Sub-5 nm Patterning and Applications by Nanoimprint Lithography and Helium Ion Beam Lithography

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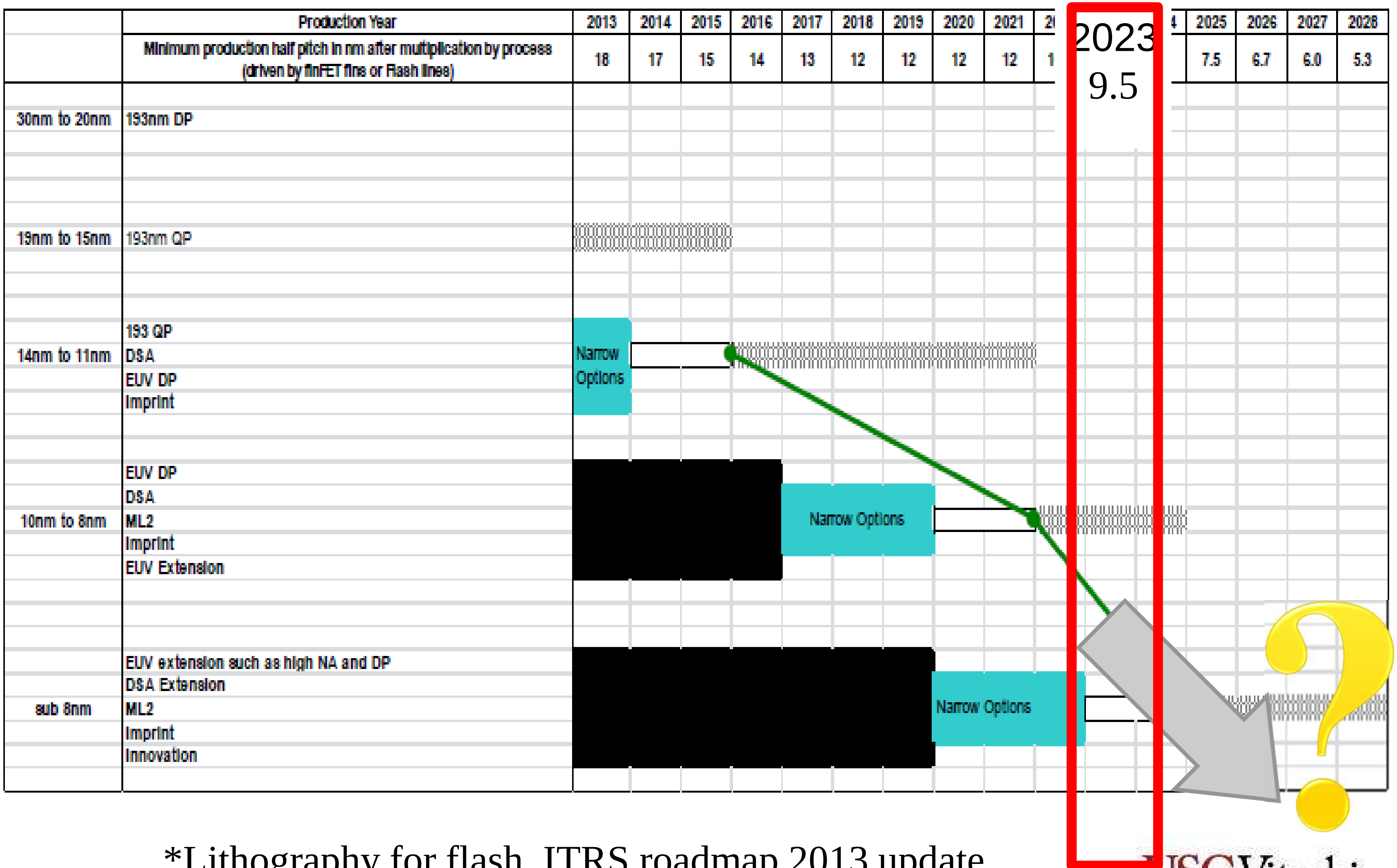
Outline

- Motivation
- Sub-5 nm lithography
  - Helium ion beam lithography
  - Nanoimprint lithography
- 5 nm graphene nanoribbons
  - Line-edge benchmarking using Raman spectroscopy
  - GNR FET and sensor
- Summary

Single-digit Nanometer Era



*Lithography for flash, ITRS roadmap 2013 update

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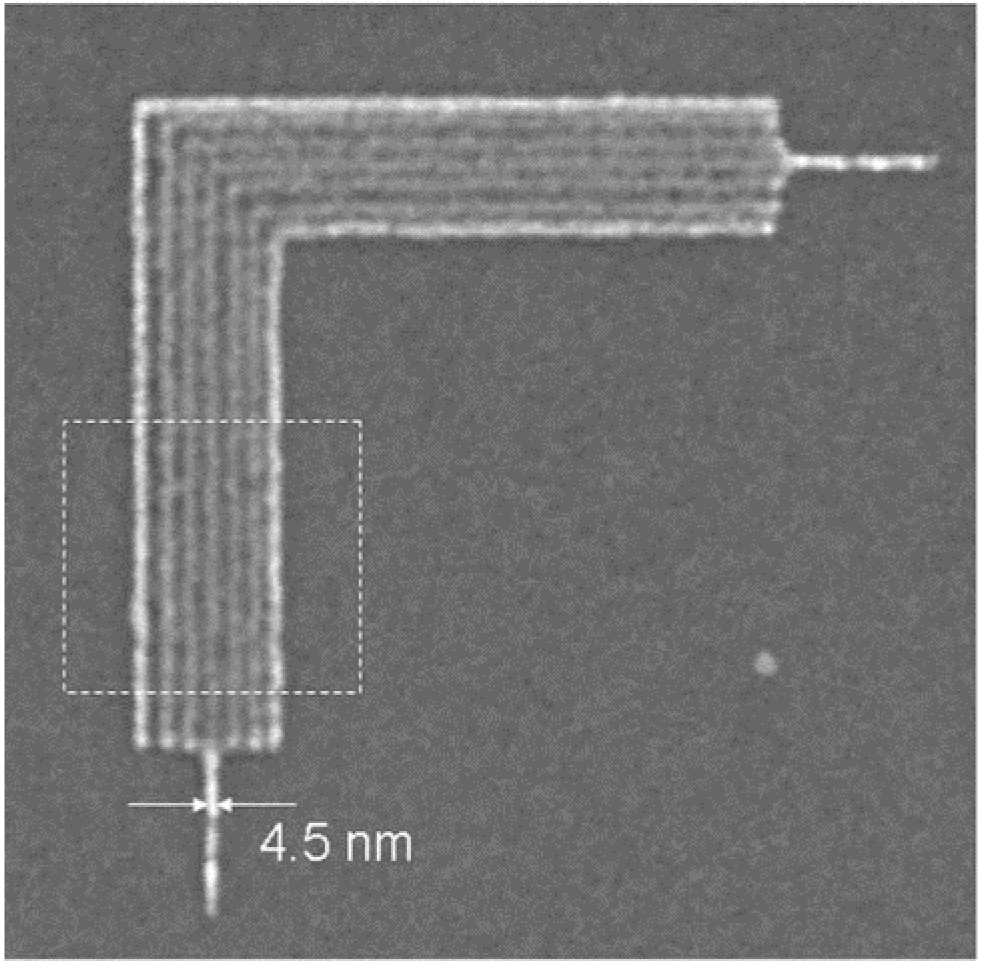
How to Achieve Better Resolution than Electron Beam Lithography?

Smallest half-pitch patterned by EBL in HSQ: 4.5 nm



Yang et al, J. Vac. Sci. Techno. 2009

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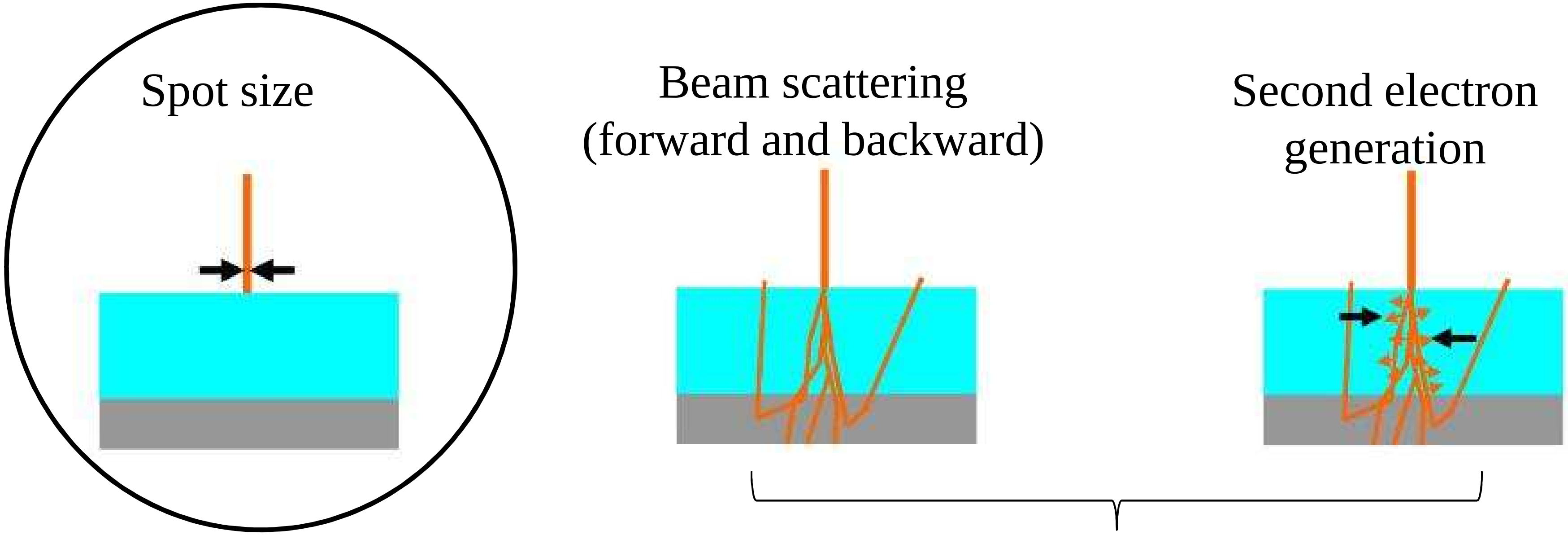
The Limiting Factor of EBL

