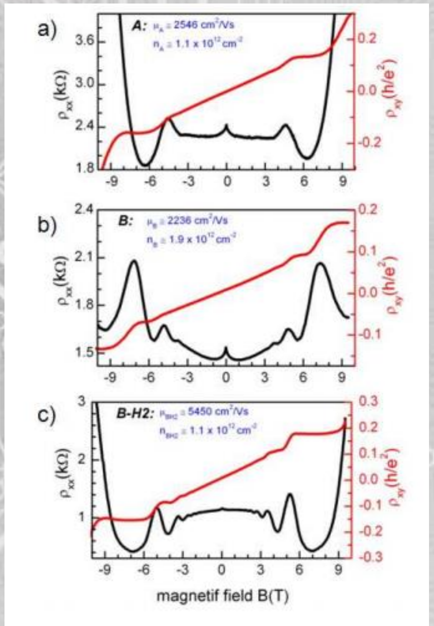


K.I. Bolotin et al., SSC,146,351, (2008)



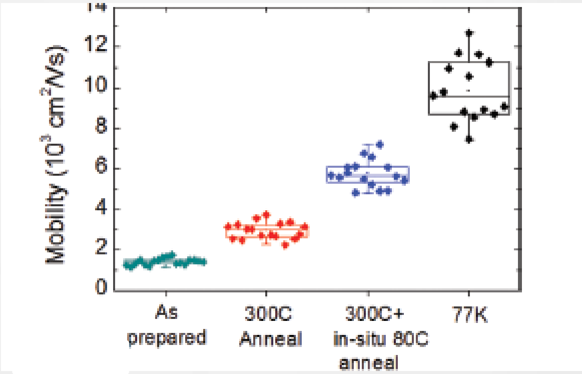
C. R Dean et al., Nature Nanotechnology 5, 722–726 (2010)

Graphene type effect

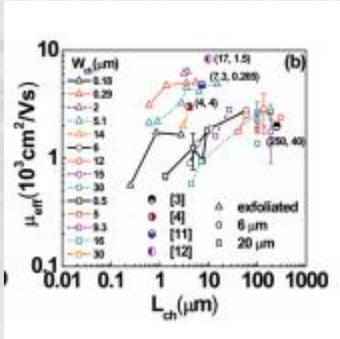


E. Pallecchi et al., Scientific Reports 4, 4558 (2014)

UHV anneal effect

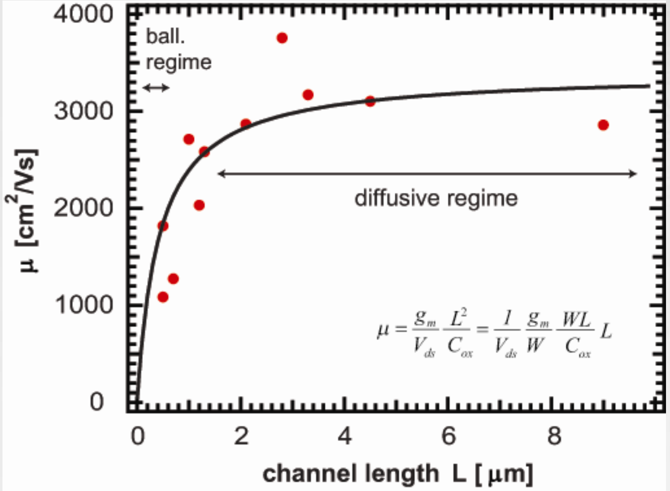


J. Chan et al., ACS Nano, 6, 3224 (2012)

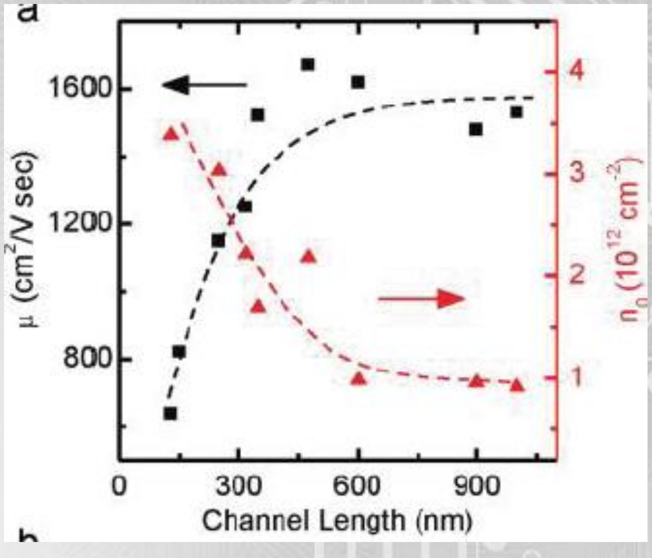


A. Venugopal et al., Journal of Appl. Phys. 109, 104511 (2011)

Mobility and channel length (L_{ch})



