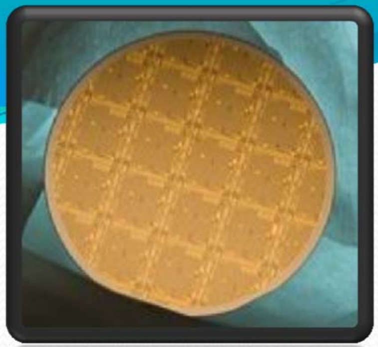
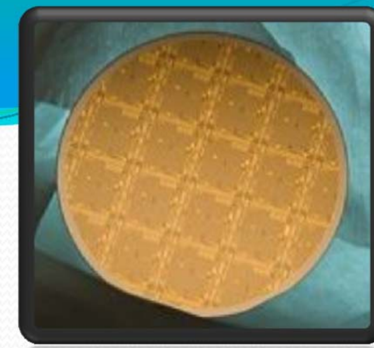


Graphene Electronics

ECE 3080

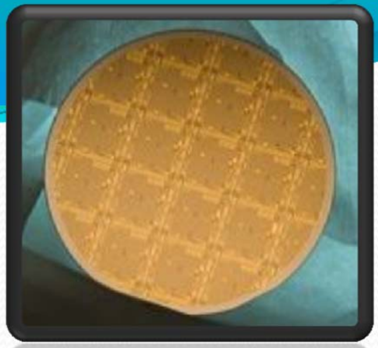
Joe Gonzalez

Objectives

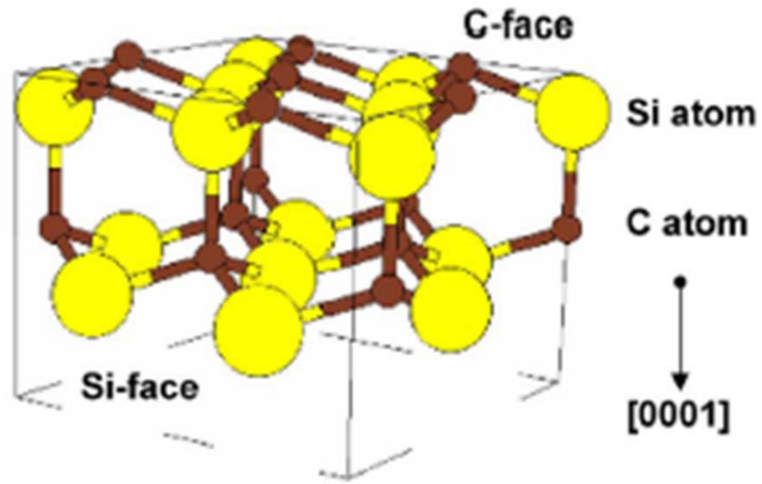


- Overview
- Issues
  - Mobility Issues
  - Integration
  - Contacts
- Present Graphene Transistors
- Critical Issues
- Conclusions/Future

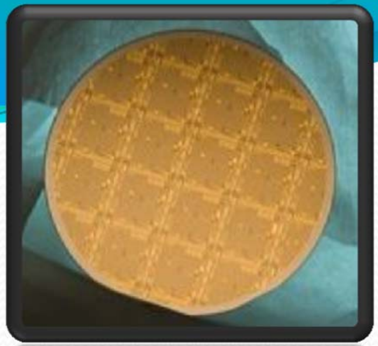
Overview



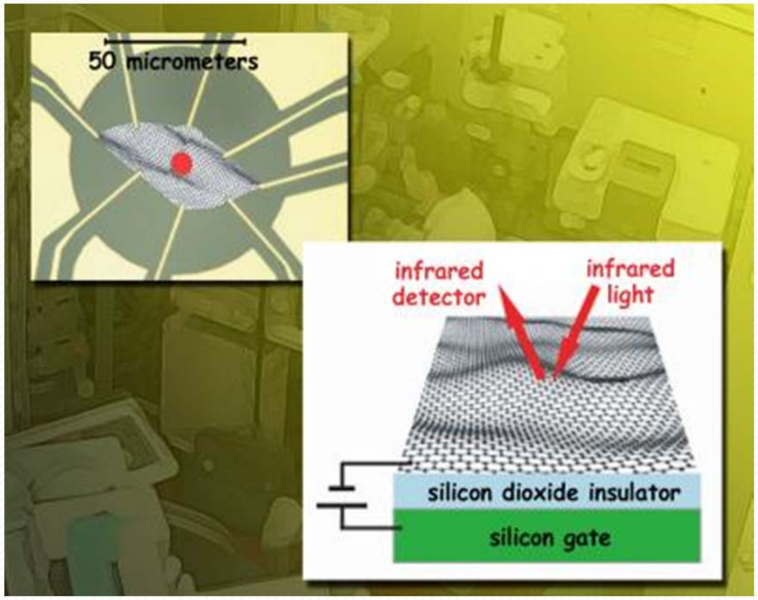
- Processing Methods
  - Exfoliated Graphene
  - Epitaxial Graphene
    - Graphene on Si
    - Graphene on SiC

