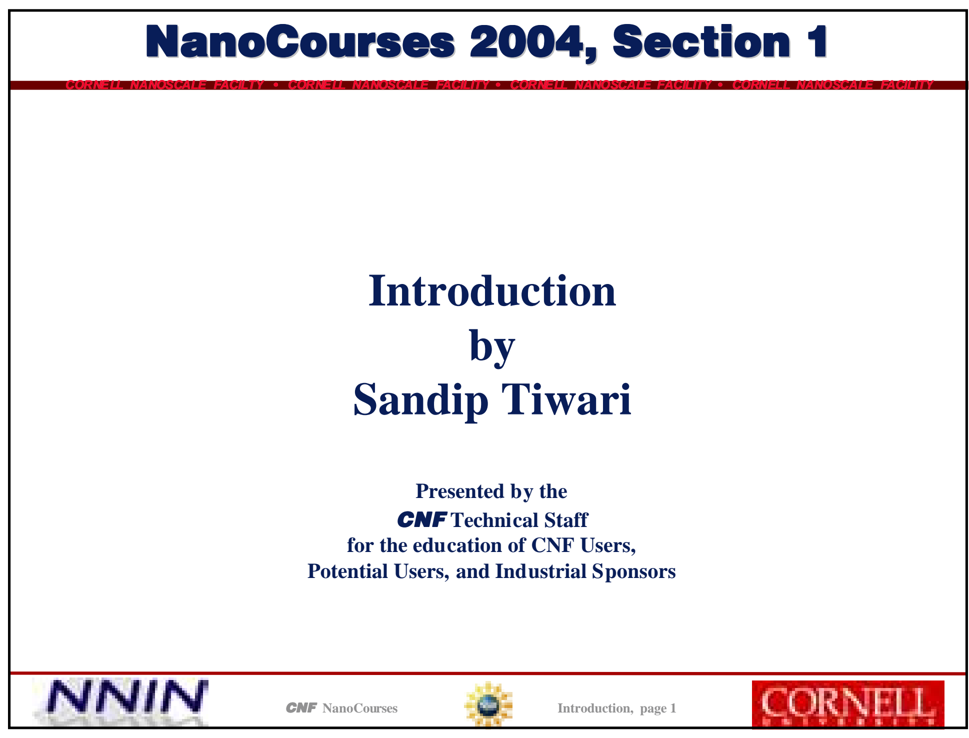
NanoCourses 2004, Section 1
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Introduction
by
Sandip Tiwari
Presented by the
CNF Technical Staff
for the education of CNF Users,
Potential Users, and Industrial Sponsors
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CNF NanoCourses
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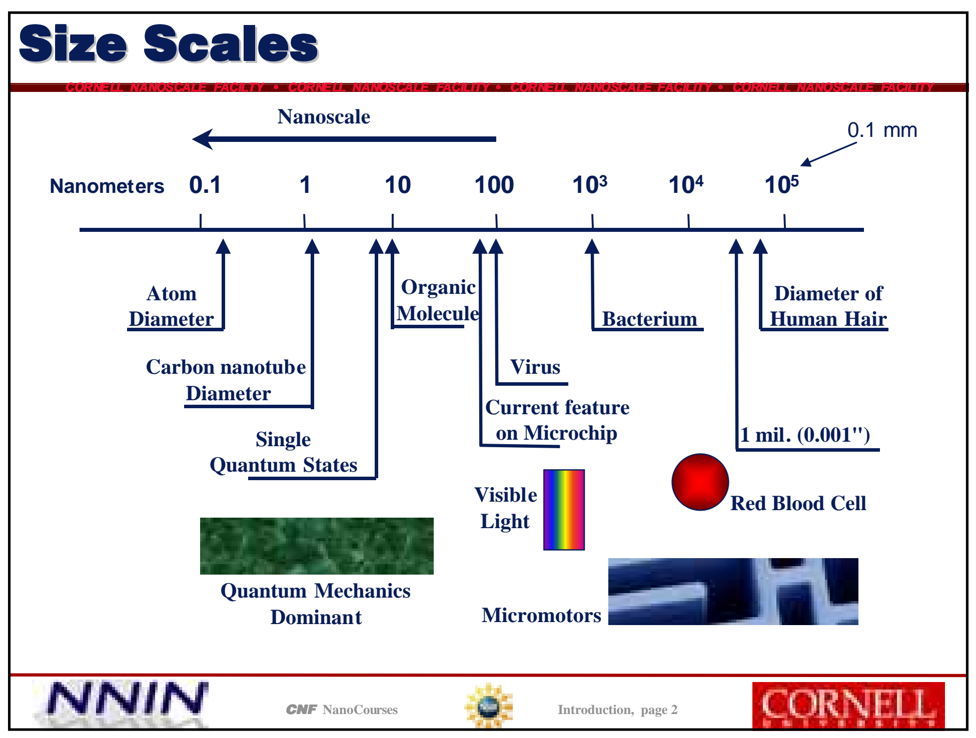
Size Scales
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Nanoscale
0.1 mm
Nanometers
0.1
1
10
100
10³
10⁴
10⁵
Atom Diameter
Carbon nanotube Diameter
Single Quantum States
Organic Molecule
Virus
Current feature on Microchip
Bacterium
Diameter of Human Hair
1 mil. (0.001")
Visible Light
Red Blood Cell
Quantum Mechanics Dominant
Micromotors
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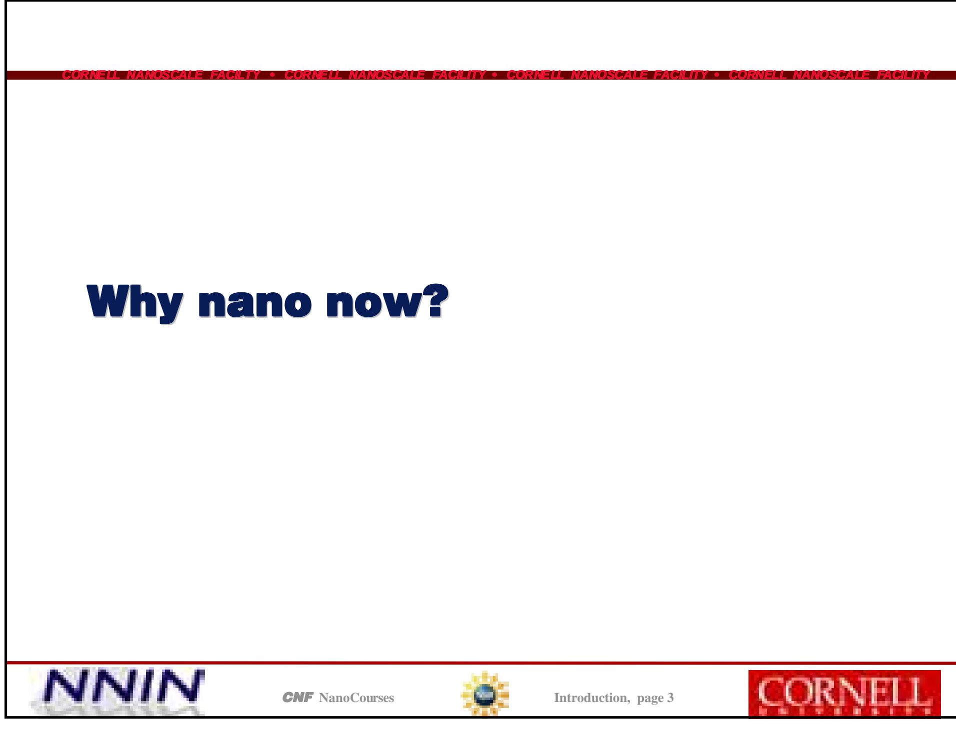
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Why nano now?
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Introduction, page 3
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Is Nanotechnology Something New?
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Materials with nanoscale components are widespread
100 nm
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Introduction, page 4
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Is Nanotechnology Something New?

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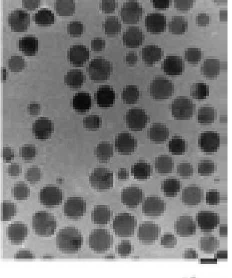
- Humans **have been** making **systems with** nanoscale components **for thousands of years**
- **We have been *engineering* materials at the nanoscale for many years.**

stained glass



nanoscale gold particles in glass give red color

So Why All of the Excitement?

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Why Now?

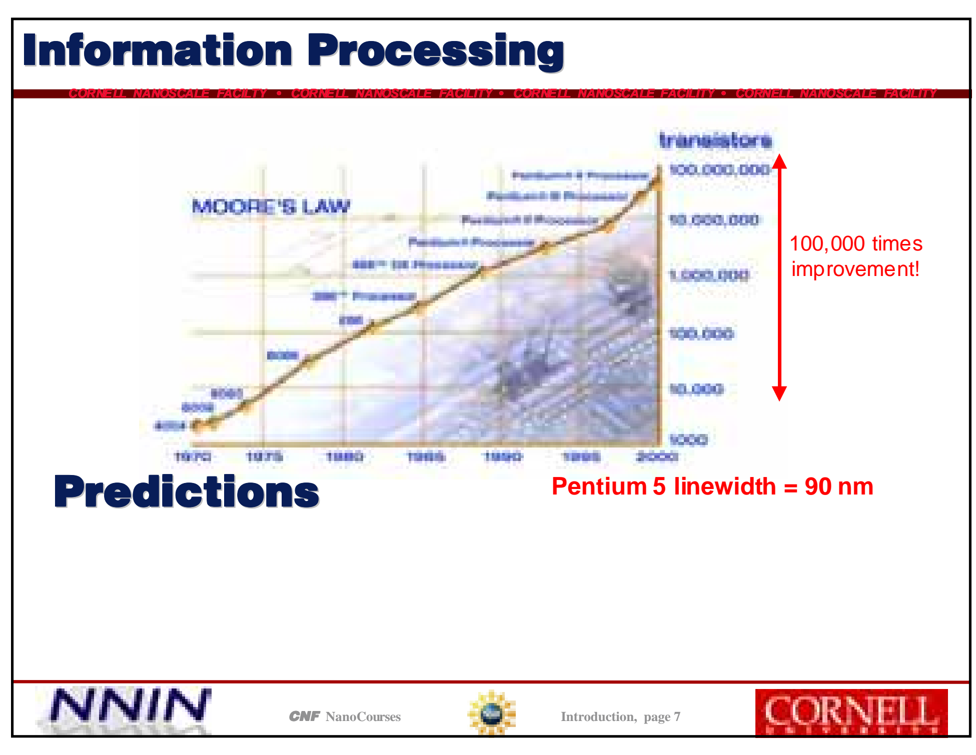
Tools for seeing and manipulating structures on nanometer scales have been developed in the last 10-20 years.

Once you can see what you are doing and make changes, you can begin to do interesting work.

Why Nano?

New scientific opportunities: An unexplored world, new properties to understand.

New technologies:
electronics, computer memory, bio-technology, nano-mechanical devices, new materials, other applications


Information Processing
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
MOORE'S LAW
transistors
100,000,000
10,000,000
1,000,000
100,000
10,000
1000
1970
1975
1980
1985
1990
1995
2000
100,000 times improvement!
Predictions
Pentium 5 linewidth = 90 nm
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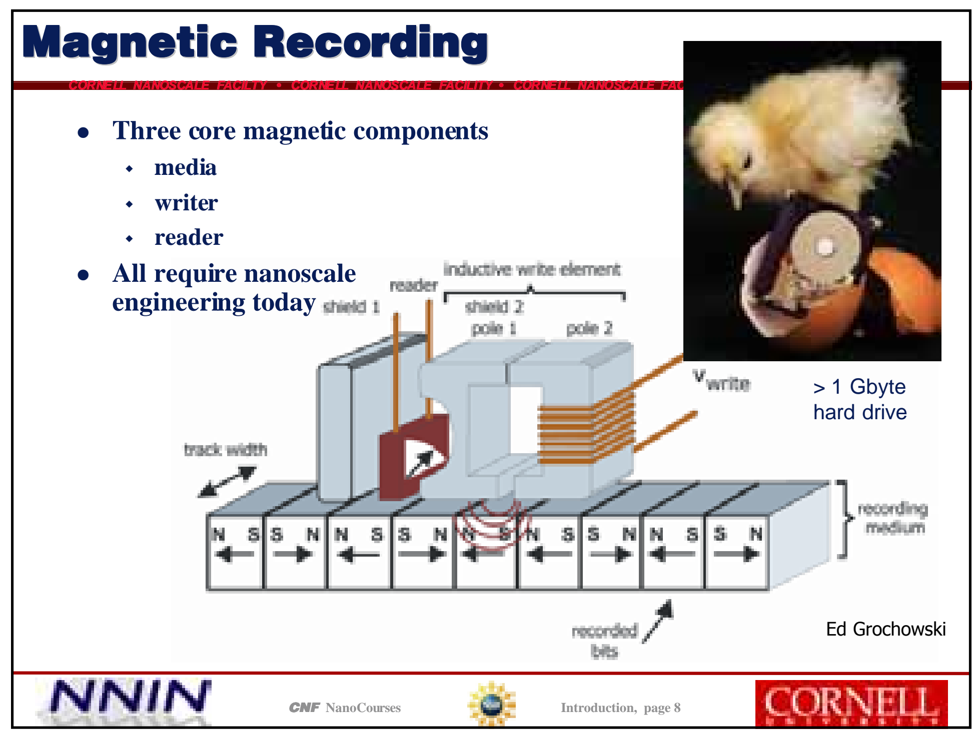
Magnetic Recording
• Three core magnetic components
  • media
  • writer
  • reader
• All require nanoscale engineering today
inductive write element
reader
shield 1
shield 2
pole 1
pole 2
V_{write}
track width
recording medium
recorded bits
> 1 Gbyte hard drive
Ed Grochowski
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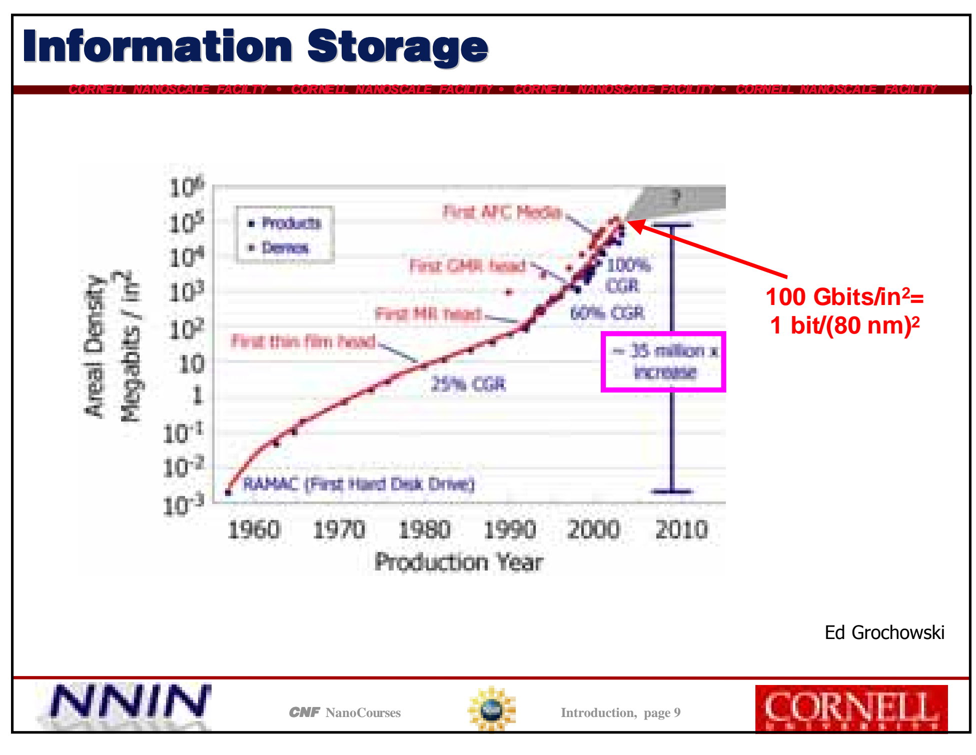
Information Storage
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Areal Density Megabits / in²
Production Year
Products
Demos
First AFC Media
First GMR head
First MR head
First thin film head
RAMAC (First Hard Disk Drive)
100% CGR
60% CGR
25% CGR
~ 35 million x increase
100 Gbits/in²= 1 bit/(80 nm)²
Ed Grochowski
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Introduction, page 9
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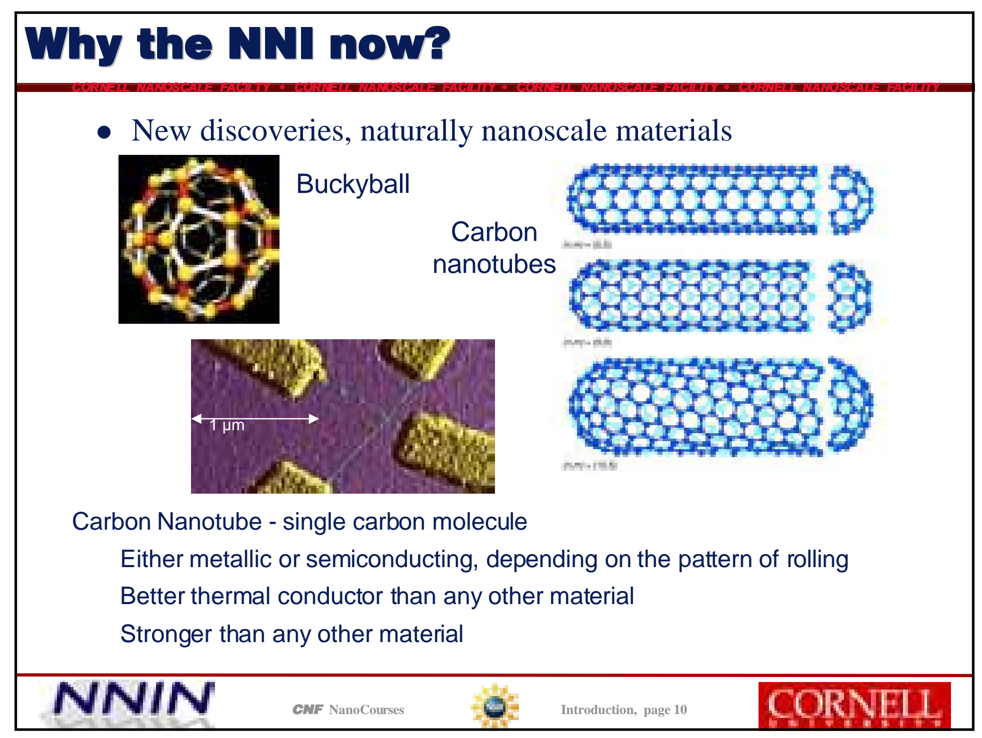
Why the NNI now?
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• New discoveries, naturally nanoscale materials
Buckyball
Carbon nanotubes
1 μm
Carbon Nanotube - single carbon molecule
Either metallic or semiconducting, depending on the pattern of rolling
Better thermal conductor than any other material
Stronger than any other material
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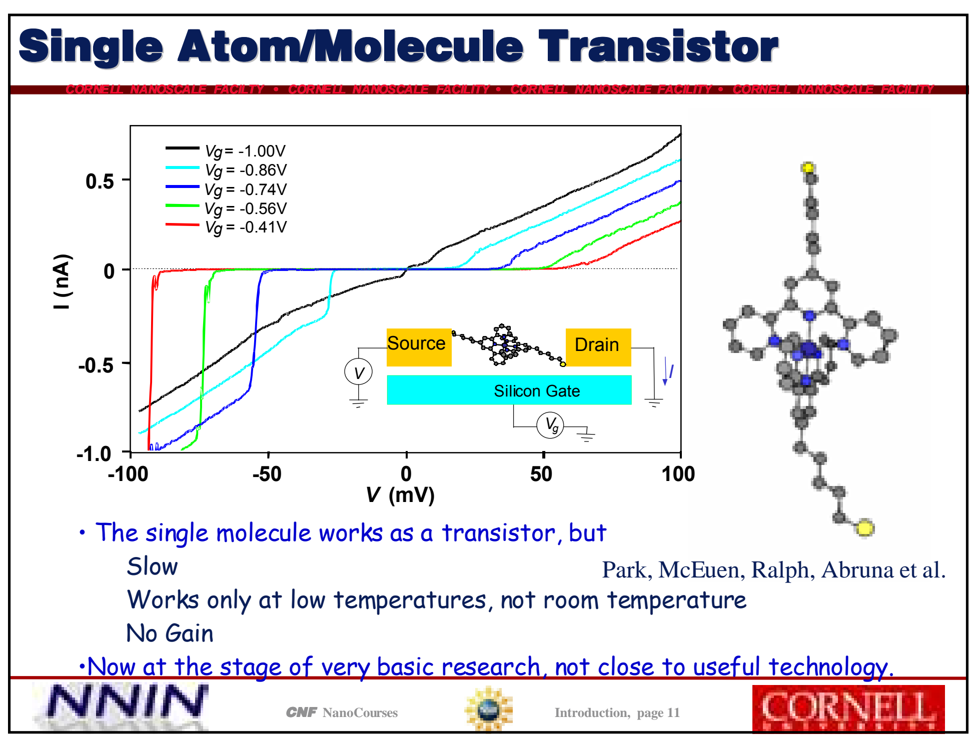
Single Atom/Molecule Transistor
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Vg = -1.00V
Vg = -0.86V
Vg = -0.74V
Vg = -0.56V
Vg = -0.41V
I (nA)
0.5
0
-0.5
-1.0
-100
-50
0
50
100
V (mV)
Source
Drain
Silicon Gate
V
Vg
I
• The single molecule works as a transistor, but
Slow
Works only at low temperatures, not room temperature
No Gain
Park, McEuen, Ralph, Abruna et al.
•Now at the stage of very basic research, not close to useful technology.
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Introduction, page 11
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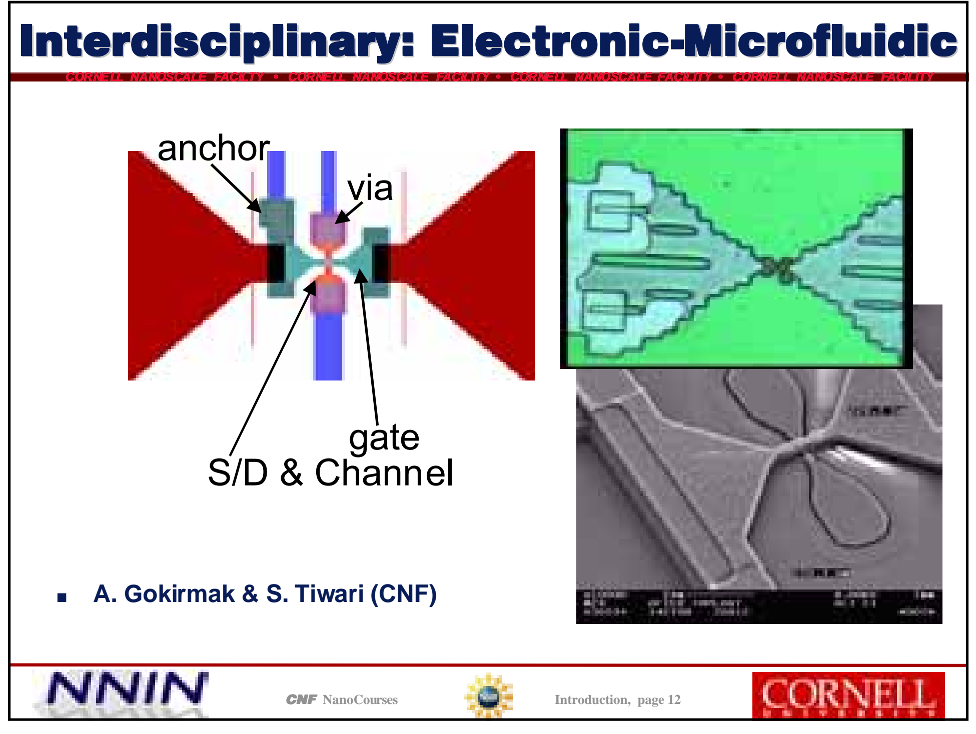
Interdisciplinary: Electronic-Microfluidic
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anchor
via
gate
S/D & Channel
A. Gokirmak & S. Tiwari (CNF)
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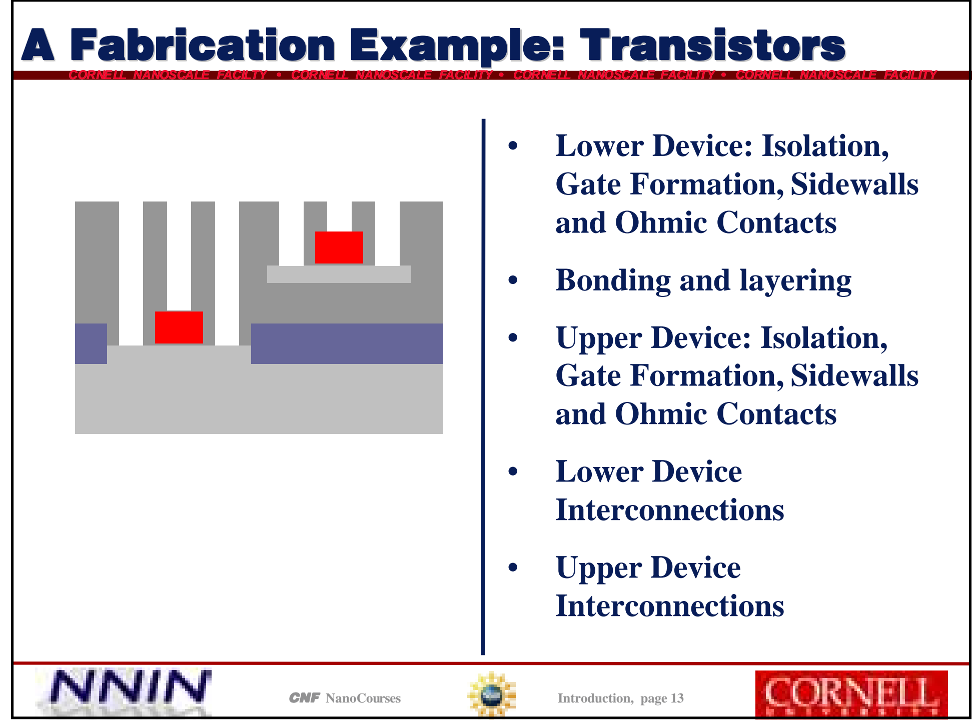
A Fabrication Example: Transistors
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Lower Device: Isolation, Gate Formation, Sidewalls and Ohmic Contacts
Bonding and layering
Upper Device: Isolation, Gate Formation, Sidewalls and Ohmic Contacts
Lower Device Interconnections
Upper Device Interconnections
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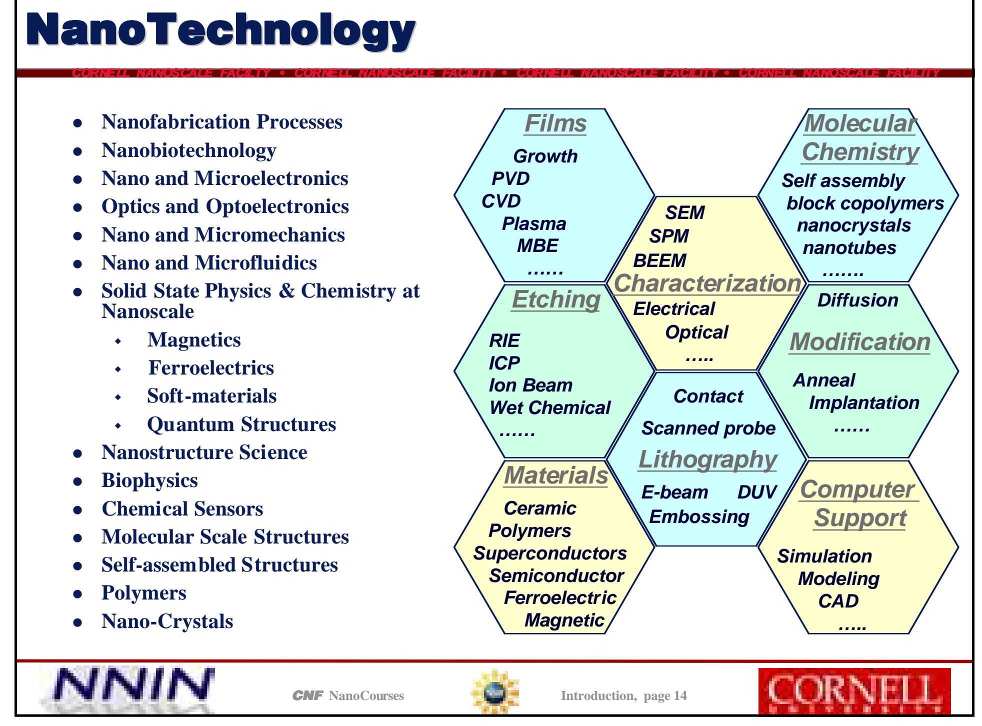
NanoTechnology
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Nanofabrication Processes
Nanobiotechnology
Nano and Microelectronics
Optics and Optoelectronics
Nano and Micromechanics
Nano and Microfluidics
Solid State Physics & Chemistry at Nanoscale
Magnetics
Ferroelectrics
Soft-materials
Quantum Structures
Nanostructure Science
Biophysics
Chemical Sensors
Molecular Scale Structures
Self-assembled Structures
Polymers
Nano-Crystals
Films
Growth
PVD
CVD
Plasma
MBE
……
Molecular Chemistry
Self assembly
block copolymers
nanocrystals
nanotubes
…….
SEM
SPM
BEEM
Characterization
Electrical
Optical
…..
Etching
RIE
ICP
Ion Beam
Wet Chemical
……
Diffusion
Modification
Anneal
Implantation
……
Contact
Scanned probe
Lithography
E-beam
DUV
Embossing
Materials
Ceramic
Polymers
Superconductors
Semiconductor
Ferroelectric
Magnetic
Computer Support
Simulation
Modeling
CAD
…..
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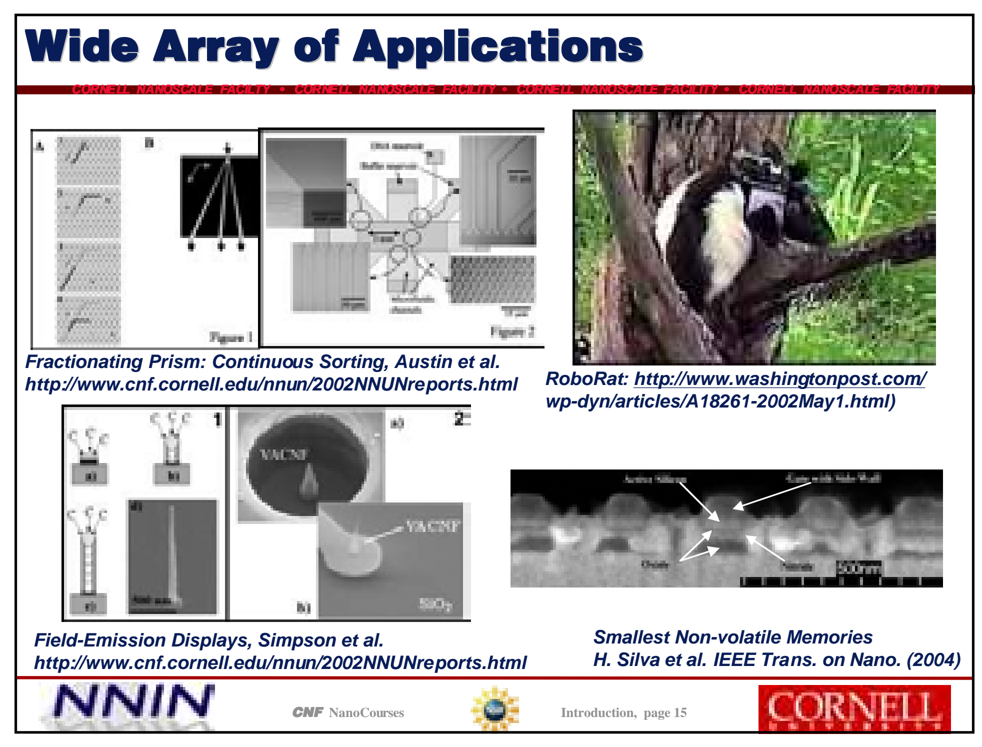
Wide Array of Applications
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Fractionating Prism: Continuous Sorting, Austin et al.
http://www.cnf.cornell.edu/nnun/2002NNUNreports.html
RoboRat: http://www.washingtonpost.com/wp-dyn/articles/A18261-2002May1.html)
VACNF
Field-Emission Displays, Simpson et al.
http://www.cnf.cornell.edu/nnun/2002NNUNreports.html
Smallest Non-volatile Memories
H. Silva et al. IEEE Trans. on Nano. (2004)
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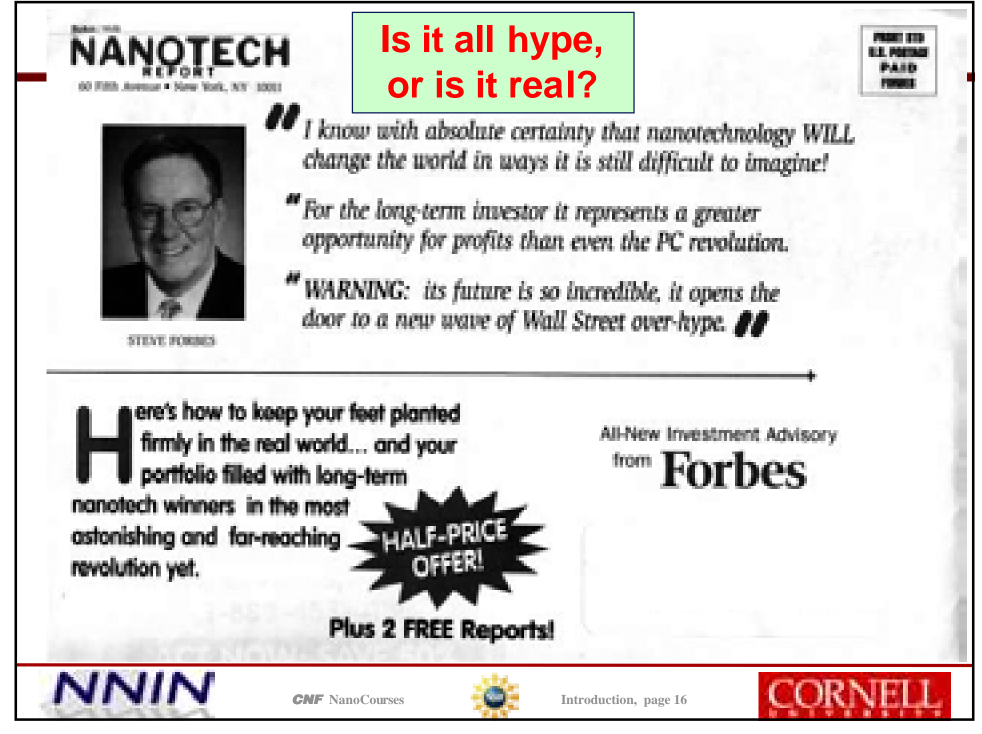
NANOTECH REPORT
Is it all hype, or is it real?
"I know with absolute certainty that nanotechnology WILL change the world in ways it is still difficult to imagine!
"For the long-term investor it represents a greater opportunity for profits than even the PC revolution.
"WARNING: its future is so incredible, it opens the door to a new wave of Wall Street over-hype."
STEVE FORBES
Here's how to keep your feet planted firmly in the real world... and your portfolio filled with long-term nanotech winners in the most astonishing and far-reaching revolution yet.
HALF-PRICE OFFER!
Plus 2 FREE Reports!
All-New Investment Advisory from Forbes
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A Caution

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Nanotechnology is big, but
do not believe everything you read or
see in popular press.

Be perceptive, use your knowledge and
critical thinking.

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Practical Lithography:

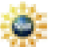
The Art and Science of Microlithography

Optical Lithography

by

Garry J. Bordonaro

Presented by the
CNF Technical Staff
for the education of CNF Users,
Potential Users, and Industrial Sponsors



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Optical Lithography

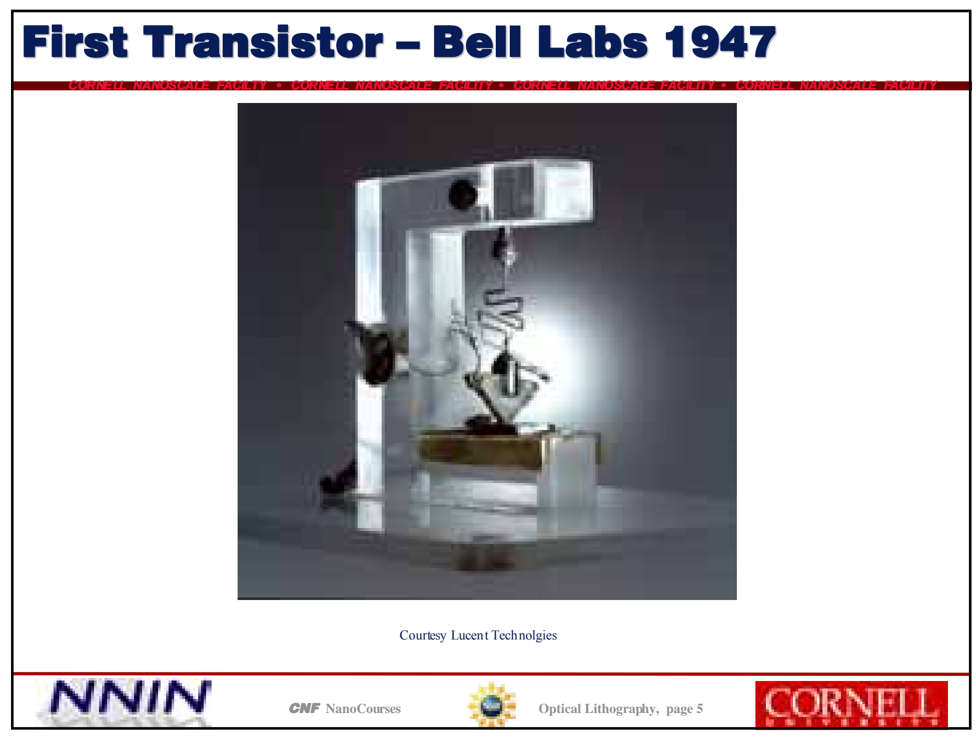
Introduction

Introduction

- Optical Lithography - Mask Making
- Optical Lithography - Exposure Tool
- Optical Lithography - Techniques
- Pattern Design (CAD)

A Brief History

- The first transistor - 1947 at Bell Labs by researchers Bardeen, Brattain, and Shockley
- The first integrated circuit - 1959 at Texas Instruments by Jack Kilby.
- 1959 - Fairchild Camera, Robert Noyce - planar technology, and silicon dioxide as an insulating material on a silicon substrate.