Resolution limiting factors of electron beam (with a perfect resist):



~ 4 nm

Proximity effect 10 nm ~ microns

Overall beam spot diameter

$$d = \sqrt{d_g^2 + d_s^2 + d_c^2 + d_d^2}$$ (assume no astigmation)

$$d_g = \frac{d_v}{M}$$

d_v: virtual source diameter
M: demagnefication

$$d_s = \frac{1}{2} C_s \alpha^3$$

Spherical aberration

$$d_c = C_c \alpha \frac{\Delta V}{V}$$

Chromatic aberration

$$d_d = 1.22 \frac{\lambda}{\alpha}, \lambda = \frac{1.2}{\sqrt{V}} nm$$

Diffraction

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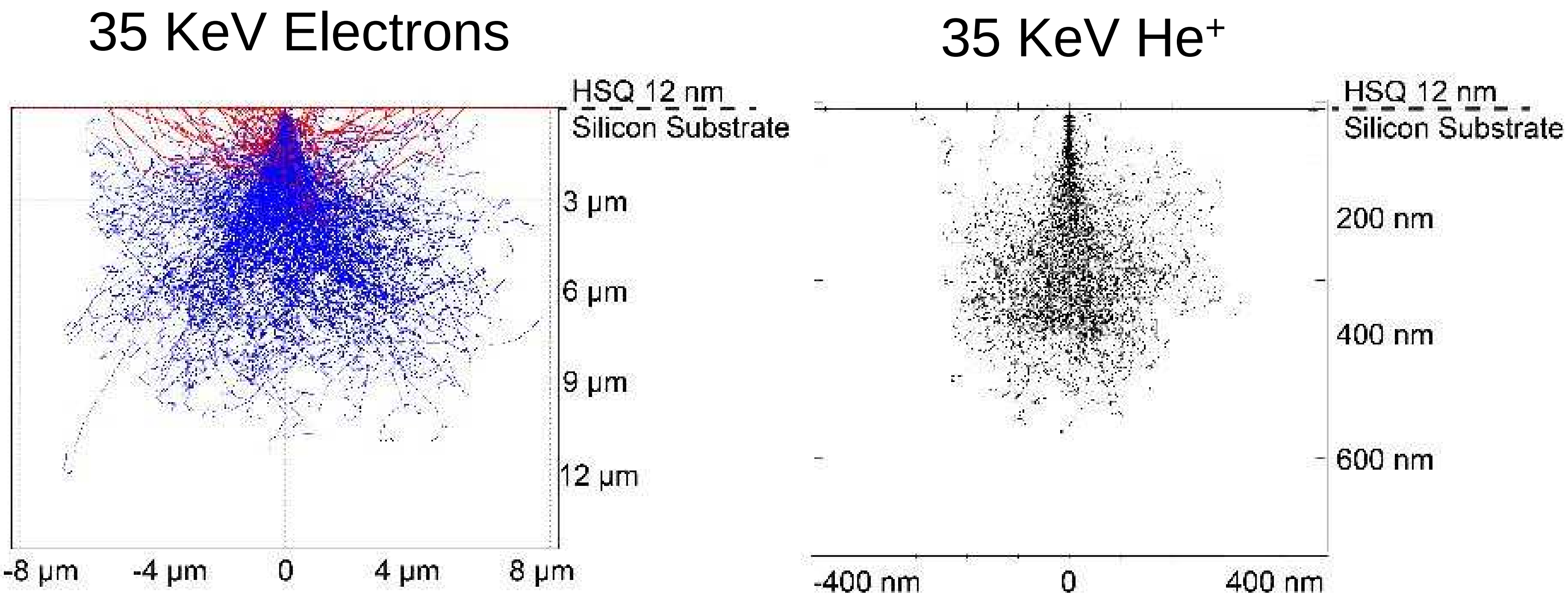
Helium Ion Microscope, Orion Plus, System Review

Beam spot: 3.5 Å

- HIM SE Mode Resolution
  - ≤ 0.35 nm
- Beam Landing Energy
  - 10 to 35 keV
- Beam Current
  - .1pA - 25pA
- Detectors
  - Everhart Thornley for Secondary Electrons (SE) imaging
  - MCP for Rutherford Backscattered Ion imaging (RBI)
  - SE & RBI images acquired simultaneously
- In-Situ Chamber and Sample Cleaning
  - Avoids carbon contamination
- Sample Neutralization
  - Maintained by low energy electron flood
  - Flood electrons are line or frame interlaced with the ions to compensate for any positive sample surface charge

~$2M

He Ion is Scattered Over Shorter Ranges



W.-D. Li, W. Wu and R. S. Williams, Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures 30 (6), 06F304 (2012).

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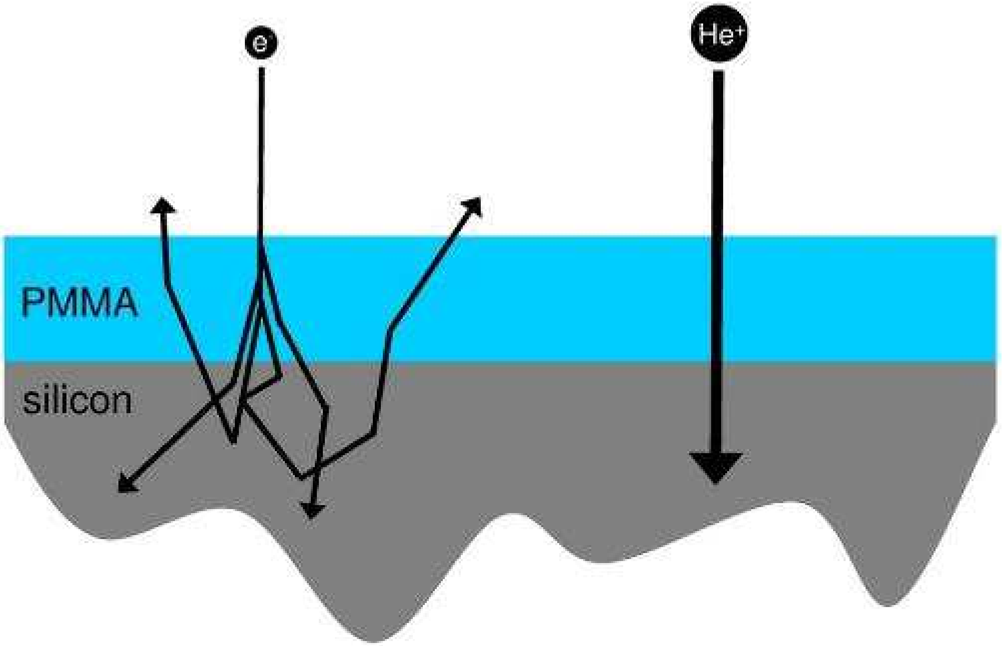
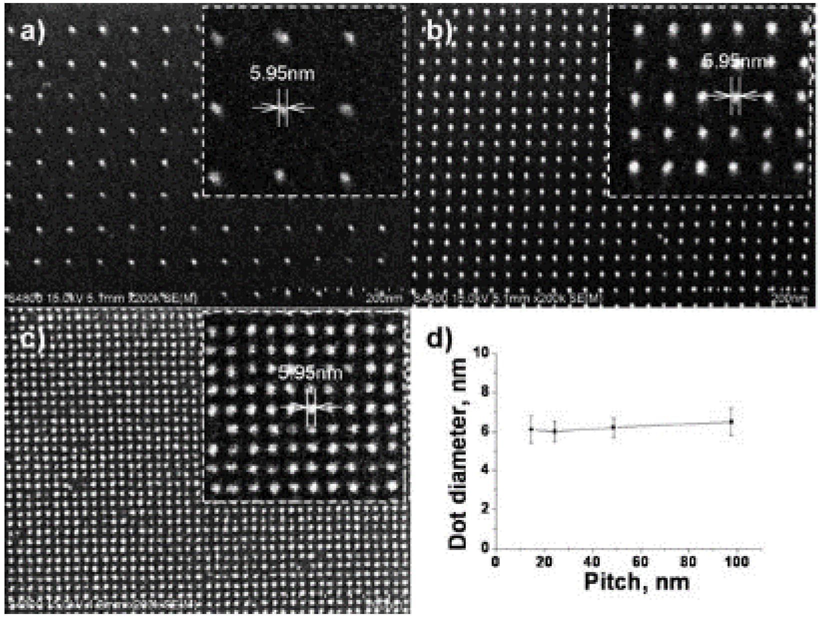
He Ion: Much Less Proximity Effect

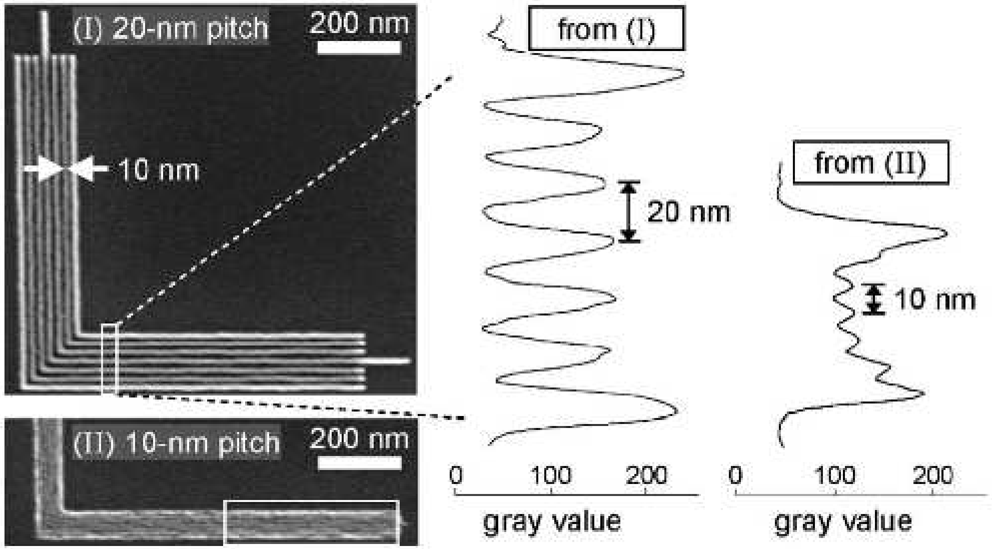
Beam scattering



Small spot + little proximity effect --> better beam for lithography!