Z. Chen et al., IEDM (2008)



I. Meric et al., Nanoletters 11, 1093(2011)

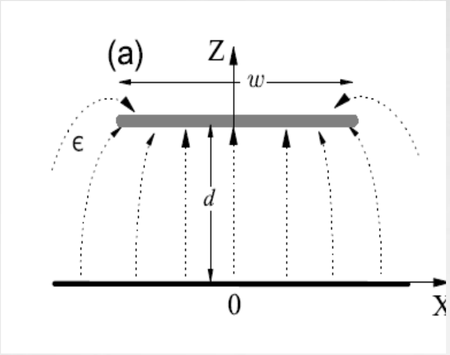
Mobility previously determined to be dependent on the channel length.

L_{ch} dependence attributed to

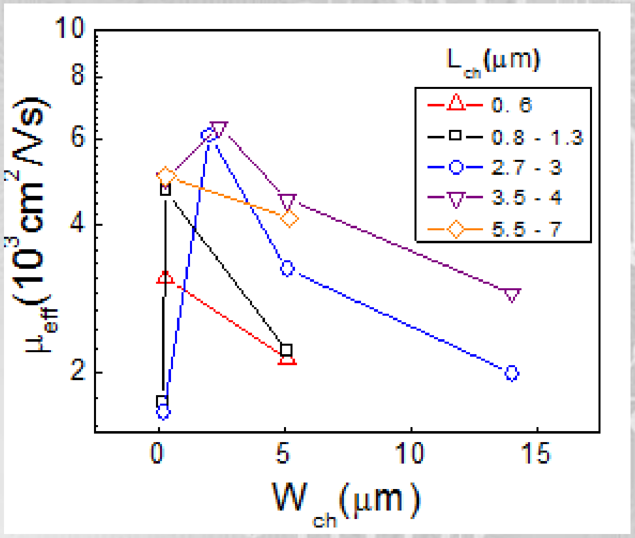
- device operating partially in the ballistic and diffusive regime
- damage from e beam lithography

Mobility and channel width (W_{ch})

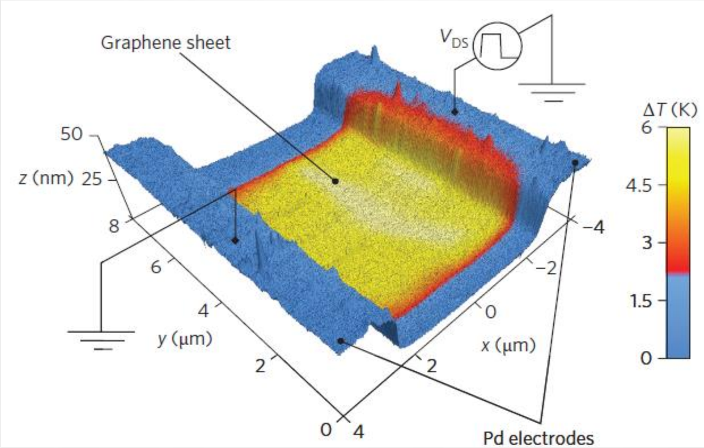
F.T. Vasko et al., Appl. Phys. Lett. 97, 092115 (2010)



A. Venugopal et al., Journal of Appl. Phys. 109, 104511 (2011)



K.L. Grosse et al., Nature Nano. (2011)



Issue – the geometry effect on mobility in graphene devices is typically not corrected for

W_{ch} dependence attributed partially to edge scattering and partially to electrostatics

Industry Standard vs. Graphene Process

Parameter	Industry	Current Graphene flow	Potential solution
Contact resistance	~ 10^{-8} ohm – cm^2	~ 10^{-6} ohm –cm^2	Contact engineering on a standardized baseline flow
Temperature	< 300 C for BEOL, 700 – 1000 C for FEOL	> 1000 C for CVD type process on Cu, followed by transfer	PECVD growth on arbitrary substrates
Metal deposition	Etch	Liftoff	Develop etch processes to identify and work on etch related issues
Substrate	Si or III-V’s	90 or 300 nmSiO_2 and now BN	PECVD growth on arbitrary substrates including thin oxides and BN
Mobility	Geometry independent	Geometry dependent	Standardized mobility formulation that corrects for geometry effects

Summary

- There are demonstrated applications that are unique or enhance what is available in the market today

- Effort toward consistent/reliable graphene device fabrication and large scale integration is still immature

- Issues that need to be addressed include:
    - High contact resistance
    - Geometry dependent mobility
    - No well defined path to integration into Si flow

- A prerequisite towards adoption by industry is effort on correcting the known issues and fabricating devices that are consistent and reliable