First Transistor – Bell Labs 1947
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Courtesy Lucent Technolgies
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Optical Lithography, page 5
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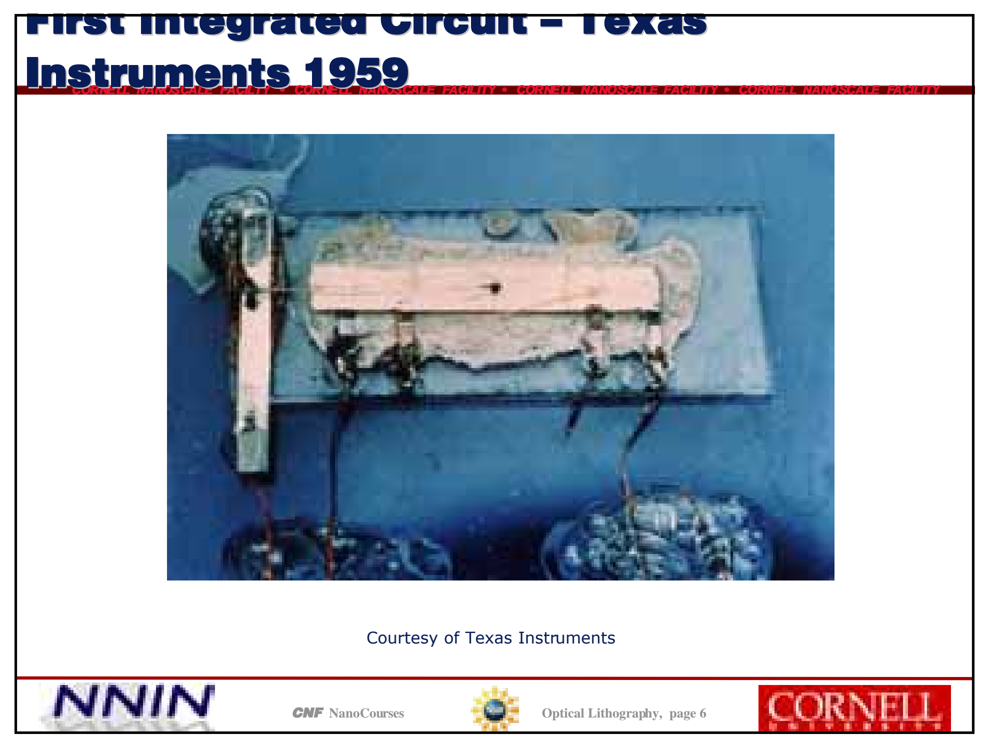
First Integrated Circuit – Texas Instruments 1959
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Courtesy of Texas Instruments
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Industry Foundation – The Silicon Wafer
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Courtesy Intel
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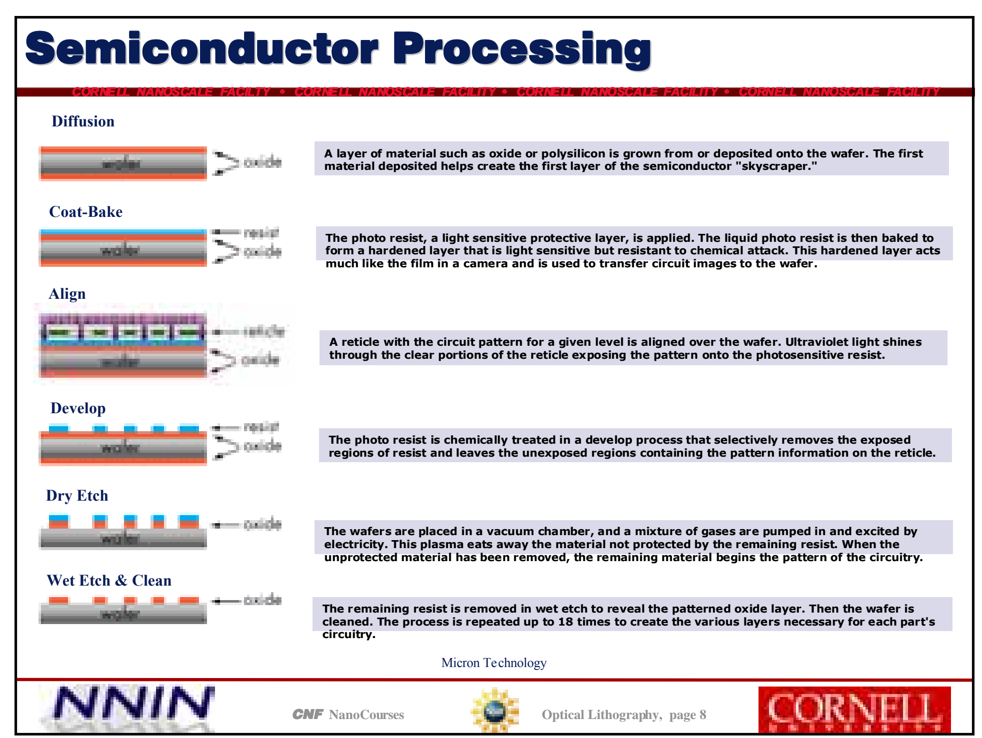
Semiconductor Processing
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Diffusion
wafer
oxide
A layer of material such as oxide or polysilicon is grown from or deposited onto the wafer. The first material deposited helps create the first layer of the semiconductor "skyscraper."
Coat-Bake
resist
oxide
wafer
The photo resist, a light sensitive protective layer, is applied. The liquid photo resist is then baked to form a hardened layer that is light sensitive but resistant to chemical attack. This hardened layer acts much like the film in a camera and is used to transfer circuit images to the wafer.
Align
reticle
oxide
wafer
A reticle with the circuit pattern for a given level is aligned over the wafer. Ultraviolet light shines through the clear portions of the reticle exposing the pattern onto the photosensitive resist.
Develop
resist
oxide
wafer
The photo resist is chemically treated in a develop process that selectively removes the exposed regions of resist and leaves the unexposed regions containing the pattern information on the reticle.
Dry Etch
oxide
wafer
The wafers are placed in a vacuum chamber, and a mixture of gases are pumped in and excited by electricity. This plasma eats away the material not protected by the remaining resist. When the unprotected material has been removed, the remaining material begins the pattern of the circuitry.
Wet Etch & Clean
oxide
wafer
The remaining resist is removed in wet etch to reveal the patterned oxide layer. Then the wafer is cleaned. The process is repeated up to 18 times to create the various layers necessary for each part's circuitry.
Micron Technology
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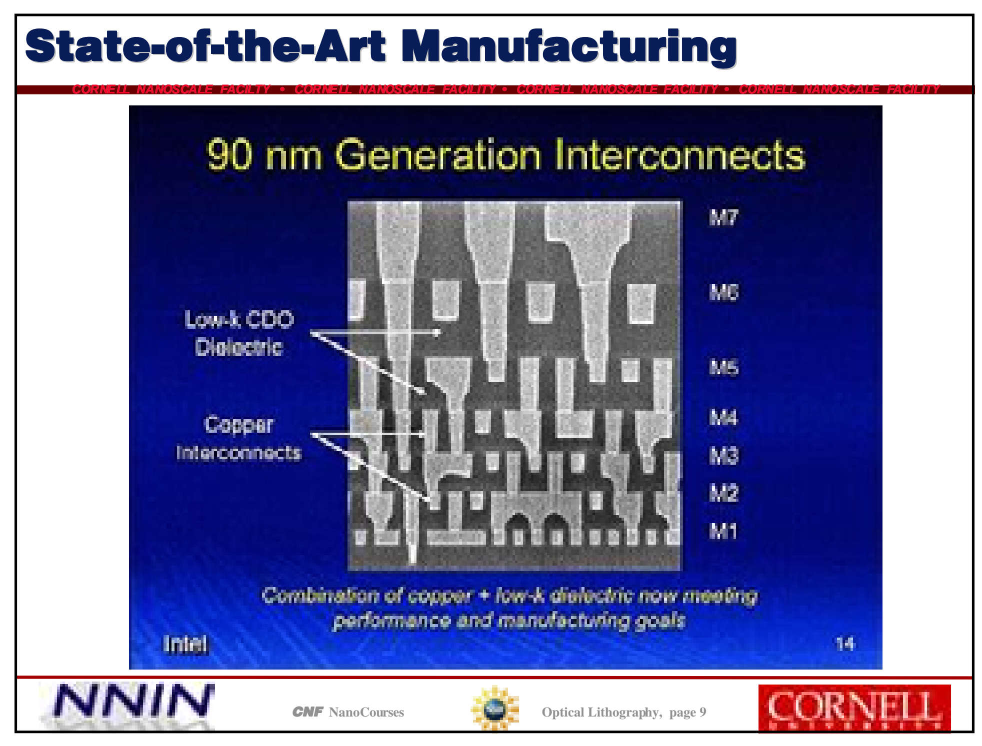
State-of-the-Art Manufacturing
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
90 nm Generation Interconnects
M7
M6
M5
M4
M3
M2
M1
Low-k CDO Dielectric
Copper Interconnects
Combination of copper + low-k dielectric now meeting performance and manufacturing goals
Intel
14
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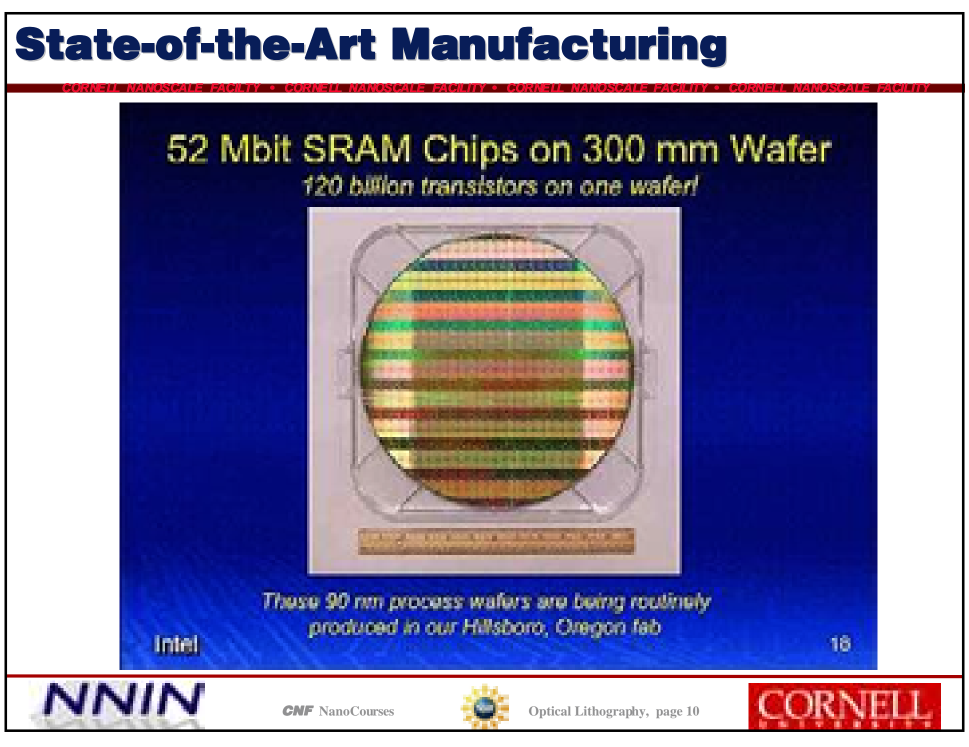
State-of-the-Art Manufacturing
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
52 Mbit SRAM Chips on 300 mm Wafer
120 billion transistors on one wafer!
These 90 nm process wafers are being routinely produced in our Hillsboro, Oregon fab
Intel
18
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IBM East Fishkill Wafer Fab
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Courtesy IBM
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Market-Driven Technology
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NVIDIA.
GeForce 6800
Revolutionary performance & complete Shader Model 3.0
Complete Native Shader Model 3.0 Support
Full support for shader model 3.0
Vertex Texture Fetch / Long programs / Pixel Shader flow control
Full speed fp32 shading
OpenEXR High Dynamic Range Rendering
Floating point frame buffer blending
Floating point texture filtering
Unparalleled Performance
222M xtors / 0.13um @ IBM
6 vertex units / 16 pixel pipelines
Next Generation Video
VMR / High quality compositing
Hardware MPEG encode / decode
HDTV Output
PCI Express
[H]
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Personal Computer Products
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PowerPC 970FX
IBM
Intel Xeon
IBM Power PC
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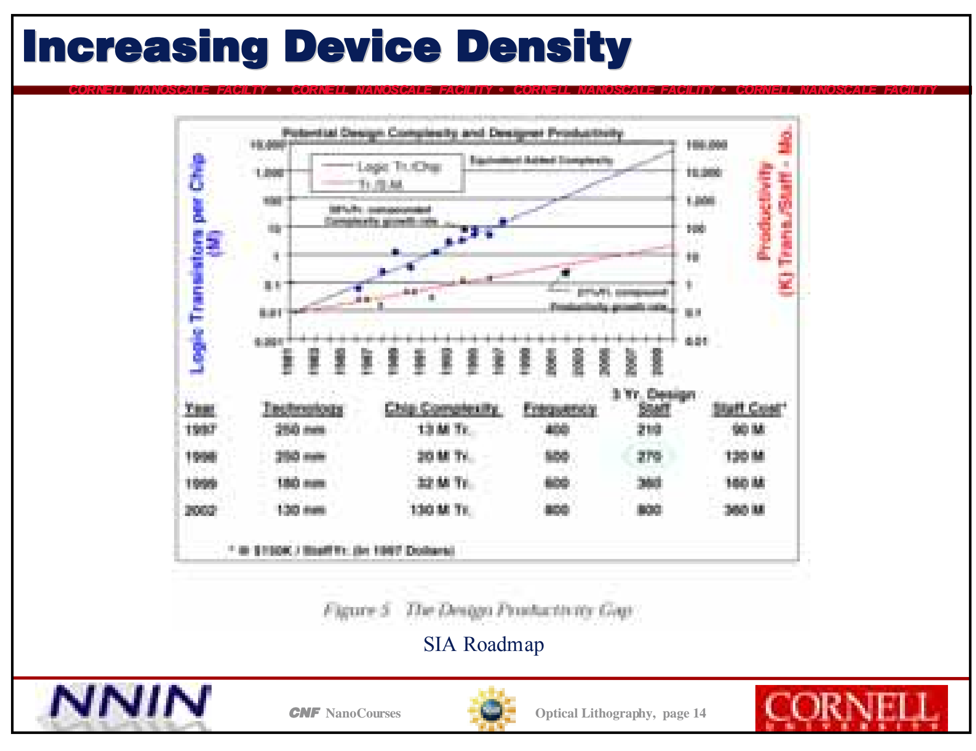

Increasing Device Density
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Potential Design Complexity and Designer Productivity
Logic Transistors per Chip (M)
Productivity (K) Trans./Staff - Mo.
Logic Tr./Chip
Tr./S.M.
Equivalent Added Complexity
Year
Technology
Chip Complexity
Frequency
3 Yr. Design Staff
Staff Cost*
1997
250 nm
13 M Tr.
400
210
90 M
1998
250 nm
20 M Tr.
500
270
120 M
1999
180 nm
32 M Tr.
600
360
160 M
2002
130 nm
130 M Tr.
800
800
360 M
Figure 5 The Design Productivity Gap
SIA Roadmap
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Leading-Edge Processes

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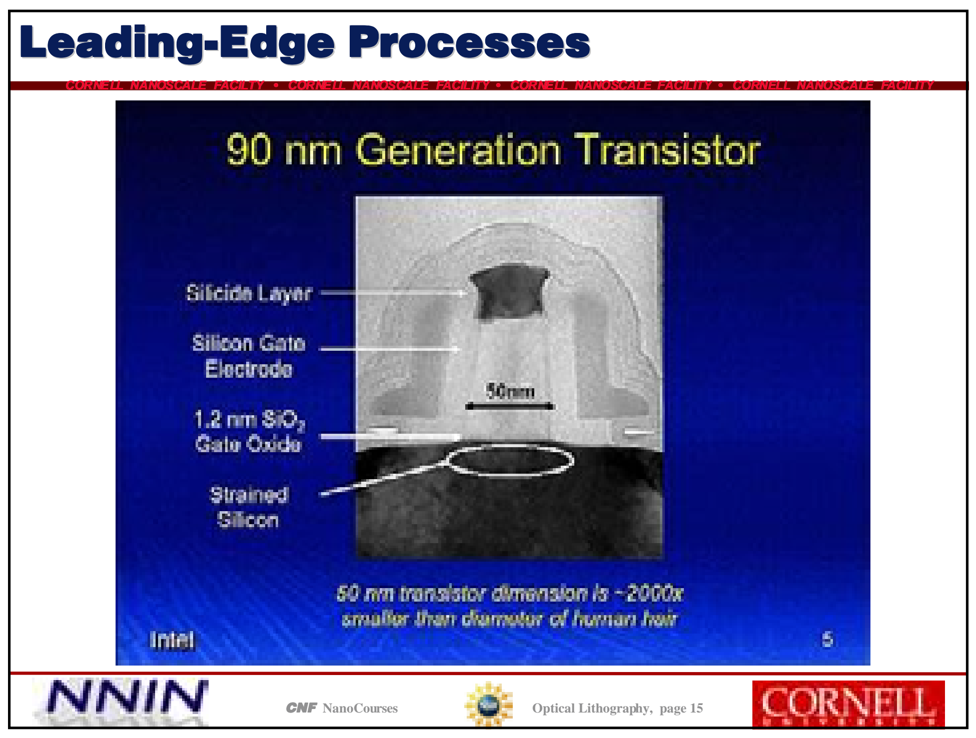

Semiconductor Processing

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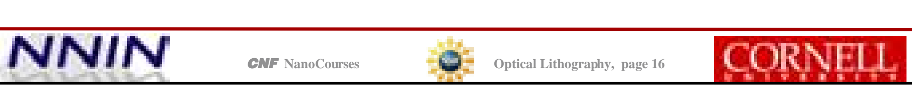
- Manufacture of devices depends on selective processes:
  - Removal of material -- Etching
  - Addition of material -- Deposition
  - Modification of material -- Implantation, diffusion, etc.



Types of Exposure

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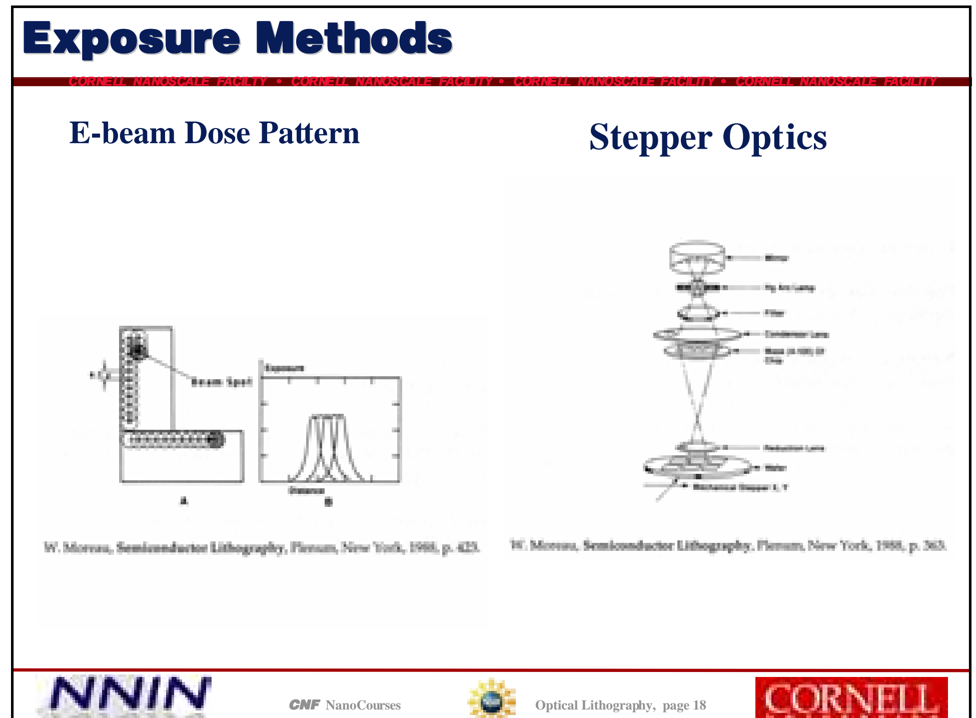
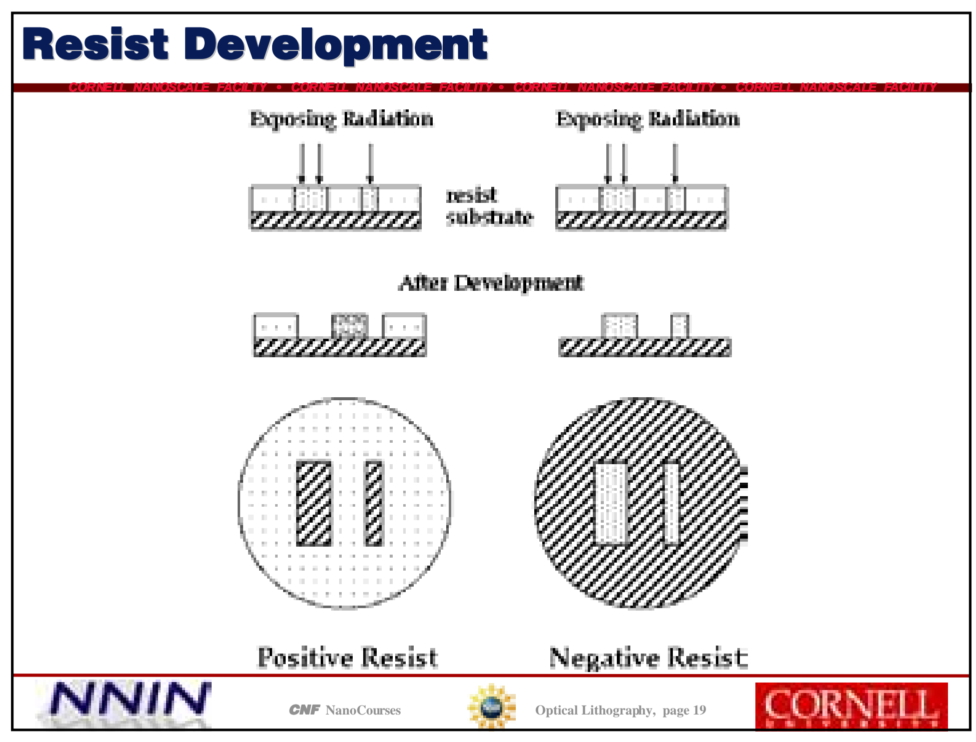
- Light -- 436 nm - 157 nm; near UV to Deep UV optical lithography
- X-rays -- 13 nm - 0.4 nm; x-ray lithography
- Electrons -- 10 keV - 100 keV; electron beam lithography
- Ions -- 50 keV - 200 keV; focused ion beam lithography




Resist Development
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Exposing Radiation
Exposing Radiation
resist
substrate
After Development
Positive Resist
Negative Resist
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Optical Lithography, page 19
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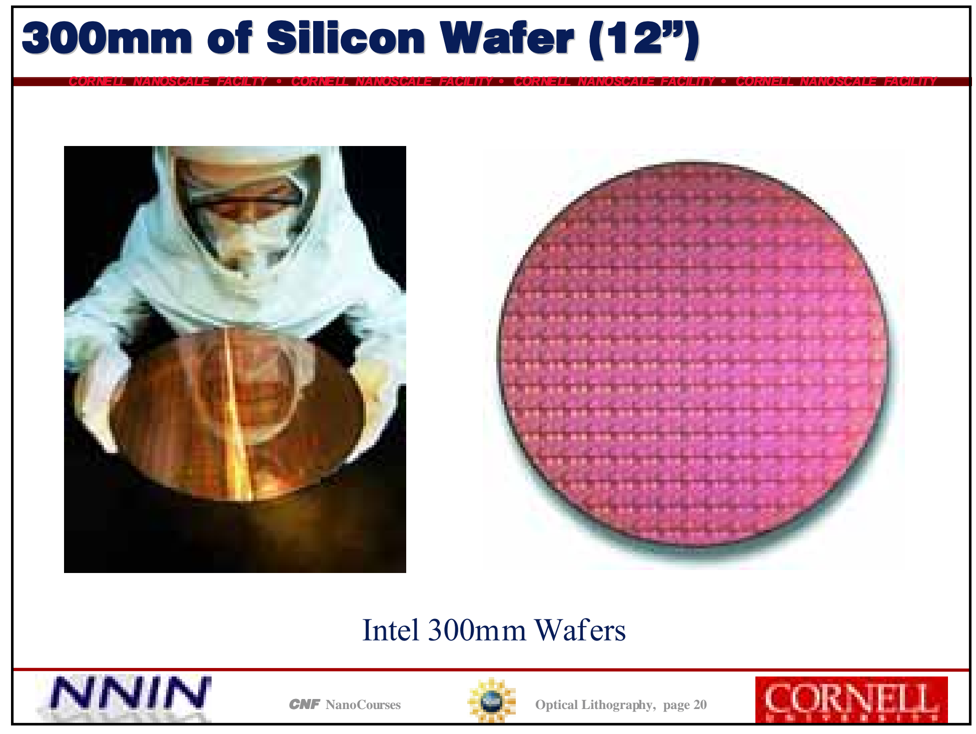
300mm of Silicon Wafer (12")
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Intel 300mm Wafers
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Optical Lithography, page 20
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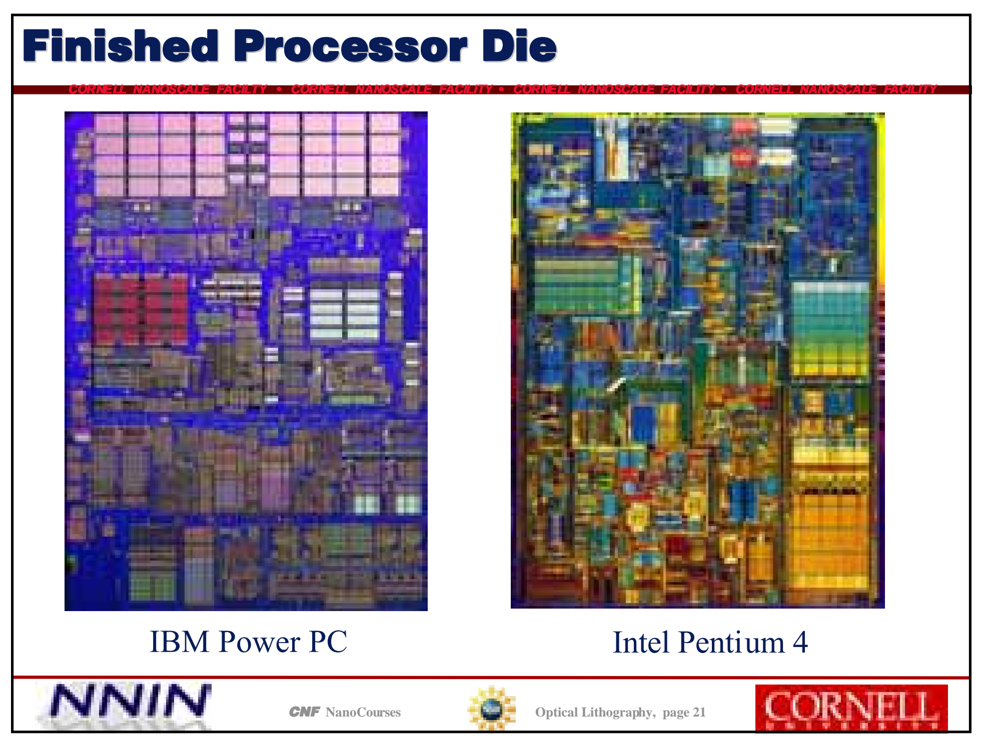
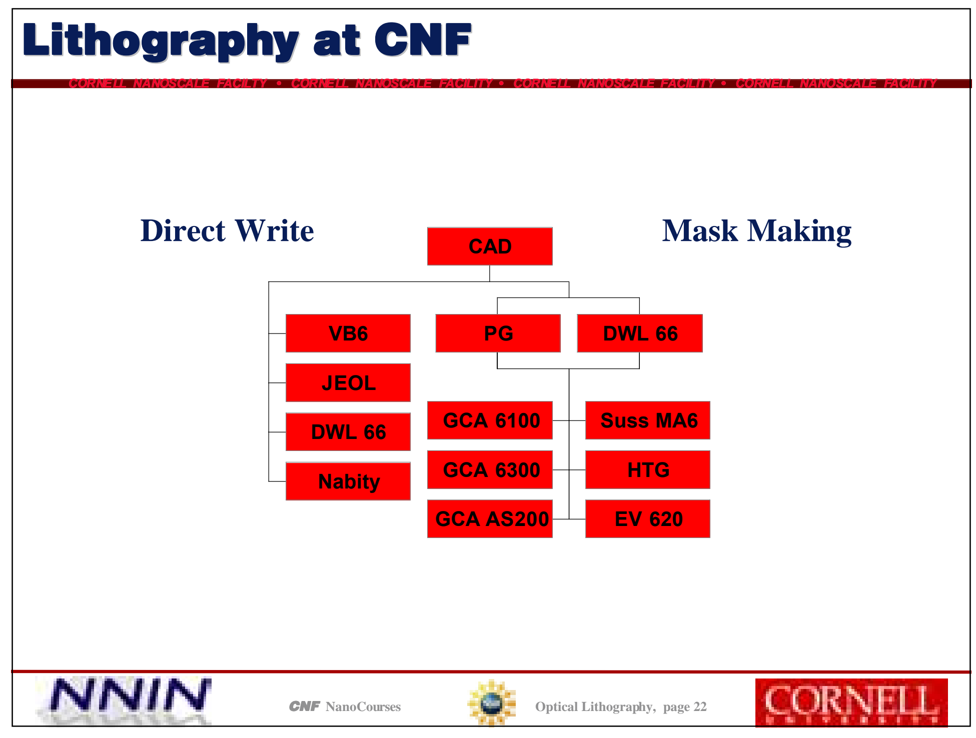

Finished Processor Die
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
IBM Power PC
Intel Pentium 4
NNIN
CNF NanoCourses
Optical Lithography, page 21
CORNELL


Lithography at CNF
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Direct Write
CAD
Mask Making
VB6
PG
DWL 66
JEOL
GCA 6100
Suss MA6
DWL 66
GCA 6300
HTG
Nabity
GCA AS200
EV 620
NNIN
CNF NanoCourses
Optical Lithography, page 22
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Your Pattern Requirements

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- **Considerations:**
  - **The requirements of the lithography tool**
  - **The requirements of the technique you will use for the pattern transfer**

Starting Suggestions

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- **Think** about what type of design you want and how to implement it.
- **Gather information** from the course notes, staff members, and other students about the best tools and techniques to use before you actually sit down and design the pattern.
- **Design the pattern** using the information you have gathered paying careful attention to the requirements listed above.
- **Perform** lithography, pattern transfer, etc.
- **Repeat steps 1 - 4** as many times as necessary to get it right.

To Aid the Staff (and you)

- The more thinking and preparation you do, the more intelligent the questions you ask, and the more time you end up saving the staff member.
- The more advance notice you can give about when you would like to talk about your process or be trained on equipment, the better.
- The more responsible you can be around the lab, the less we have to clean up after you, and the more time we have for answering your questions.
- **And, last but not least, please be patient!**

Microlithography

Optical Lithography

Mask Making

GCA/Mann 3600F

GCA/Mann 3600F Specifications

- Data input: 0.1 µm; this is the least count for object placement
- Aperture: 2 µm - 1500 µm in 0.5µm increments
- Rotation: 0 - 89.9º in 0.1º increments
- Image positioning accuracy: ± 0.6 µm over 150 mm of stage motion -- this is 4 ppm
- Aperture error:
  - ± 0.35 µm from 2 µm - 125 µm
  - ± 0.3 % from 125 µm - 425 µm
  - ± 1.25 µm from 425 µm - 1500 µm

Heidelberg DWL66 Specifications

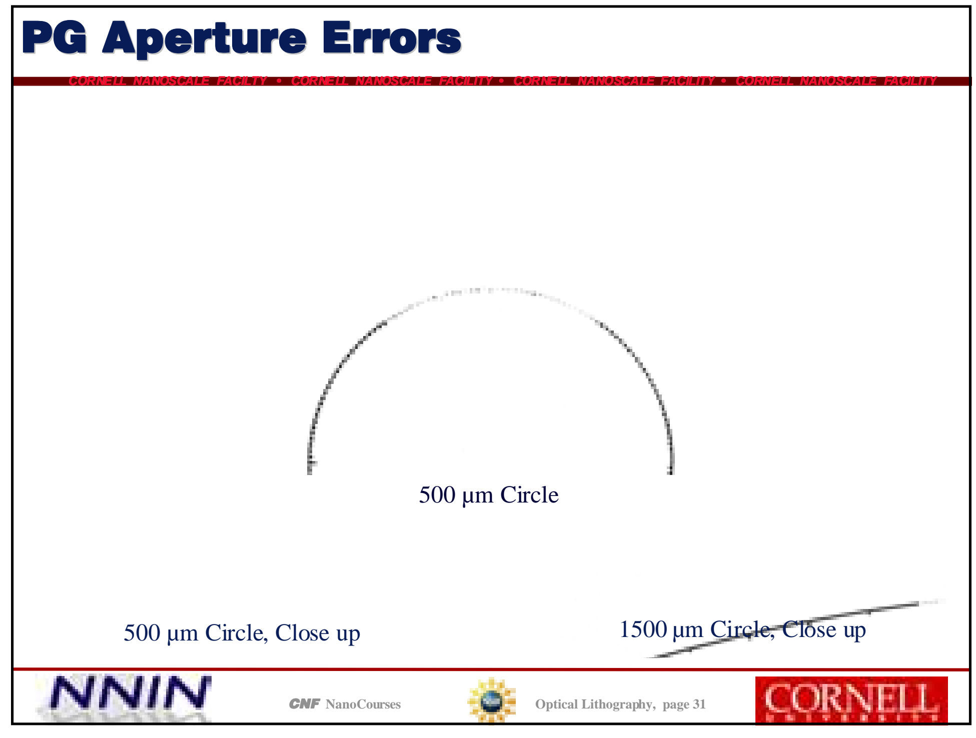
CORNELL NANOSCALE FACILTY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

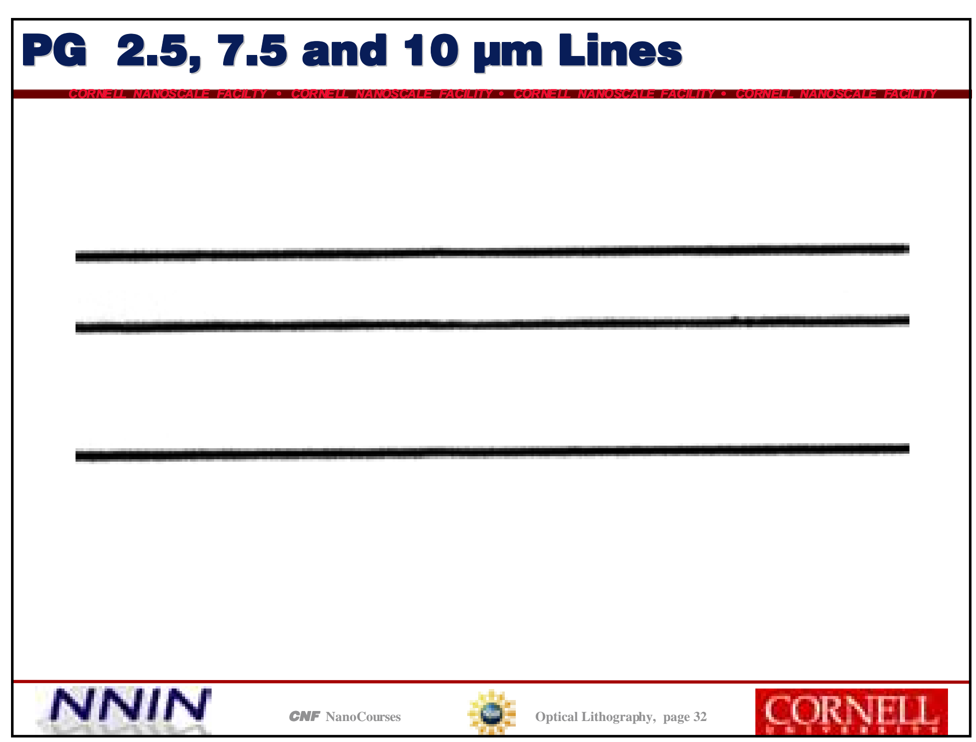
- **Data input: 0.01 µm; this is the least count for object placement**
- **Spot size: 0.6 µm with 2 mm lens; 2 µm with 10 mm lens**
- **Stage motion range: 200 mm**
- **Image positioning accuracy: ± 0.05 µm over 100 mm of stage motion -- this is 0.5 ppm**
- **Alignment error: +/- 100 nm**