Helium Ion Beam Lithography

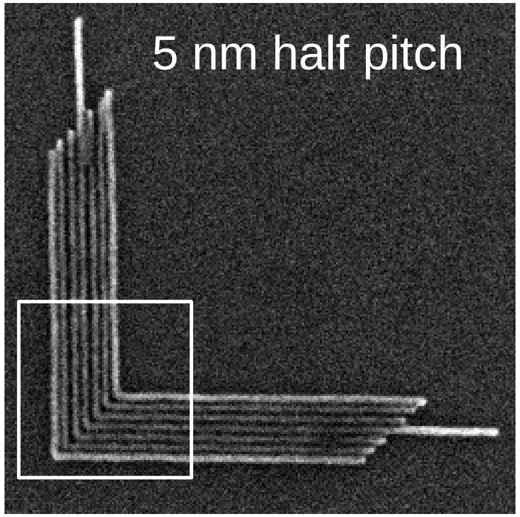


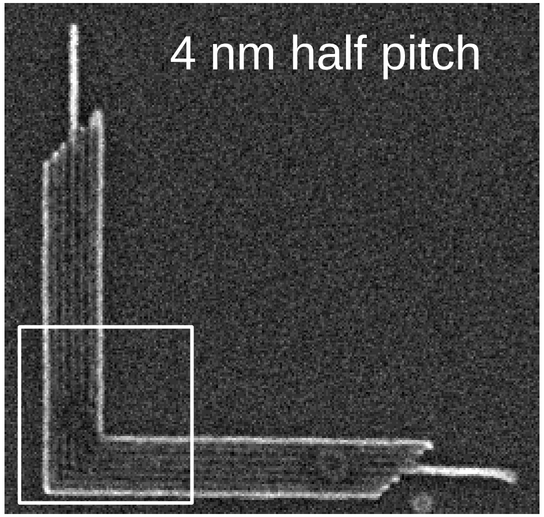


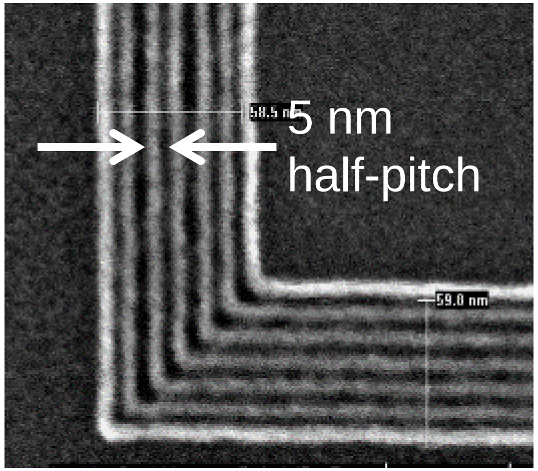
V. Sidorkin et al, J. Vac. Sci. Technol. B, 2009

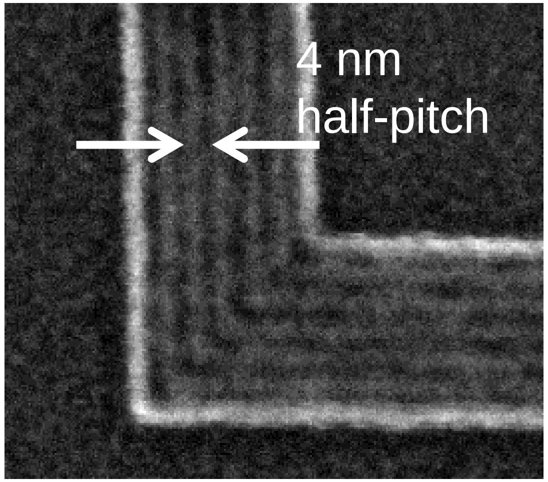
D. Winston et al, J. Vac. Sci. Technol. B, 2009

HIBL for Sub-5 nm Patterning on HSQ Resist









W.-D. Li, W. Wu and R. S. Williams, Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures 30 (6), 06F304 (2012).

He Ion: Much Less Proximity Effect

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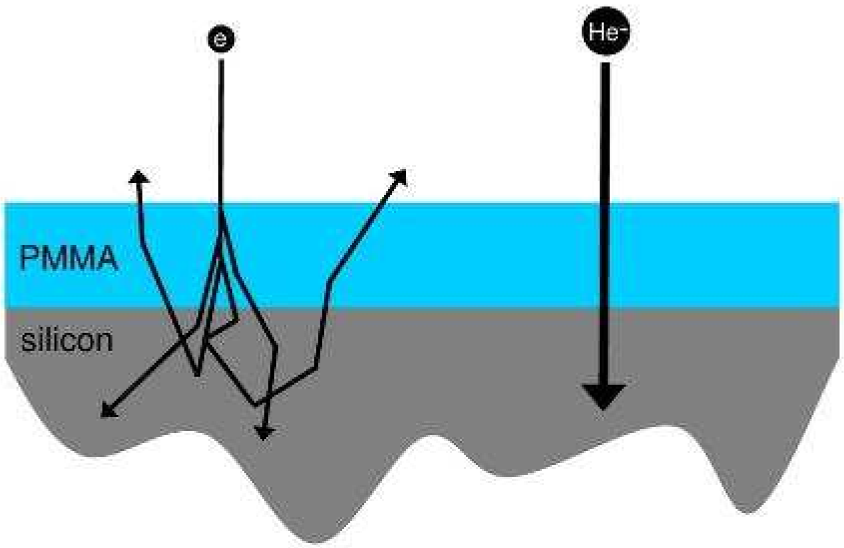
Beam scattering



•Small spot + little proximity effect --> better beam for lithography!

Issues with He ion beam:

- •Slow (low beam current)
- •He ion beam is not for every substrate (He bubble formation)

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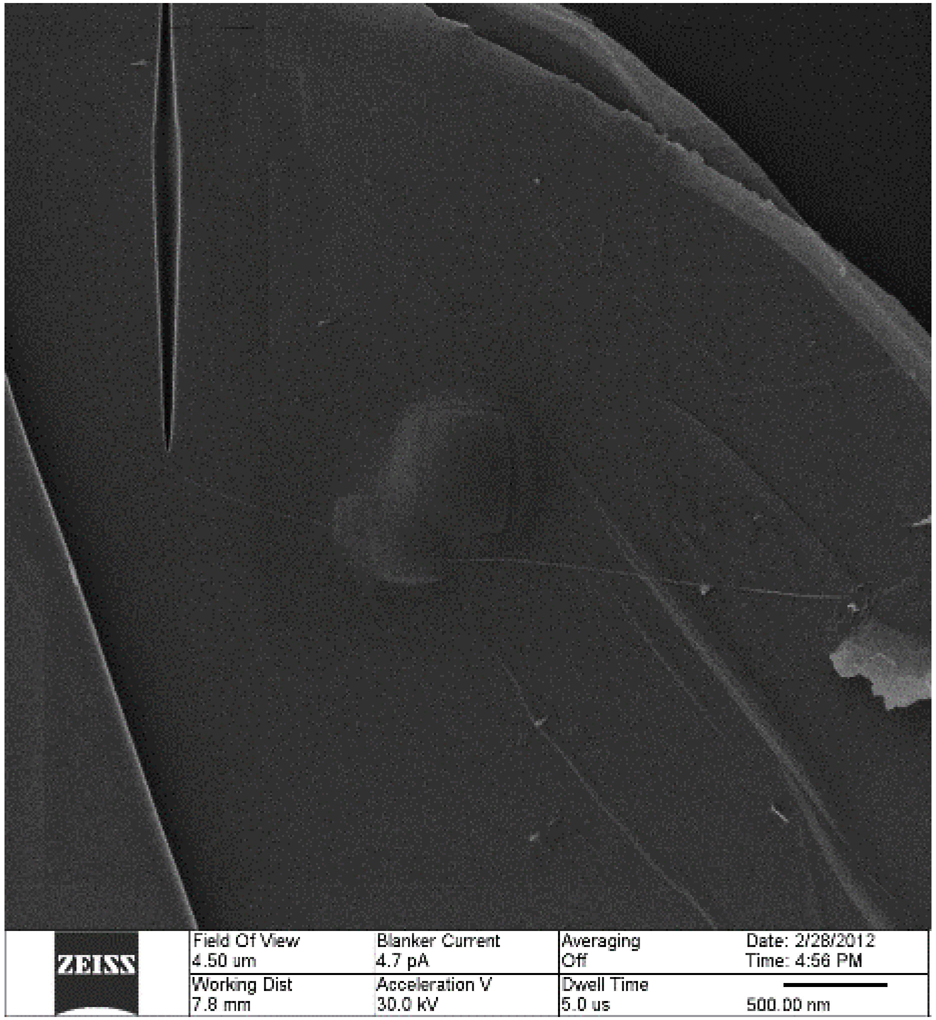
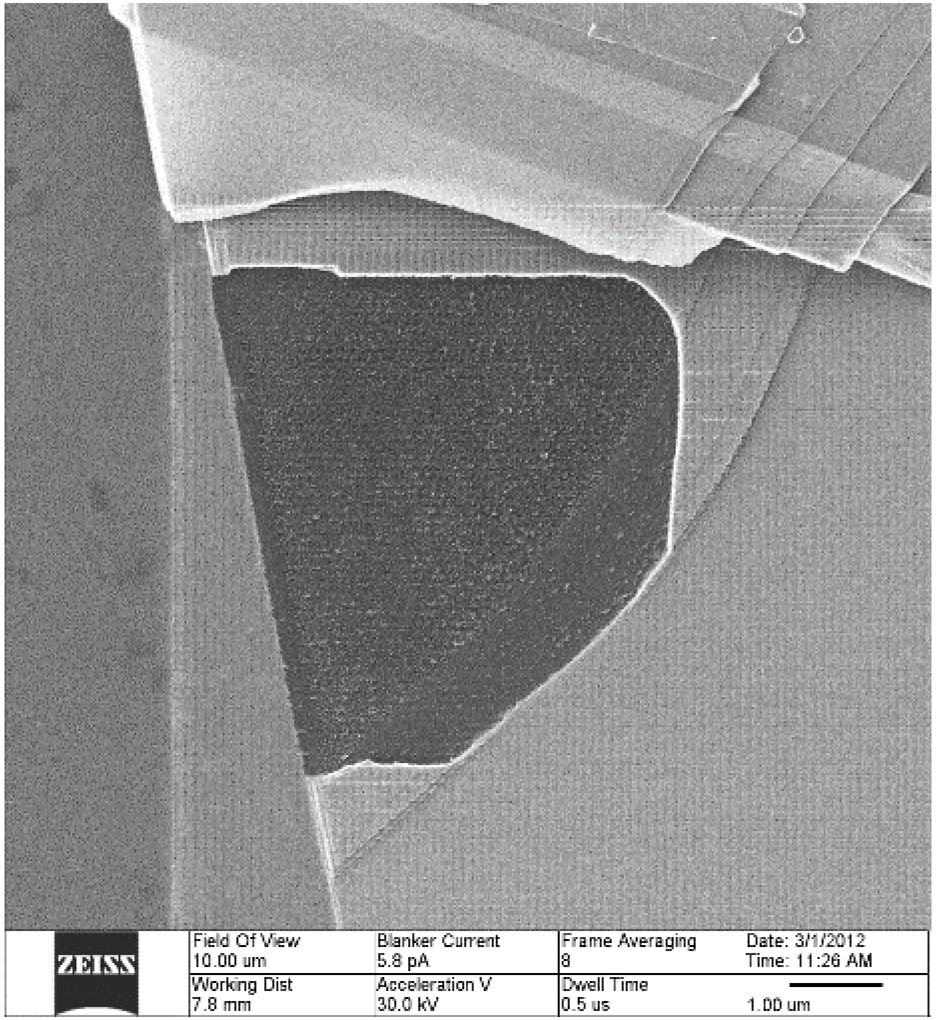
Helium Bubbles