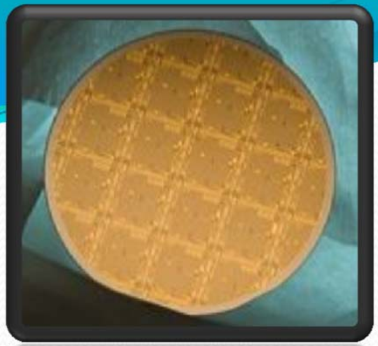


Exfoliated Graphene



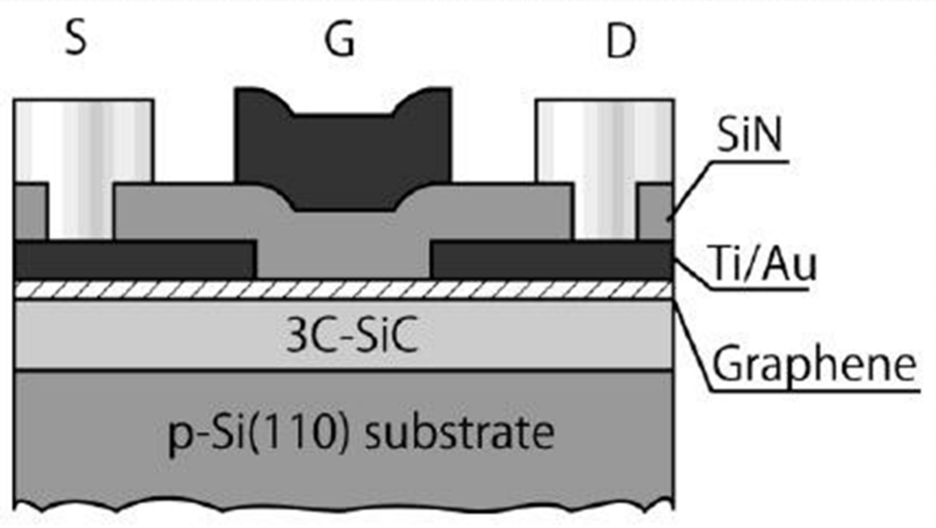
- Uses cohesive tape to split graphite crystals into smaller segments
- Dry deposition





Epitaxial Growth on Si

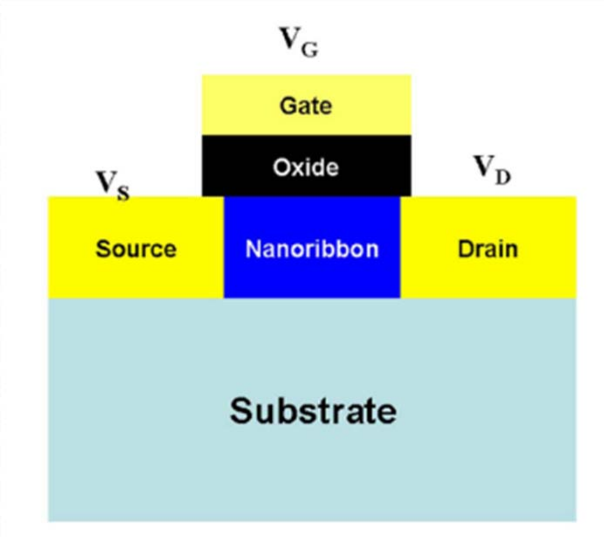
- Two-step process
  - Epitaxial growth of SiC on Si (CVD)
    - Sacrificial Layer
  - Thermal decomposition of SiC to Graphene