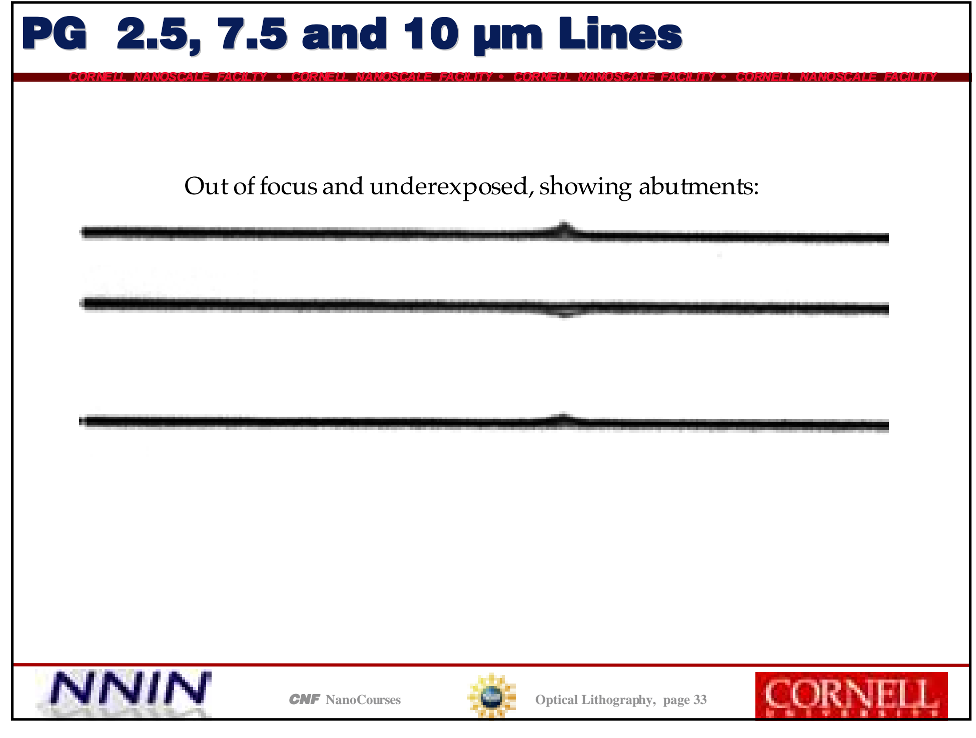
PG Aperture and Positioning Errors

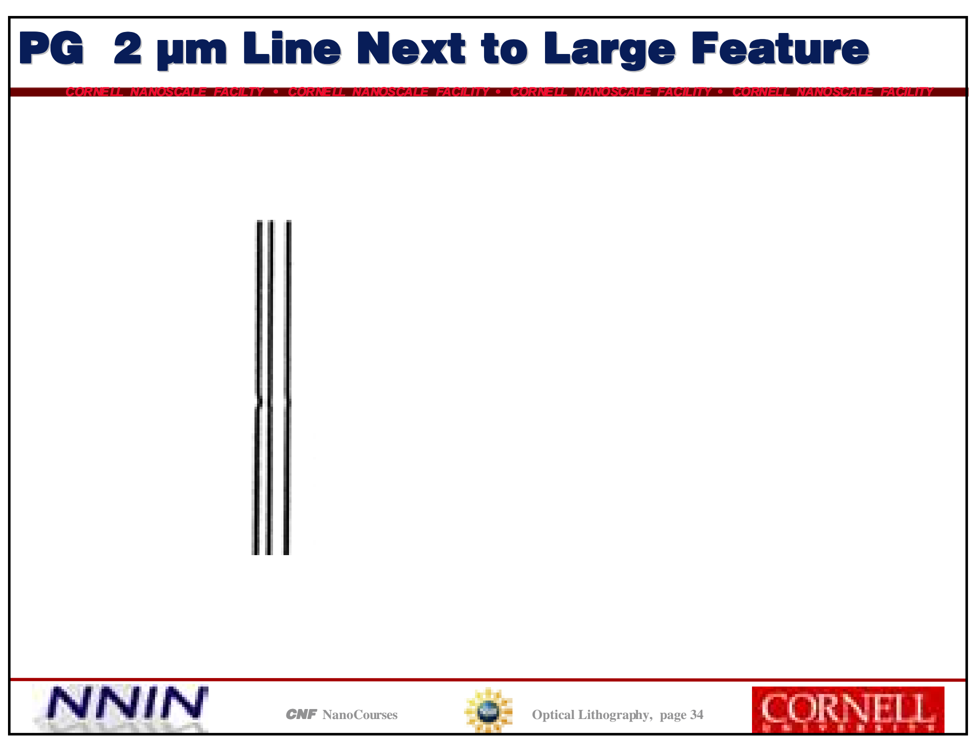
CORNELL NANOSCALE FACILTY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

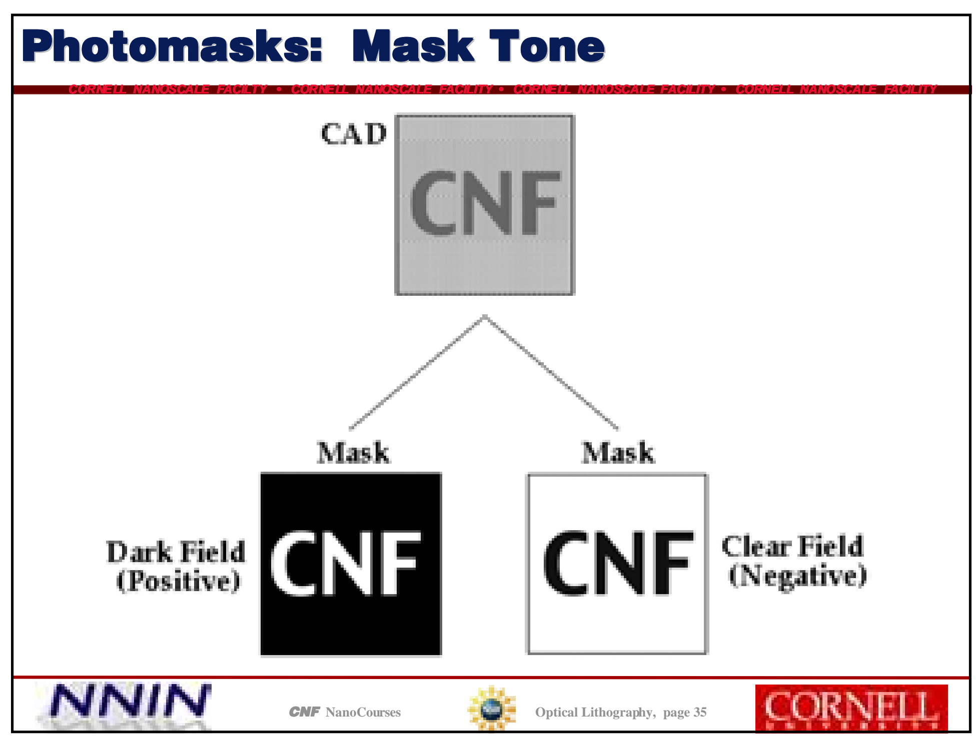
Contact (1:1)	2.0 μm	2.0 μm	17.5 %
Stepper (5:1)	5.0 μm	1.0 μm	7.0 %
Stepper (10:1)	6.0 μm	0.6 μm	5.0 %

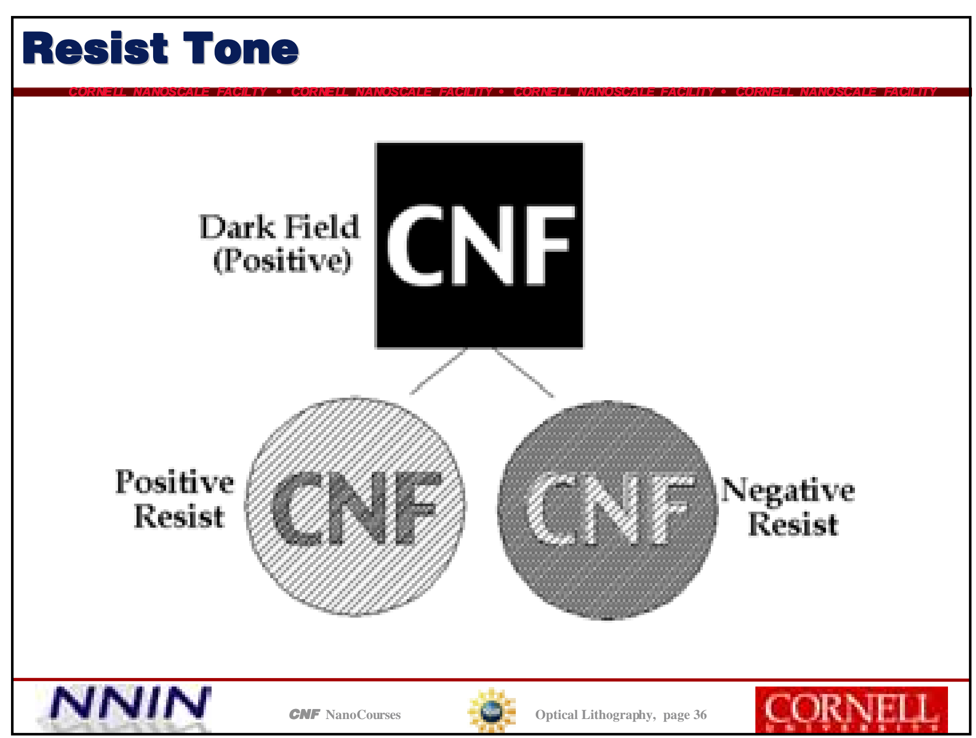

PG Aperture Errors
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
500 µm Circle
500 µm Circle, Close up
1500 µm Circle, Close up
NNIN
CNF NanoCourses
Optical Lithography, page 31
CORNELL

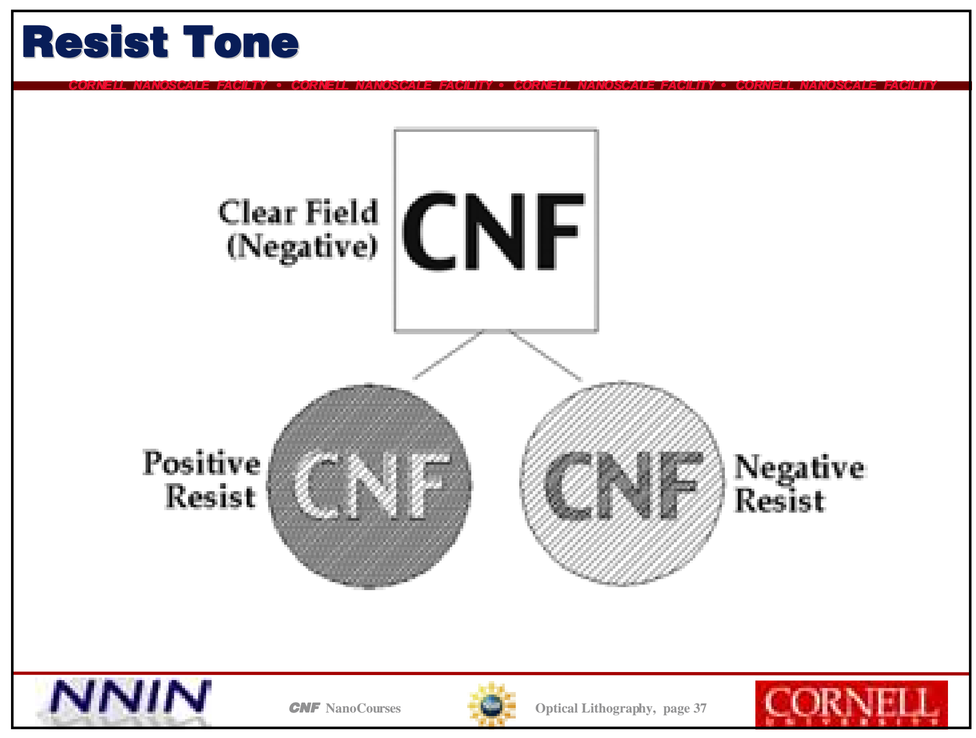

PG 2.5, 7.5 and 10 µm Lines
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
NNIN
CNF NanoCourses
Optical Lithography, page 32
CORNELL


PG 2.5, 7.5 and 10 µm Lines
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Out of focus and underexposed, showing abutments:
NNIN
CNF NanoCourses
Optical Lithography, page 33
CORNELL


PG 2 µm Line Next to Large Feature
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
NNIN
CNF NanoCourses
Optical Lithography, page 34
CORNELL

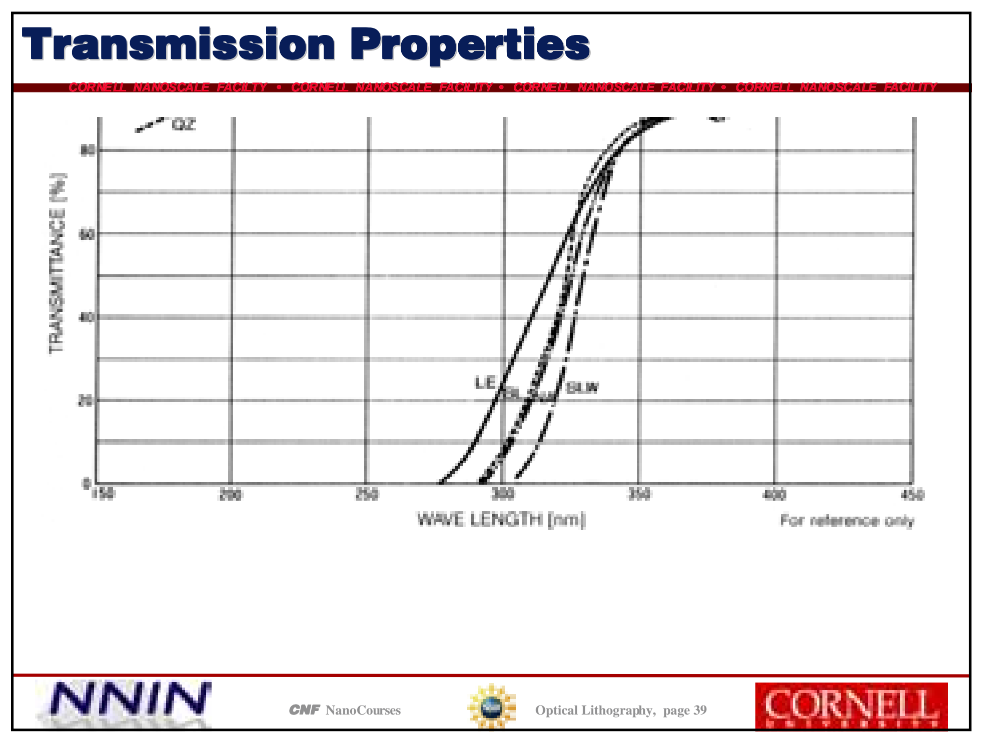

Photomasks: Mask Tone
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
CAD
CNF
Mask
Mask
Dark Field
(Positive)
CNF
CNF
Clear Field
(Negative)
NNIN
CNF NanoCourses
Optical Lithography, page 35
CORNELL

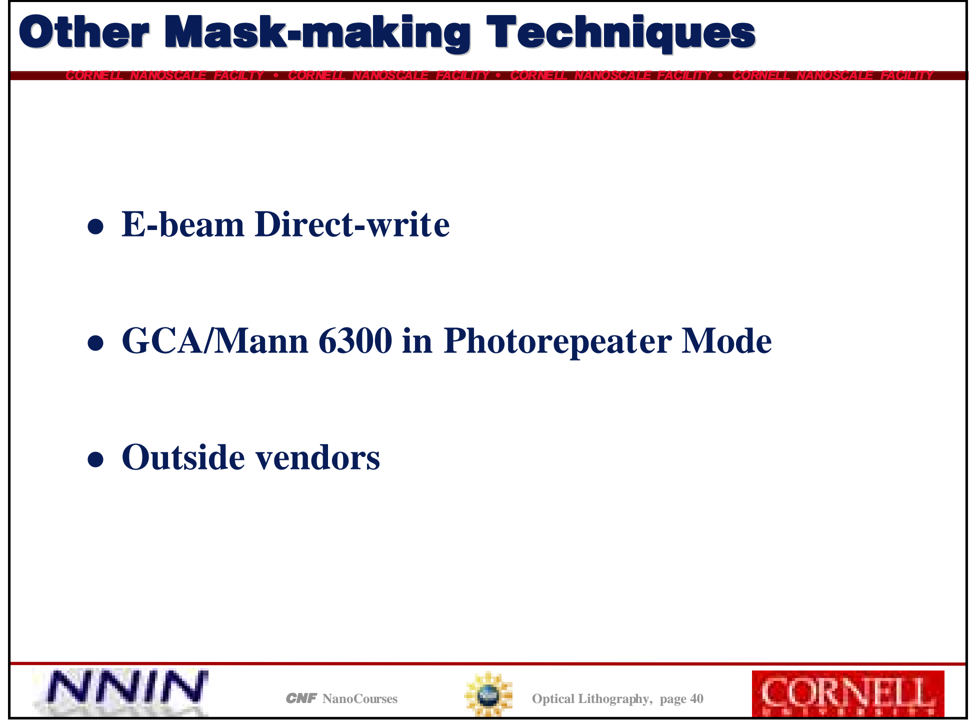

Resist Tone
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Dark Field
(Positive)
CNF
Positive
Resist
CNF
CNF
Negative
Resist
NNIN
CNF NanoCourses
Optical Lithography, page 36
CORNELL

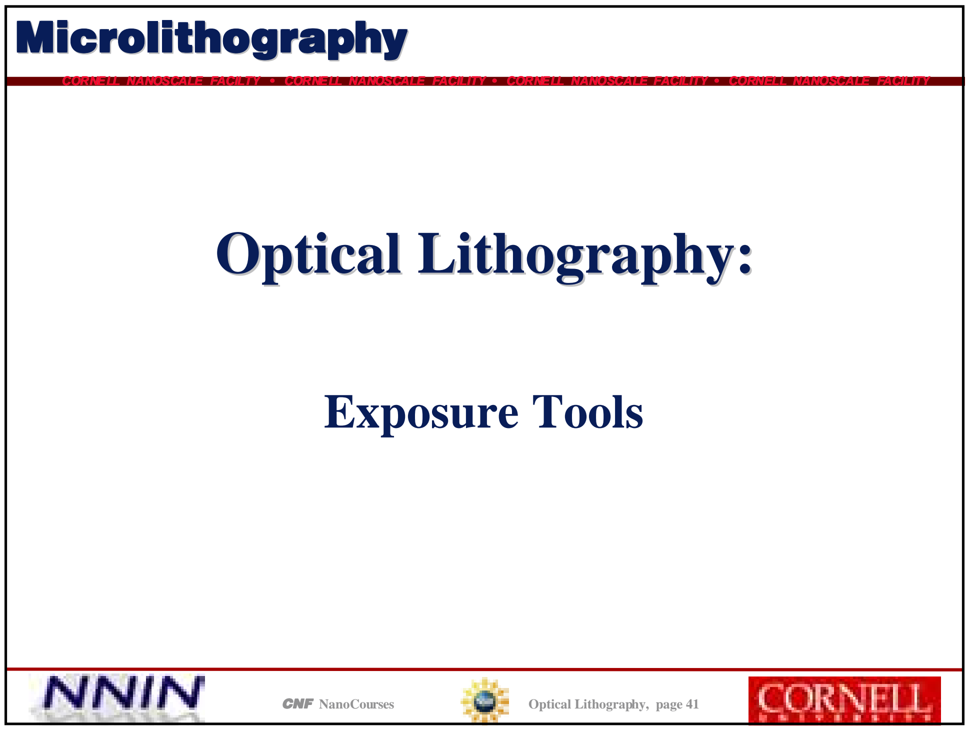


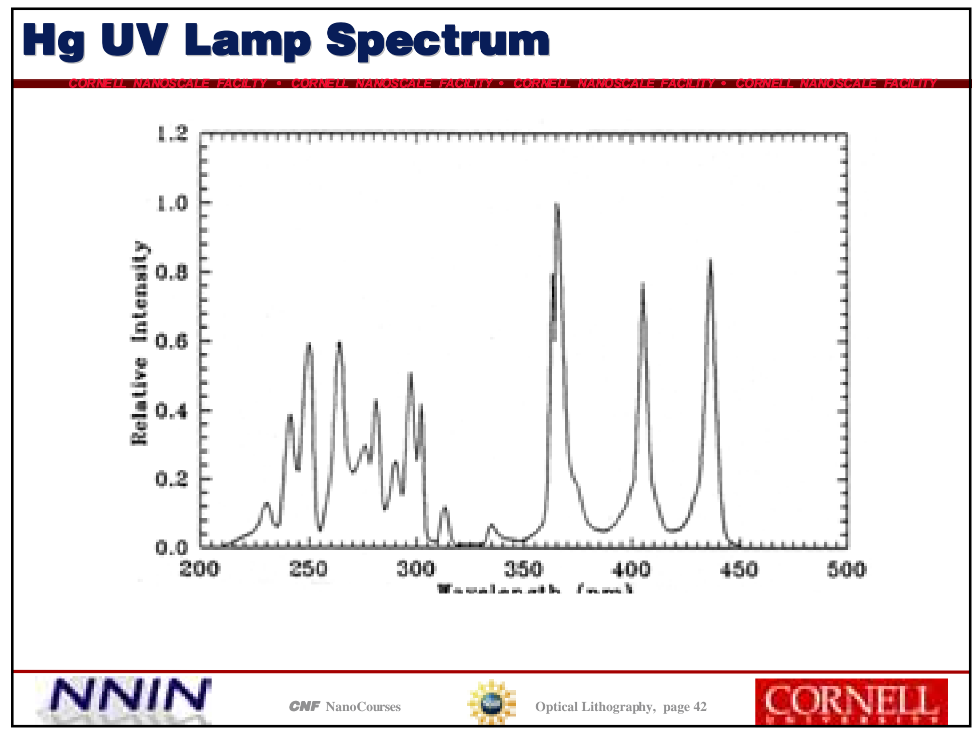
Types of Glass

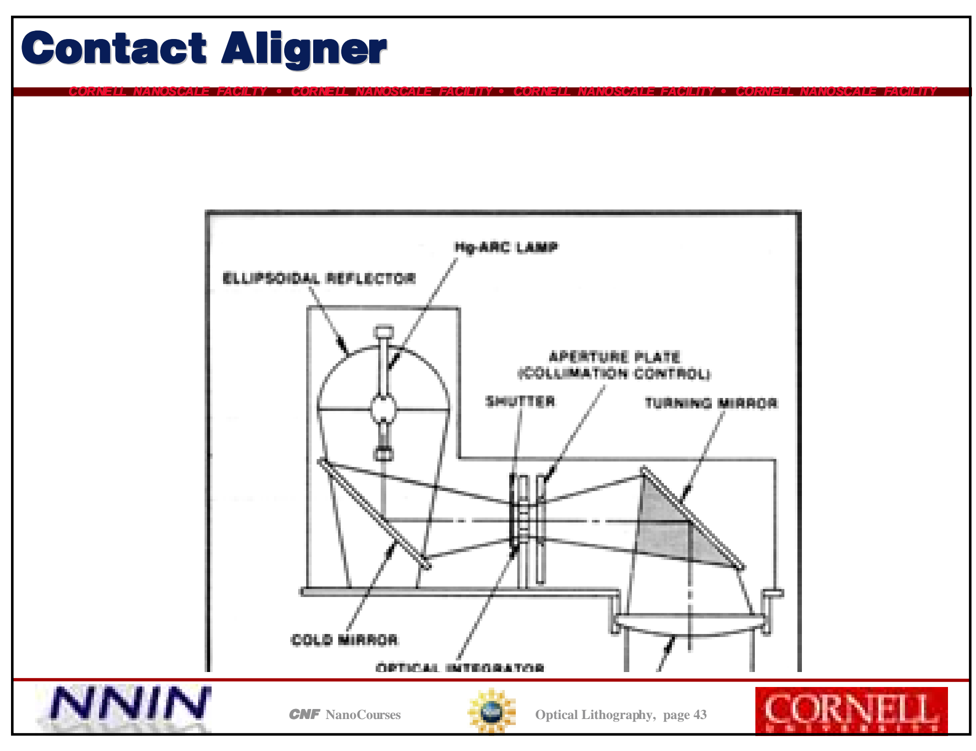
- Thermal coefficients for different types of glass:
  - Soda-lime: 9.3 ppm/ºC
  - Borosilicate: 3.7 ppm/ºC
  - Quartz: 0.5 ppm/ºC

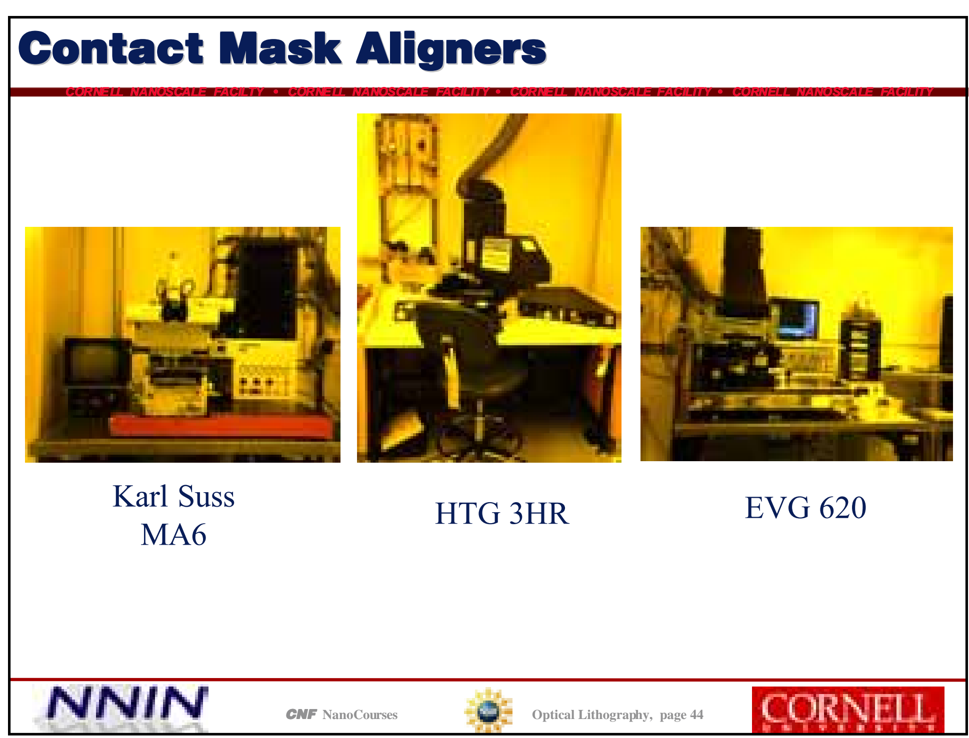

Transmission Properties
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
QZ
TRANSMITTANCE [%]
LE
SLW
WAVE LENGTH [nm]
For reference only
NNIN
CNF NanoCourses
Optical Lithography, page 39
CORNELL

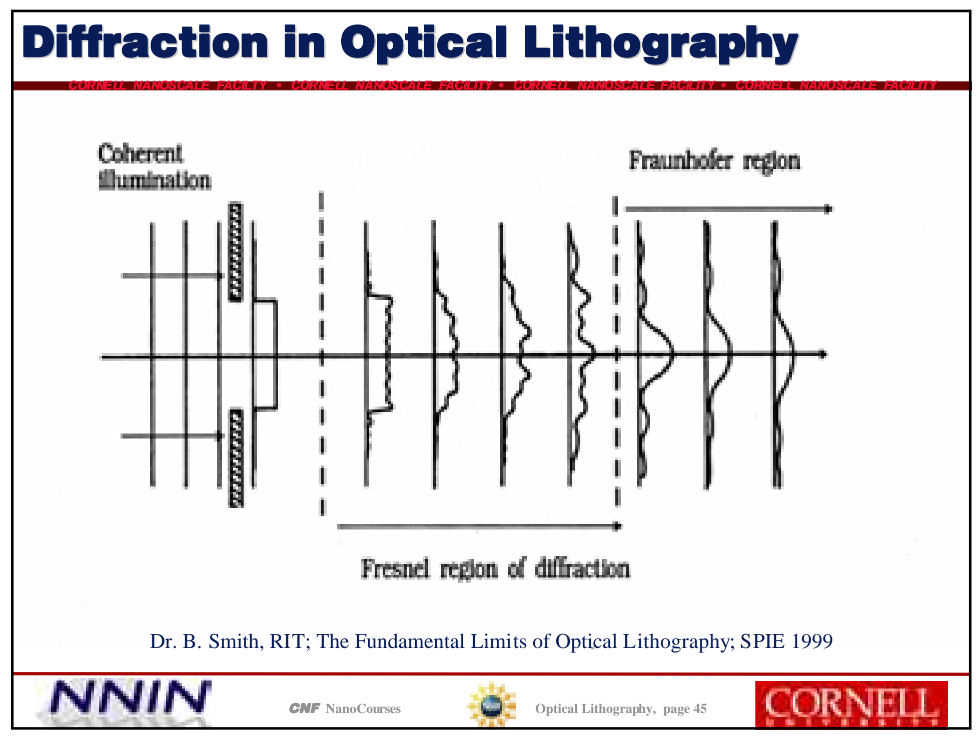

Other Mask-making Techniques
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• E-beam Direct-write
• GCA/Mann 6300 in Photorepeater Mode
• Outside vendors
NNIN
CNF NanoCourses
Optical Lithography, page 40
CORNELL

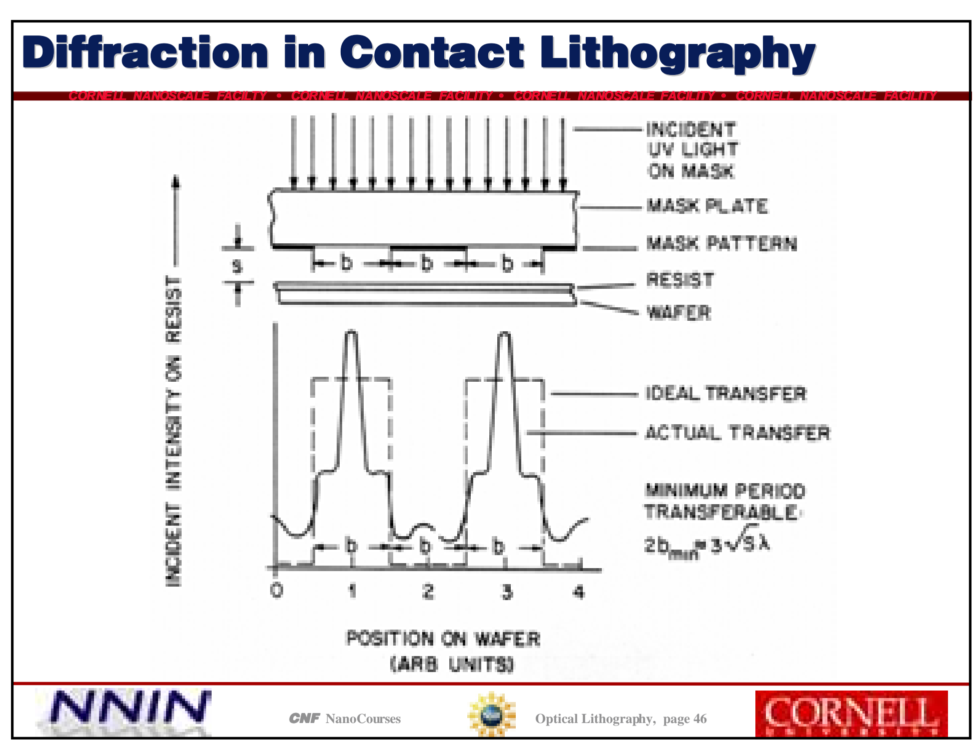

Microlithography
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Optical Lithography:
Exposure Tools
NNIN
CNF NanoCourses
Optical Lithography, page 41
CORNELL

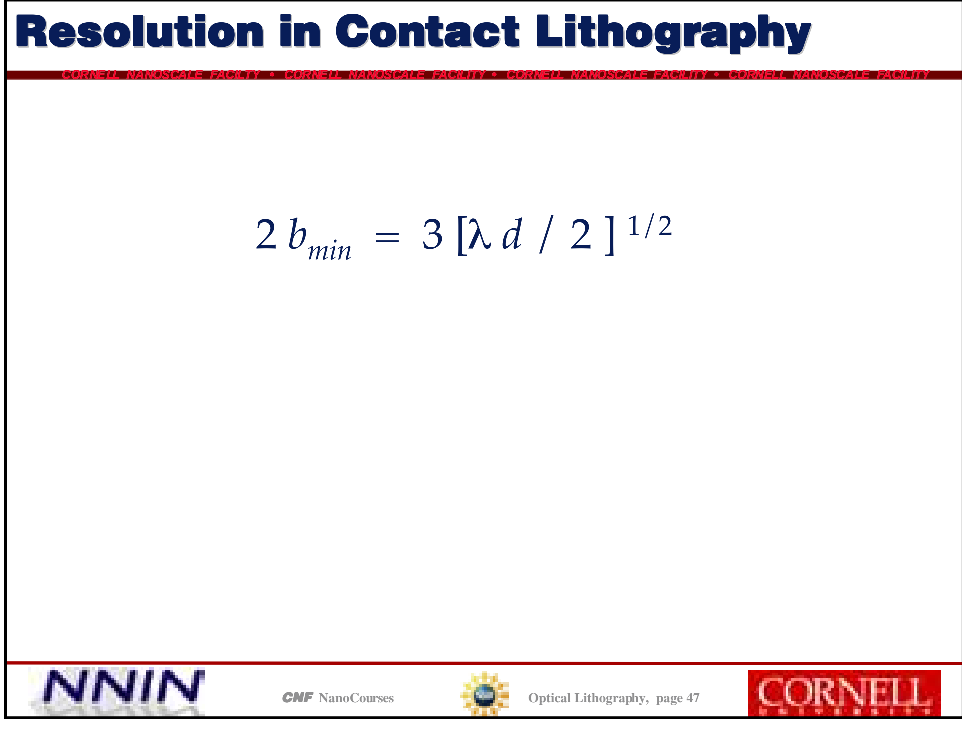

Hg UV Lamp Spectrum
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Relative Intensity
0.0
0.2
0.4
0.6
0.8
1.0
1.2
200
250
300
350
400
450
500
NNIN
CNF NanoCourses
Optical Lithography, page 42
CORNELL


Contact Aligner
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Hg-ARC LAMP
ELLIPSOIDAL REFLECTOR
APERTURE PLATE
(COLLIMATION CONTROL)
SHUTTER
TURNING MIRROR
COLD MIRROR
OPTICAL INTEGRATOR
NNIN
CNF NanoCourses
Optical Lithography, page 43
CORNELL
UNIVERSITY

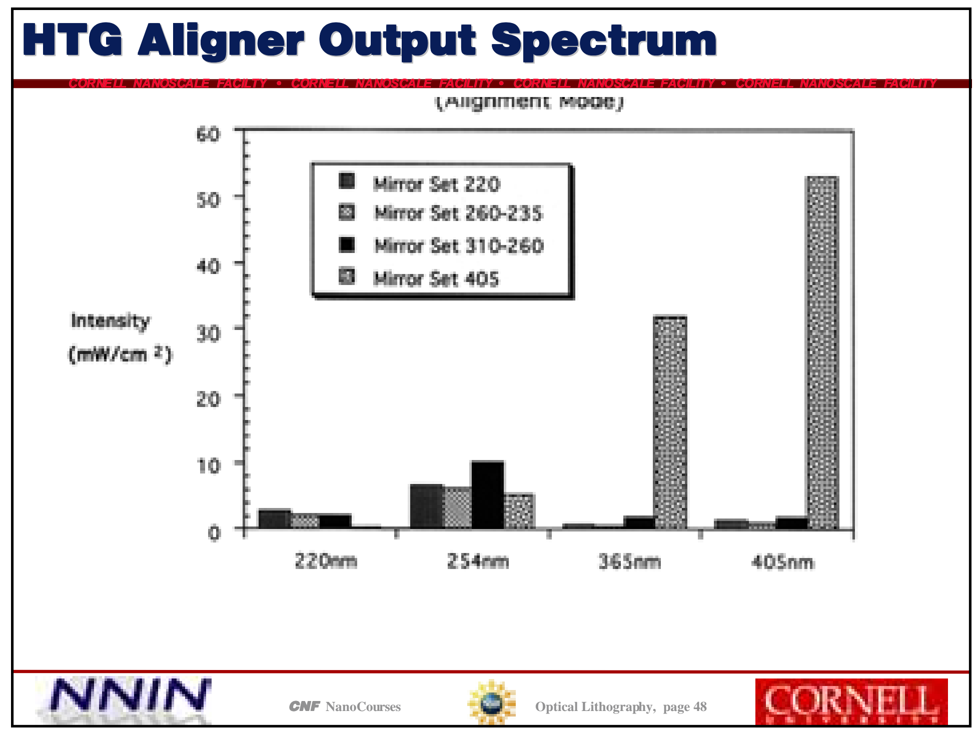

Contact Mask Aligners
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Karl Suss
MA6
HTG 3HR
EVG 620
NNIN
CNF NanoCourses
Optical Lithography, page 44
CORNELL
UNIVERSITY


Diffraction in Optical Lithography
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Coherent illumination
Fraunhofer region
Fresnel region of diffraction
Dr. B. Smith, RIT; The Fundamental Limits of Optical Lithography; SPIE 1999
NNIN
CNF NanoCourses
Optical Lithography, page 45
CORNELL

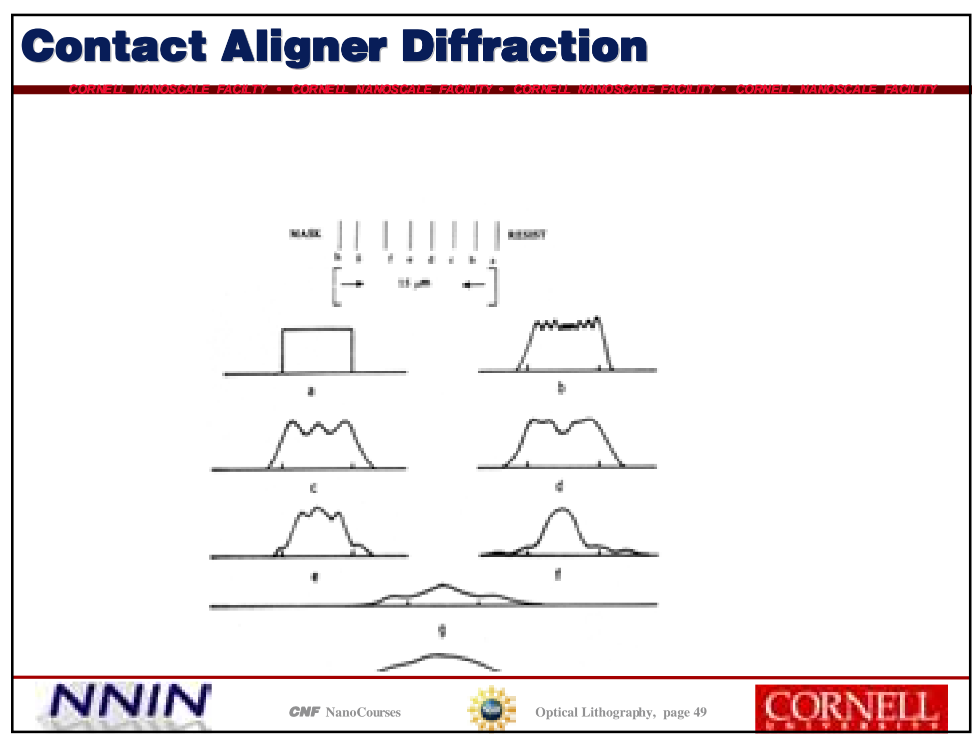

Diffraction in Contact Lithography
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
INCIDENT UV LIGHT ON MASK
MASK PLATE
MASK PATTERN
RESIST
WAFER
s
b
INCIDENT INTENSITY ON RESIST
IDEAL TRANSFER
ACTUAL TRANSFER
MINIMUM PERIOD TRANSFERABLE
$2b_{min} \approx 3\sqrt{s\lambda}$
0
1
2
3
4
POSITION ON WAFER (ARB UNITS)
NNIN
CNF NanoCourses
Optical Lithography, page 46
CORNELL

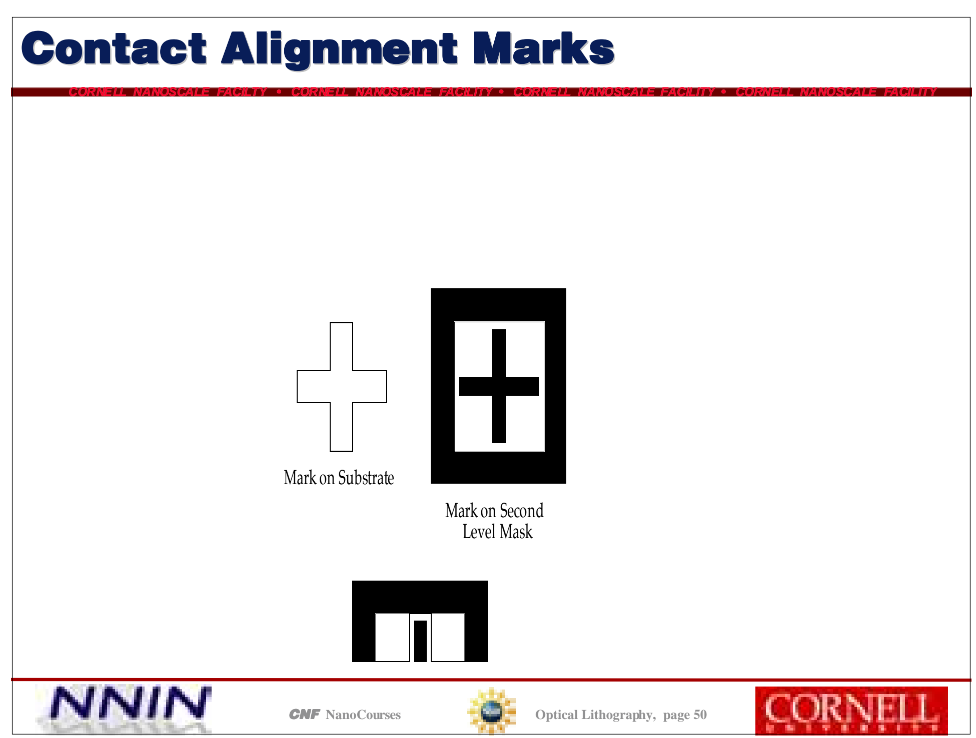


Resolution in Contact Lithography
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
$2\, b_{min} = 3\, [\lambda\, d\, /\, 2\,]^{1/2}$
NNIN
CNF NanoCourses
Optical Lithography, page 47
CORNELL



HTG Aligner Output Spectrum
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
(Alignment Mode)
Mirror Set 220
Mirror Set 260-235
Mirror Set 310-260
Mirror Set 405
Intensity
(mW/cm 2)
0
10
20
30
40
50
60
220nm
254nm
365nm
405nm
NNIN
CNF NanoCourses
Optical Lithography, page 48
CORNELL


Contact Aligner Diffraction
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
MASK
RESIST
NNIN
CNF NanoCourses
Optical Lithography, page 49
CORNELL


Contact Alignment Marks
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Mark on Substrate
Mark on Second
Level Mask
NNIN
CNF NanoCourses
Optical Lithography, page 50
CORNELL

Contact Lithography Advantages

- 1:1 pattern transfer means field size can be large. The HTG can expose wafers up to 4 inches in diameter using 5 inch masks, while the MA6 can expose wafers up to 6 inches in diameter using 7 inch masks.
- Substrates of various sizes and thicknesses can be used because there are no focus problems to consider.
- Substrates which have non-parallel front and back sides (wedge error) can be used because chucks on the aligners can tilt to planarize the sample.
- High resolution can be obtained in DUV mode, or mix and match lithography with e-beam resists can be performed.
- Contact lithography is easier to learn than projection.