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Combination of HIBL and NIL to Reach Single-digit Design at Low-cost and High Throughput

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1. **Fabricate NIL template using a scanning helium ion beam**

Expecting superior resolution compared with EBL based fabrication

2. **NIL to transfer high-resolution patterns**

Molecular resolution; low cost; and high throughput

3. **Device fabrication at sub-10 nm**

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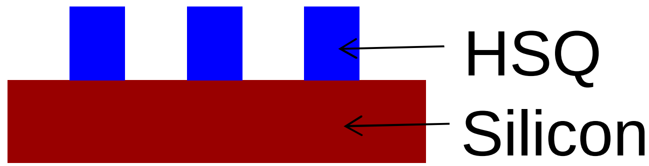
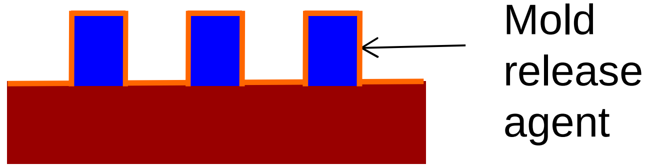
Nanoimprint Using HIBL Template

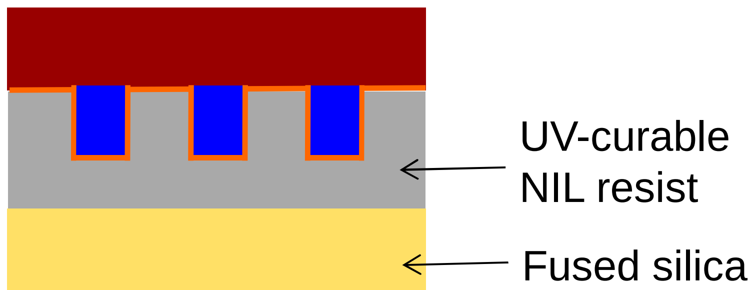
Template after HIBL
and development



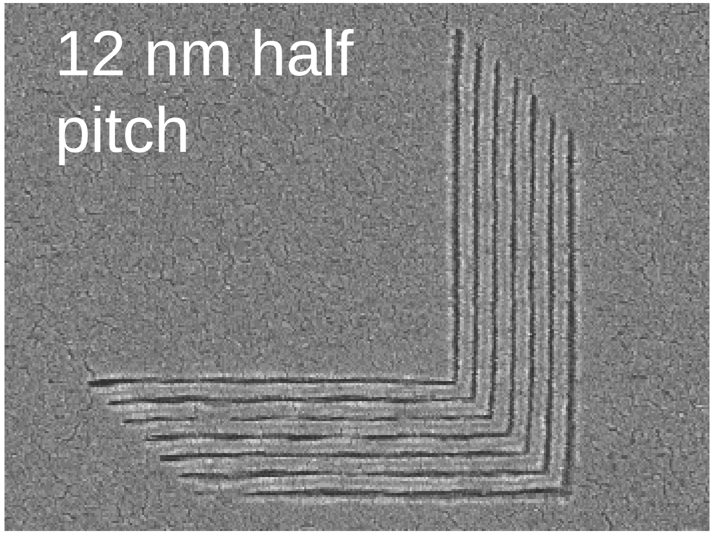
Short exposure to O_2 plasma and
coating of mold release agent