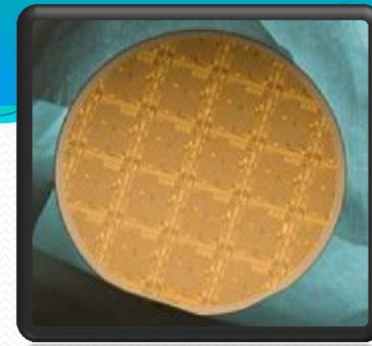
http://arxiv.org/ftp/arxiv/papers/1001/1001.4955.pdf

GNRFET

- Graphene Nanoribbon FET
- Bandgap attainable via decreasing nanoribbon width
  - Mobility tradeoff



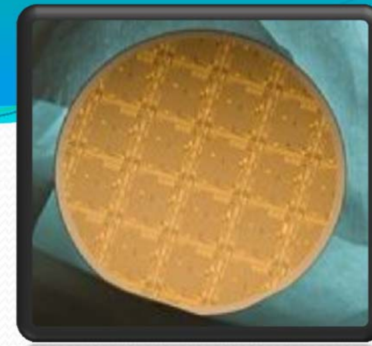
Issues



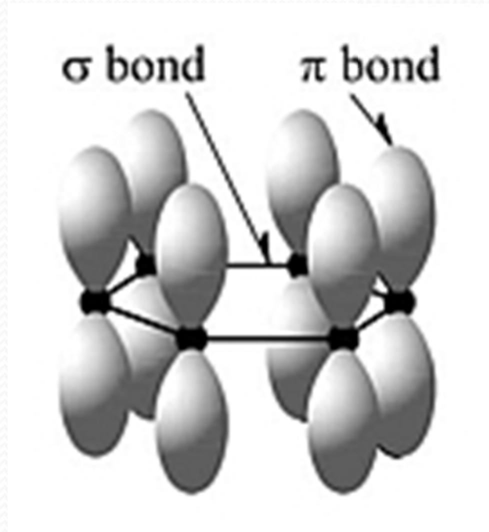
- The critical issues for graphene include the ability to:
  - 1. Achieve a high mobility on a silicon compatible substrate
  - 2. Form reproducible low resistance contacts to graphene (contacting without etching through a monolayer film)
  - 3. Integration, doping, and compatibility with CMOS

From International Technology Roadmap for Semiconductors, 2009 Edition, Emerging Research Materials

Mobility Primer

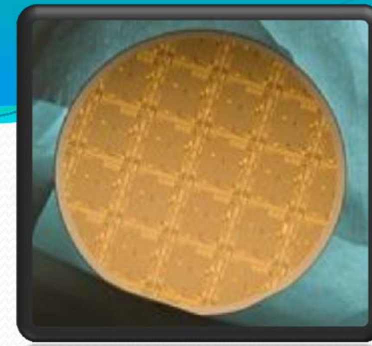


- Unique bond structure
- 2D macromolecule
- Carriers behave like Dirac fermions
  - $m^* \approx 0$
  - $E_g = 0$
- Weak electron-phonon interaction



http://www.andrew.cmu.edu/user/feenstra/graphene/

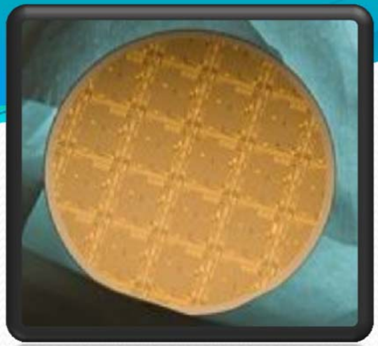
Exfoliated vs. Epitaxial



- Mechanically exfoliated
  - Monolayers
  - Intrinsic mobility > 200,000 $cm^2/V \cdot s$
- Epitaxial
  - Multilayers
  - Si-face mobility ~ 600-1200 $cm^2/V \cdot s$
  - C-face mobility ~ 500-5000 $cm^2/V \cdot s$