Contact Lithography Disadvantages

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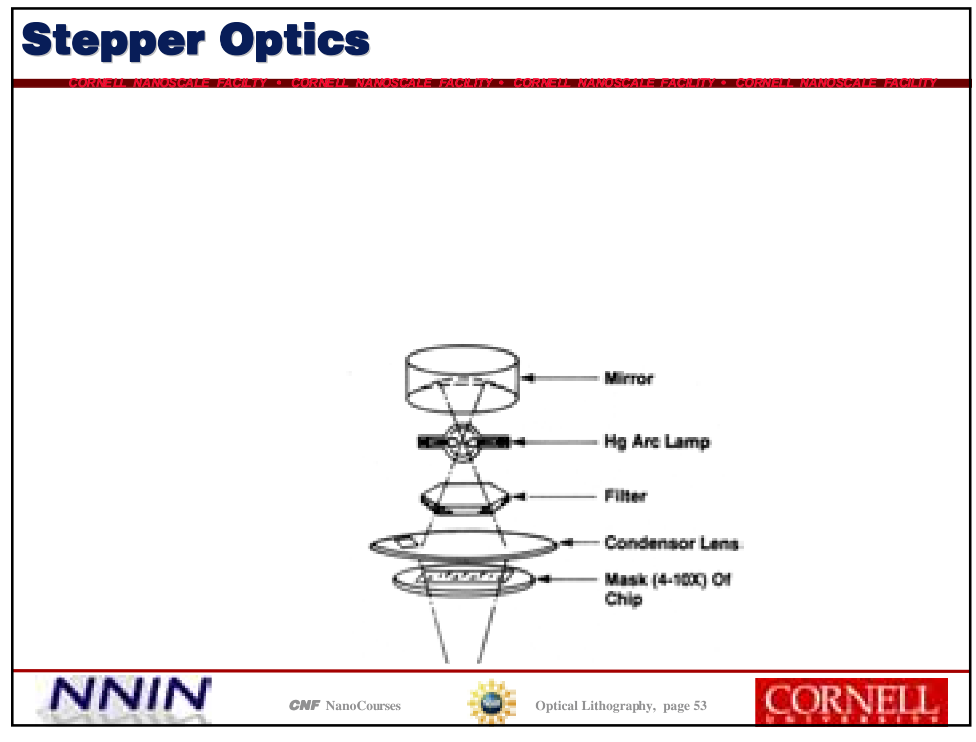
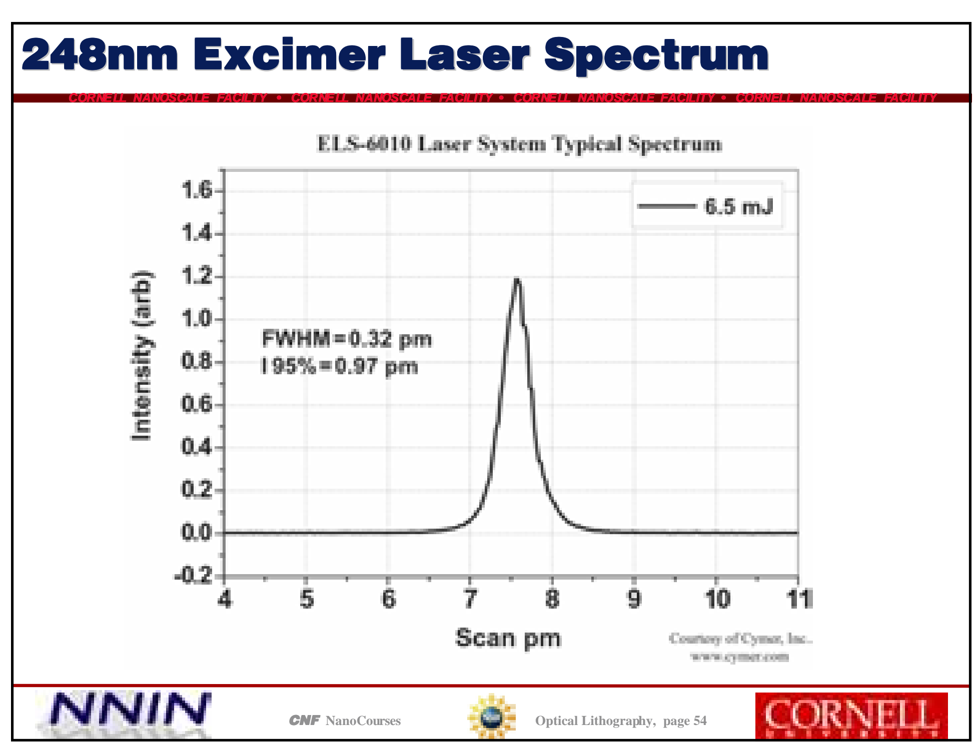
- Good contact is difficult to achieve because of particulates between mask and substrate, and flatness variations.
- As a result of particulate contamination, defects are more numerous than in projection lithography.
- Small geometries (< 2 µm) require a mask made on an e-beam system.
- DUV exposures require a quartz mask.
- Alignment can be time consuming and is not very accurate (especially if the scheme for marks has not been well thought out).


Stepper Optics
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Mirror
Hg Arc Lamp
Filter
Condensor Lens
Mask (4-10X) Of
Chip
NNIN
CNF NanoCourses
Optical Lithography, page 53
CORNELL


248nm Excimer Laser Spectrum
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
ELS-6010 Laser System Typical Spectrum
6.5 mJ
FWHM=0.32 pm
I 95%=0.97 pm
Intensity (arb)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
4
5
6
7
8
9
10
11
Scan pm
Courtesy of Cymer, Inc.
www.cymer.com
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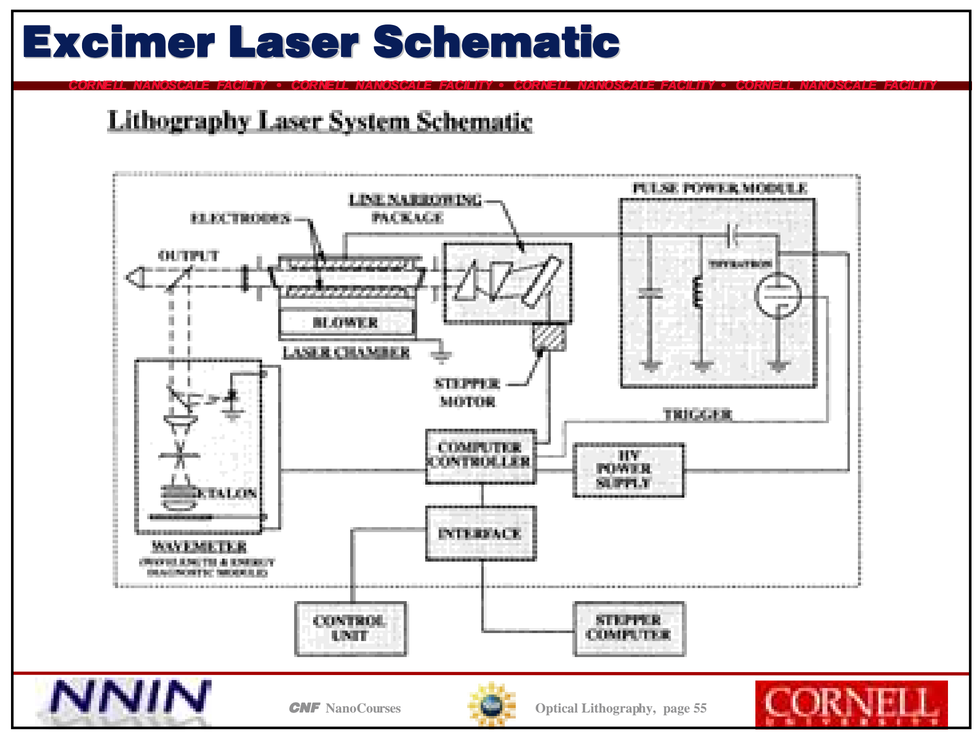
CNF NanoCourses
Optical Lithography, page 54
CORNELL


Excimer Laser Schematic
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Lithography Laser System Schematic
PULSE POWER MODULE
LINE NARROWING PACKAGE
ELECTRODES
OUTPUT
BLOWER
LASER CHAMBER
STEPPER MOTOR
TRIGGER
COMPUTER CONTROLLER
HV POWER SUPPLY
ETALON
INTERFACE
WAVEMETER
CONTROL UNIT
STEPPER COMPUTER
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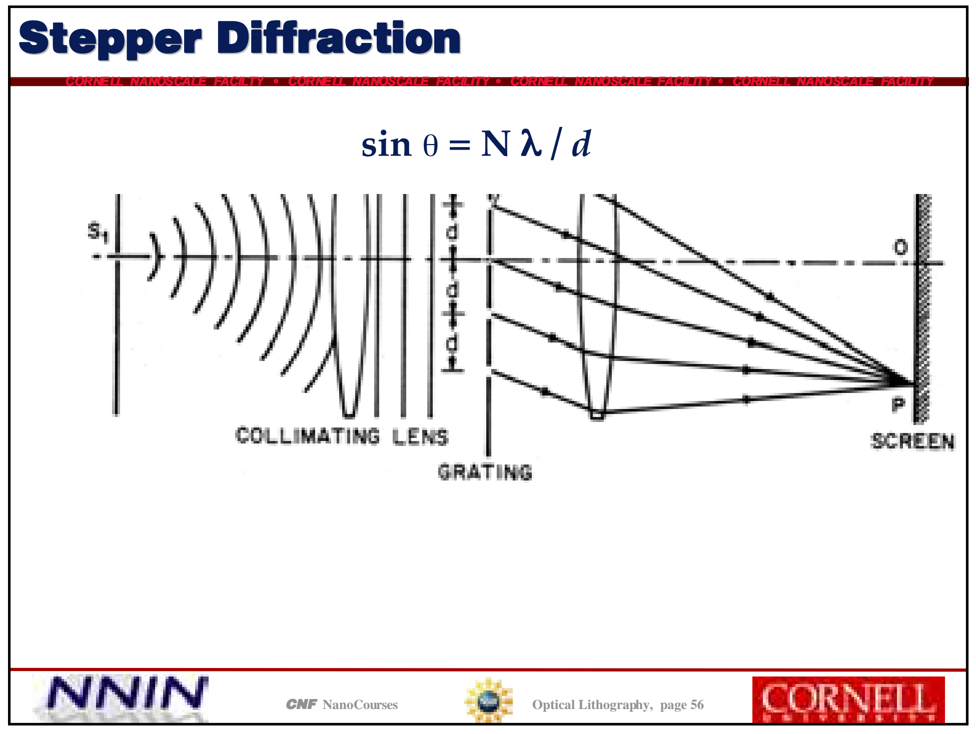
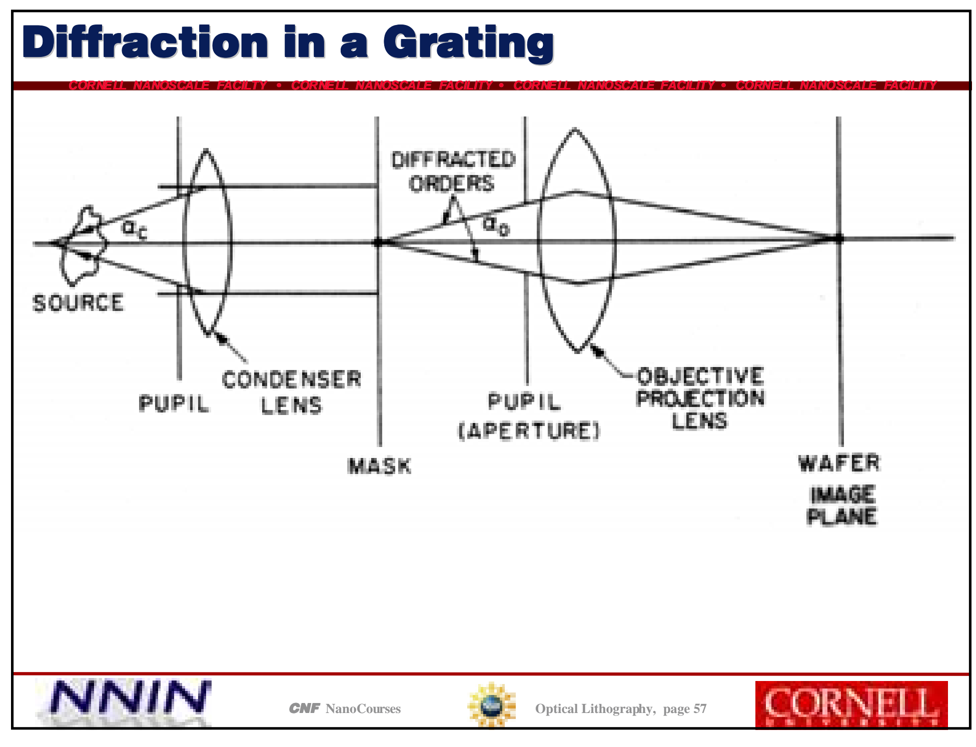
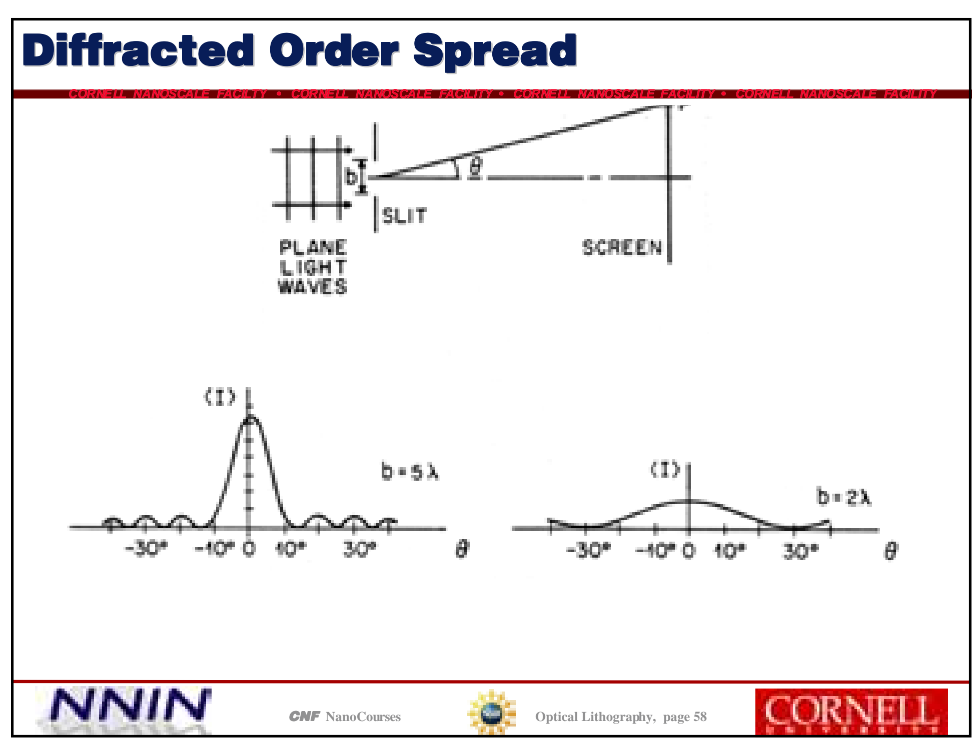
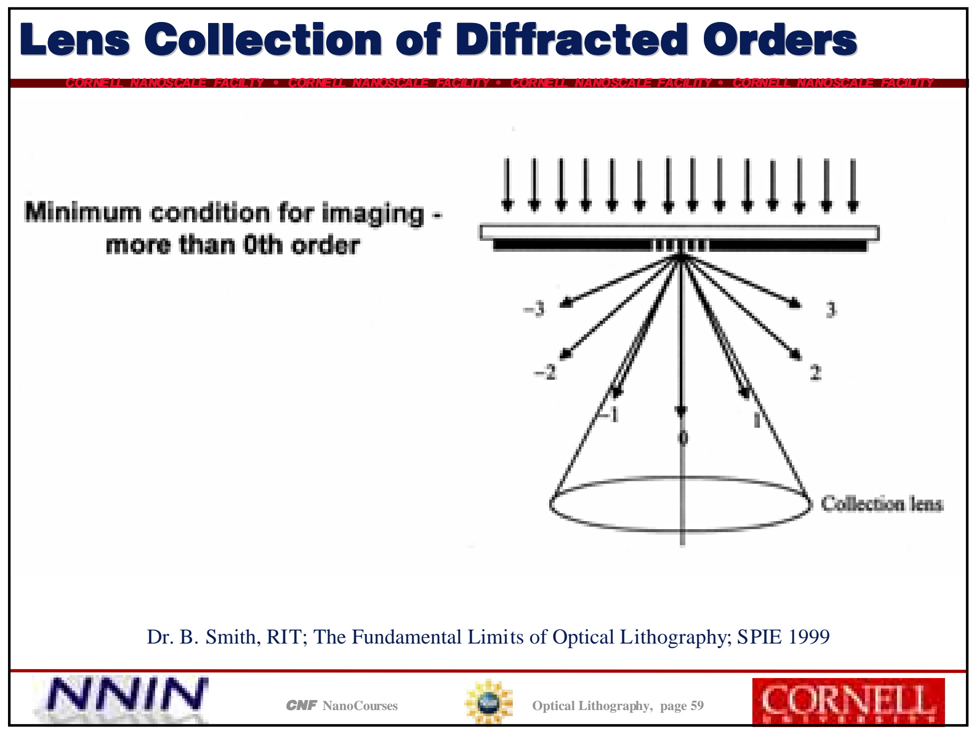
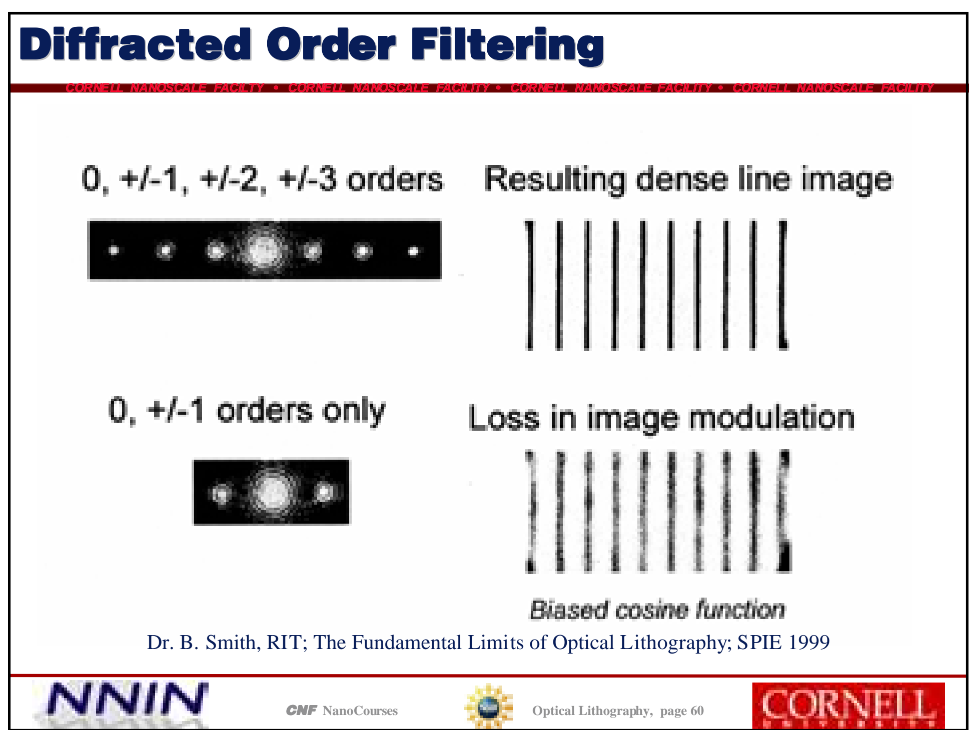
Optical Lithography, page 55
CORNELL

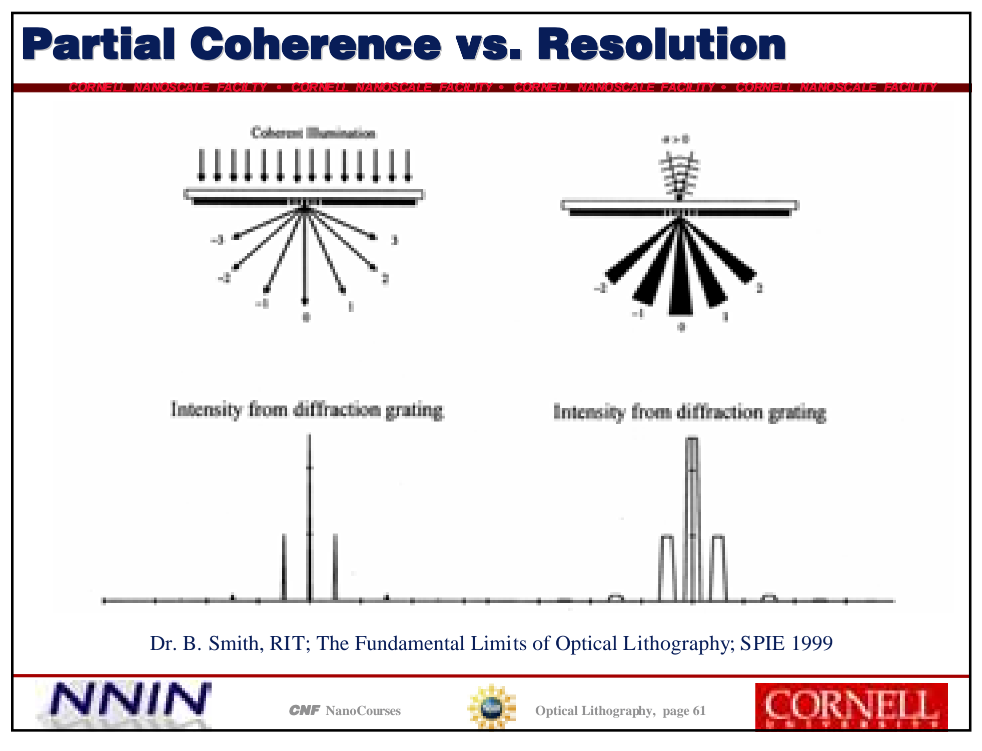

Stepper Diffraction
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
$\sin\theta = N\lambda / d$
S_1
d
d
d
O
P
COLLIMATING LENS
GRATING
SCREEN
NNIN
CNF NanoCourses
Optical Lithography, page 56
CORNELL

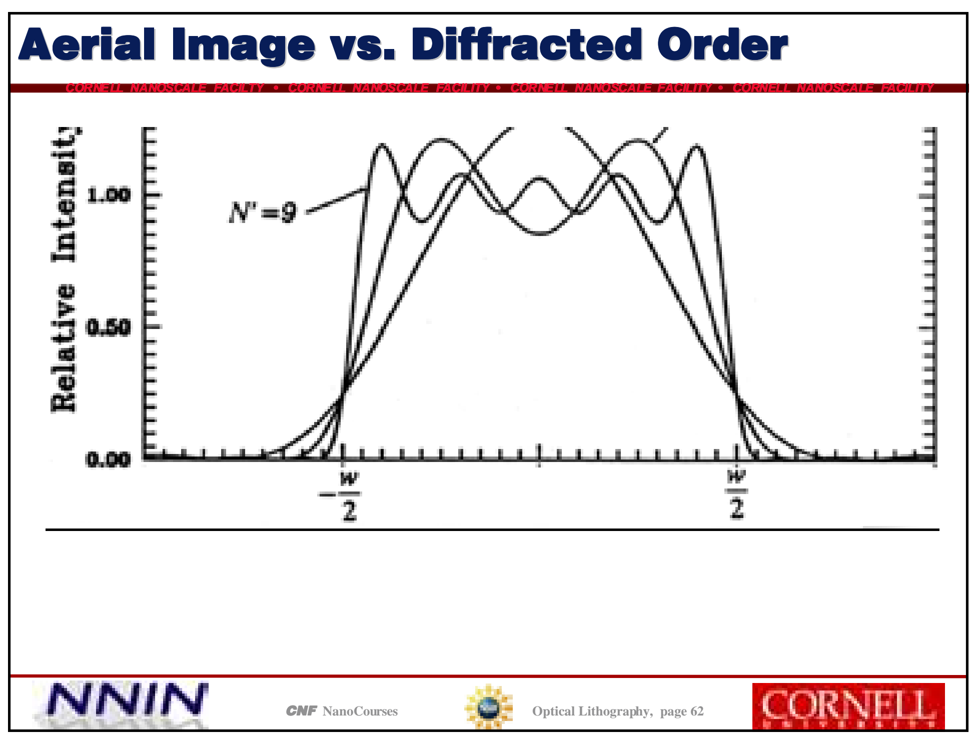

Diffraction in a Grating
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
DIFFRACTED ORDERS
α_c
α_o
SOURCE
PUPIL
CONDENSER LENS
MASK
PUPIL (APERTURE)
OBJECTIVE PROJECTION LENS
WAFER
IMAGE PLANE
NNIN
CNF NanoCourses
Optical Lithography, page 57
CORNELL UNIVERSITY


Diffracted Order Spread
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
b
θ
SLIT
SCREEN
PLANE LIGHT WAVES
(I)
b = 5λ
-30° -10° 0 10° 30°
θ
(I)
b = 2λ
-30° -10° 0 10° 30°
θ
NNIN
CNF NanoCourses
Optical Lithography, page 58
CORNELL UNIVERSITY


Lens Collection of Diffracted Orders
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Minimum condition for imaging - more than 0th order
−3
−2
−1
0
1
2
3
Collection lens
Dr. B. Smith, RIT; The Fundamental Limits of Optical Lithography; SPIE 1999
NNIN
CNF NanoCourses
Optical Lithography, page 59
CORNELL


Diffracted Order Filtering
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
0, +/-1, +/-2, +/-3 orders
Resulting dense line image
0, +/-1 orders only
Loss in image modulation
Biased cosine function
Dr. B. Smith, RIT; The Fundamental Limits of Optical Lithography; SPIE 1999
NNIN
CNF NanoCourses
Optical Lithography, page 60
CORNELL


Partial Coherence vs. Resolution
Coherent Illumination
Intensity from diffraction grating
Intensity from diffraction grating
Dr. B. Smith, RIT; The Fundamental Limits of Optical Lithography; SPIE 1999
NNIN
CNF NanoCourses
Optical Lithography, page 61
CORNELL

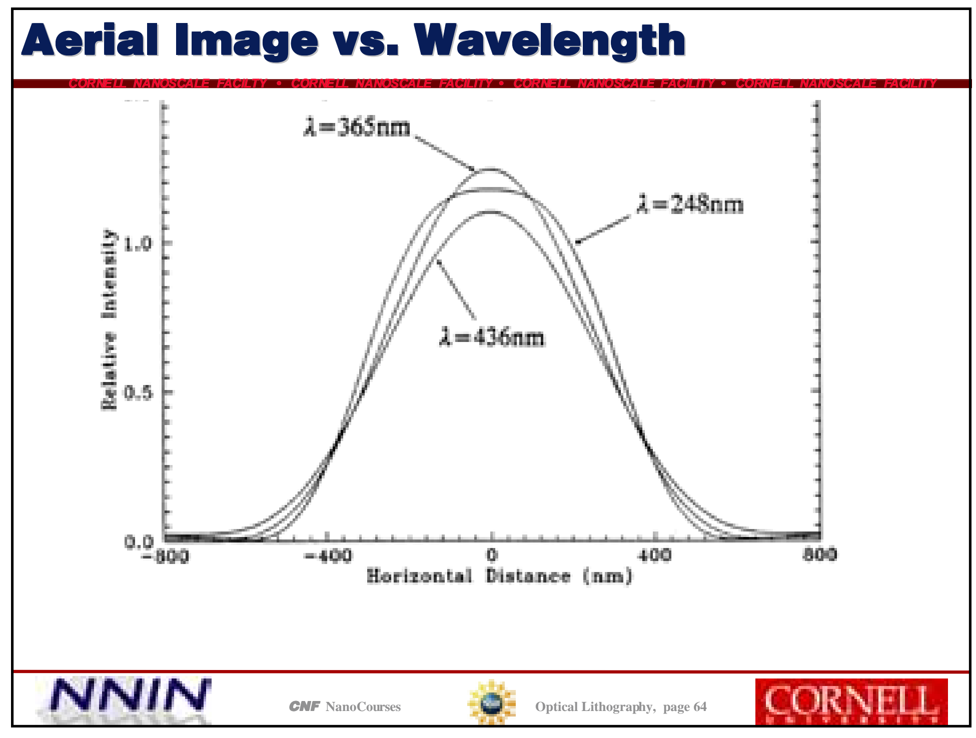

Aerial Image vs. Diffracted Order
Relative Intensit
1.00
0.50
0.00
N' =9
−w/2
w/2
NNIN
CNF NanoCourses
Optical Lithography, page 62
CORNELL

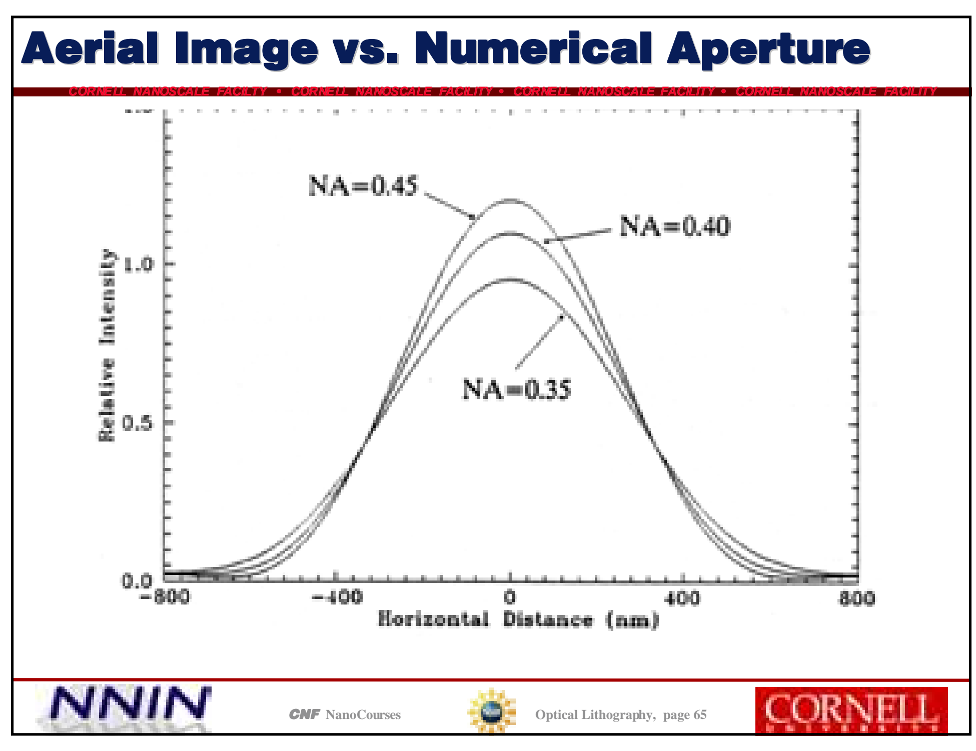
Optical Lithography Limits

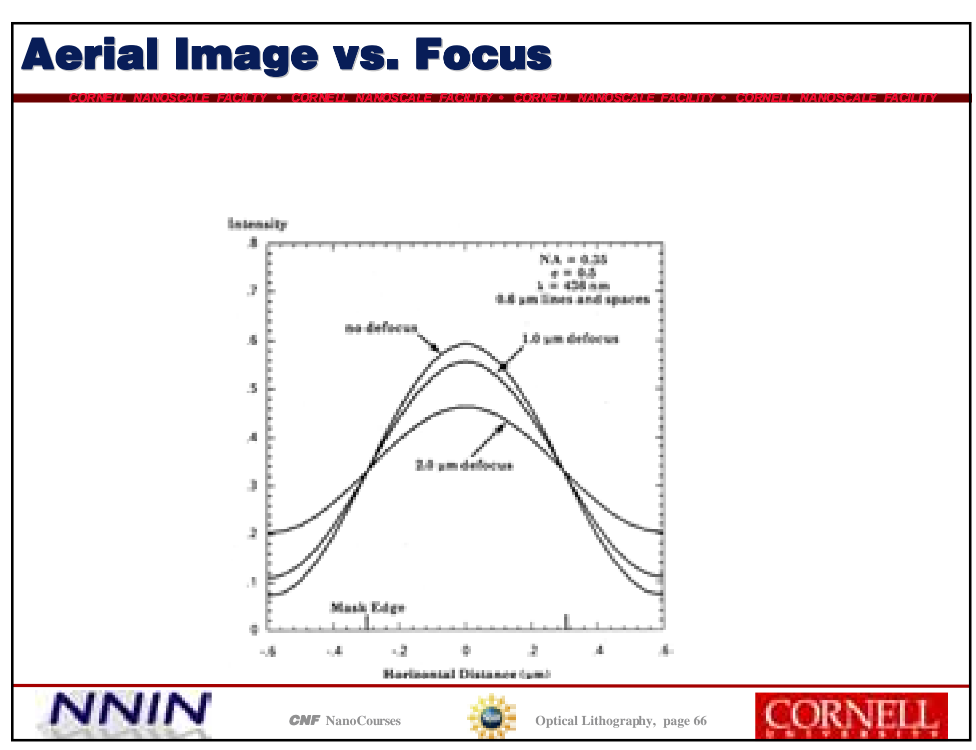
- Minimum Feature Size
  - $d_{min} = k\lambda / NA$
- Depth of Focus
  - $D = k\lambda / 2\,(NA)^2$

Aerial Image vs. Wavelength

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY




Aerial Image vs. Numerical Aperture
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
NA=0.45
NA=0.40
NA=0.35
Relative Intensity
1.0
0.5
0.0
−800
−400
0
400
800
Horizontal Distance (nm)
NNIN
CNF NanoCourses
Optical Lithography, page 65
CORNELL