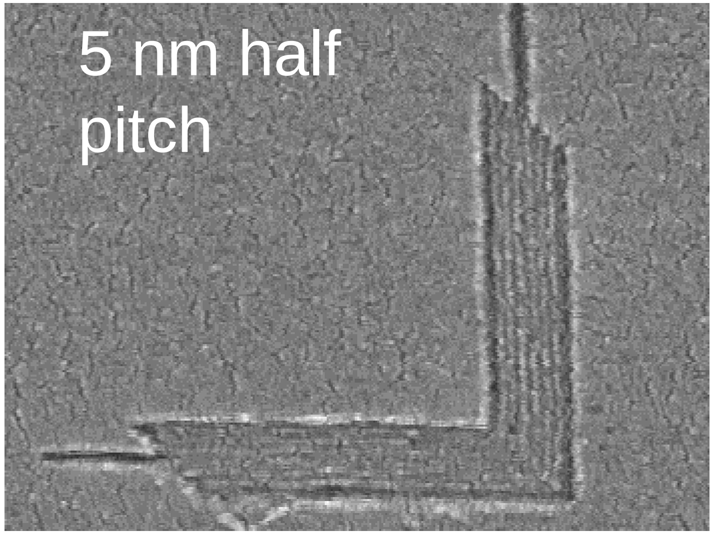


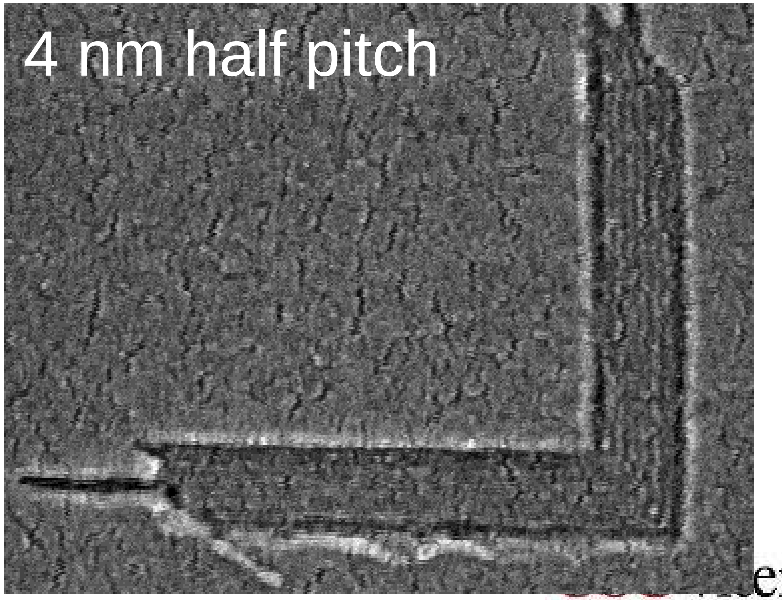
UV nanoimprint using
HIBL template



Imprinted Resist with 4-nm Half-pitch Lines



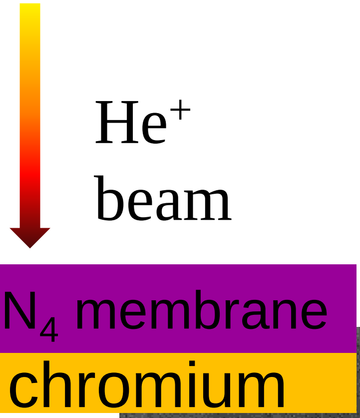


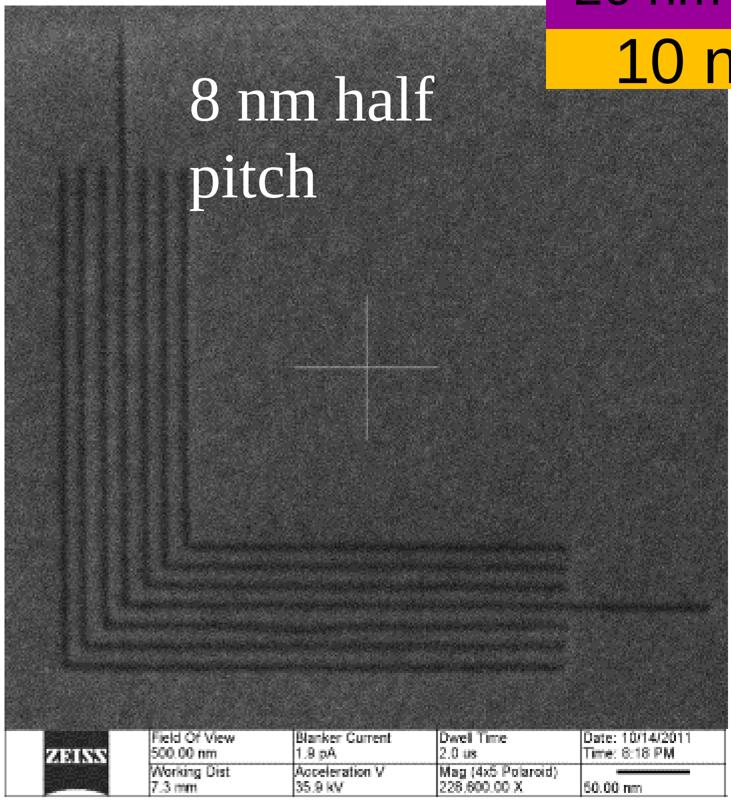


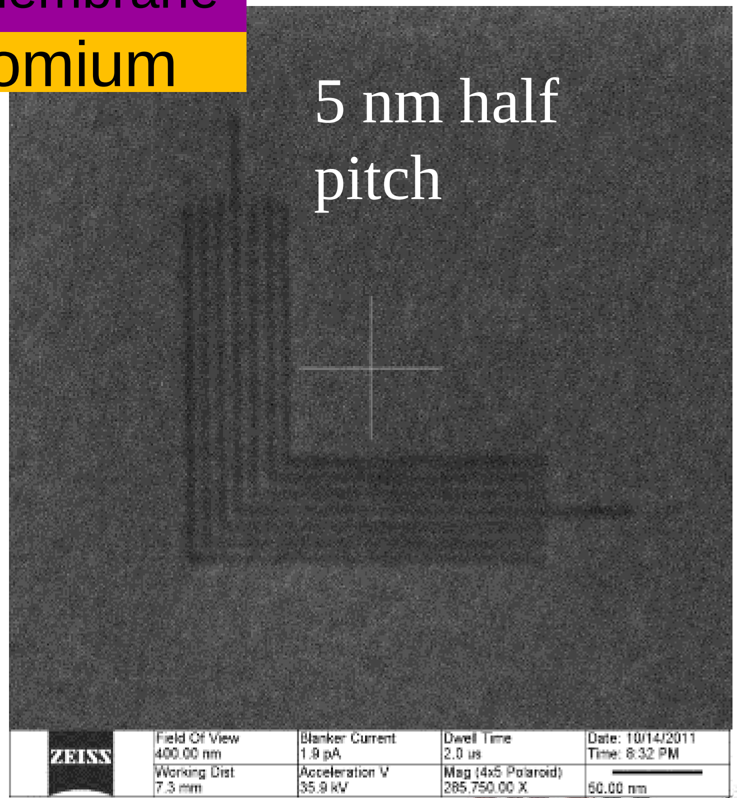
Sample coated with 2 nm platinum and imaged under XL30 SEM at 20kV

W.-D. Li, W. Wu and R. S. Williams, Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures 30 (6), 06F304 (2012).

5 nm Half Pitch Lines Patterned in 10 nm Thick Chromium USC







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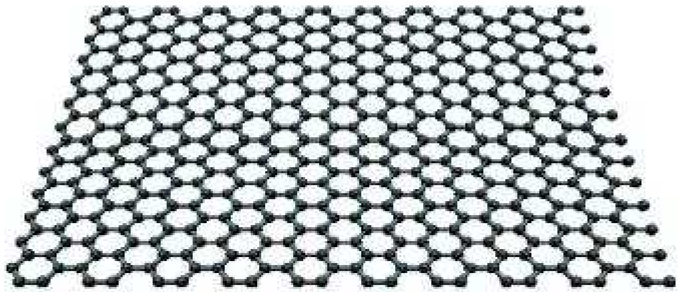
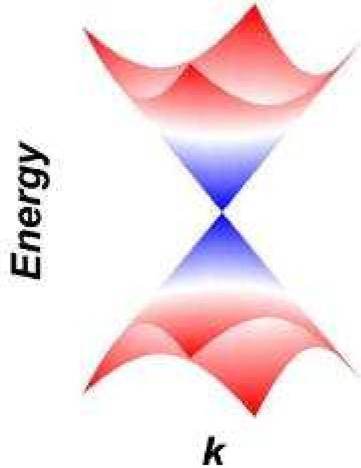
Sub-5 nm Graphene Nanoribbons

Create Bandgap with Graphene Nanoribbon

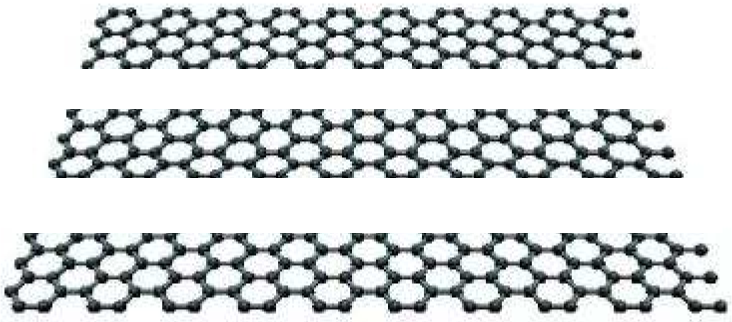
Graphene





- High mobility
- Zero bandgap

Graphene Nanoribbon



- $\Delta E \approx \frac{\alpha}{w}$
- α ≈0.2~0.8 eV*nm

K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva and A. A. Firsov, Science 306 (5696), 666-669 (2004).

M. Y. Han, B. Özyilmaz, Y. Zhang and P. Kim, Physical Review Letters 98 (20), 206805 (2007).

X. Li, X. Wang, L. Zhang, S. Lee and H. Dai, Science 319 (5867), 1229-1232 (2008).

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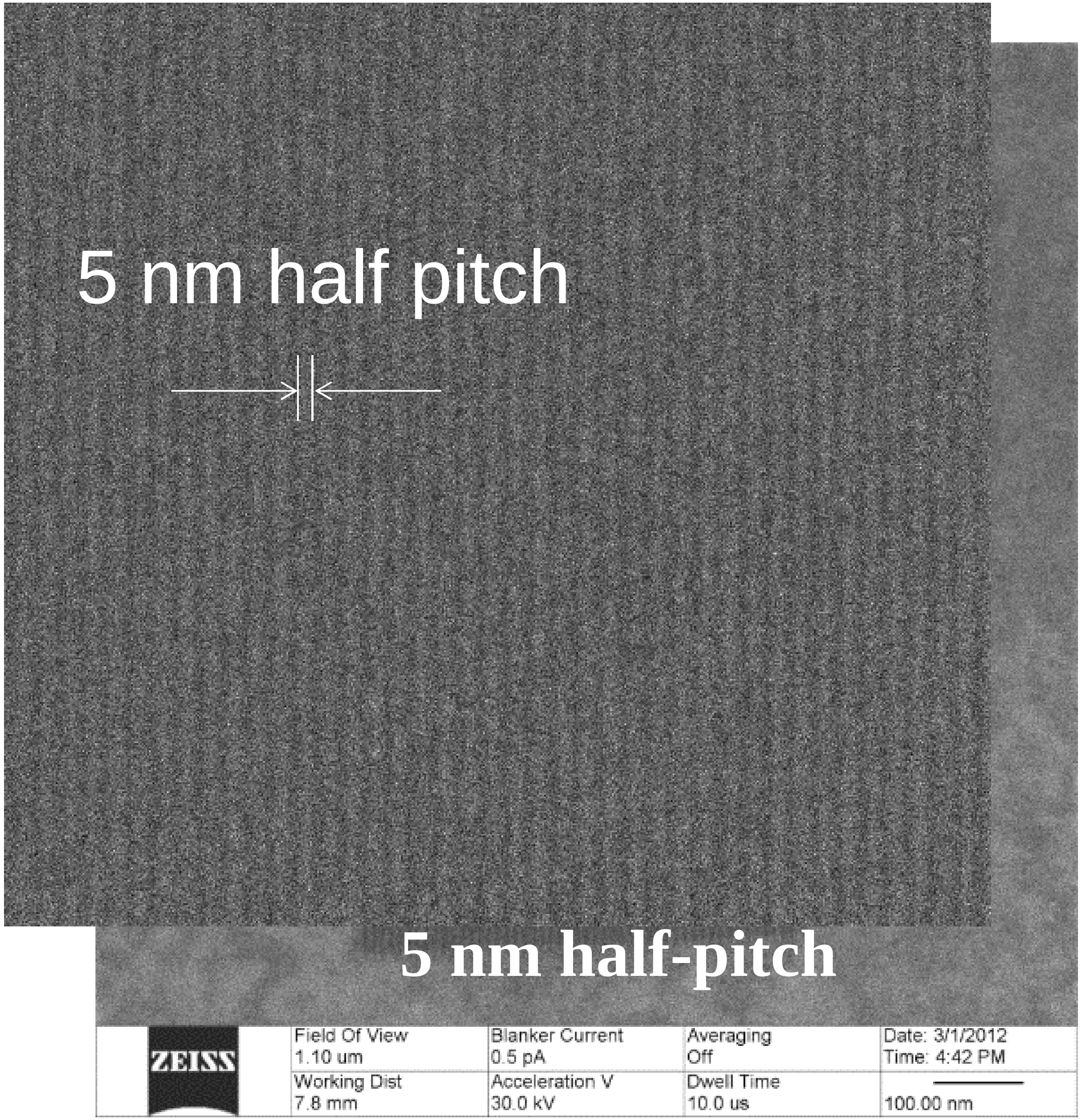
Patterning of Graphene Nanoribbons using He Ion Beam USC



- Single layer of Graphene on 50 nm SiO_2/Si
- 30 KV
- 5µm aperture
- 0.7 pA beam current
- Dose: 5 nC/cm
- HIM images
- **5 nm half-pitch!**

Ahmad N. Abbas, He Liu, Yuhan Yao, Gang Liu, Chongwu Zhou, Douglas A. A. Ohlberg, R. Stanley Williams and Wei Wu, EIPBN 2013
A. N. Abbas, G. Liu, B. Liu, L. Zhang, H. Liu, D. Ohlberg, W. Wu and C. Zhou, Acs Nano 8 (2), 1538-1546 (2014).

