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

Yuanrui Li¹, Ahmed Abbas¹, Yuhan Yao¹, Yifei Wang¹, Wen-Di Li², Chongwu Zhou¹ and Wei Wu¹*

¹Department of Electrical Engineering, University of Southern California
²Department of Mechanical Engineering, University Of Hong Kong

*wu.w@usc.edu
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
How to Achieve Better Resolution than Electron Beam Lithography?

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

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

- Spot size: ~4 nm
- Beam scattering (forward and backward)
- Second electron generation
- 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 astigmatism)

\[ d_g = \frac{d_v}{M} \]  
d\(_v\): virtual source diameter  
M: demagnification

\[ d_s = \frac{1}{2} C_s \alpha^3 \]  
Spherical aberration

\[ d_c = C_c \alpha \frac{\Delta V}{V} \]  
Chromatic aberration

\[ d_d = 1.22 \frac{\lambda}{\alpha}, \lambda = \frac{1.2}{\sqrt{V}} \text{ nm} \]  
Diffraction
Beam spot: 3.5 Å

~$2M

- **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
He Ion is Scattered Over Shorter Ranges

35 KeV Electrons

35 KeV He⁺

He Ion: Much Less Proximity Effect

Beam scattering

Small spot + little proximity effect --> better beam for lithography!
Helium Ion Beam Lithography

He Ion: Much Less Proximity Effect

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

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
Nanoimprint Using HIBL Template

Template after HIBL and development

Short exposure to O\textsubscript{2} plasma and coating of mold release agent

UV nanoimprint using HIBL template

- HSQ
- Silicon
- Mold release agent
- UV-curable NIL resist
- Fused silica
Imprinted Resist with 4-nm Half-pitch Lines

12 nm half pitch

5 nm half pitch

4 nm half pitch

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

5 nm Half Pitch Lines Patterned in 10 nm Thick Chromium
Sub-5 nm Graphene Nanoribbons
Create Bandgap with Graphene Nanoribbon

- High mobility
- Zero bandgap

Graphene

Graphene Nanoribbon

- \( \Delta E \approx \frac{\alpha}{w} \)
- \( \alpha \approx 0.2\sim0.8 \text{ eV}\cdot\text{nm} \)


Patterning of Graphene Nanoribbons using He Ion Beam

- 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
Patterning of Graphene Nanoribbons using He Ion Beam

6 nm half pitch

7.5 nm half pitch
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

15 nm half-pitch GNRs by He ion beam milling

Higher IG/ID means smoother edges.

Comparison:
GNRs patterned by EBL

Comparison with Reported Raman Spectra Shows Smoother Line Edges

The gate dielectric got damaged by He$^+$ ion.
5 nm GNR Has a Bandgap of 88 meV

\[ V_g = 0 \text{ V} \]

\[ G_{\text{min}} = G_1 e^{\frac{-E_A}{k_B T}} \]

\[ E_A = 44 \text{ meV} \]

\[ E_G \geq 2 E_A = 88 \text{ meV} \]

GNR FET as Gas Sensor

- NO₂ acts as an electron attractor
- Bandgap opening provides higher sensitivity
- Edge states are more active site to bond with NO₂
- Safe level of NO₂ is 0.2 ppm
- Detection of 20 ppb NO₂ has been demonstrated
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
Thank you...

wu.w@usc.edu

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