Aerial Image vs. Focus
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Intensity
no defocus
1.0 µm defocus
2.0 µm defocus
Mask Edge
Horizontal Distance (µm)
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Optical Lithography, page 66
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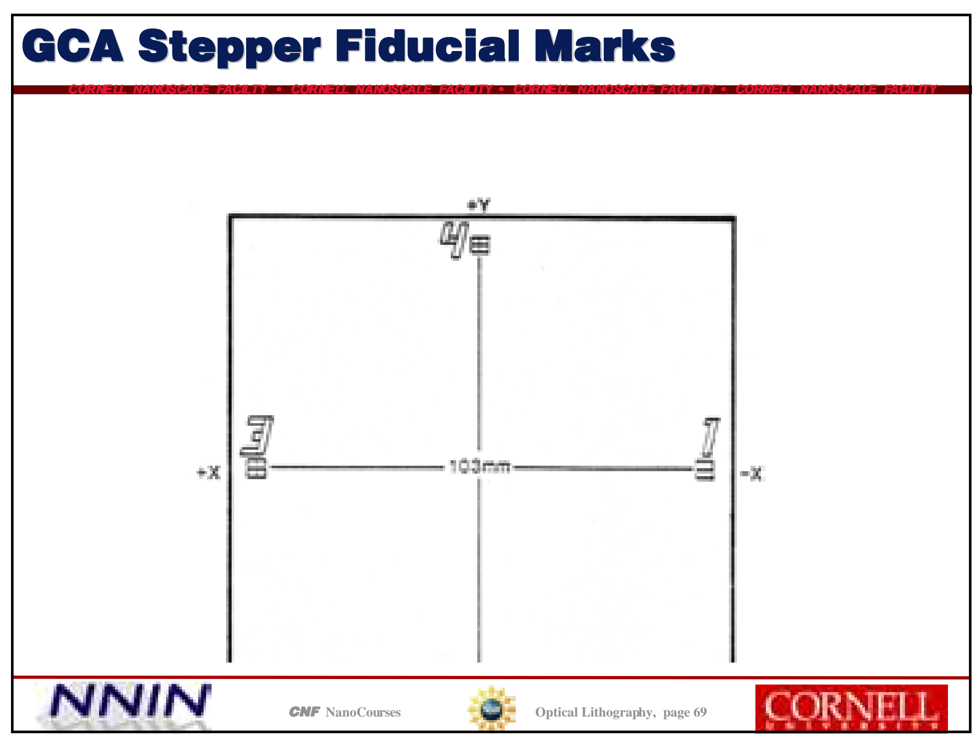
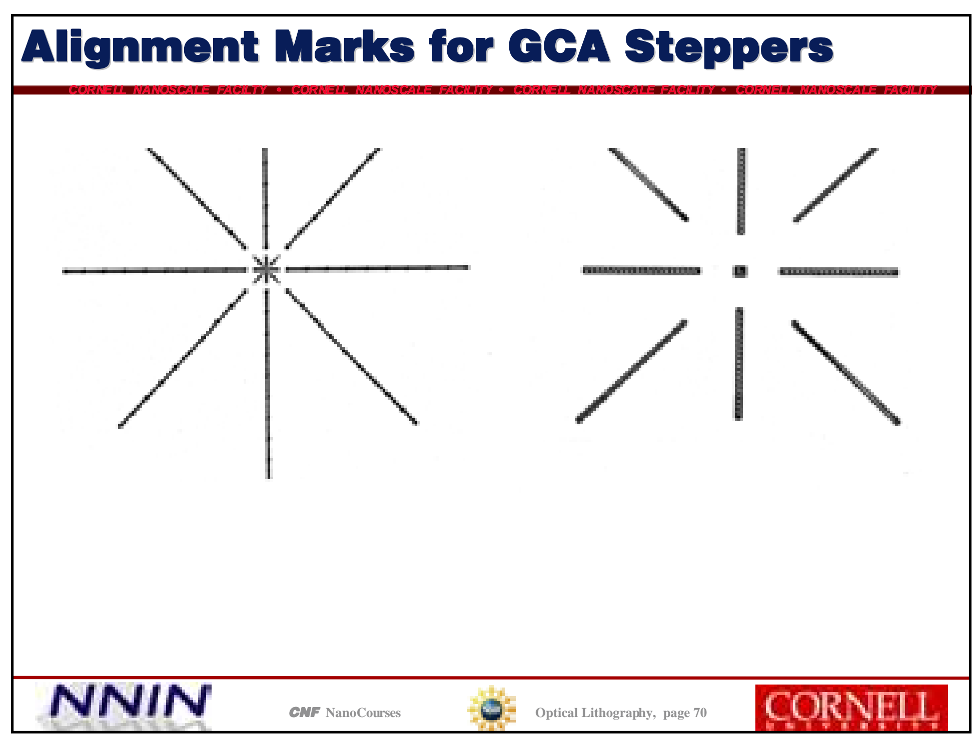
CNF Stepper Characteristics

cus			


GCA Stepper Fiducial Marks
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
+Y
4
3
1
+X
103mm
-X
NNIN
CNF NanoCourses
Optical Lithography, page 69
CORNELL


Alignment Marks for GCA Steppers
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
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CNF NanoCourses
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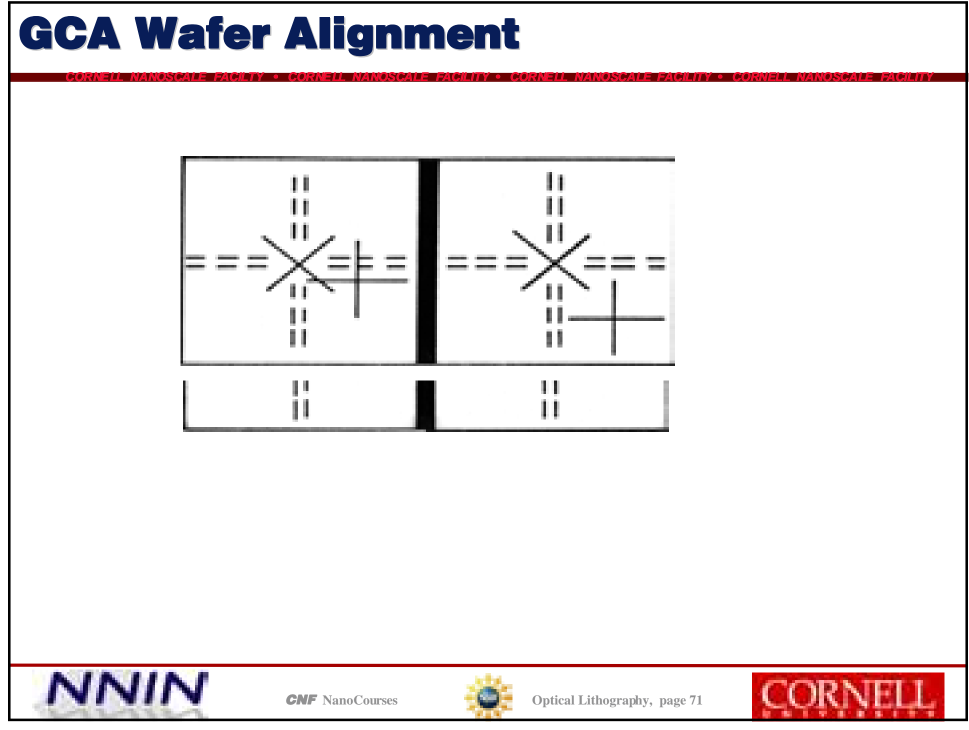
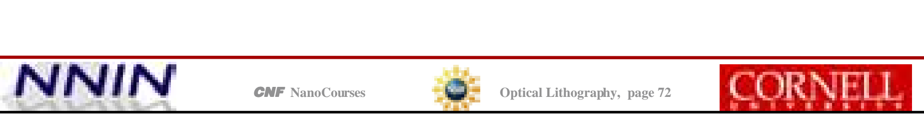
CORNELL



Projection Lithography Advantages

- Resolution comparable to the best contact lithography with no degradation of mask or resist.
- More tolerant of mask errors since mask image is reduced in size on the substrate. Almost all masks can be made on the PG.
- Step and repeat means many exposures per wafer, with the flexibility of computer control.
- Better alignment accuracy, typically ± 0.25 μm for the older GCA steppers.



Projection Lithography Disadvantages

- Focus requirement means that substrate thickness is limited, as well as wedge error (newer steppers have leveling).
- Field size is limited.
- More complicated to learn than contact lithography.

Lithography Considerations

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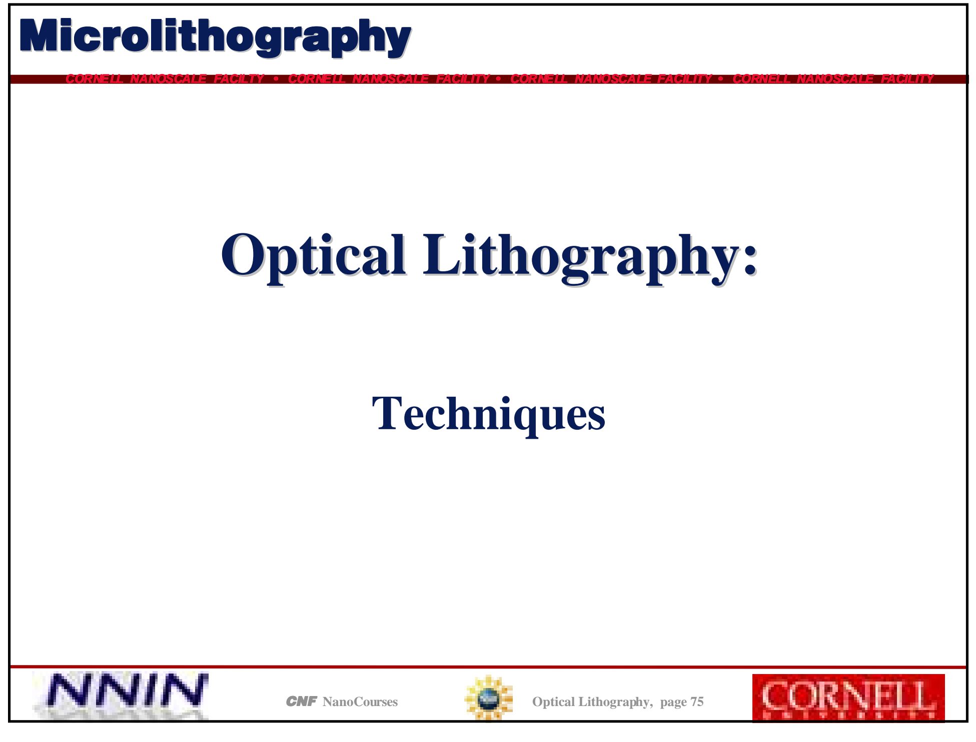
- Your pattern requirements:
  - Pattern size, feature size, alignment accuracy
- The requirements of the lithography tool:
  - Field size, mask size, mask type, alignment marks
- The requirements of the technique you will use for the pattern transfer:
  - Mask tone, resist type, resist thickness


Microlithography
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Optical Lithography:
Techniques
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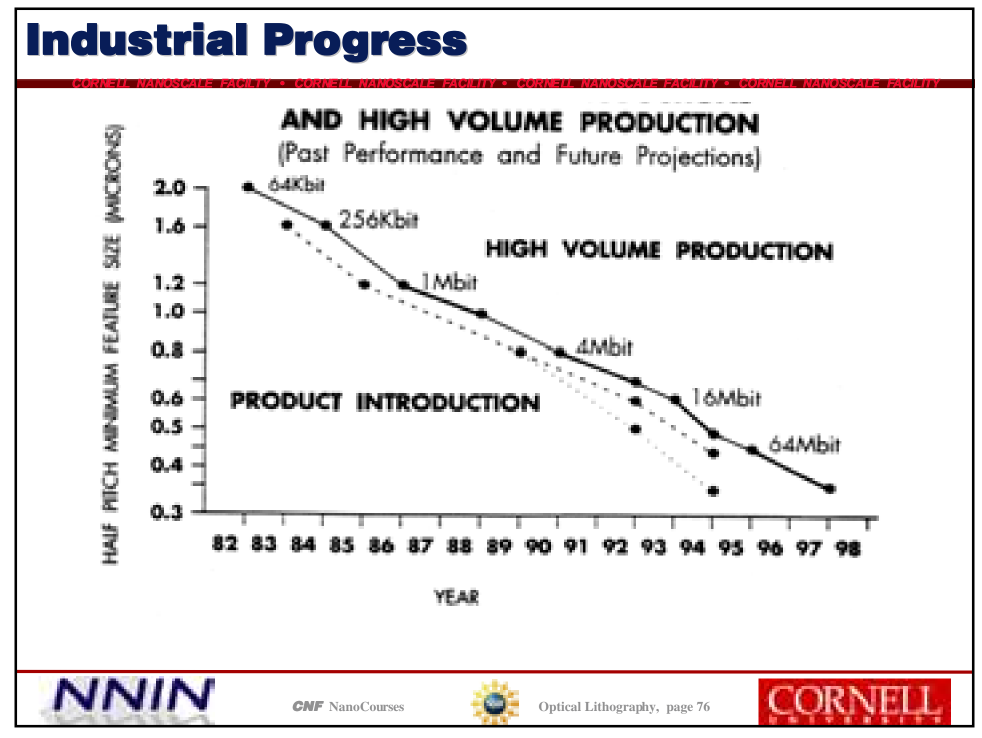
Optical Lithography, page 75
CORNELL


Industrial Progress
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
AND HIGH VOLUME PRODUCTION
(Past Performance and Future Projections)
HALF PITCH MINIMUM FEATURE SIZE (MICRONS)
2.0
1.6
1.2
1.0
0.8
0.6
0.5
0.4
0.3
64Kbit
256Kbit
1Mbit
4Mbit
16Mbit
64Mbit
HIGH VOLUME PRODUCTION
PRODUCT INTRODUCTION
82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98
YEAR
NNIN
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Optical Lithography, page 76
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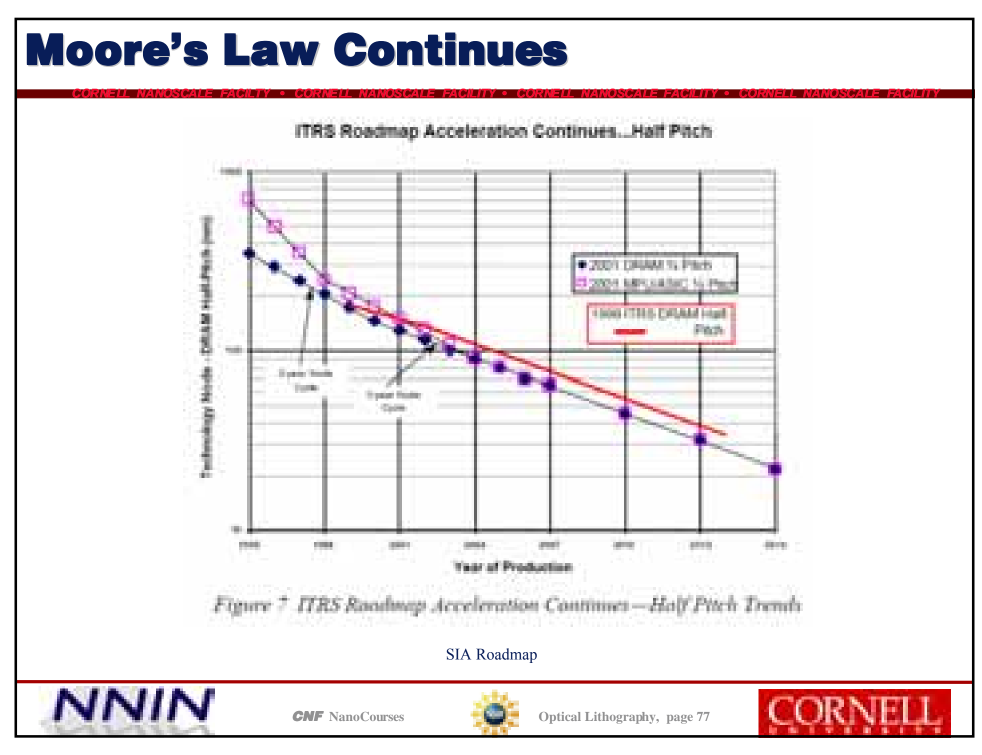
Moore's Law Continues
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
ITRS Roadmap Acceleration Continues...Half Pitch
Technology Node - DRAM Half-Pitch (nm)
Year of Production
2001 DRAM ½ Pitch
2001 MPU/ASIC ½ Pitch
1999 ITRS DRAM Half Pitch
Figure 7 ITRS Roadmap Acceleration Continues—Half Pitch Trends
SIA Roadmap
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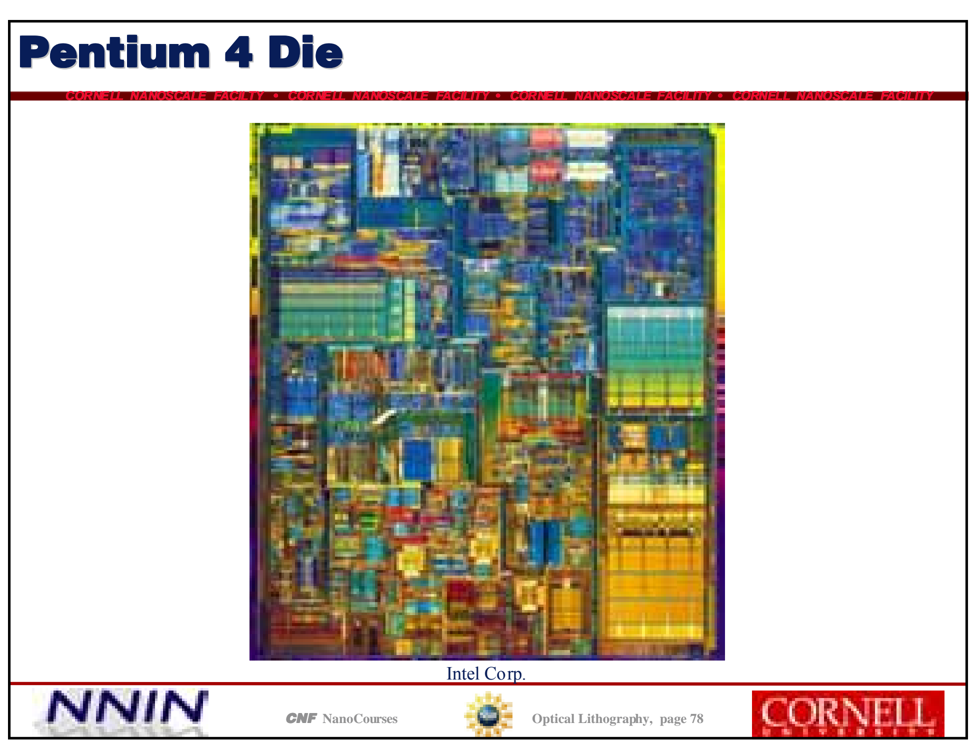
Pentium 4 Die
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Intel Corp.
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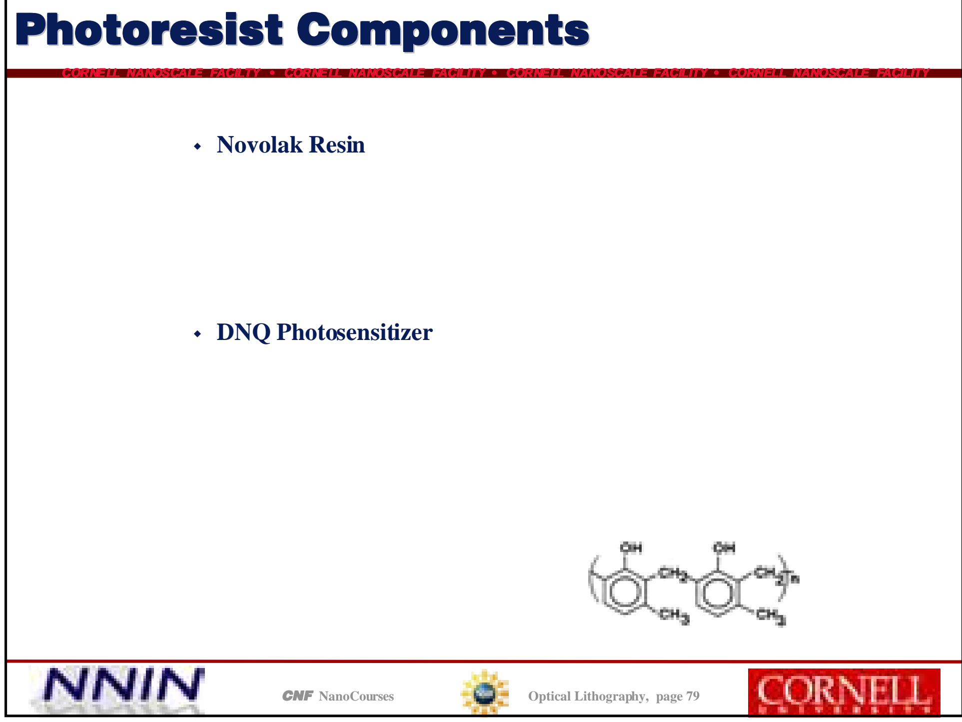
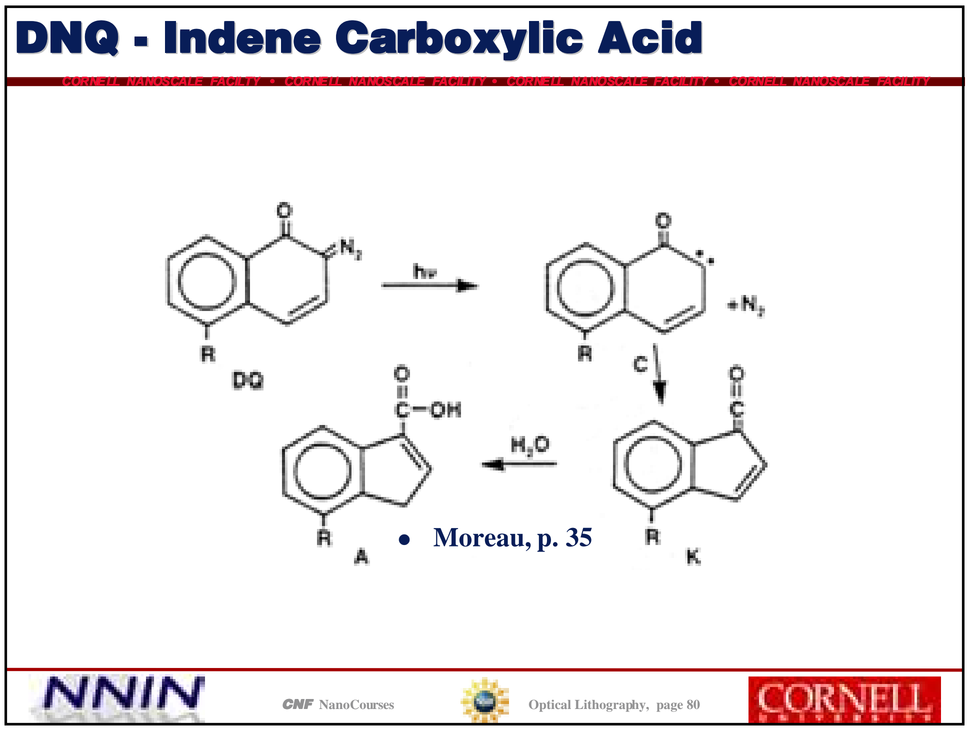

Photoresist Components
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Novolak Resin
• DNQ Photosensitizer
OH
OH
CH2
CH2
CH3
CH3
n
NNIN
CNF NanoCourses
Optical Lithography, page 79
CORNELL


DNQ - Indene Carboxylic Acid
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
O
N2
hν
O
+N2
R
DQ
R
C
C-OH
H2O
R
A
R
K
• Moreau, p. 35
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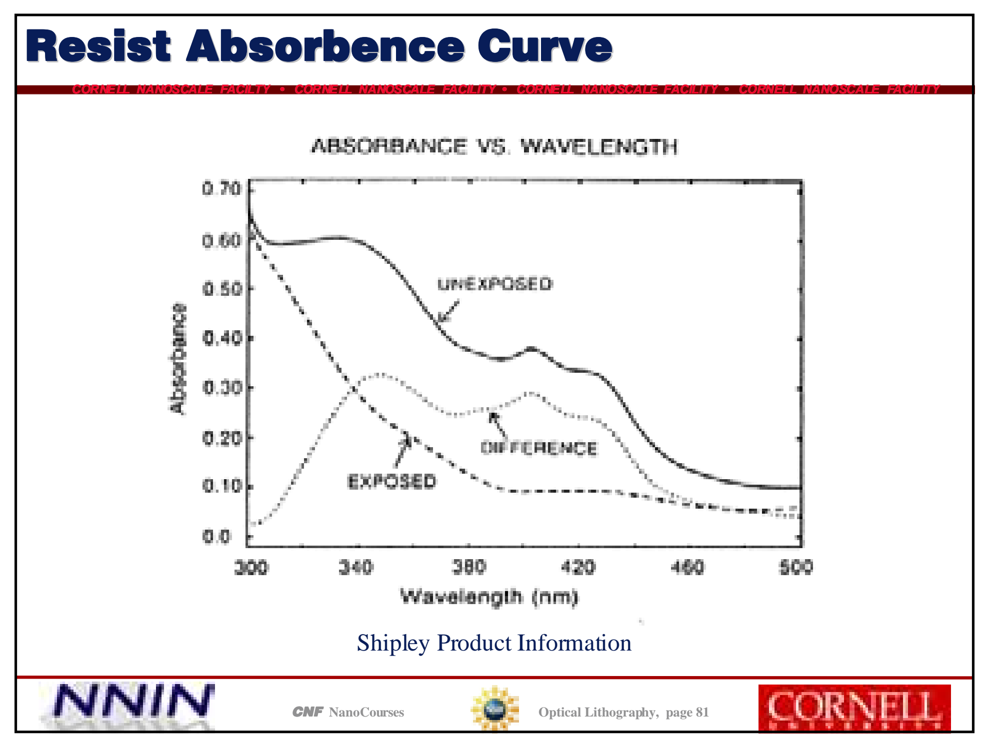
CORNELL


Resist Absorbence Curve
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
ABSORBANCE VS. WAVELENGTH
Absorbance
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.0
300
340
380
420
460
500
Wavelength (nm)
UNEXPOSED
DIFFERENCE
EXPOSED
Shipley Product Information
NNIN
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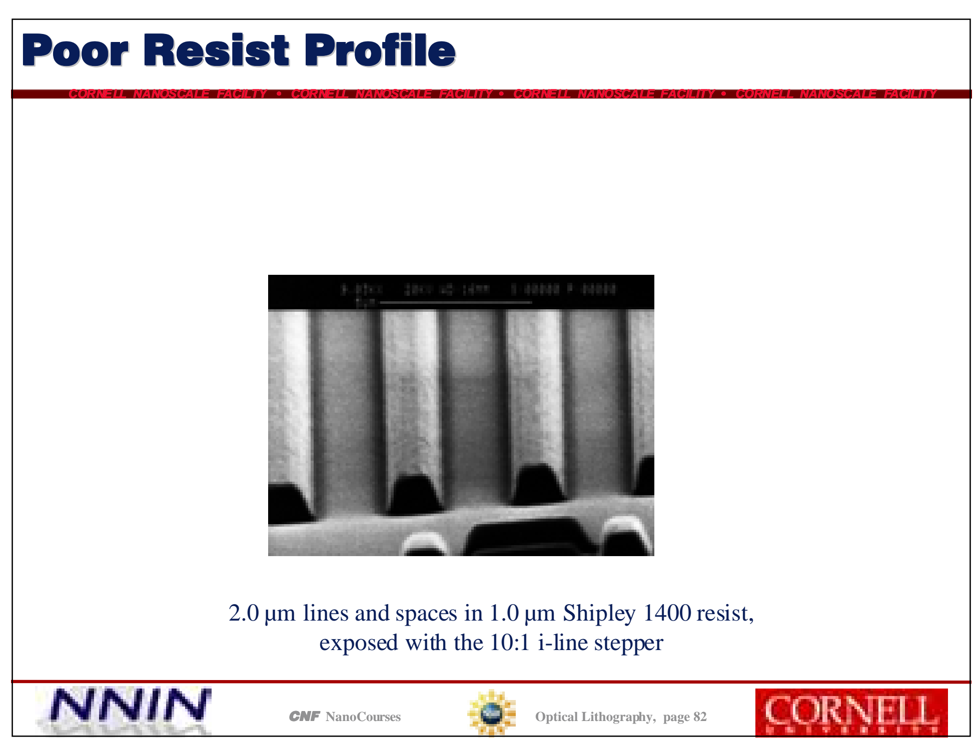
Optical Lithography, page 81
CORNELL


Poor Resist Profile
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
2.0 µm lines and spaces in 1.0 µm Shipley 1400 resist,
exposed with the 10:1 i-line stepper
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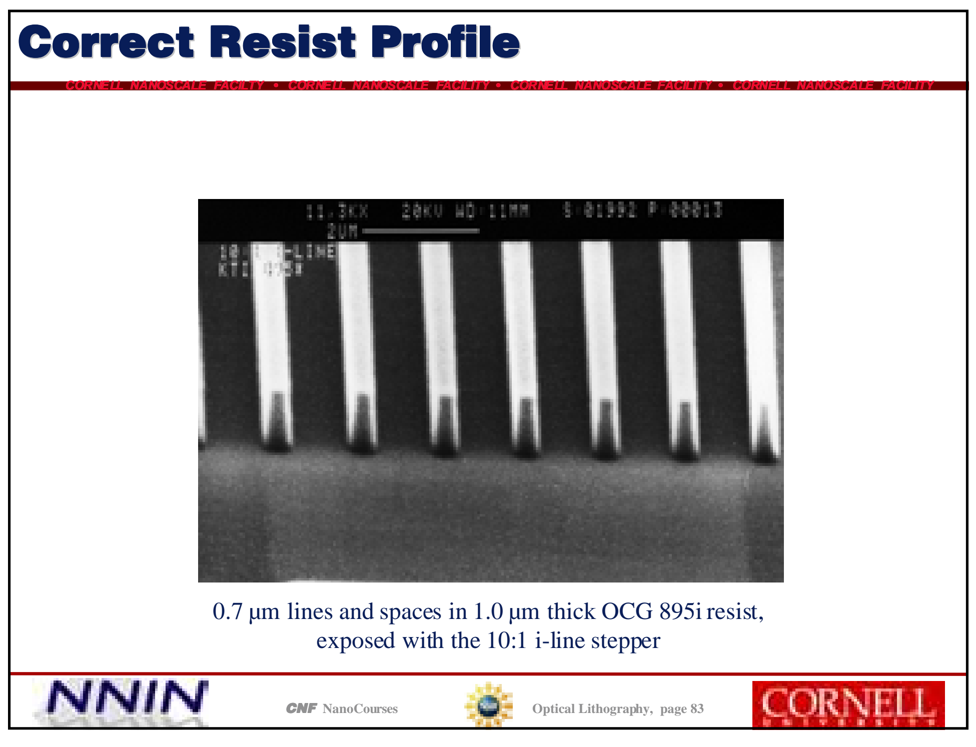
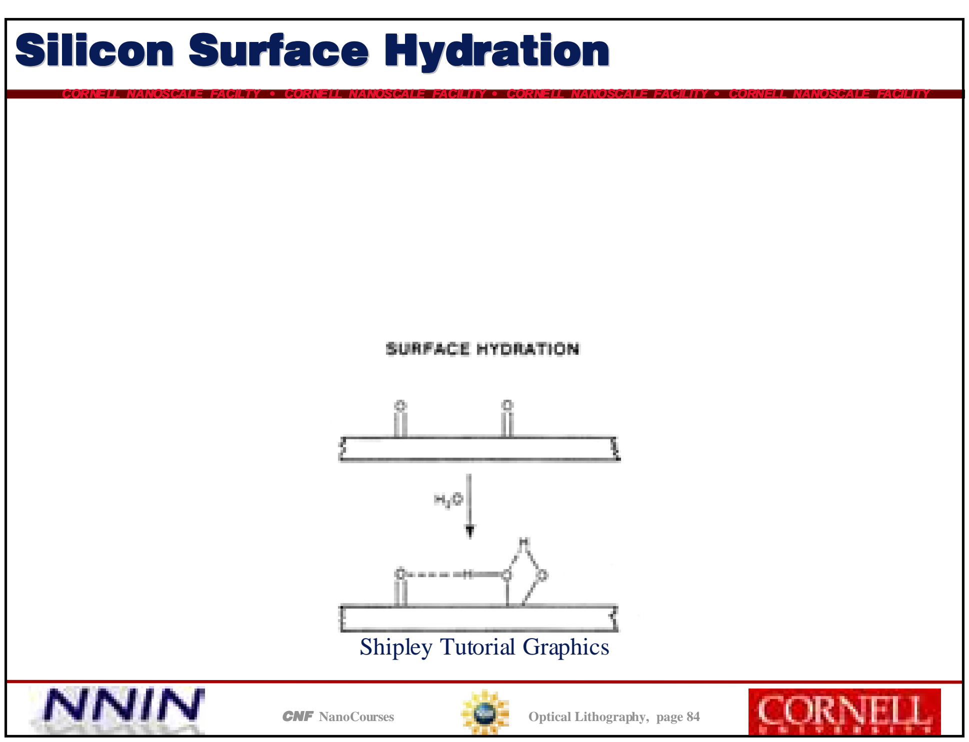
CNF NanoCourses
Optical Lithography, page 82
CORNELL


Correct Resist Profile
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
0.7 µm lines and spaces in 1.0 µm thick OCG 895i resist,
exposed with the 10:1 i-line stepper
NNIN
CNF NanoCourses
Optical Lithography, page 83
CORNELL


Silicon Surface Hydration
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
SURFACE HYDRATION
H2O
Shipley Tutorial Graphics
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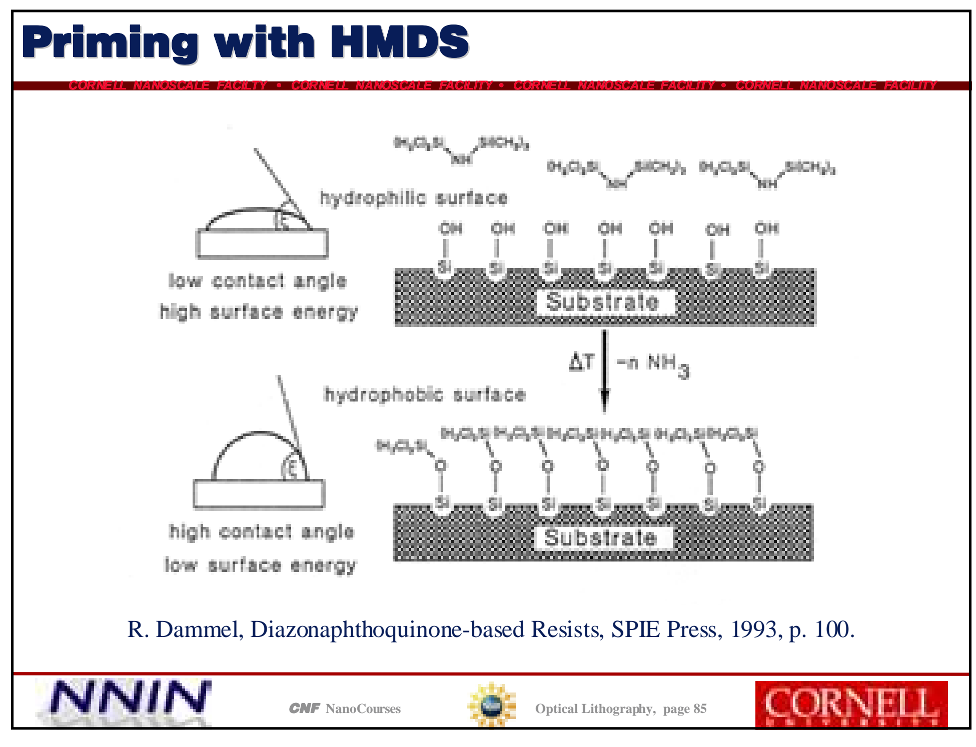
Optical Lithography, page 84
CORNELL


Priming with HMDS
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
hydrophilic surface
low contact angle
high surface energy
Substrate
ΔT
-n NH3
hydrophobic surface
high contact angle
low surface energy
Substrate
R. Dammel, Diazonaphthoquinone-based Resists, SPIE Press, 1993, p. 100.
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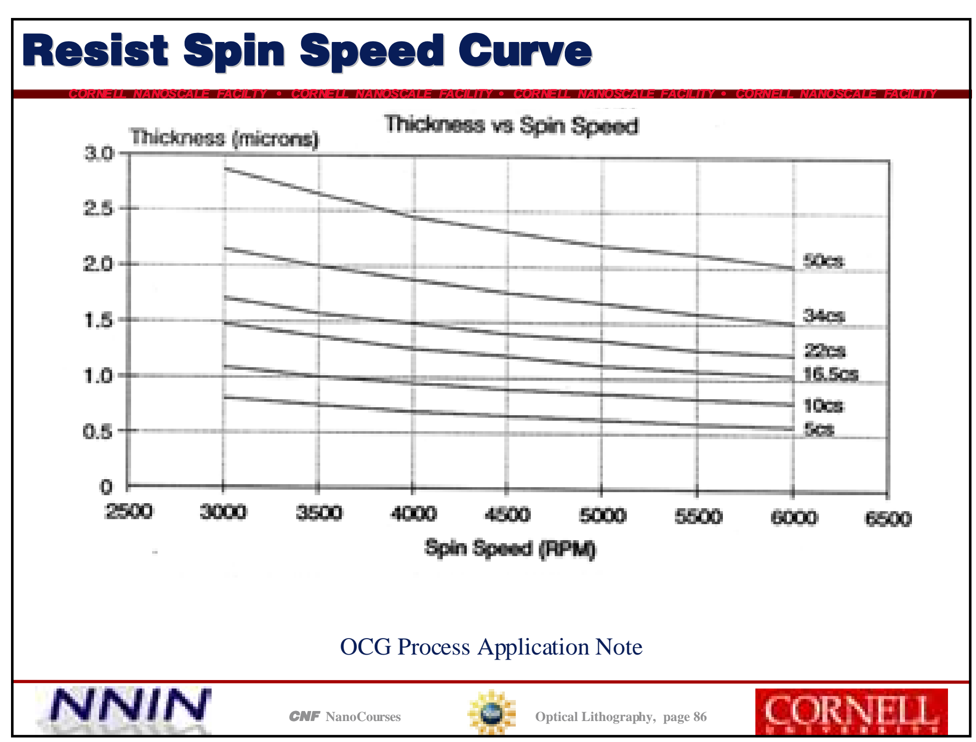
Optical Lithography, page 85
CORNELL


Resist Spin Speed Curve
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Thickness (microns)
Thickness vs Spin Speed
3.0
2.5
2.0
1.5
1.0
0.5
0
2500
3000
3500
4000
4500
5000
5500
6000
6500
Spin Speed (RPM)
50cs
34cs
22cs
16.5cs
10cs
5cs
OCG Process Application Note
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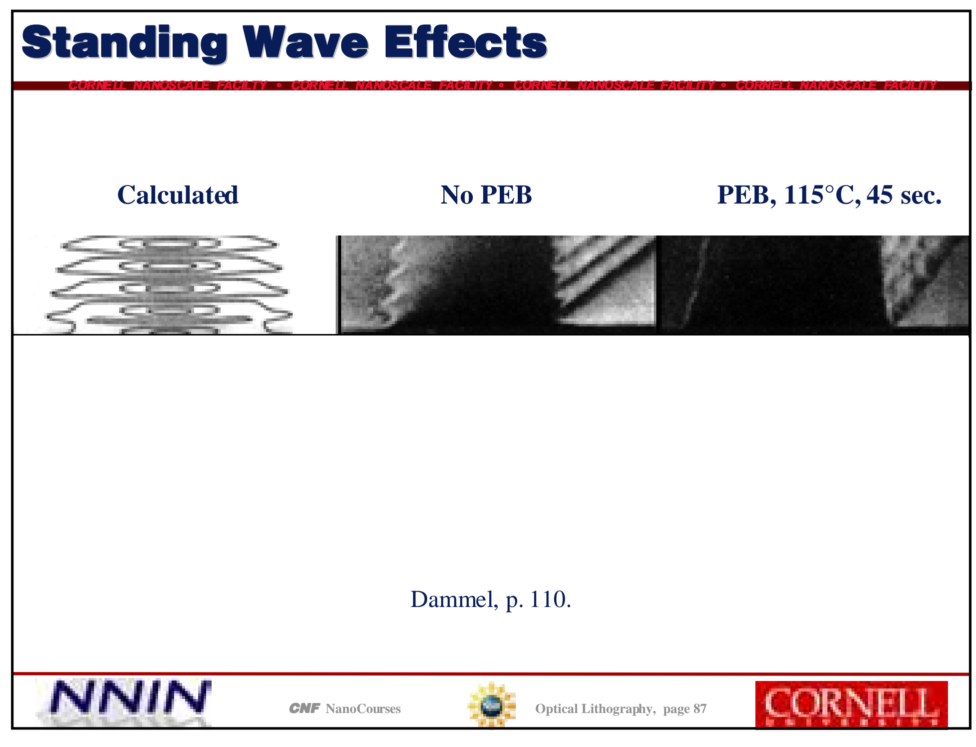
Optical Lithography, page 86
CORNELL