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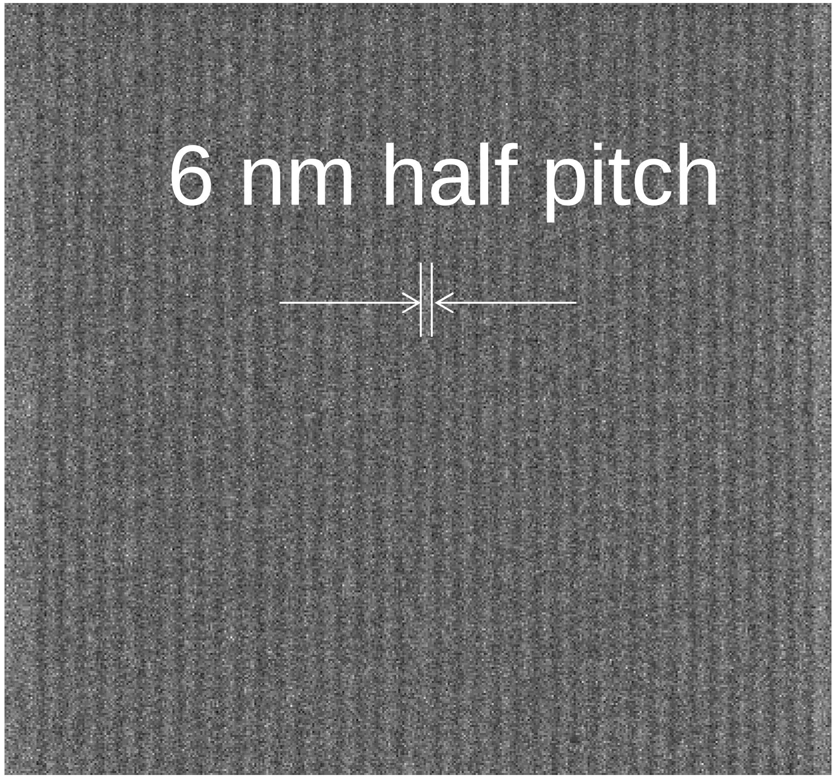
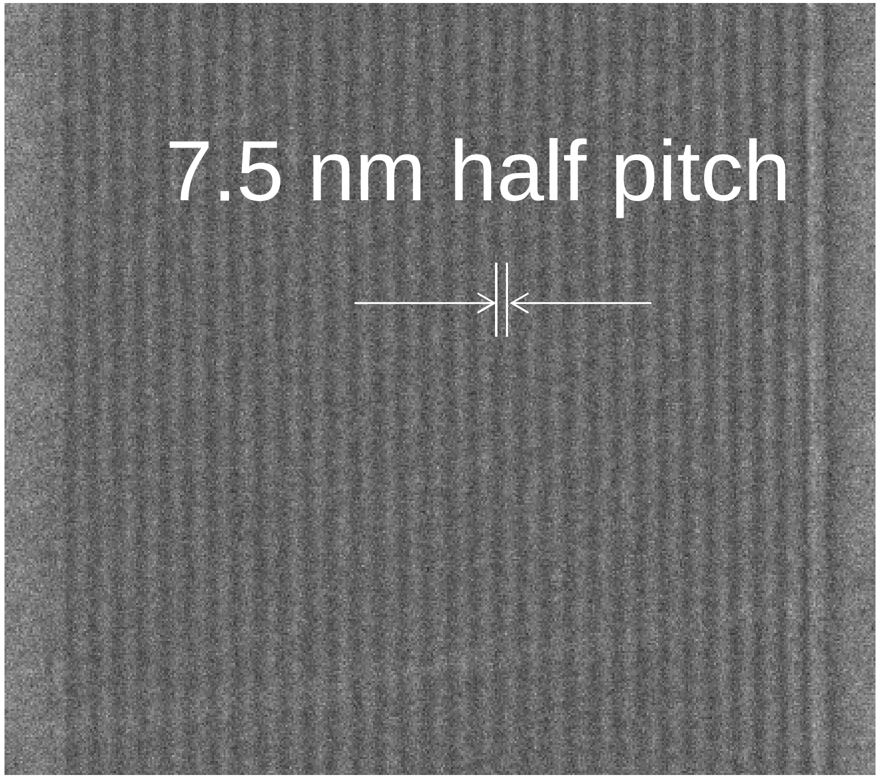
Patterning of Graphene Nanoribbons using He Ion Beam





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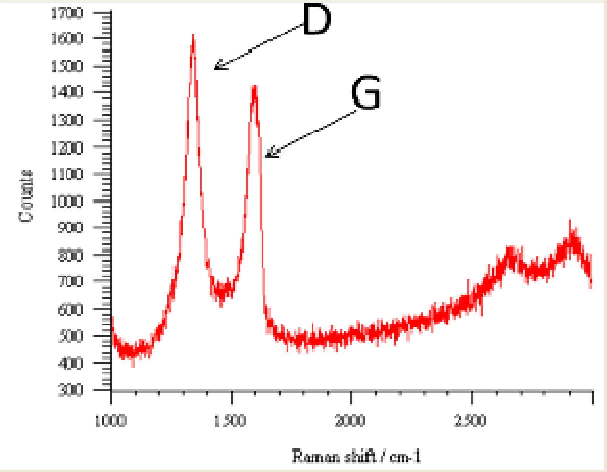
Benchmark Graphene Line-edge roughness with Raman Spectroscopy

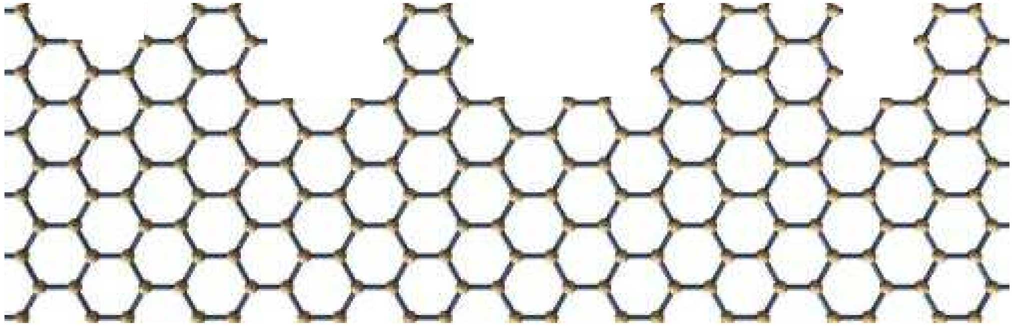
How smooth are those line edges?

- Beyond the resolution of SEM, HIM…
- TEM? Maybe…
- How about Raman spectroscopy?

10 nm half-pitch GNRs by He ion beam milling



- G: breathing mode
- D: defect mode, mainly from edges
- Rougher edges, more atoms on the edges, so higher D peak
- Using IG/ID as benchmark of the smoothness of edges



A. C. Ferrari, J. C. Meyer, V. Scardaci, C. Casiraghi, M. Lazzeri, F. Mauri, S. Piscanec, D. Jiang, K. S. Novoselov, S. Roth and A. K. Geim, Phys. Rev. Lett. **97** (18), 187401 (2006).

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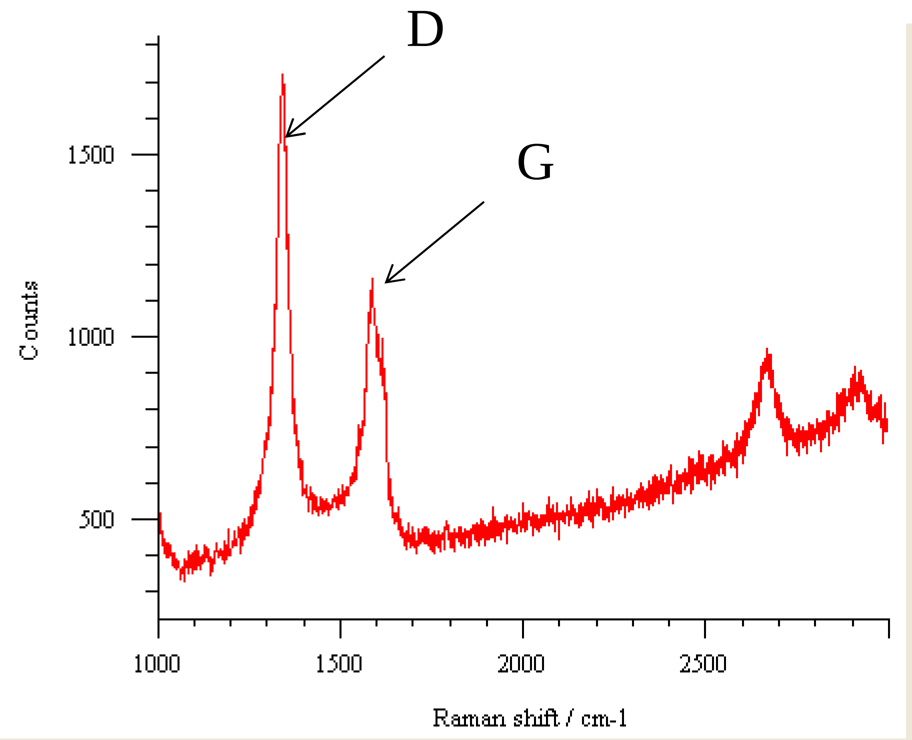
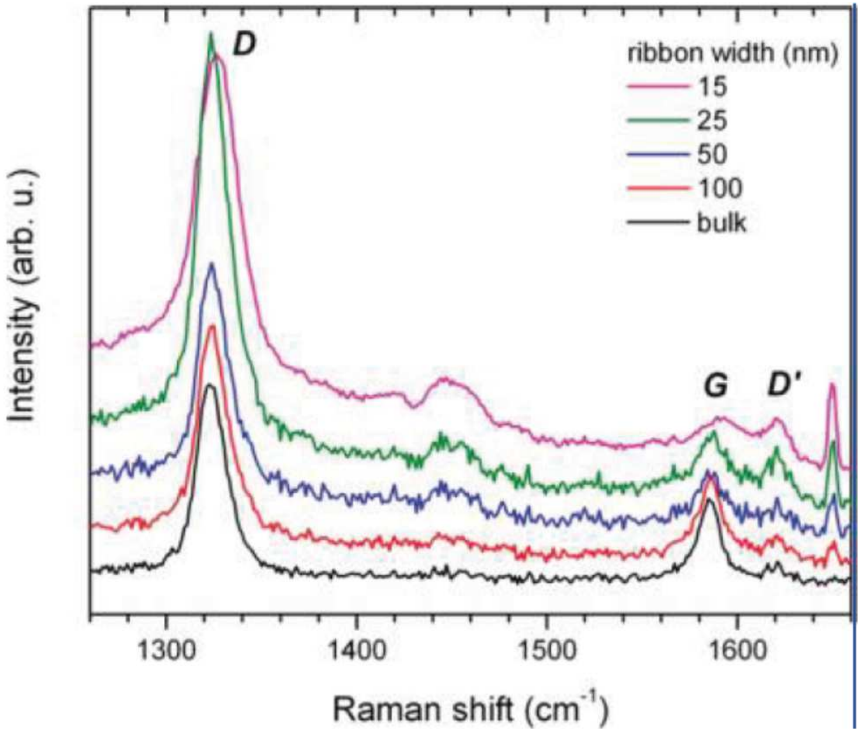
Benchmark Graphene Line-edge roughness with Raman Spectroscopy