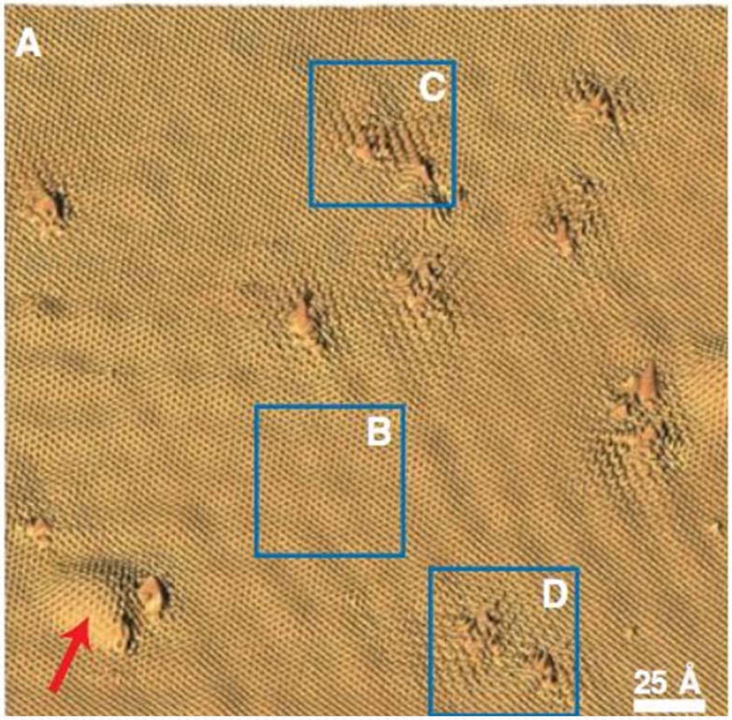
K.I. Bolotin, K.J. Sikes, Z. Jiang, M. Klima, G. Fudenberg, J. Hone, P. Kim, H.L. Stormer, "Ultrahigh electron mobility in suspended graphene," Solid State Communications, Vol. 146, pp. 351–355 (2008).

Kedzierski, J., Pei-Lan Hsu, Healey, P., Wyatt, P.W., Keast, C.L., Sprinkle, M., Berger, C., de Heer, W.A., "Epitaxial Graphene Transistors on SiC Substrates," IEEE Transactions on Electron Devices, Vol. 55 (8), pp. 2078 - 2085 (Aug. 2008).



Scattering - Intrinsic

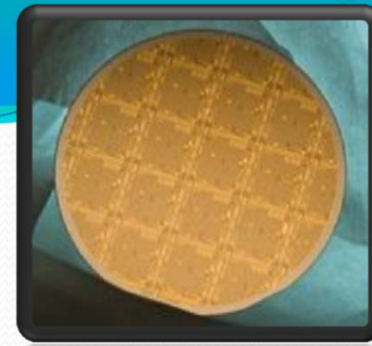
- Graphene corrugation
  - Material stability
- Type A defects
  - Continuous hills
  - SiC interface
- Type B defects
  - Atomic defects
  - Dominant scattering centers



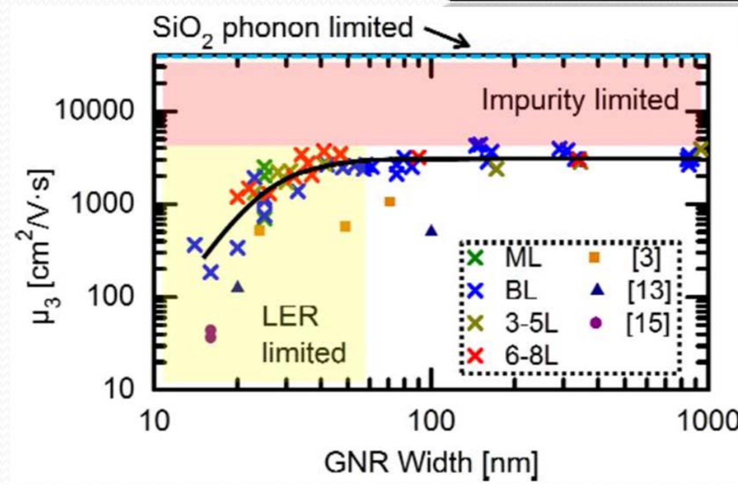
Meyer, J. C., Geim, A. K., Katsnelson, M. I., Novoselov, K. S., Booth, T. J., and Roth, S., "The structure of suspended graphene sheets," Nature, vol. 446, no. 7131, pp. 60–63, 2007.