Standing Wave Effects
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Calculated
No PEB
PEB, 115°C, 45 sec.
Dammel, p. 110.
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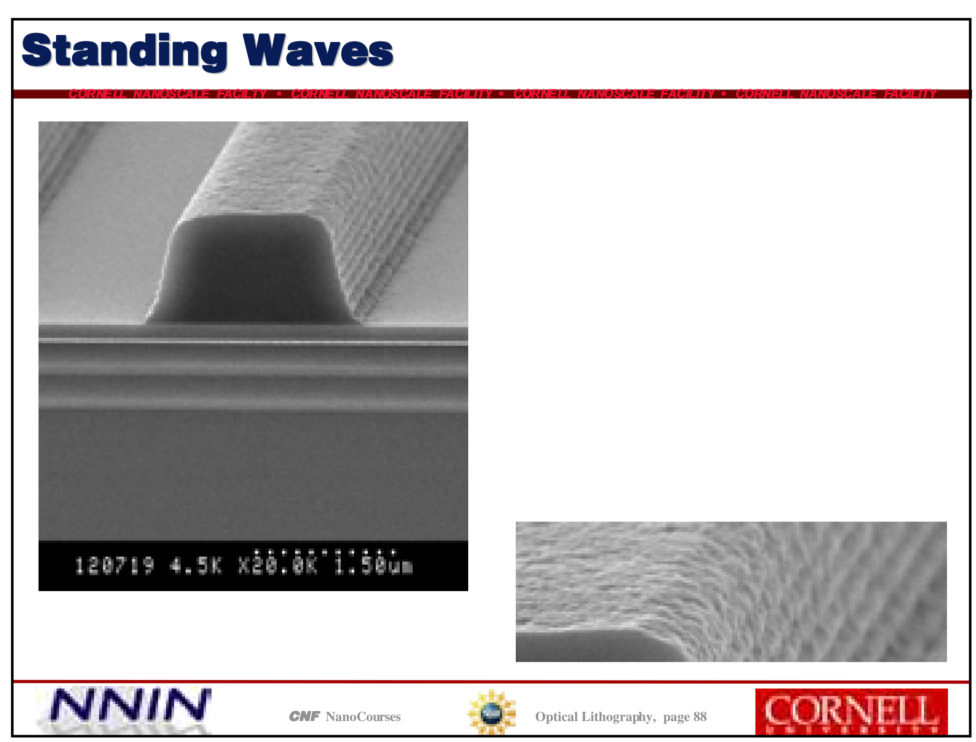
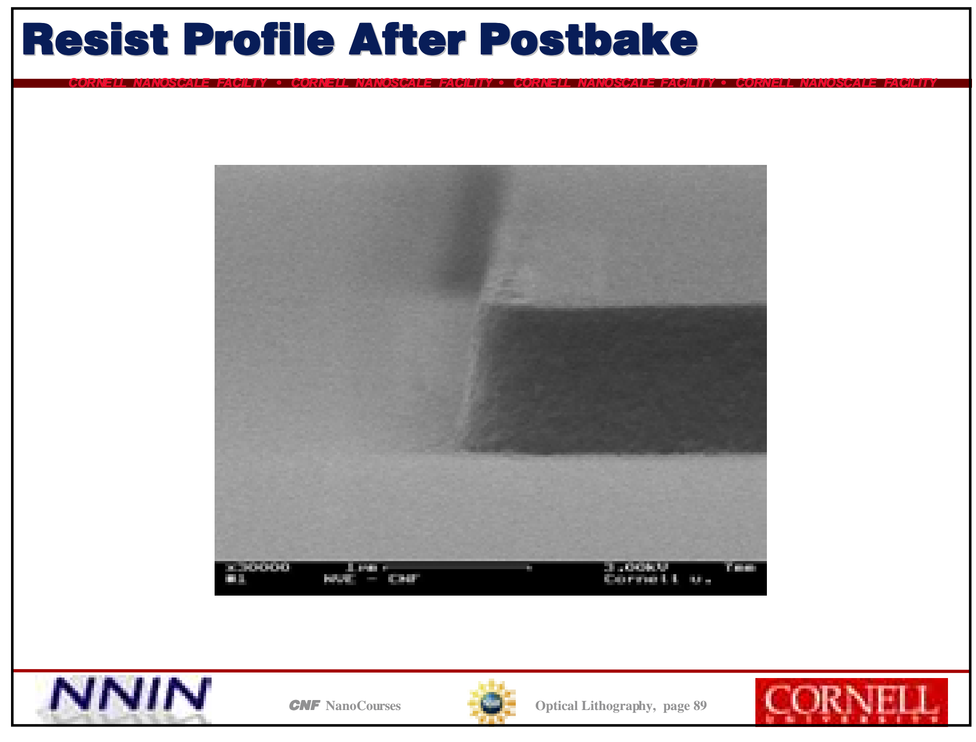
CNF NanoCourses
Optical Lithography, page 87
CORNELL


Standing Waves
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
120719 4.5K X20.0K 1.50um
NNIN
CNF NanoCourses
Optical Lithography, page 88
CORNELL


Resist Profile After Postbake
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
NNIN
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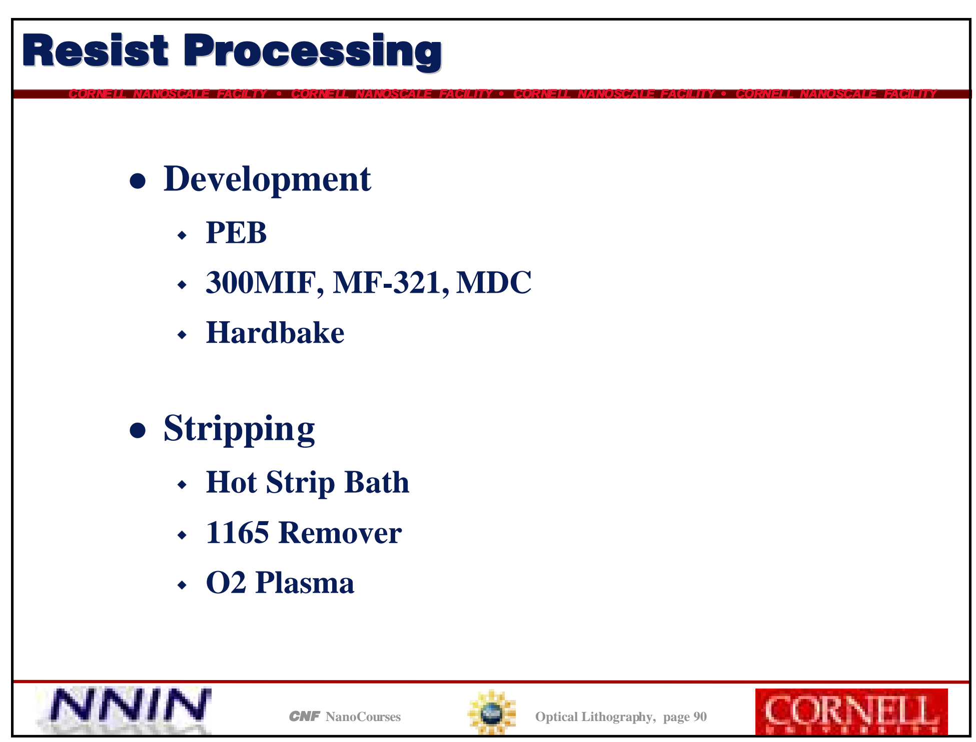
Optical Lithography, page 89
CORNELL


Resist Processing
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Development
PEB
300MIF, MF-321, MDC
Hardbake
Stripping
Hot Strip Bath
1165 Remover
O2 Plasma
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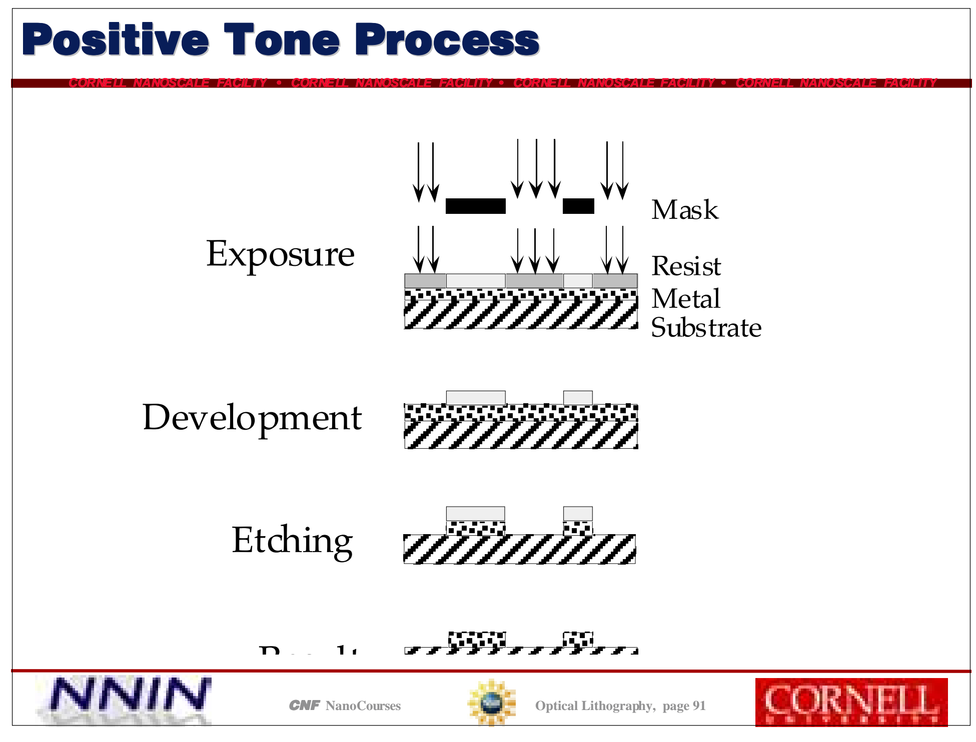
Optical Lithography, page 90
CORNELL


Positive Tone Process
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Mask
Exposure
Resist
Metal
Substrate
Development
Etching
NNIN
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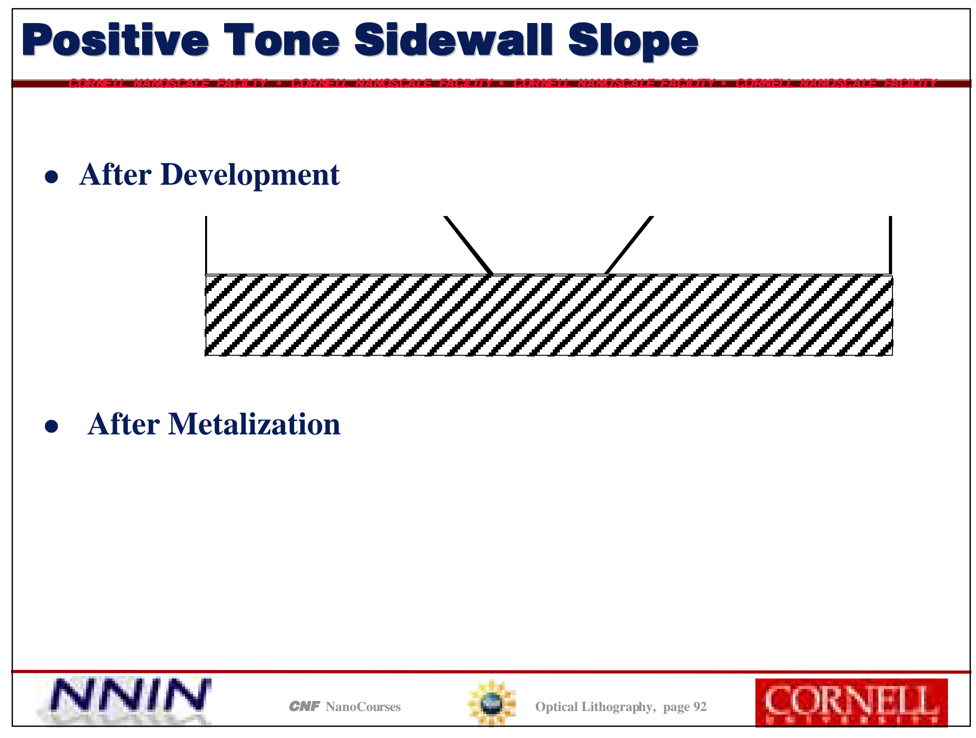
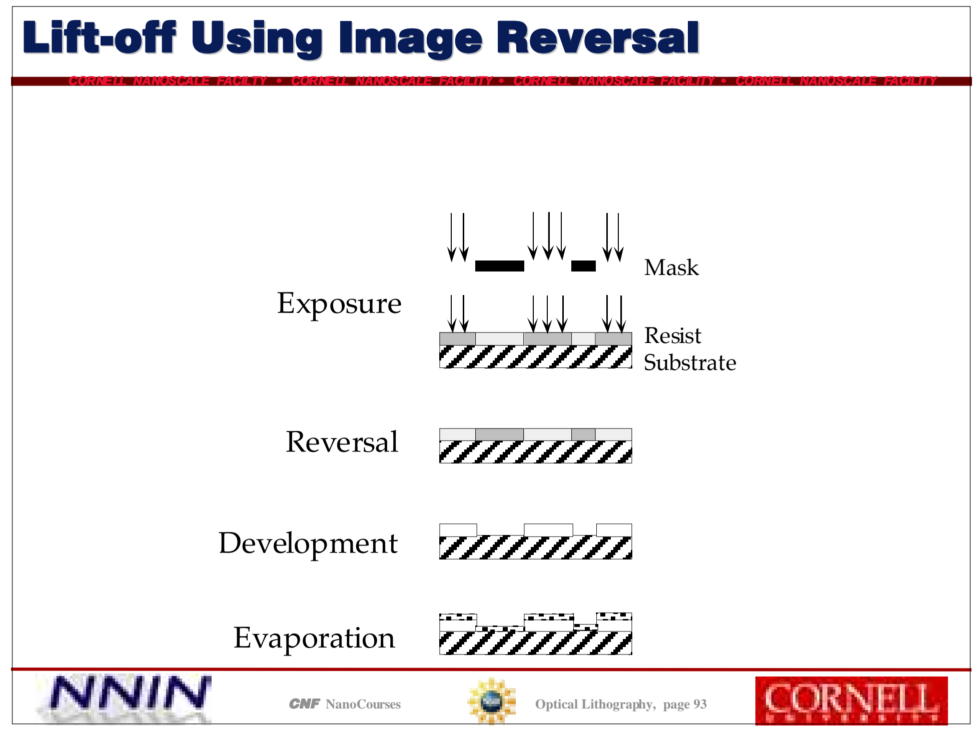
Optical Lithography, page 91
CORNELL


Positive Tone Sidewall Slope
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• After Development
• After Metalization
NNIN
CNF NanoCourses
Optical Lithography, page 92
CORNELL


Lift-off Using Image Reversal
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Mask
Exposure
Resist
Substrate
Reversal
Development
Evaporation
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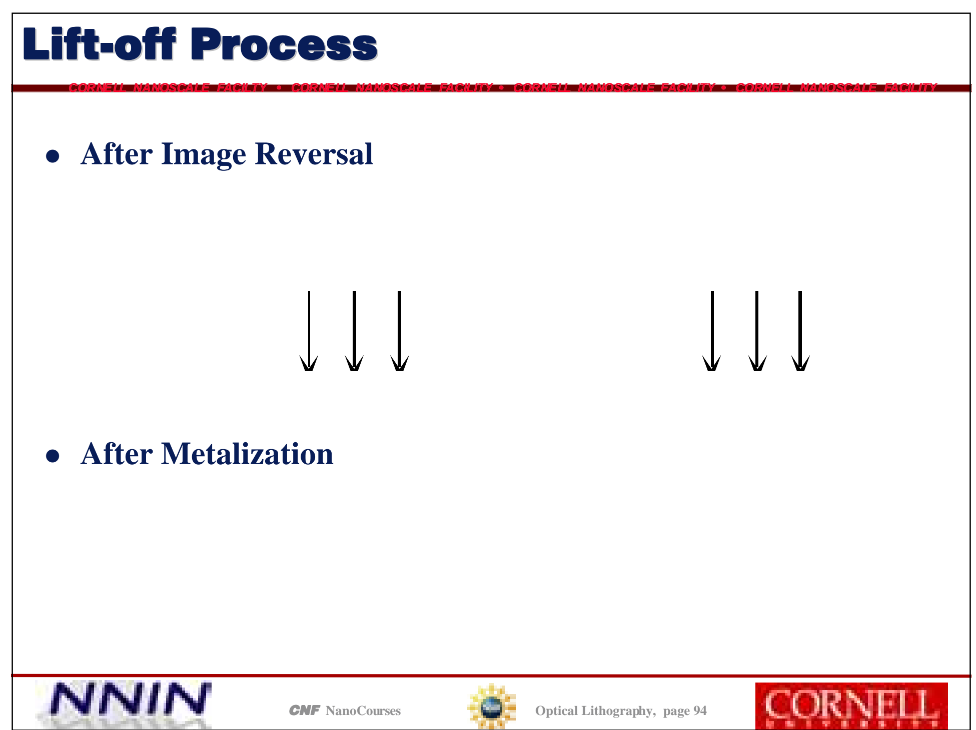
CORNELL


Lift-off Process
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• After Image Reversal
• After Metalization
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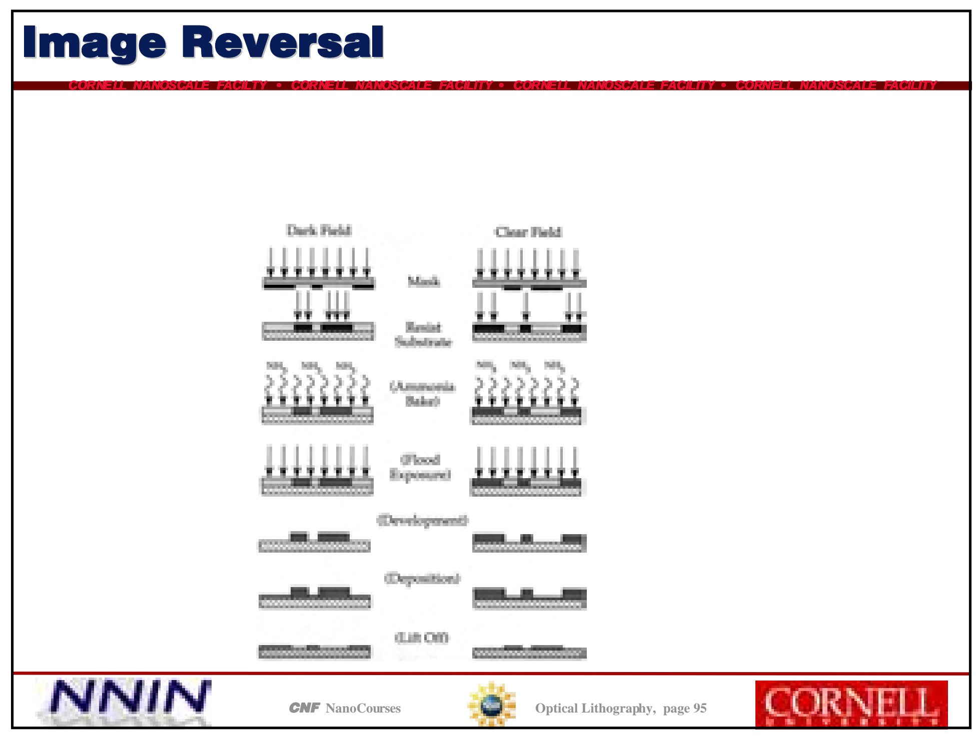
Image Reversal
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Dark Field
Clear Field
Mask
Resist
Substrate
(Ammonia
Bake)
(Flood
Exposure)
(Development)
(Deposition)
(Lift Off)
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Image Reversed Resist Profile
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
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CNF NanoCourses
Optical Lithography, page 96
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Summary of Considerations

- Your pattern requirements:
  - Pattern size, feature size, alignment accuracy
- The requirements of the lithography tool:
  - Field size, mask size, mask type, alignment marks
- The requirements of the technique you will use for the pattern transfer:
  - Mask tone, resist type, resist thickness

8” Intel Wafer

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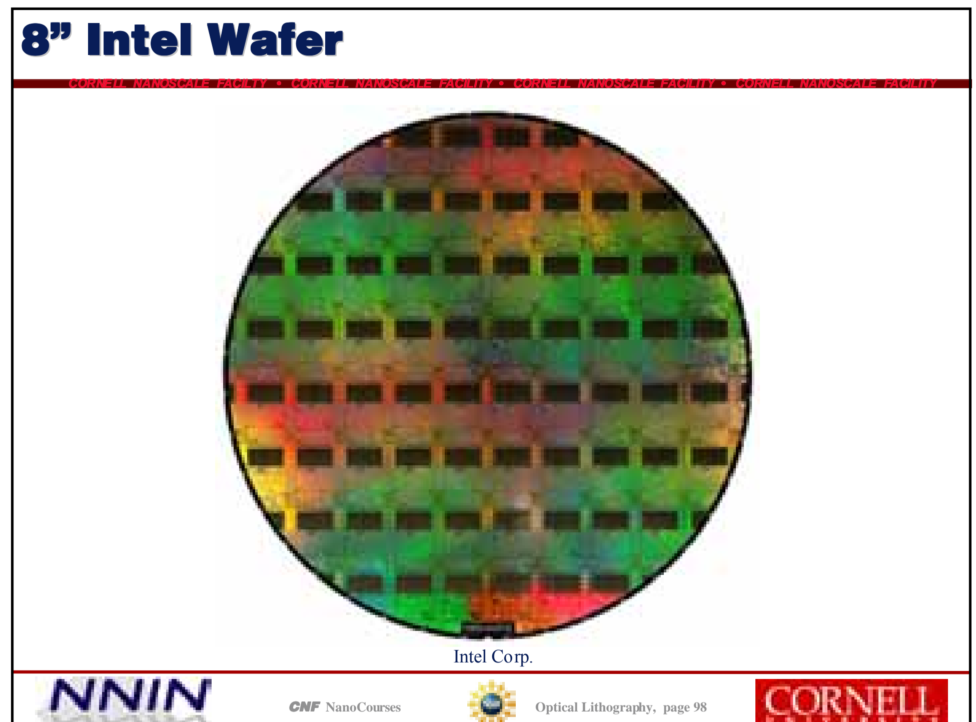
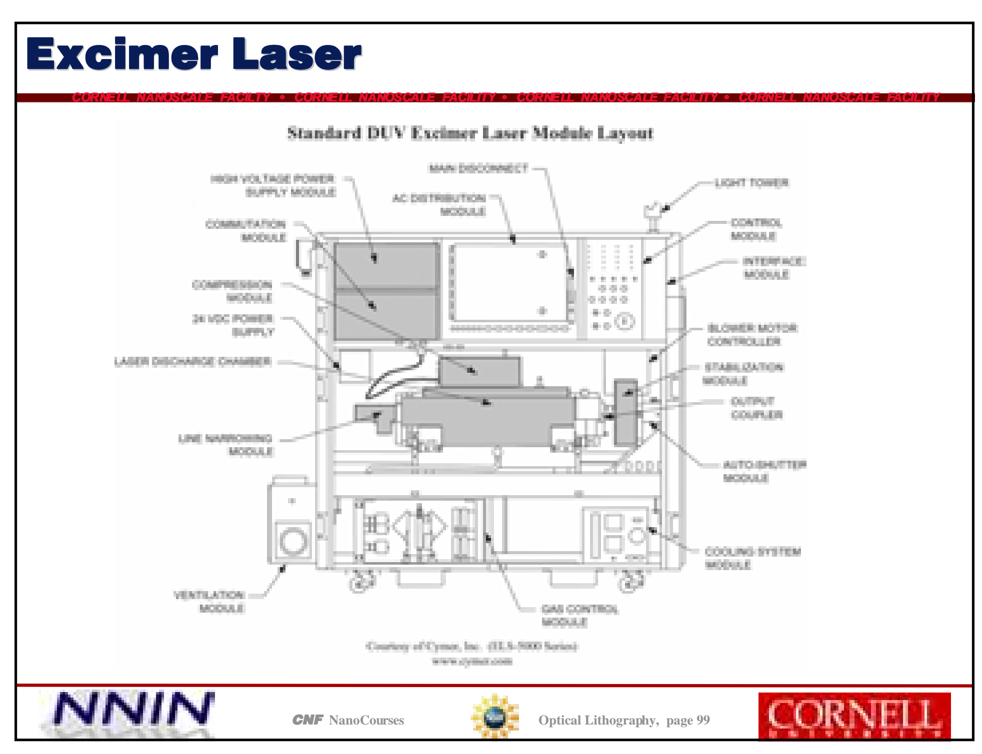


Intel Corp.


Excimer Laser
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Standard DUV Excimer Laser Module Layout
HIGH VOLTAGE POWER SUPPLY MODULE
MAIN DISCONNECT
AC DISTRIBUTION MODULE
LIGHT TOWER
COMMUTATION MODULE
CONTROL MODULE
INTERFACE MODULE
COMPRESSION MODULE
24 VDC POWER SUPPLY
BLOWER MOTOR CONTROLLER
LASER DISCHARGE CHAMBER
STABILIZATION MODULE
OUTPUT COUPLER
LINE NARROWING MODULE
AUTO-SHUTTER MODULE
COOLING SYSTEM MODULE
VENTILATION MODULE
GAS CONTROL MODULE
Courtesy of Cymer, Inc. (ELS-5000 Series)
www.cymer.com
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Optical Lithography, page 99
CORNELL UNIVERSITY

Practical Lithography:

The Art and Science of Microlithography

Computer-Aided Design (CAD)

by

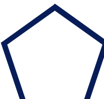
Karlis Musa

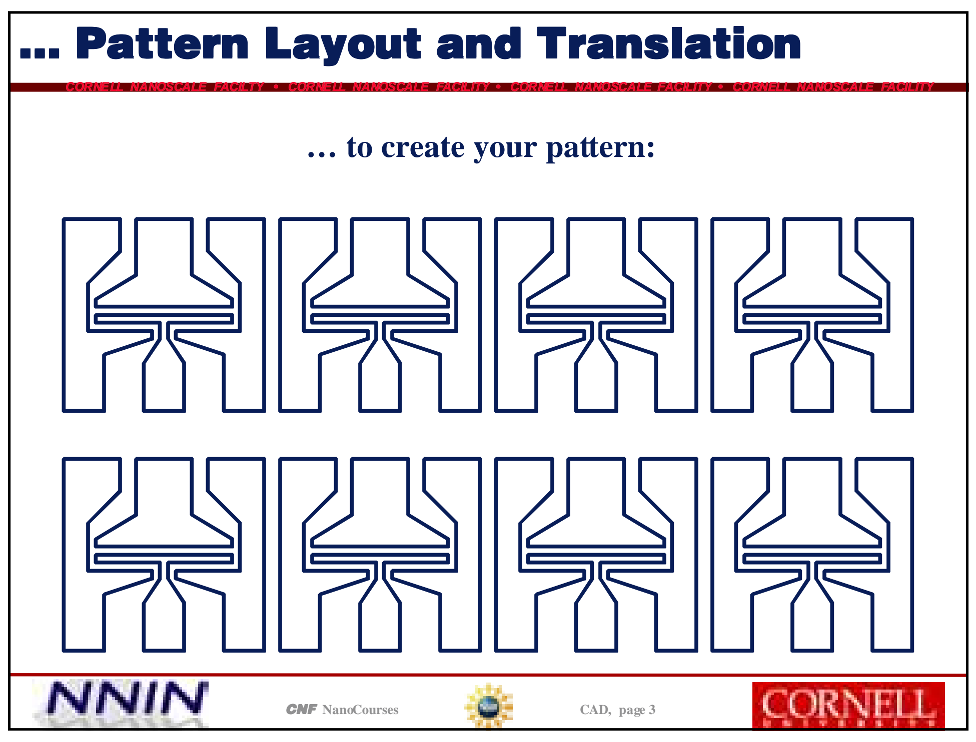
Presented by the
CNF Technical Staff
for the education of CNF Users,
Potential Users, and Industrial Sponsors

Pattern Layout and Translation ...

This part of the process is where you take what you think you want, and put it into a form that the instruments at the CNF will understand.

Typically, this starts with CAD, which uses lines, equations, polygons, algorithms, rectangles, etc…




… Pattern Layout and Translation
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
… to create your pattern:
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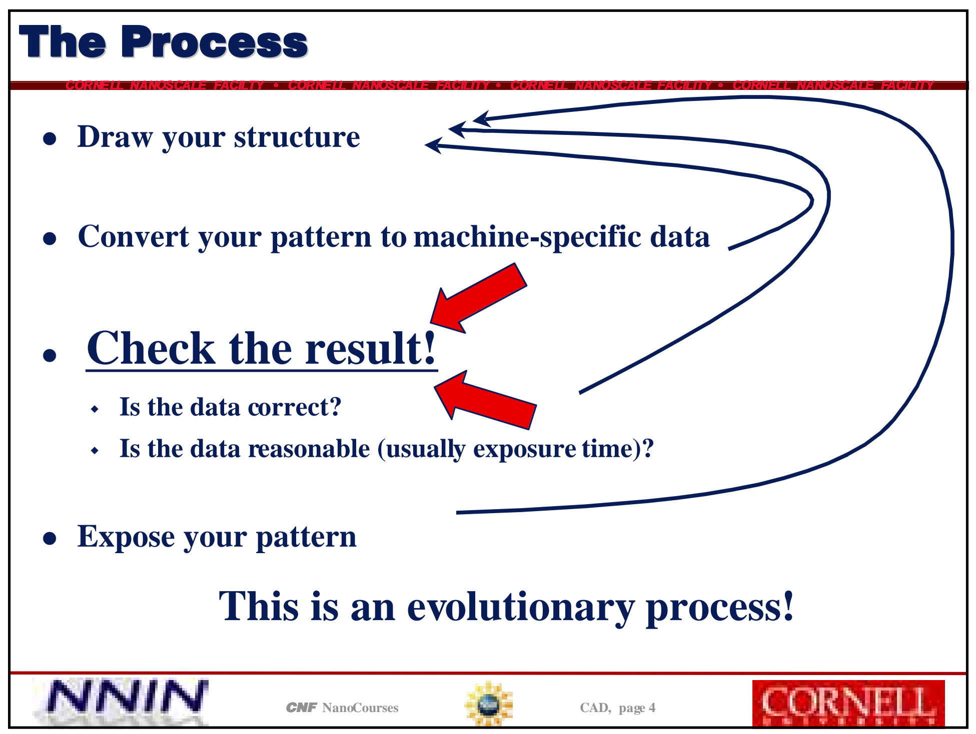
CAD, page 3
CORNELL


The Process
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Draw your structure
• Convert your pattern to machine-specific data
• Check the result!
Is the data correct?
Is the data reasonable (usually exposure time)?
• Expose your pattern
This is an evolutionary process!
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CAD, page 4
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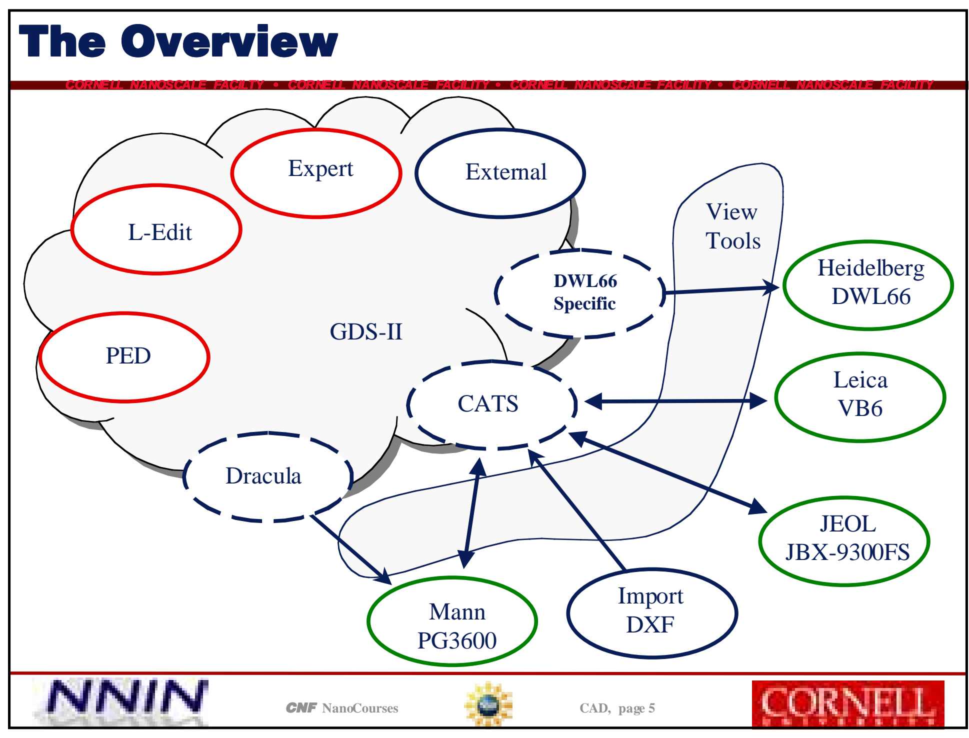

Some Terms

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- **GDS** – industry standard format for the exchange of layout data. (aka GDS-II, aka STREAM).
- **User Units** – what the user sees as the units used for their patterns. Usually in microns. (Not the lower limit of what you can use.)
- **Internal Units** – how **User Units** are defined internally**.** Usually expressed as 1000 Internal Units per User Unit (1 nanometer).
- **Datatype –** mechanism for a user to optionally associate data with a particular object. At the CNF, most commonly used to provide exposure hints for e-beam patterns.
- **CIF** – another exchange format.
- **DXF** – AutoCAD text exchange format. We can read DXF. AutoCAD can be used for nanofabrication patterns, but there are better solutions.

Some More Terms

- **Alignment Marks** – Special sets of shapes that are used to align subsequent processing steps.
  - First part would be included during an exposure.
  - The second part would be included in the next exposure, to match up with the mark already on the wafer.
  - For additional exposures, you may need additional marks.
- **Fracture** – related to the process where your shapes are broken into much smaller shapes that the tool can expose.
  - **Mann PG** – Overlapping, rotated rectangles (2 µm to 1500 µm, in _ µm steps).
  - **E-Beam** – Quadrilaterals, and single-pass lines. Generally, overlaps are removed. Overlapping figures can be used to fine-tune an exposure.

Circles, and other curved figures …

… are supported by some CAD tools, BUT

- **NOT by GDS, and**
- **NOT by the lithography tools.**

Instead, they will be approximated by regular polygons, or a series of line segments. You control the accuracy of the approximation.

A more accurate approximation will usually take more time, more space, and more money.

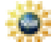
The question to ask is:

"What is good enough?"

Layers

Lithography is a 2-D exposure that, after additional processing, results in a 3-D structure. **Layers** are the mechanism in CAD used to identify these exposure steps.

- Usually, a layer in CAD will translate to a single exposure (or mask).
- In some cases, it is useful to use multiple layers for a single exposure.
- There may be other layers, for additional information, layout guides, or tone-reversal.
- Layer definitions apply to all of the cells in a layout or library. However, a cell will typically not use all of these layers**.**



Cell

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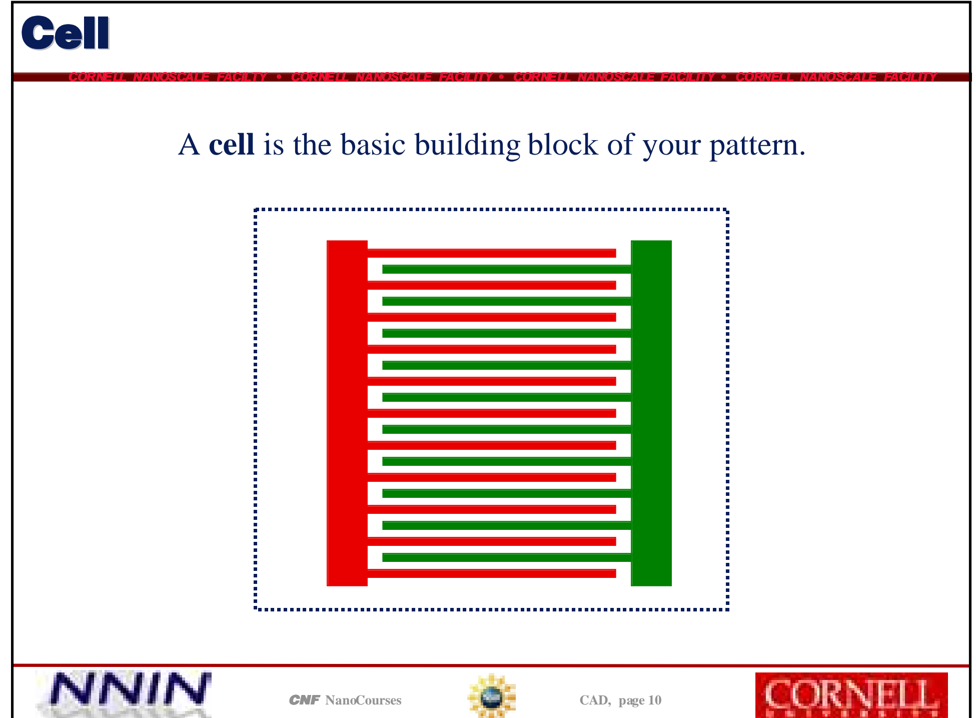
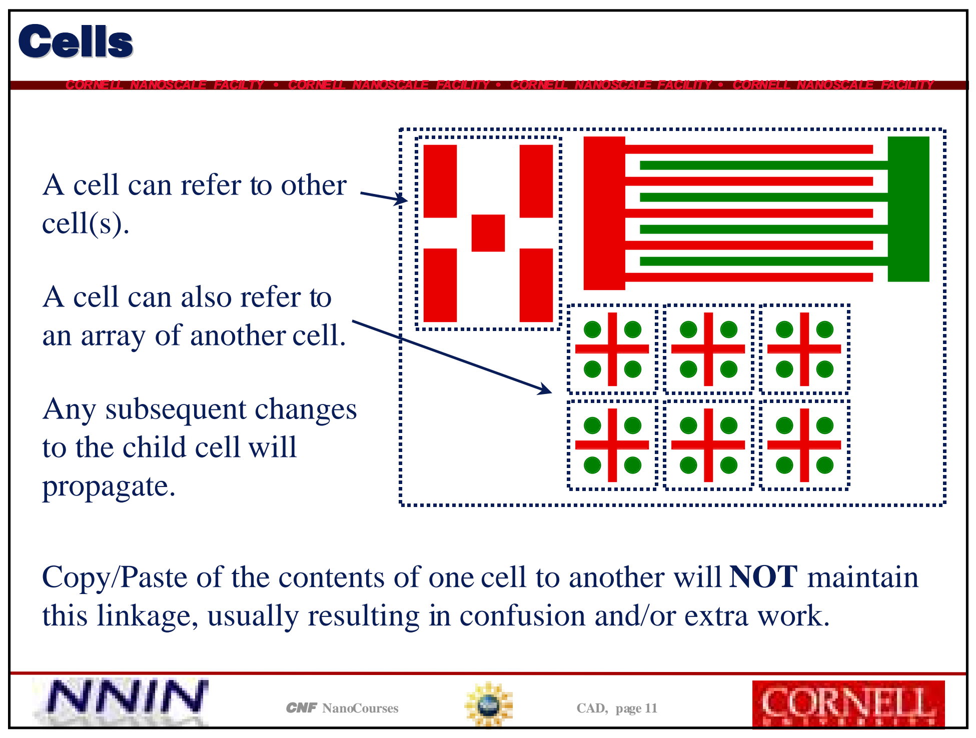
A **cell** is the basic building block of your pattern.