15 nm half-pitch GNRs by He ion beam milling



Higher IG/ID means smoother edges.

Comparison:
GNRs patterned by EBL



S. Ryu, J. Maultzsch, M. Y. Han, P. Kim and L. E. Brus, Acs Nano 5 (5), 4123-4130 (2011).

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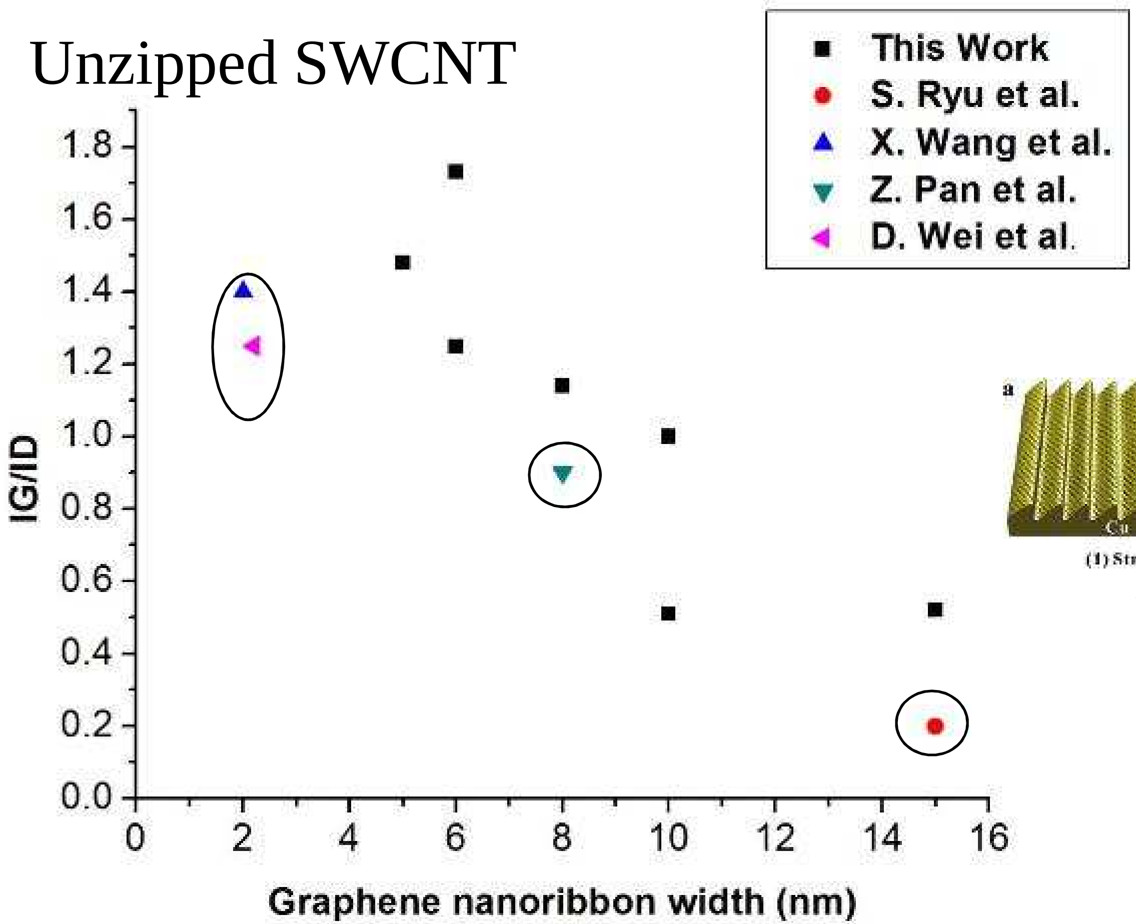
Comparison with Reported Raman Spectra Shows Smoother Line Edges

Unzipped SWCNT



Wrinkle engineering

EBL+O_2 RIE

S. Ryu, J. Maultzsch, M. Y. Han, P. Kim and L. E. Brus, Acs Nano **5** (5), 4123-4130 (2011).

Z. Pan, N. Liu, L. Fu and Z. Liu, Journal of the American Chemical Society **133** (44), 17578-17581 (2011).

X. Wang, Y. Ouyang, X. Li, H. Wang, J. Guo and H. Dai, Physical Review Letters **100** (20), 206803 (2008).

D. Wei, L. Xie, K. K. Lee, Z. Hu, S. Tan, W. Chen, C. H. Sow, K. Chen, Y. Liu and A. T. S. Wee, Nat Commun **4**, 1374 (2013).

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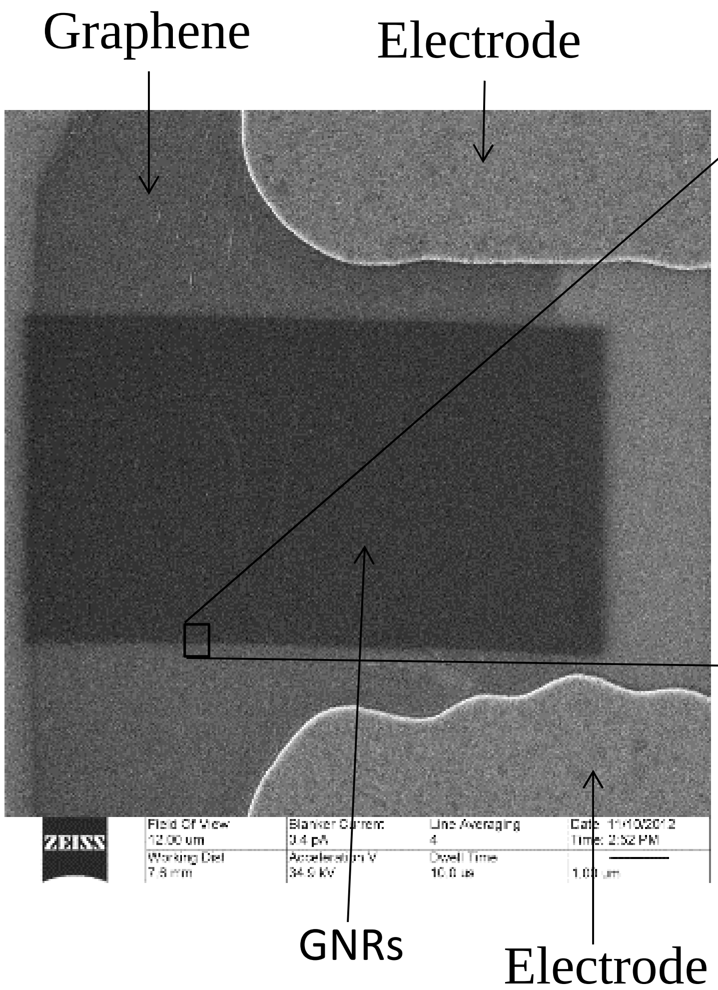
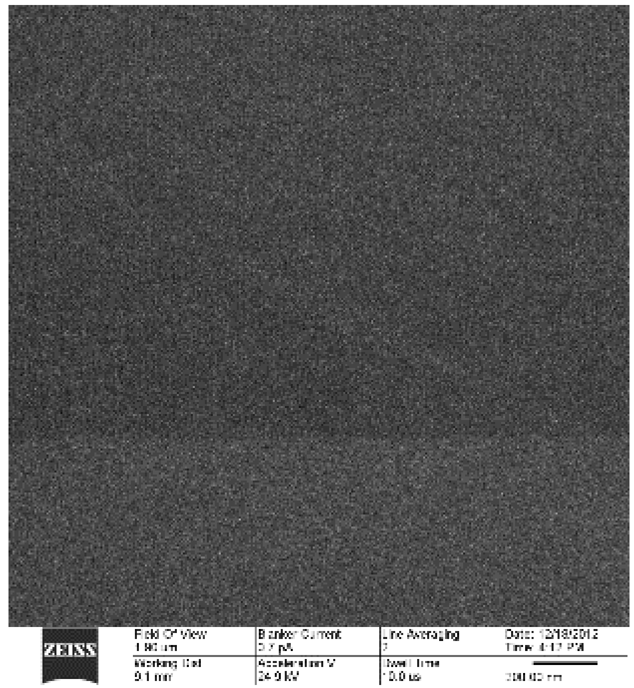
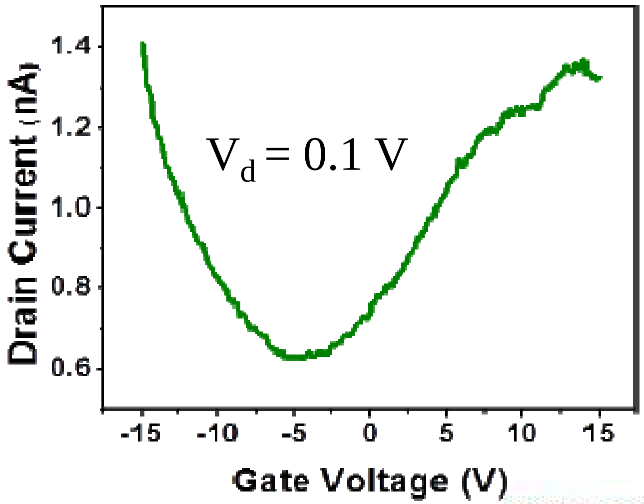
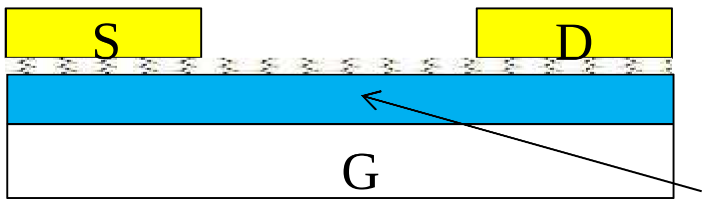
GNR MOSFET