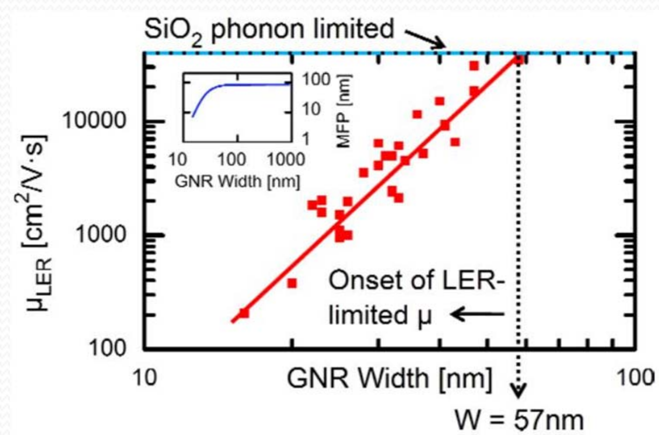
G. M. Rutter et al., "Scattering and interference in epitaxial graphene." Science 317, 219 (2007)

Scattering – LER

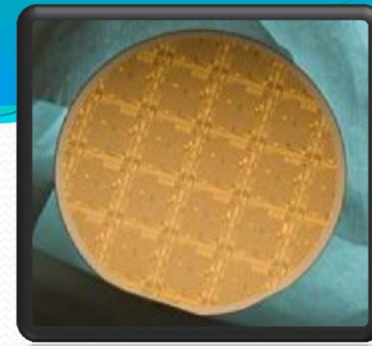


- Effect of scaling on mobility
- Exfoliated samples
- 16 nm ≤ W_{GNR} ≤ 1 μm
- W > 60 nm
  - μ > 3000 cm²/V·s
- W < 20 nm
  - μ < 200 cm²/V·s
- Bandgap implications



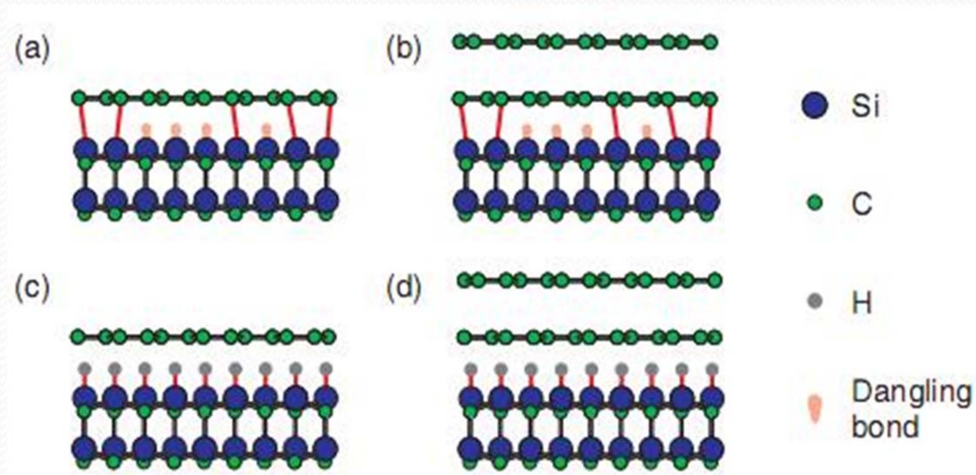


Yinxiao Yang; Murali, R.; , "Impact of Size Effect on Graphene Nanoribbon Transport," *Electron Device Letters, IEEE* , vol.31, no.3, pp.237-239, March 2010.



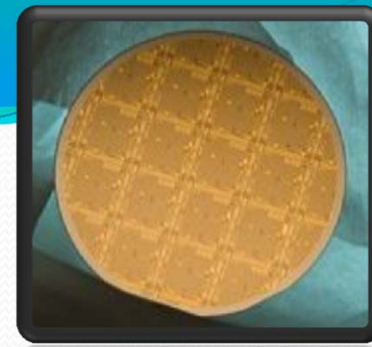
Hydrogen Intercalation

- Reconstructed C interface
  - Graphene “zerolayer”
  - Electrically inactive
  - Intrinsic *n* doping
- H intercalation
  - H breaks Si-C bonds
  - Creates buffer layer
  - Decouples graphene from Si
- Thermal cycle concerns



C. Riedl, C. Coletti, T. Iwasaki, A. A. Zakharov, and U. Starke, "Quasi-free standing epitaxial graphene on sic by hydrogen intercalation," Nov 2009. [Online]. Available: http://dx.doi.org/10.1103/PhysRevLett.103.246804