Layout / Library

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A **layout** (or **library**) is a collection of one or more cells, with one or more layers defined, plus some other information.

For very complex structures, one structure per layout.

At the CNF, people will often have multiple structures in a single layout, but this is a personal choice, and not a technical one.

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Where do I want to be?

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- Draw your structures actual size. The tool ultimately used to expose your pattern isn't significant at this time. This leaves your options open.
  - Any tool-specific scaling will be done during conversion.
  - The output of the conversion process is instrument-specific, the output of CAD is not.
  - Tone-reversal is usually done during conversion.

- **However,** some things **ARE** tool-specific…
  - Positional accuracy.
  - Alignment marks.
  - Performance characteristics.
  - …

I want to be where?

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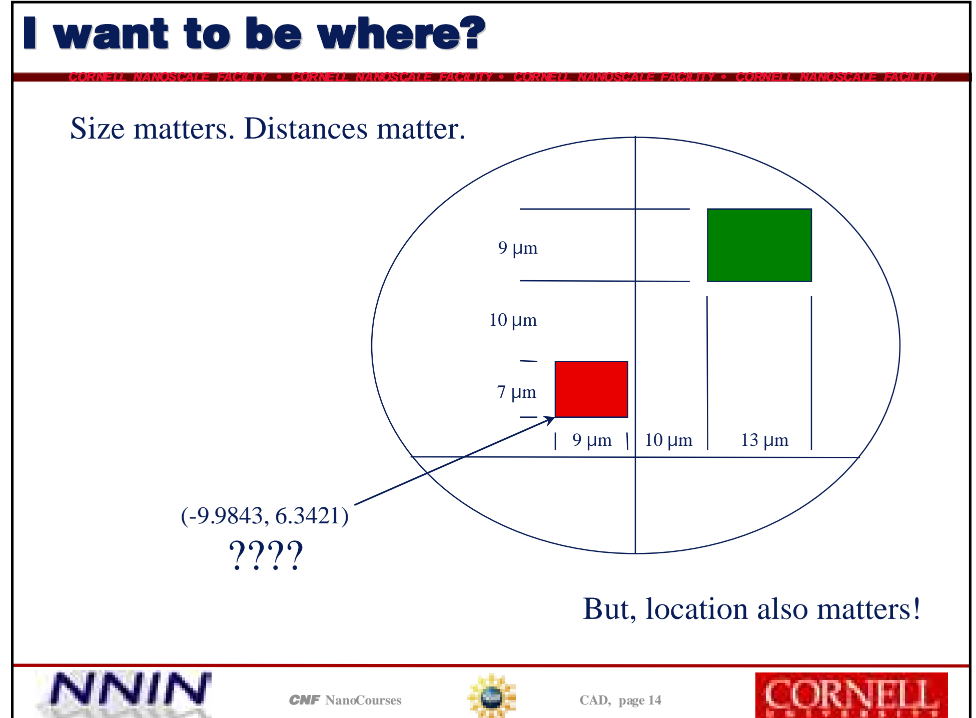
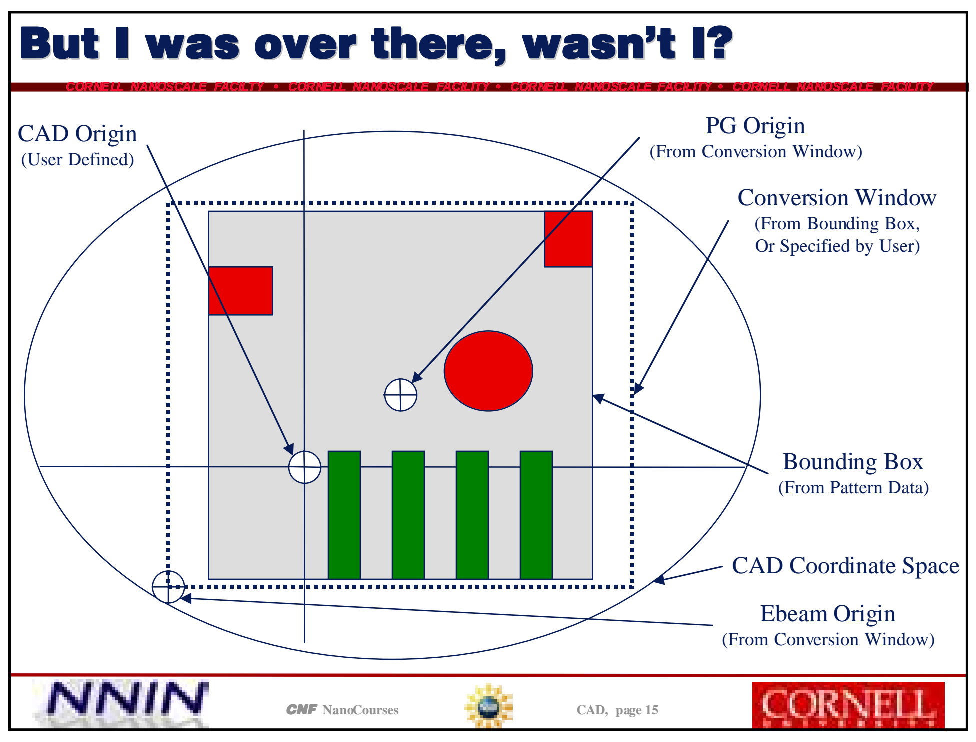
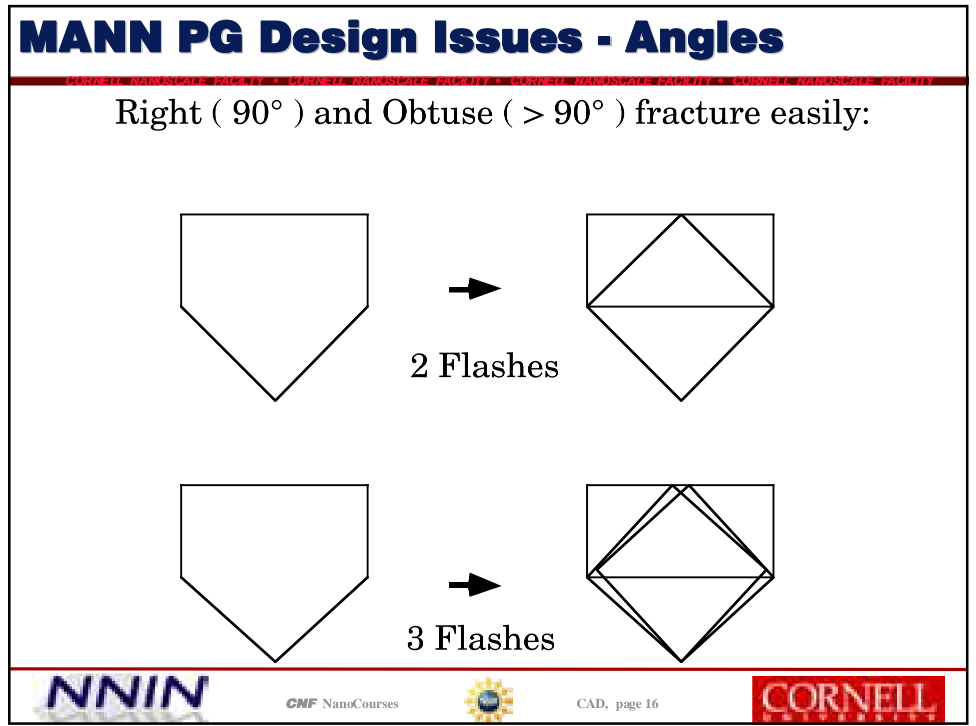
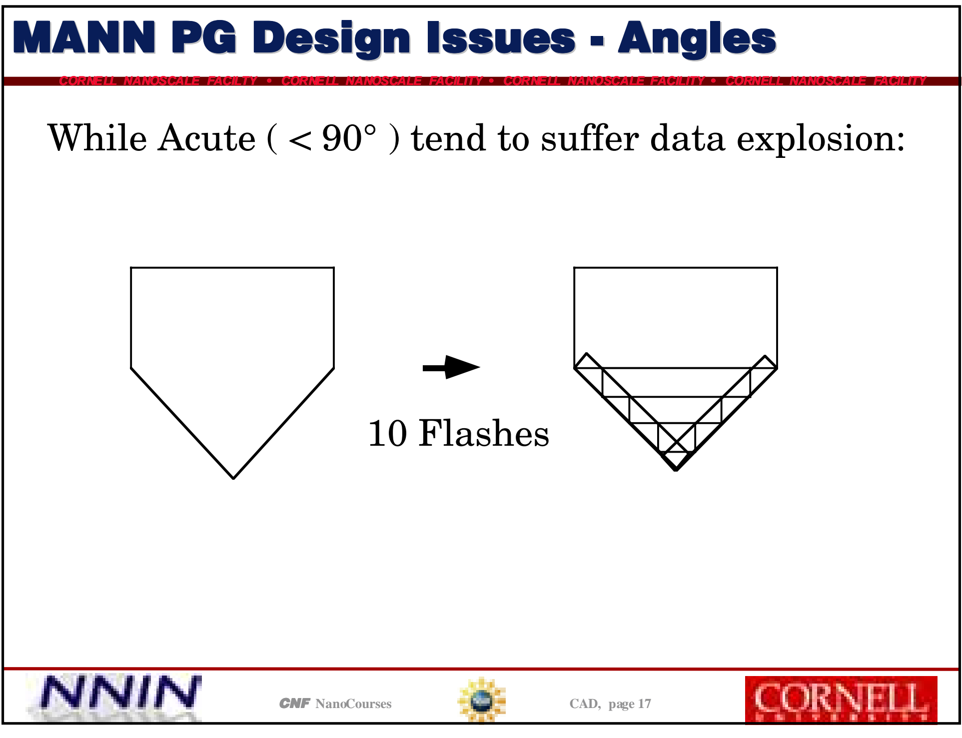
Size matters. Distances matter.

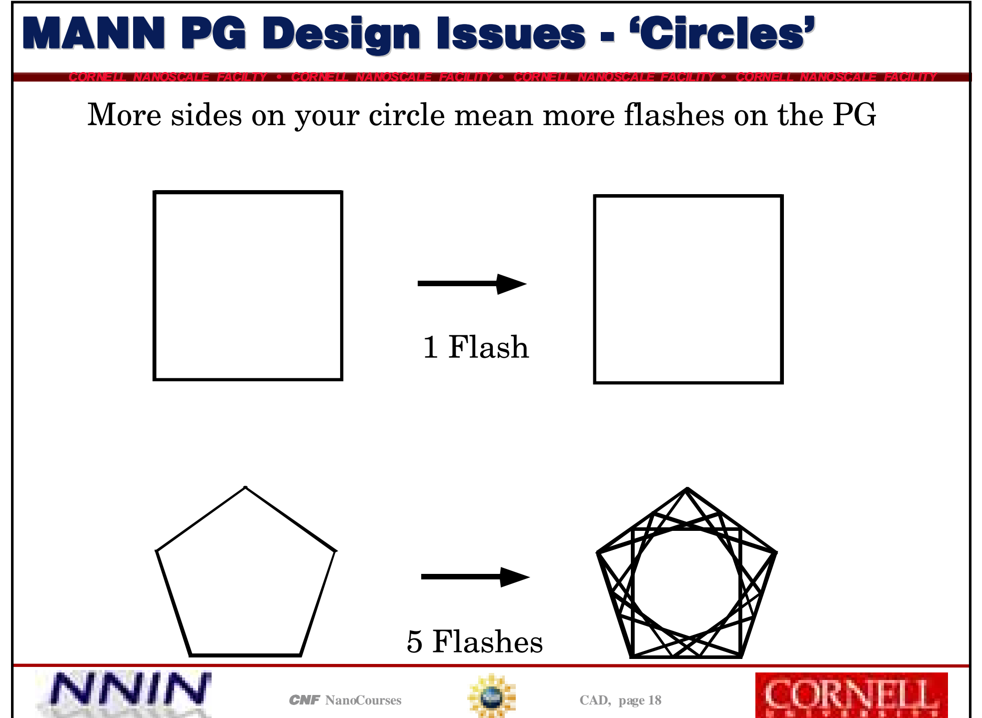


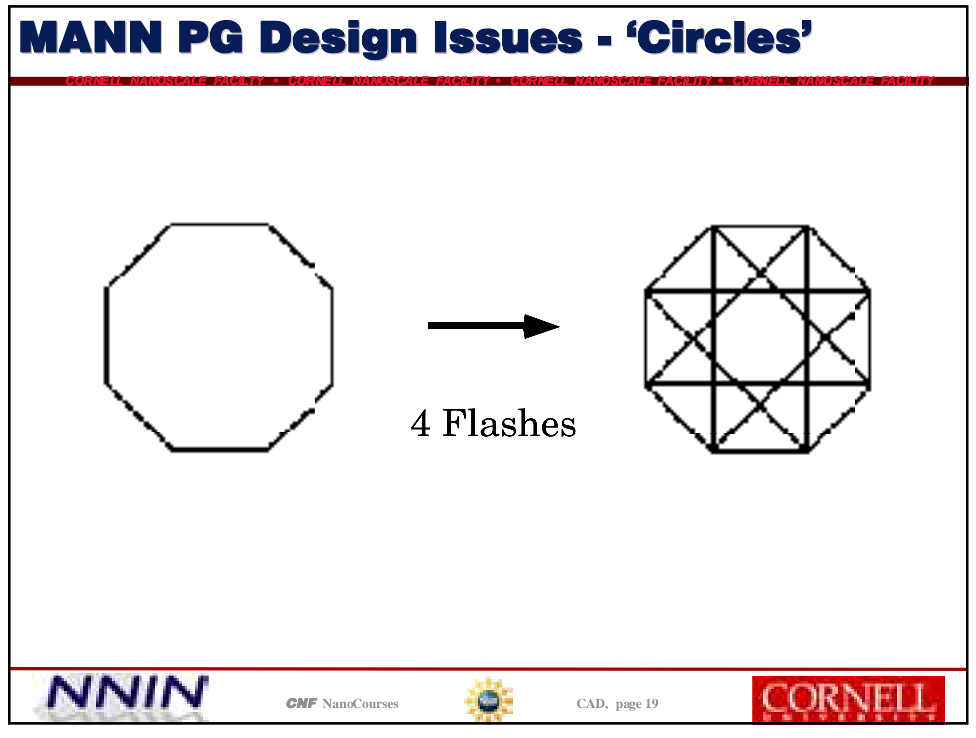
But, location also matters!

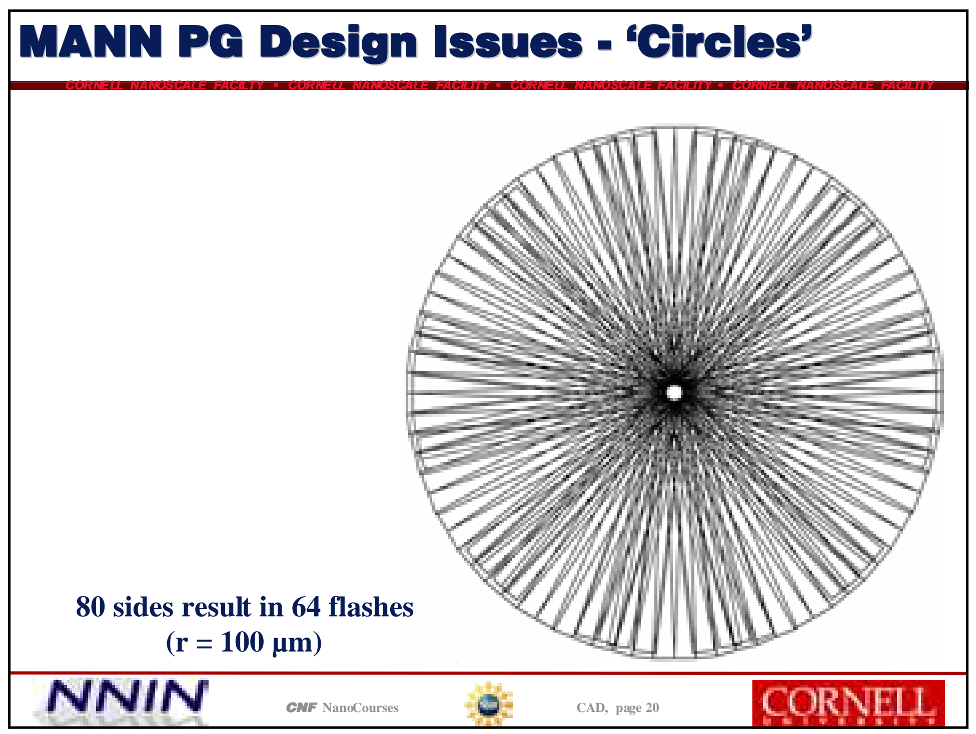

But I was over there, wasn't I?
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
CAD Origin
(User Defined)
PG Origin
(From Conversion Window)
Conversion Window
(From Bounding Box,
Or Specified by User)
Bounding Box
(From Pattern Data)
CAD Coordinate Space
Ebeam Origin
(From Conversion Window)
NNIN
CNF NanoCourses
CAD, page 15
CORNELL

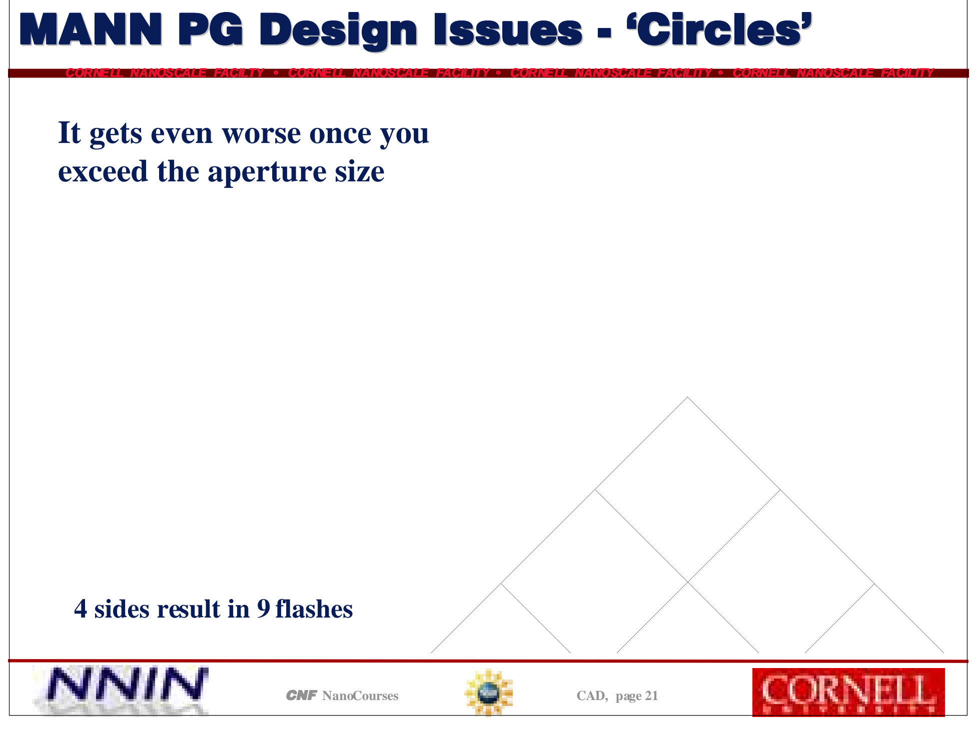

MANN PG Design Issues - Angles
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Right (90°) and Obtuse (> 90°) fracture easily:
2 Flashes
3 Flashes
NNIN
CNF NanoCourses
CAD, page 16
CORNELL

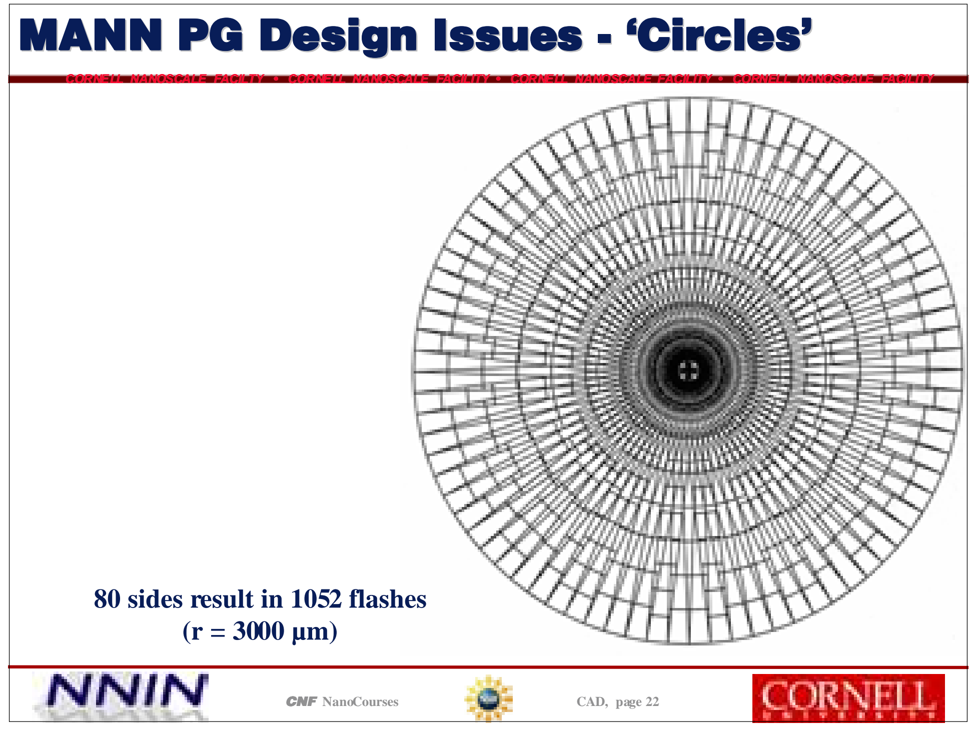

MANN PG Design Issues - Angles
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
While Acute (< 90°) tend to suffer data explosion:
10 Flashes
NNIN
CNF NanoCourses
CAD, page 17
CORNELL

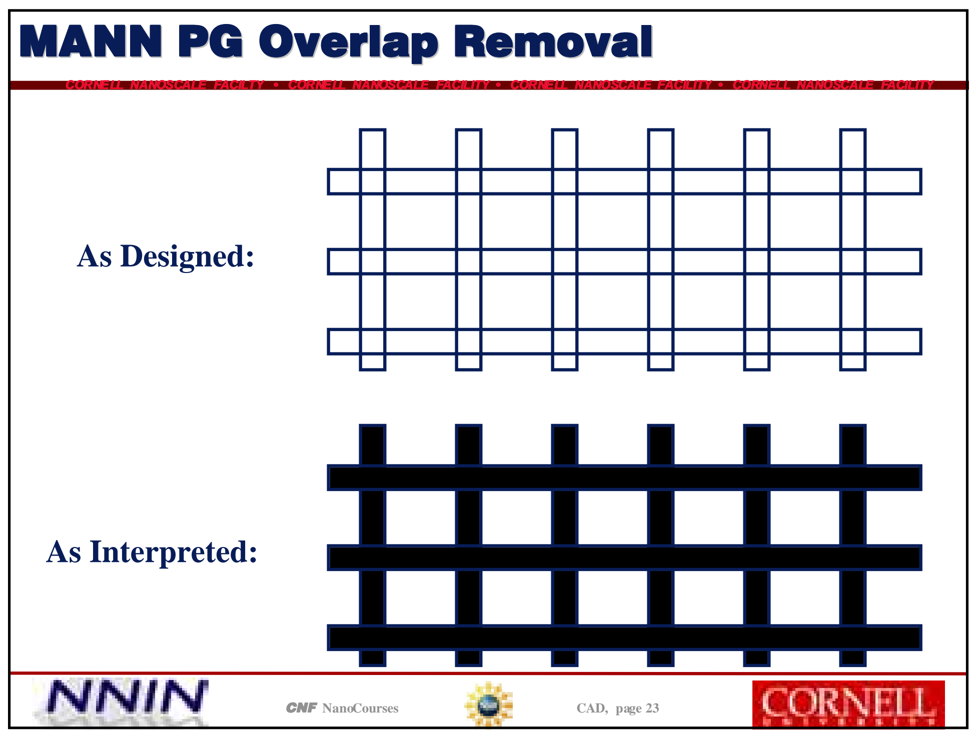

MANN PG Design Issues - 'Circles'
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
More sides on your circle mean more flashes on the PG
1 Flash
5 Flashes
NNIN
CNF NanoCourses
CAD, page 18
CORNELL

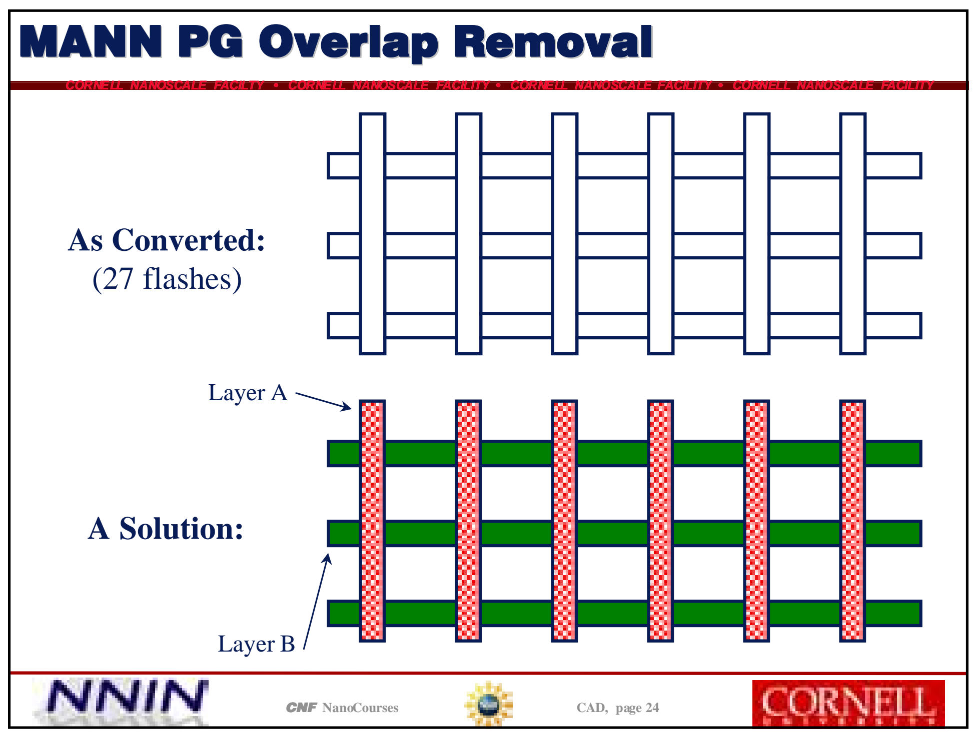

MANN PG Design Issues - 'Circles'
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
4 Flashes
NNIN
CNF NanoCourses
CAD, page 19
CORNELL


MANN PG Design Issues - 'Circles'
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
80 sides result in 64 flashes
(r = 100 µm)
NNIN
CNF NanoCourses
CAD, page 20
CORNELL


MANN PG Design Issues - 'Circles'
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
It gets even worse once you
exceed the aperture size
4 sides result in 9 flashes
NNIN
CNF NanoCourses
CAD, page 21
CORNELL


MANN PG Design Issues - 'Circles'
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
80 sides result in 1052 flashes
(r = 3000 µm)
NNIN
CNF NanoCourses
CAD, page 22
CORNELL


MANN PG Overlap Removal
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
As Designed:
As Interpreted:
NNIN
CNF NanoCourses
CAD, page 23
CORNELL


MANN PG Overlap Removal
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
As Converted:
(27 flashes)
Layer A
A Solution:
Layer B
NNIN
CNF NanoCourses
CAD, page 24
CORNELL

E-Beam Design Issues

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- The maximum area that the electron beam can trace at one time is called an exposure FIELD.
- A pattern larger than this field will require stage motion.
- The intersections between fields are called STITCHING LINES.
- STITCHING ERRORS occur along these lines.
- Therefore, keep small features in the center of the field!

GDS Issues

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- GDS is a binary format – if you are using FTP (or similar) to transfer, make sure that it transfers as Binary (or Image).
- There are various flavors of the GDS specification. There are also ‘enhancements’ that various companies made.
  - Uppercase cell names are easier. (For instance, L-Edit has an export option that will do this for you.)
  - Some software will generate polygons with thousands of vertices. 200 or less works much better.

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Practical Lithography:

The Art and Science of Microlithography

Electron Beam Lithography

by

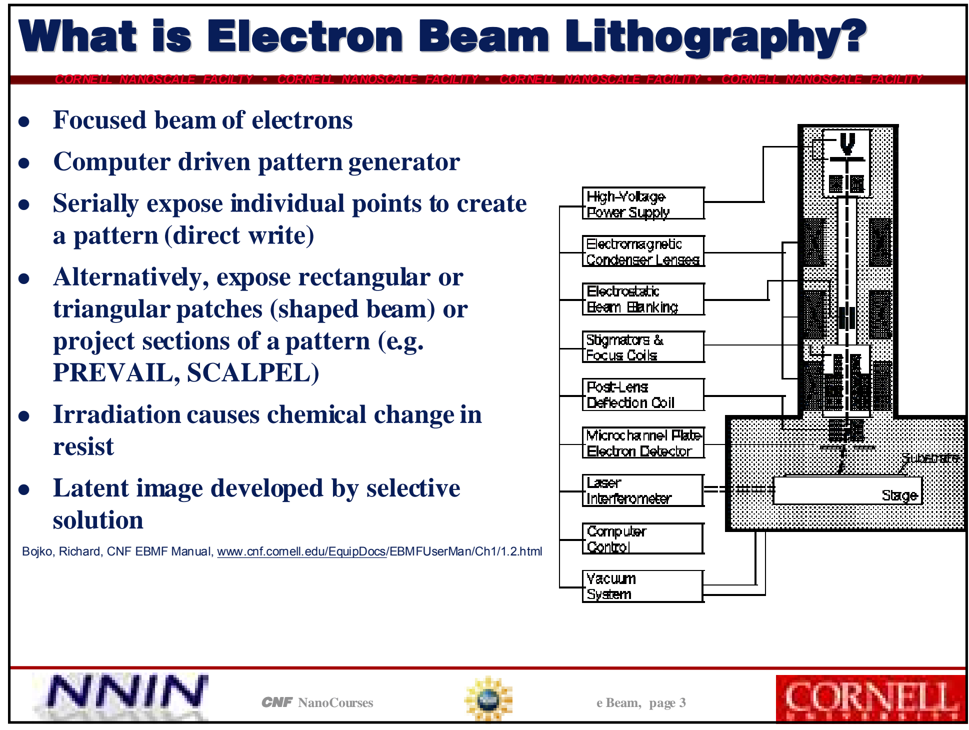
Alan Bleier

Presented by the
CNF Technical Staff
for the education of CNF Users,
Potential Users, and Industrial Sponsors

Topics Covered

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- Why use e beams for lithography?
  - Examples of research done with EBL
- A little physics
- Practical description of using e beams
  - in the order you would actually do things
- CNF e-beam systems



Why Use Electron Beams?

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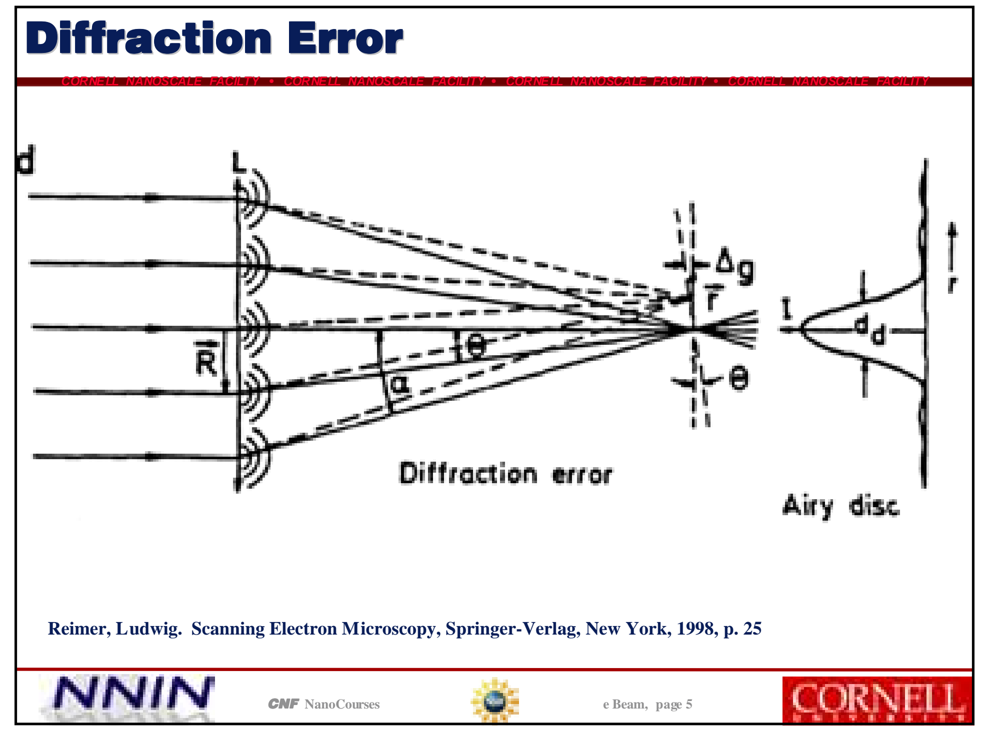
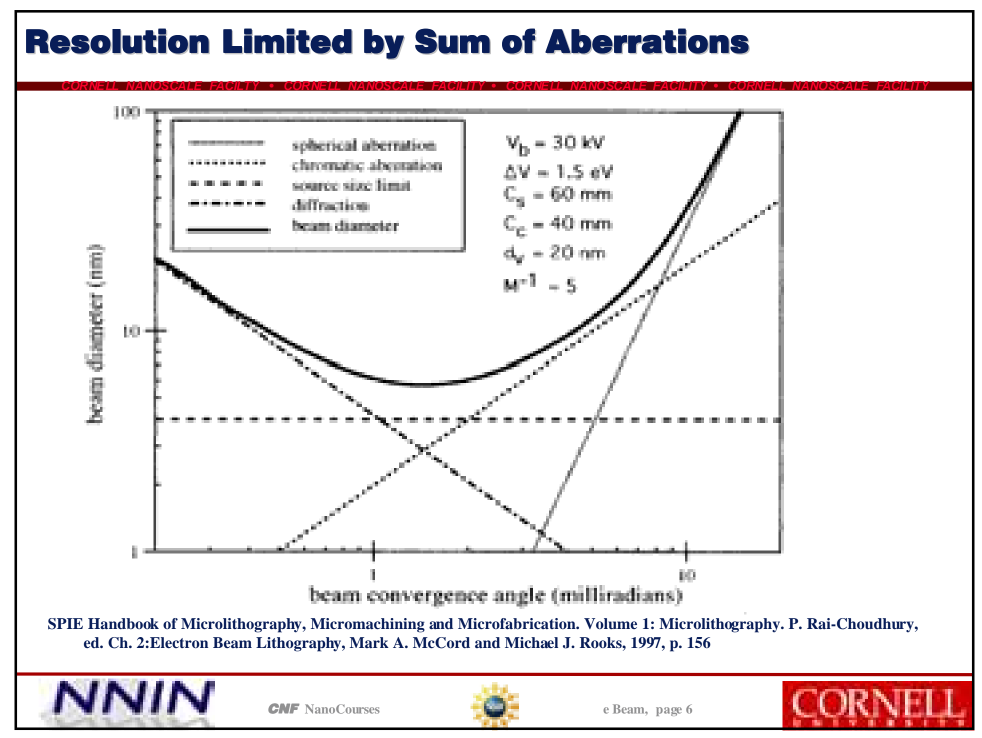
Optical Lithography	e-Beam Lithography
High speed for large shapes	High speed for complex Patterns
High Speed, Parallel Exposure	Point by Point Exposure Limits Speed
Light Diffraction Limits Minimum Feature Size to 50 nm at best	Not Diffraction-limited; Resolution 20 nm

NNIN CNF NanoCourses e Beam, page 4 CORNELL


Diffraction Error
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
d
L
R
α
θ
Δg
r
I
d_d
Diffraction error
Airy disc
Reimer, Ludwig. Scanning Electron Microscopy, Springer-Verlag, New York, 1998, p. 25
NNIN
CNF NanoCourses
e Beam, page 5
CORNELL