The gate dielectric got damaged by He^+ ion.

5 nm GNR Has a Bandgap of 88 meV

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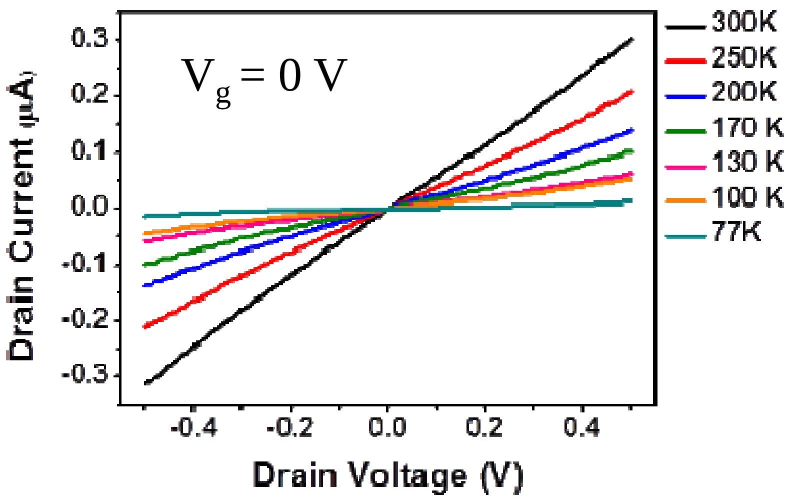

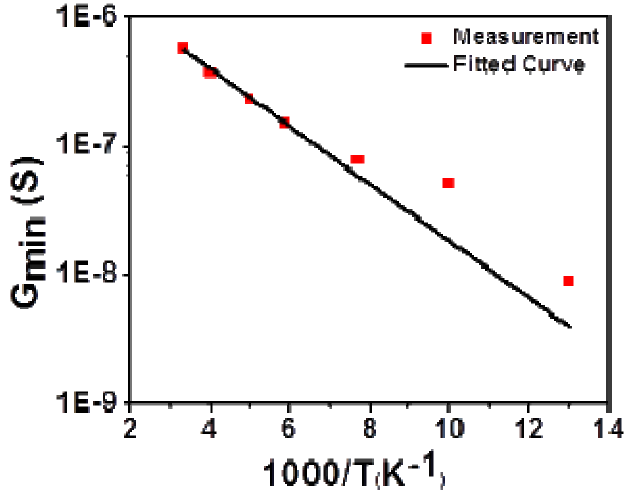

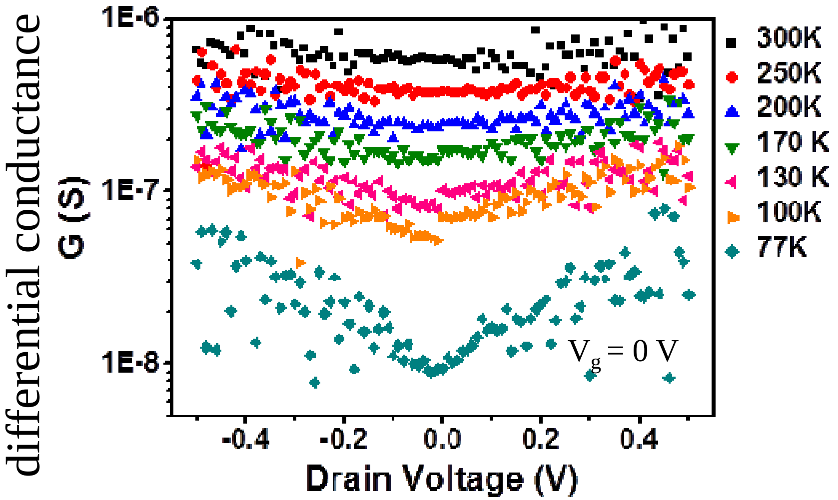

$$G_{min} = G_1 e^{\frac{-E_A}{K_B T}}$$

$$E_A = 44 \text{ meV}$$

$$E_G \geq 2\,E_A = 88 \text{ meV}$$

A. N. Abbas, G. Liu, B. Liu, L. Zhang, H. Liu, D. Ohlberg, W. Wu and C. Zhou, Acs Nano 8 (2), 1538-1546 (2014).

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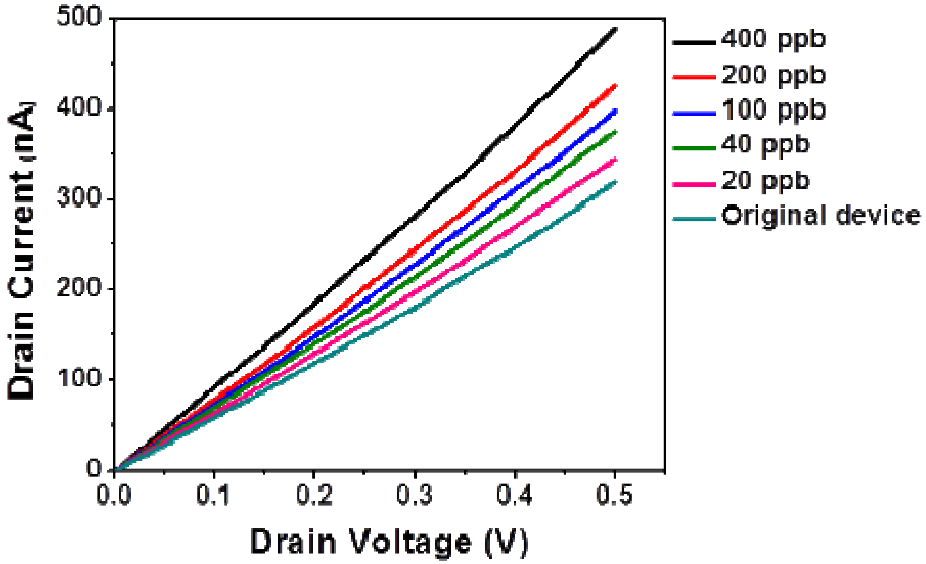
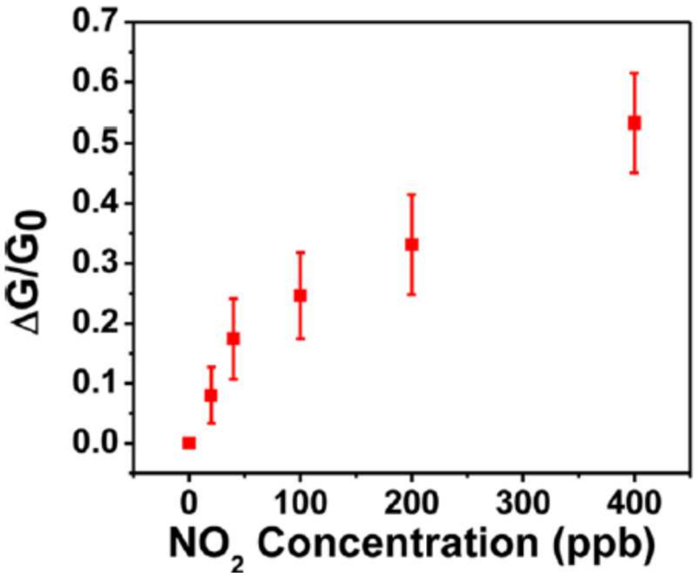
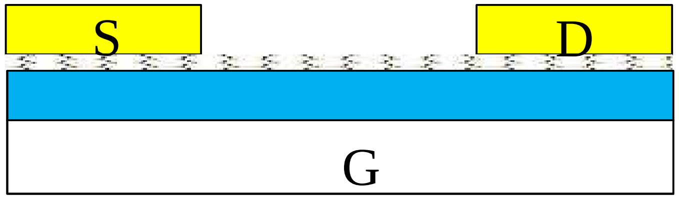
GNR FET as Gas Sensor



- NO_2 acts as an electron attractor
- bandgap opening provides higher sensitivity
- Edge states are more active site to bond with NO_2
- Safe level of NO_2 is 0.2 ppm
- Detection of 20 ppb NO_2 has been demonstrated





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Summary

- Sub-5 nm patterning using
  - HIBL and
  - NIL
  - Direct He ion milling
- Patterning of GNRs
  - Better line-edge roughness than reported results with Raman data.
  - GNR FET
    - 88 meV bandgap
    - NO_2 gas sensor

Acknowledgement

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Thank you…

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