Mobility Improvement

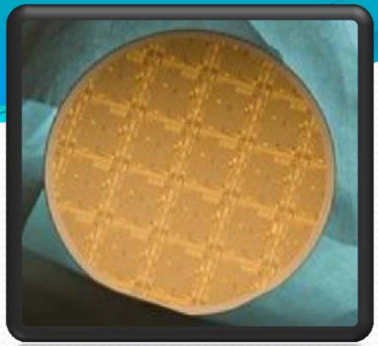


- GNR edge passivation
  - Self-passivation of metastable zigzag edges
- Different method to generate a bandgap
- Substrate improvement (Hydrogen intercalation)
- High-K gate dielectric
- Improved fabrication process
- Estimated attainable mobility: ~ 10000 $cm^2/V \cdot s$

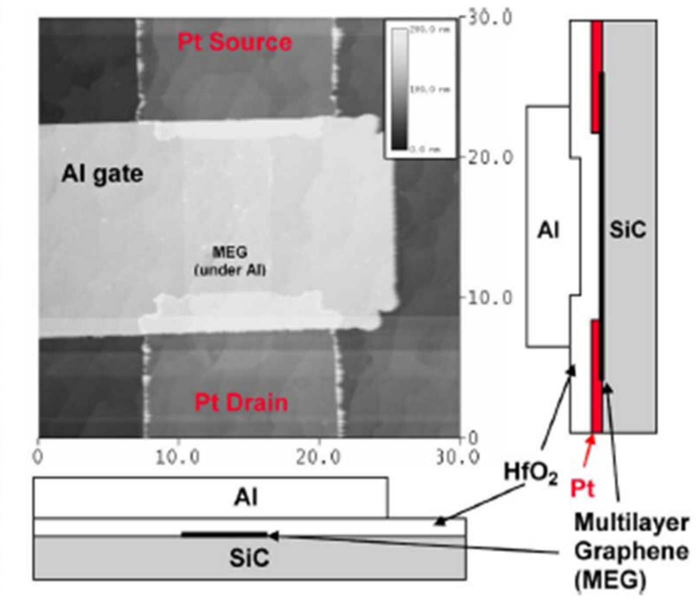
P. Koskinen, S. Malola, and H. Häkkinen, "Self-Passivating Edge Reconstructions of Graphene," Phys. Rev. Lett. **101**, 115502 (2008).

Kedzierski, J., Pei-Lan Hsu, Healey, P., Wyatt, P.W., Keast, C.L., Sprinkle, M., Berger, C., de Heer, W.A., "Epitaxial Graphene Transistors on SiC Substrates," IEEE Transactions on Electron Devices, Vol. 55 (8), pp. 2078 - 2085 (Aug. 2008).

Integration

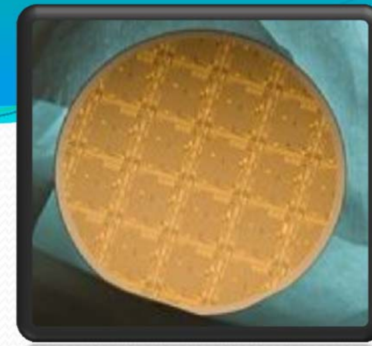


- Epitaxial Graphene Transistors on SiC
  - First Comprehensive Evaluation
- Process
  - SiC Substrate
  - Channel defined by O_2 Etch
  - Contacts Constructed of Pt & Ti
  - Gate Oxide: HfO_2
  - Aluminum Gate

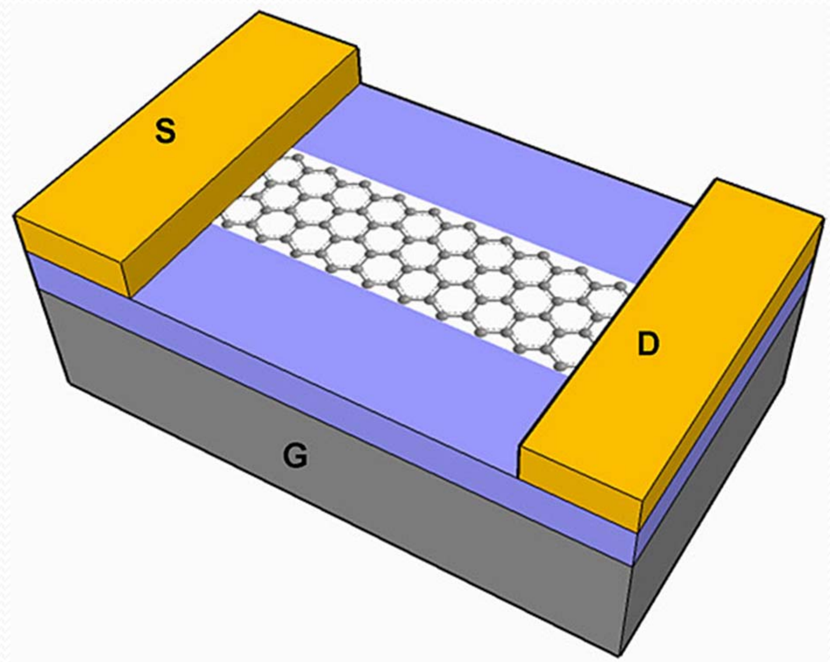


J. Kedzierski, P.-L. Hsu, P. Healey, P. W. Wyatt, C. L. Keast, M. Sprinkle, C. Berger, and W. A. de Heer, "Epitaxial graphene transistors on SiC substrates," *IEEE Trans. Electron Devices, vol. 55, no. 8, pp. 2078–2085,* Aug. 2008.

Electrodes on Graphene

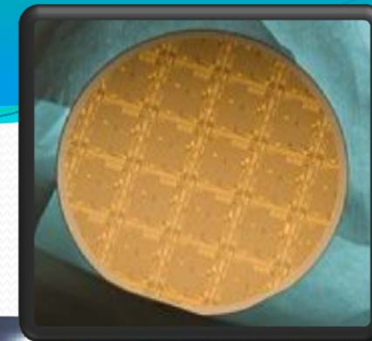


- Issues
  - Photocurrent response
    - Potential barrier
  - Film Integrity
    - Thermodynamic Stability
    - Chemical Sensitivity
- Potential Resolution
  - Single process contact and graphene formation

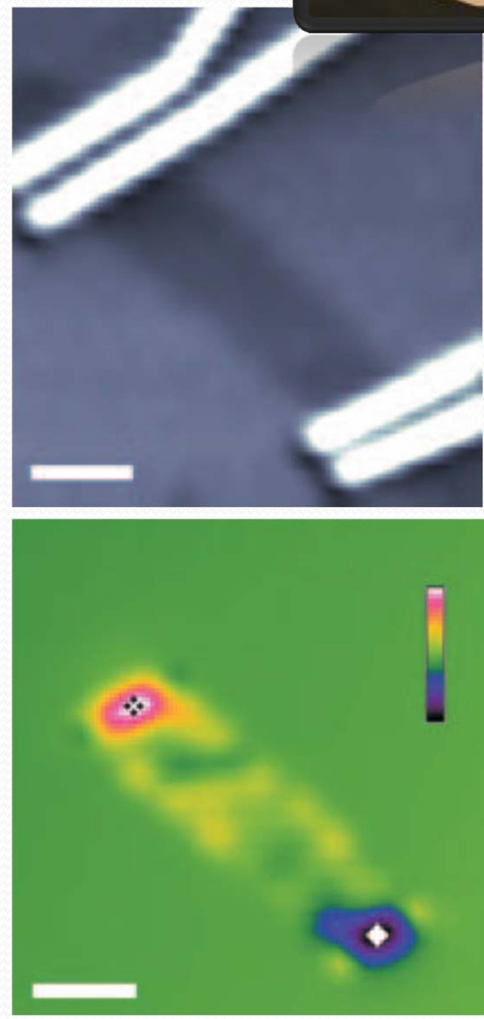


http://news.stanford.edu/news/2008/may28/ribbon-052808.html

Issues – Potential Barrier

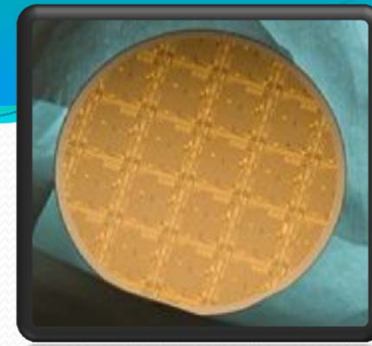


- Photocurrent response
  - Localized electric fields present
    - Charge carriers "feel" potential barrier
  - Concentrated at electrical contacts
  - Caused by interfacial doping
    - P-type – Au (High Φ_m)
    - N-type – Ti (Low Φ_m)

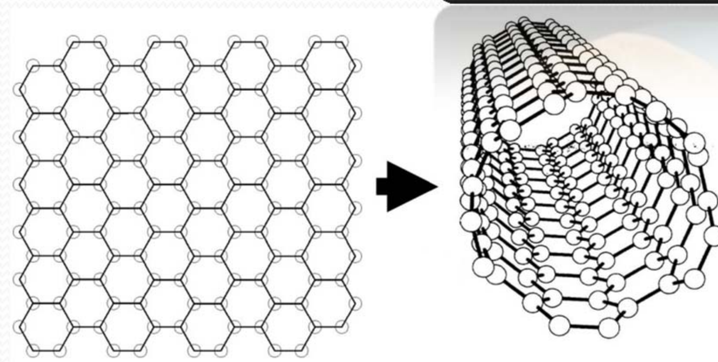


Lee, Eduardo J. H. et al.. "Contact and edge effects in graphene devices." Nature Nanotechnology, Vol. 3. 486–490 (2008)

Issues – Film Integrity

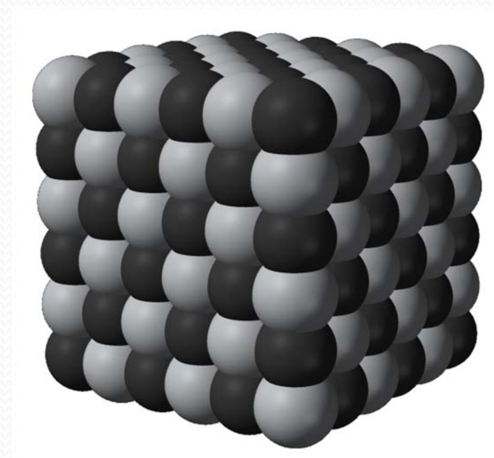


- Thermodynamic Stability
  - High-T anneals can cause graphene sheets to "roll up"
  - Unpredictable



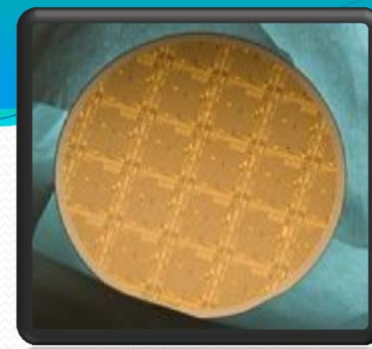
http://conf.ncku.edu.tw/research/articles/e/20071026

- Chemical Sensitivity
  - Metal-carbide formation
    - Titanium: TiC
    - Palladium: PdC



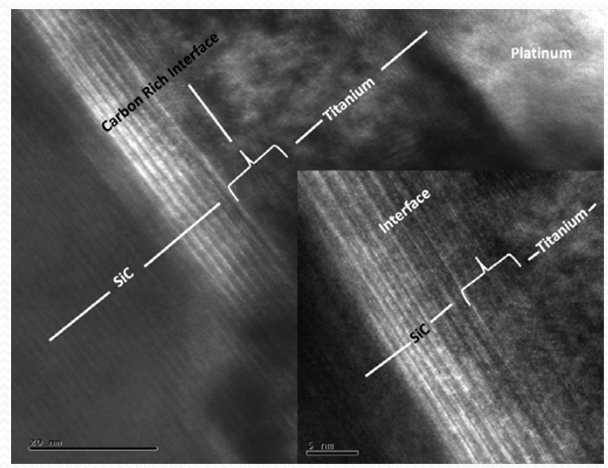
http://en.wikipedia.org/wiki/Titanium_carbide

Remarks



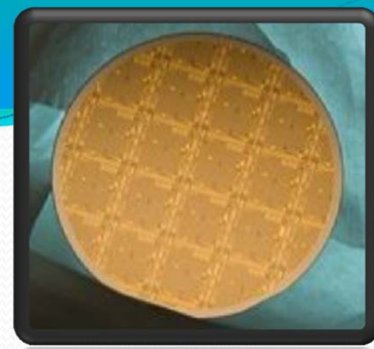
- Forming ohmic contacts to graphene can be difficult
  - Potential barrier issue
  - Film integrity issue

- New methods maintain film integrity
  - University of North Texas (2009)
    - Graphene after electrode process



Maneshian, Mohammed H. et al.. “Structural and electrical characterization of ohmic contacts to graphitized silicon carbide.” Nanotechnology, Vol. 20. 495703–495703 (2009)

Current Events/Future



- Graphene transistors have nanoscale cooling effect
- IBM introduces 155 GHz graphene transistor
- Depositing graphene via CVD on diamond-like carbon