Resolution Limited by Sum of Aberrations
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
spherical aberration
chromatic aberration
source size limit
diffraction
beam diameter
V_b = 30 kV
ΔV = 1.5 eV
C_s = 60 mm
C_c = 40 mm
d_v = 20 nm
M^{-1} = 5
beam diameter (nm)
100
10
1
1
10
beam convergence angle (milliradians)
SPIE Handbook of Microlithography, Micromachining and Microfabrication. Volume 1: Microlithography. P. Rai-Choudhury, ed. Ch. 2:Electron Beam Lithography, Mark A. McCord and Michael J. Rooks, 1997, p. 156
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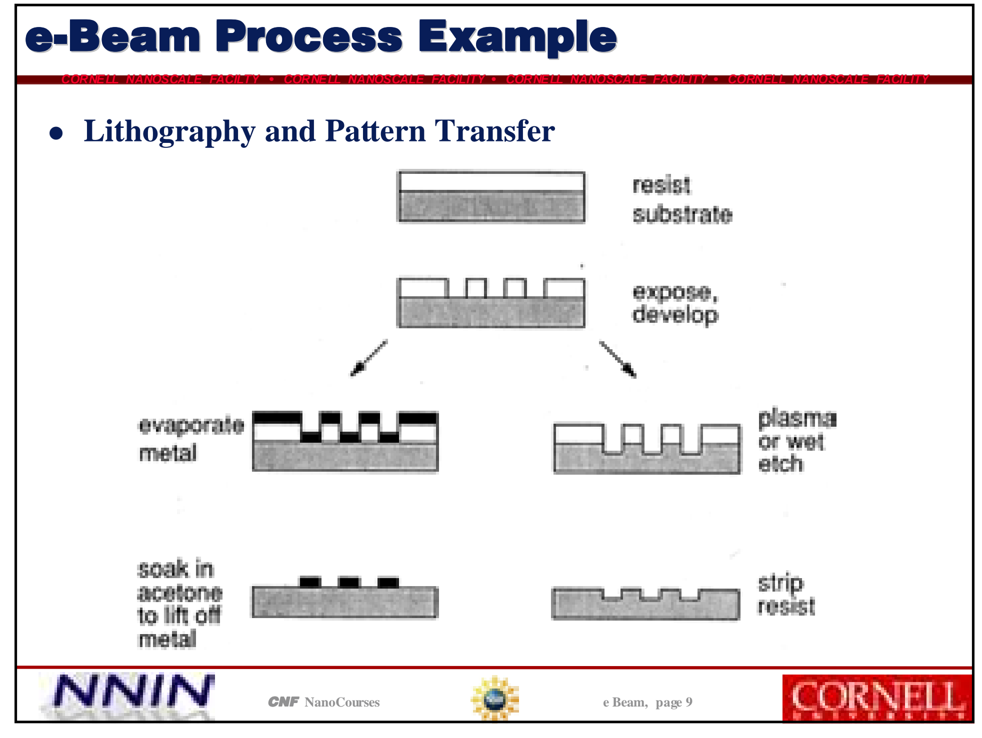
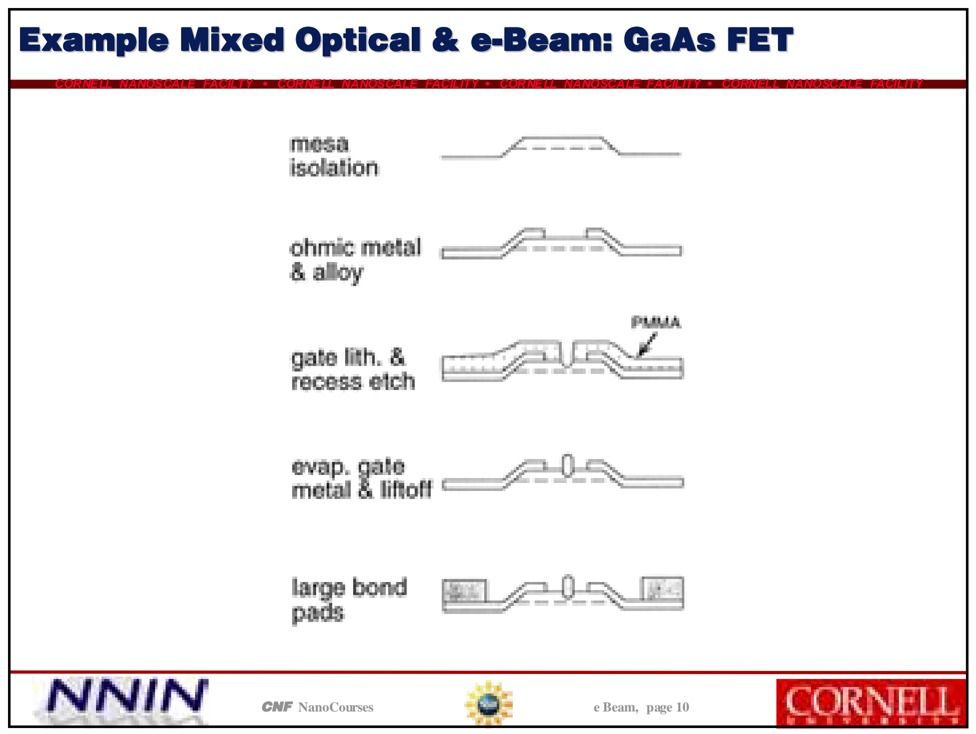
CNF NanoCourses
e Beam, page 6
CORNELL

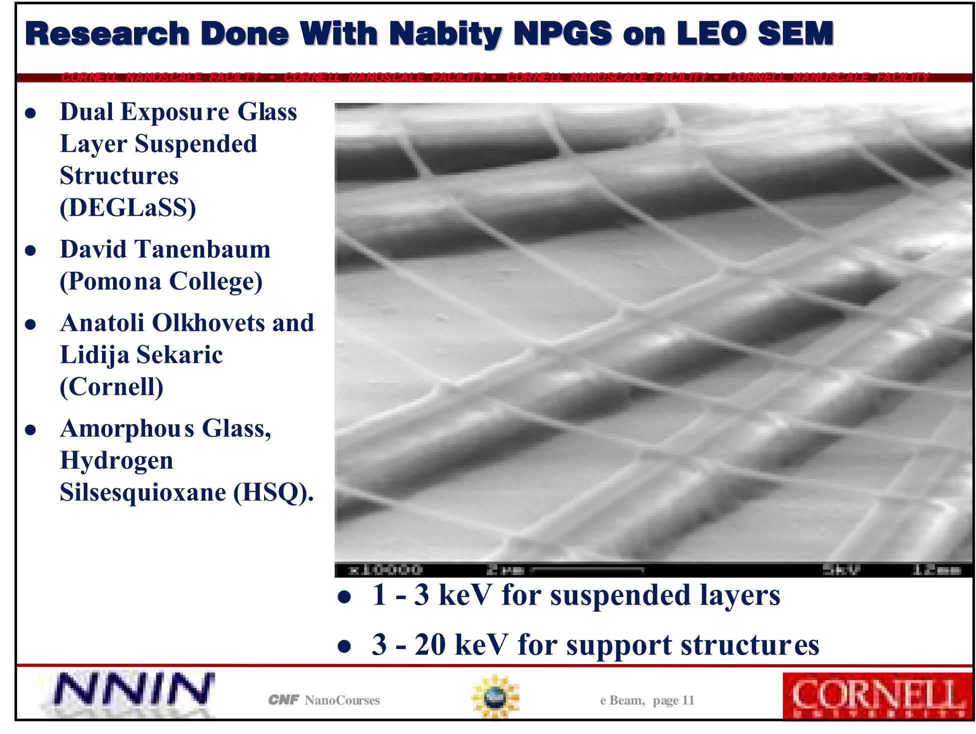
History of SEM and e-Beam Lithography

- 1926 H. Busch (Berlin) – Theory of electron trajectories
- 1939 Knoll & Theile (Berlin) – First SEM, 100 µm spot
- 1939 von Ardenne (Berlin) – First good SEM,0.1 µm spot
- 1948 C. W. Oatley & D. McMullan (Cambridge) – First modern SEM using two scan coils and secondary electron collector
- 1965 R. F. W. Pease & W. C. Nixon (Cambridge) – Everhart-Thornley detector used in prototype of first commercial SEM: Cambridge Mark I
- 1965 IBM, Cambridge, Hughes experiments with first beam writing using pump oil contamination and low-resolution Kodak resists
- 1971 M. Hatzakis, A. Broers, E. Wolf – PMMA for 60 nm lines
- 1974 EBES (Bell Labs) commercial e beam system, later spun off to Perkin Elmer
- 1985 National Nanofabrication Facility purchases JEOL JBX5DII

Examples


e-Beam Process Example
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Lithography and Pattern Transfer
resist
substrate
expose,
develop
evaporate
metal
plasma
or wet
etch
soak in
acetone
to lift off
metal
strip
resist
NNIN
CNF NanoCourses
e Beam, page 9
CORNELL


Example Mixed Optical & e-Beam: GaAs FET
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
mesa
isolation
ohmic metal
& alloy
PMMA
gate lith. &
recess etch
evap. gate
metal & liftoff
large bond
pads
NNIN
CNF NanoCourses
e Beam, page 10
CORNELL


Research Done With Nabity NPGS on LEO SEM
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Dual Exposure Glass Layer Suspended Structures (DEGLaSS)
• David Tanenbaum (Pomona College)
• Anatoli Olkhovets and Lidija Sekaric (Cornell)
• Amorphous Glass, Hydrogen Silsesquioxane (HSQ).
• 1 - 3 keV for suspended layers
• 3 - 20 keV for support structures
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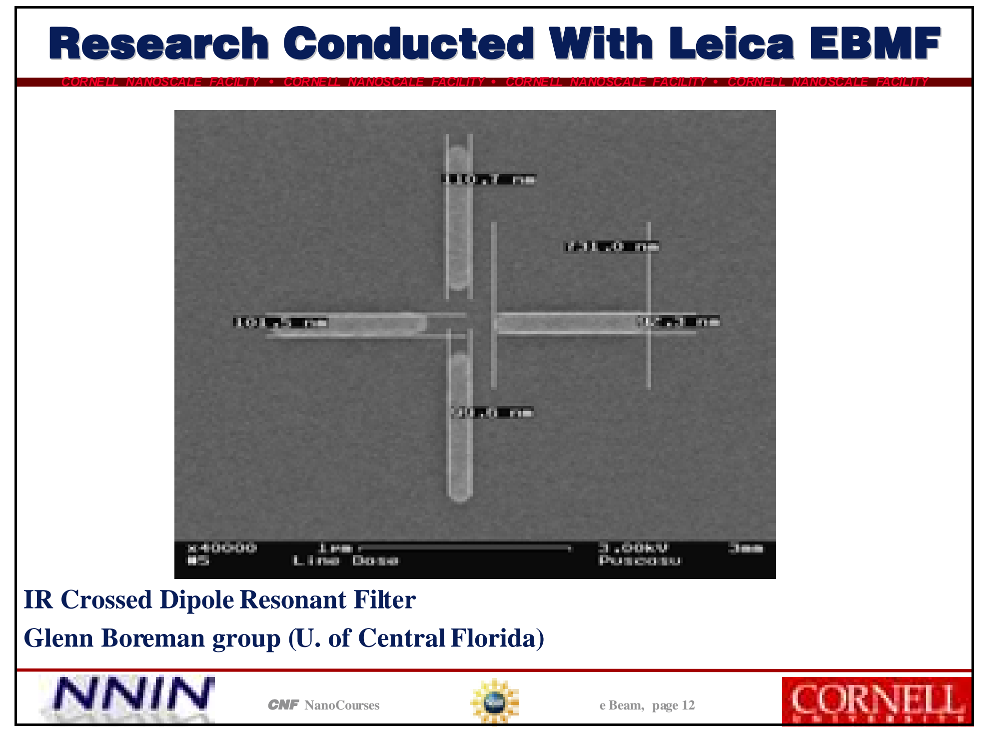
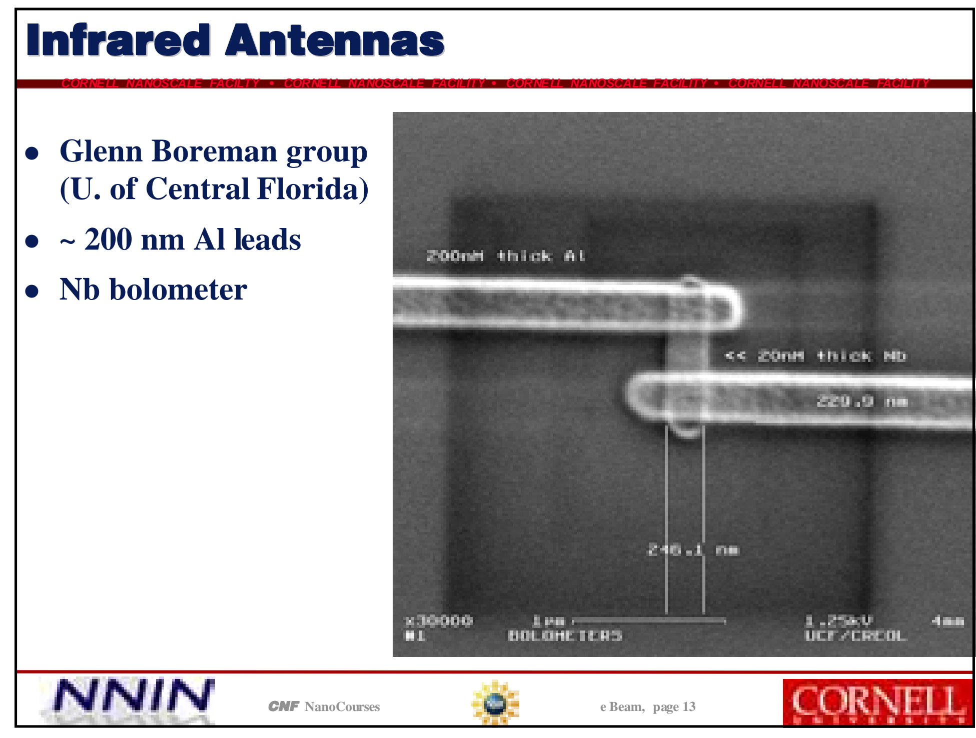
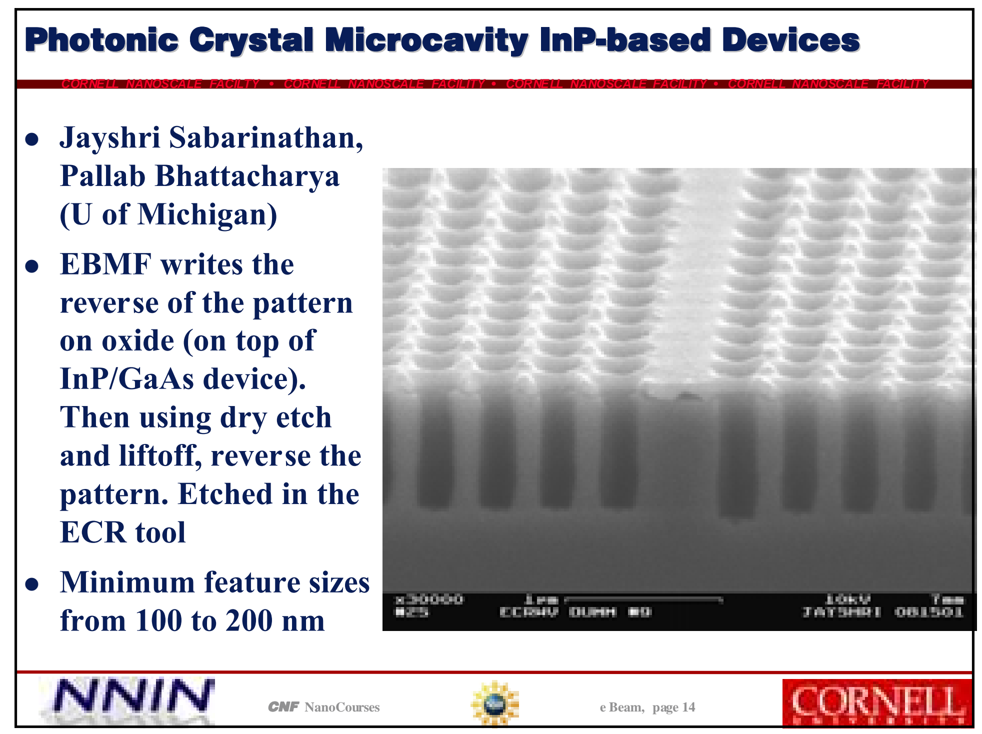
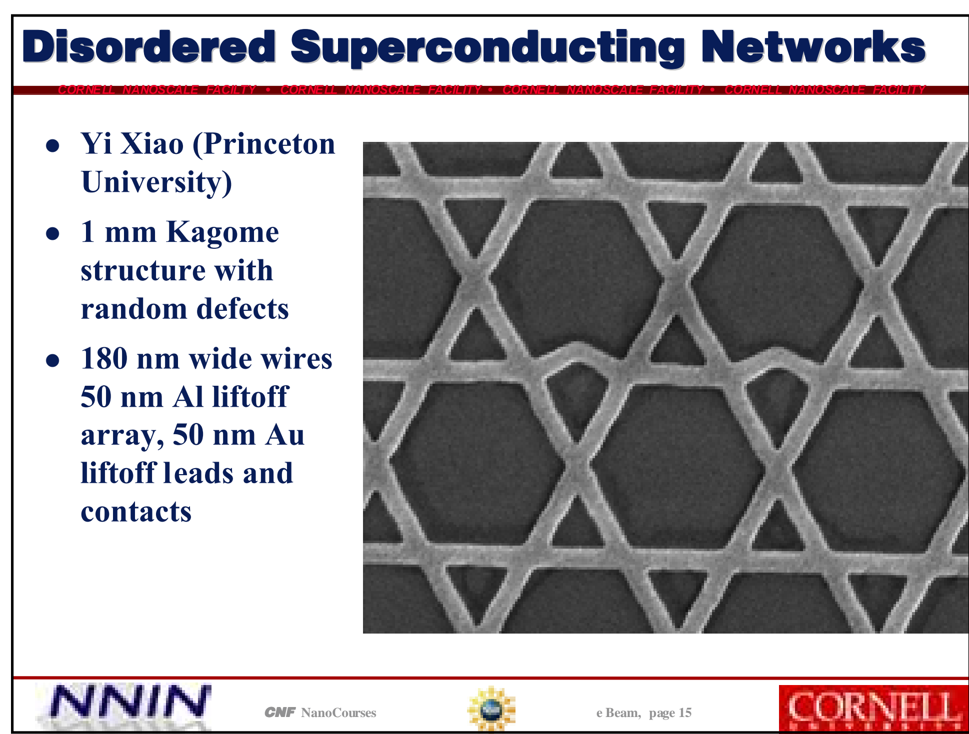
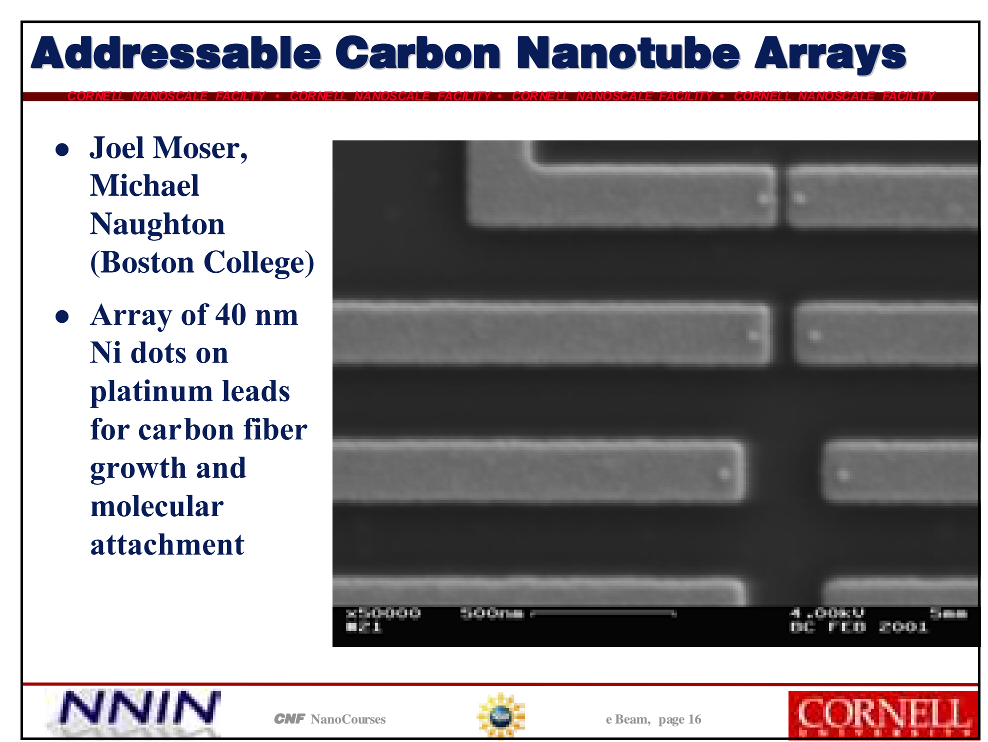
e Beam, page 11
CORNELL

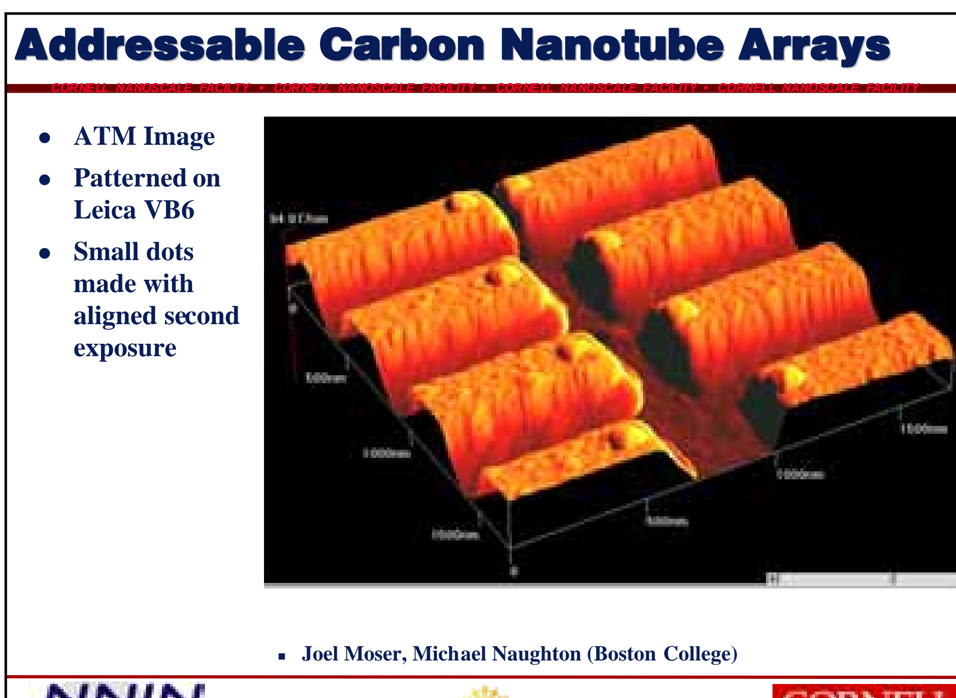

Research Conducted With Leica EBMF
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
IR Crossed Dipole Resonant Filter
Glenn Boreman group (U. of Central Florida)
NNIN
CNF NanoCourses
e Beam, page 12
CORNELL

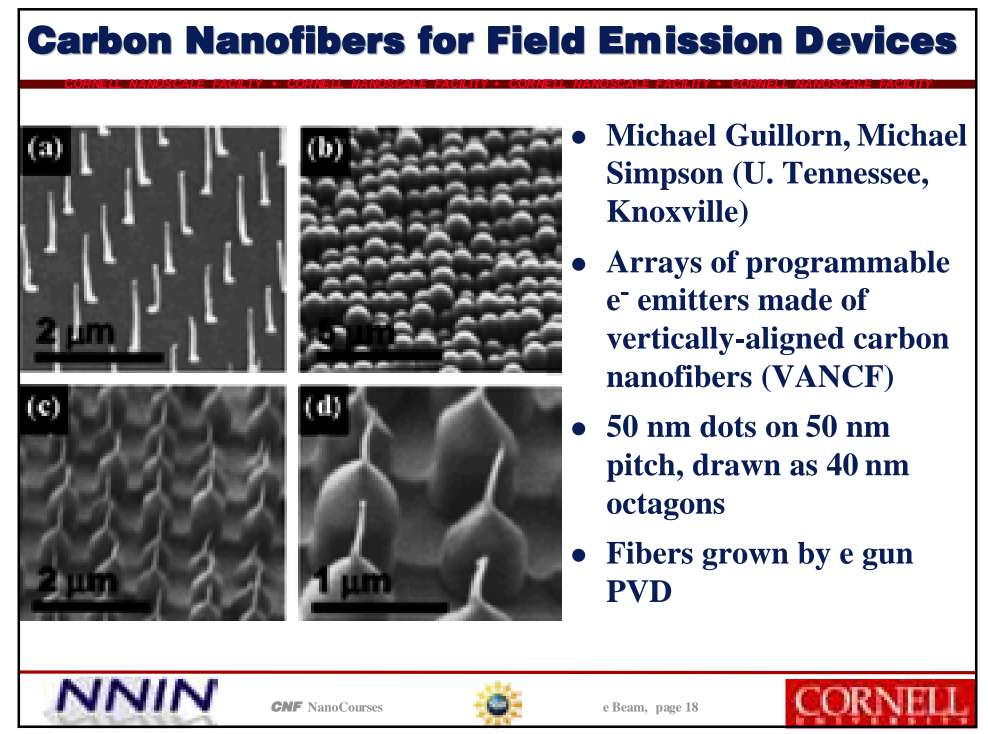

Infrared Antennas
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Glenn Boreman group (U. of Central Florida)
• ~ 200 nm Al leads
• Nb bolometer
200nM thick Al
<< 20nM thick Nb
220.9 nm
246.1 nm
x30000
1μm
BOLOMETERS
1.25kV
4mm
UCF/CREOL
NNIN
CNF NanoCourses
e Beam, page 13
CORNELL

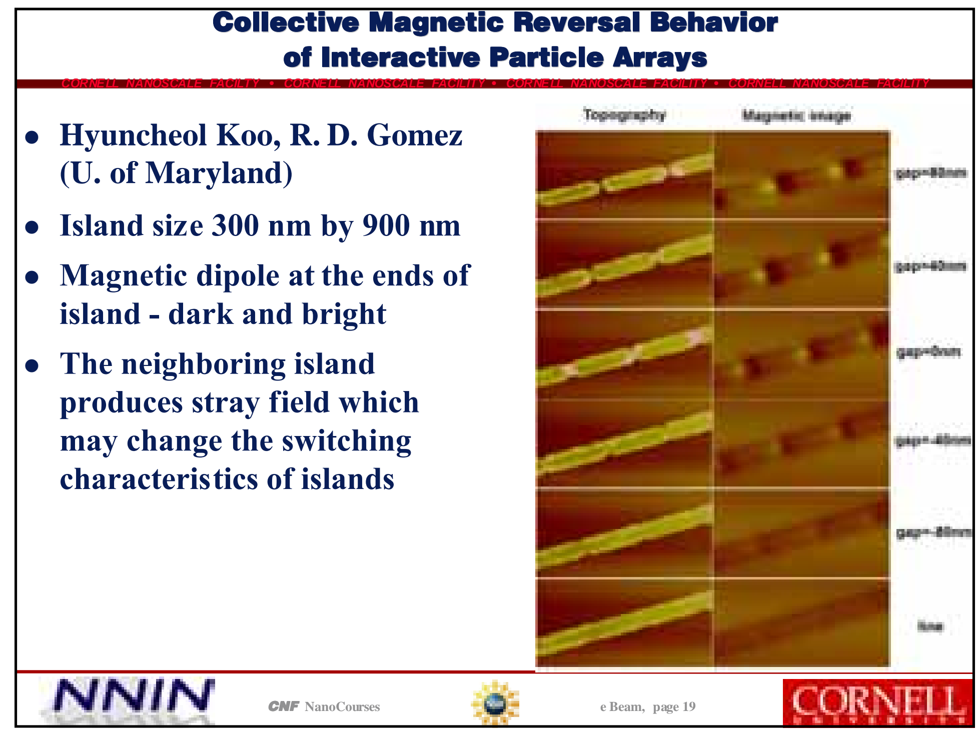

Photonic Crystal Microcavity InP-based Devices
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Jayshri Sabarinathan, Pallab Bhattacharya (U of Michigan)
• EBMF writes the reverse of the pattern on oxide (on top of InP/GaAs device). Then using dry etch and liftoff, reverse the pattern. Etched in the ECR tool
• Minimum feature sizes from 100 to 200 nm
x30000
1μm
10kV
7mm
NNIN
CNF NanoCourses
e Beam, page 14
CORNELL


Disordered Superconducting Networks
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Yi Xiao (Princeton University)
• 1 mm Kagome structure with random defects
• 180 nm wide wires 50 nm Al liftoff array, 50 nm Au liftoff leads and contacts
NNIN
CNF NanoCourses
e Beam, page 15
CORNELL
UNIVERSITY


Addressable Carbon Nanotube Arrays
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Joel Moser, Michael Naughton (Boston College)
• Array of 40 nm Ni dots on platinum leads for carbon fiber growth and molecular attachment
x50000
500nm
4.00kV
BC FEB 2001
NNIN
CNF NanoCourses
e Beam, page 16
CORNELL
UNIVERSITY


Addressable Carbon Nanotube Arrays
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• ATM Image
• Patterned on Leica VB6
• Small dots made with aligned second exposure
Joel Moser, Michael Naughton (Boston College)
NNIN
CNF NanoCourses
e Beam, page 17
CORNELL


Carbon Nanofibers for Field Emission Devices
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
(a)
2 µm
(b)
5 µm
(c)
2 µm
(d)
1 µm
• Michael Guillorn, Michael Simpson (U. Tennessee, Knoxville)
• Arrays of programmable e- emitters made of vertically-aligned carbon nanofibers (VANCF)
• 50 nm dots on 50 nm pitch, drawn as 40 nm octagons
• Fibers grown by e gun PVD
NNIN
CNF NanoCourses
e Beam, page 18
CORNELL


Collective Magnetic Reversal Behavior
of Interactive Particle Arrays
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Hyuncheol Koo, R. D. Gomez (U. of Maryland)
• Island size 300 nm by 900 nm
• Magnetic dipole at the ends of island - dark and bright
• The neighboring island produces stray field which may change the switching characteristics of islands
Topography
Magnetic image
line
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e Beam, page 19
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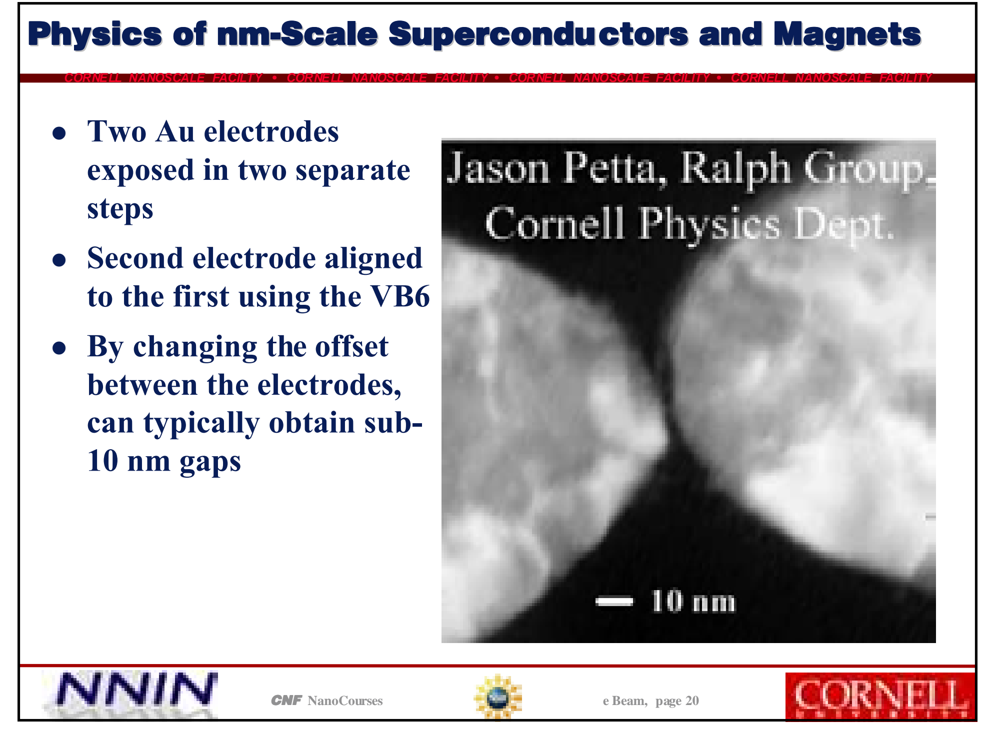
Physics of nm-Scale Superconductors and Magnets
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Two Au electrodes exposed in two separate steps
• Second electrode aligned to the first using the VB6
• By changing the offset between the electrodes, can typically obtain sub-10 nm gaps
Jason Petta, Ralph Group
Cornell Physics Dept.
10 nm
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e Beam, page 20
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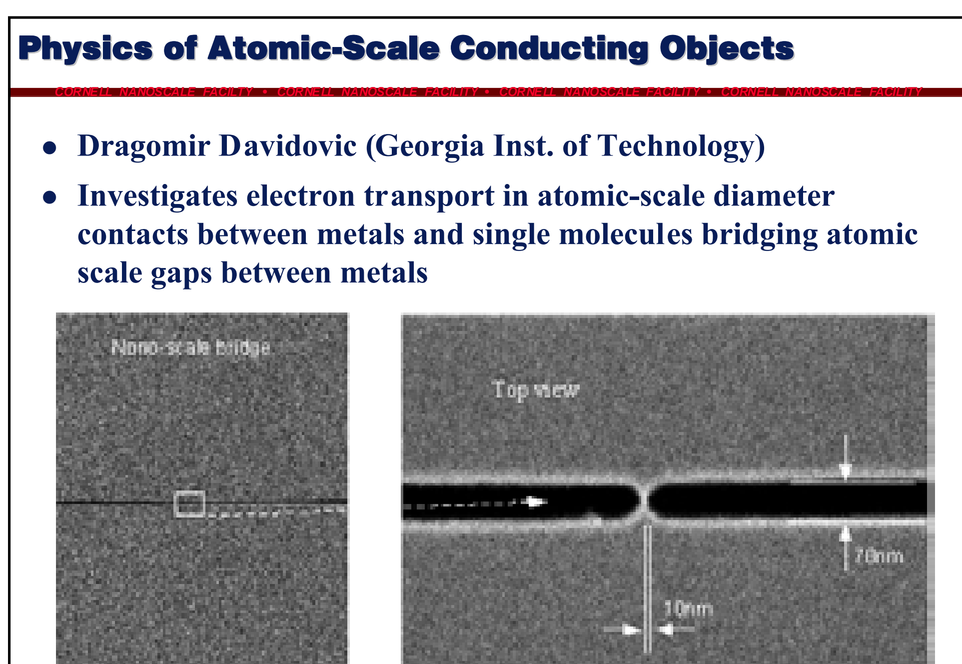
Physics of Atomic-Scale Conducting Objects
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Dragomir Davidovic (Georgia Inst. of Technology)
• Investigates electron transport in atomic-scale diameter contacts between metals and single molecules bridging atomic scale gaps between metals
Nano-scale bridge
Top view
70nm
10nm
NNIN
CNF NanoCourses
e Beam, page 21
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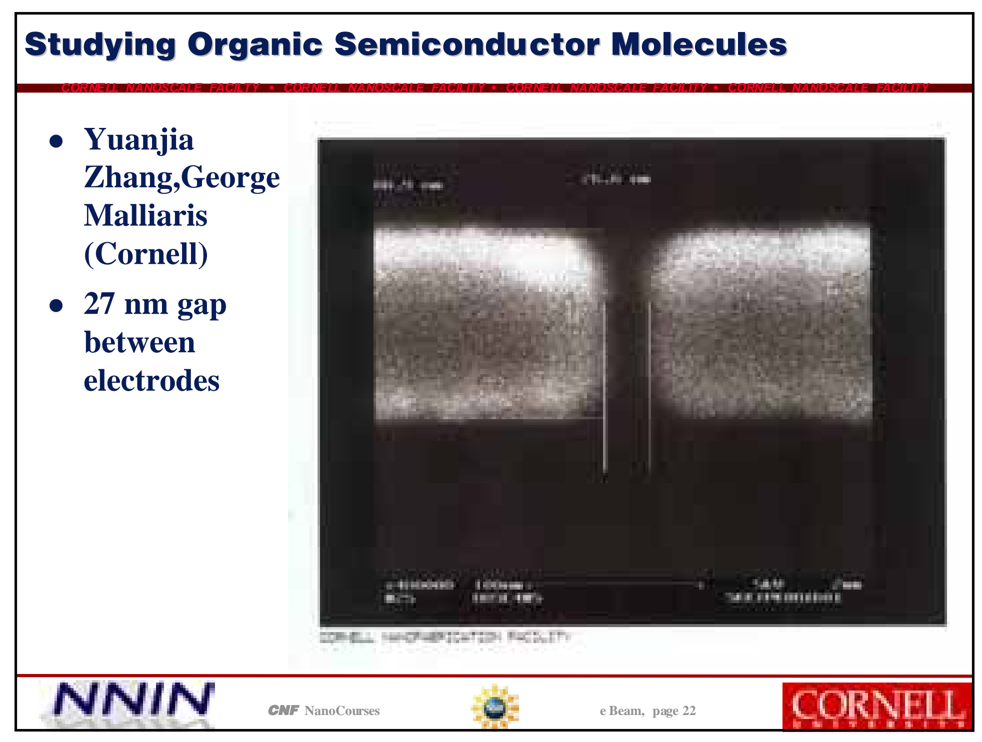
Studying Organic Semiconductor Molecules
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Yuanjia Zhang,George Malliaris (Cornell)
• 27 nm gap between electrodes
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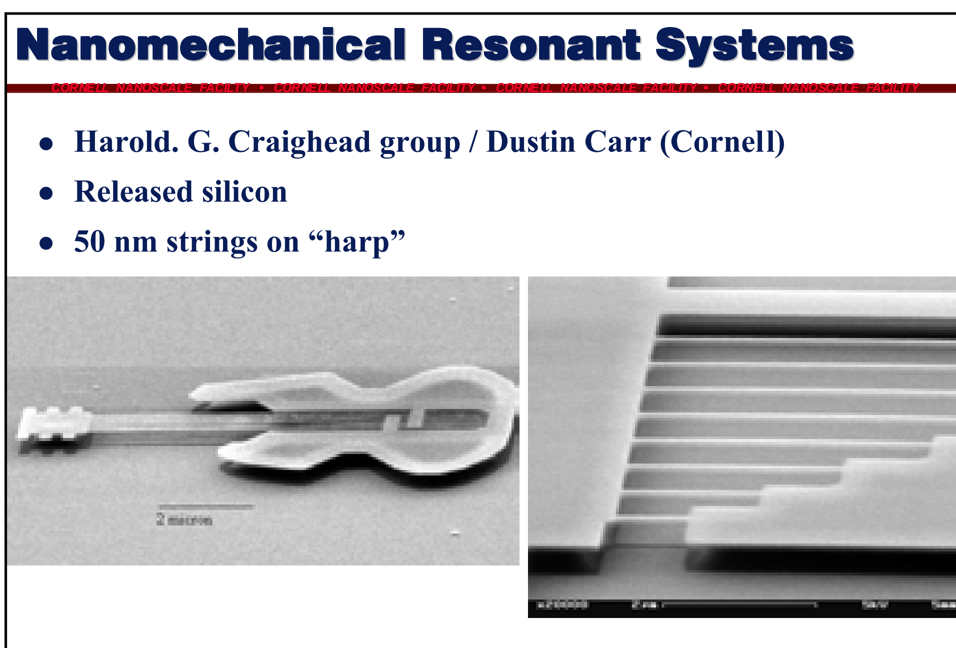
Nanomechanical Resonant Systems
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Harold. G. Craighead group / Dustin Carr (Cornell)
• Released silicon
• 50 nm strings on “harp”
2 micron
NNIN
CNF NanoCourses
e Beam, page 23
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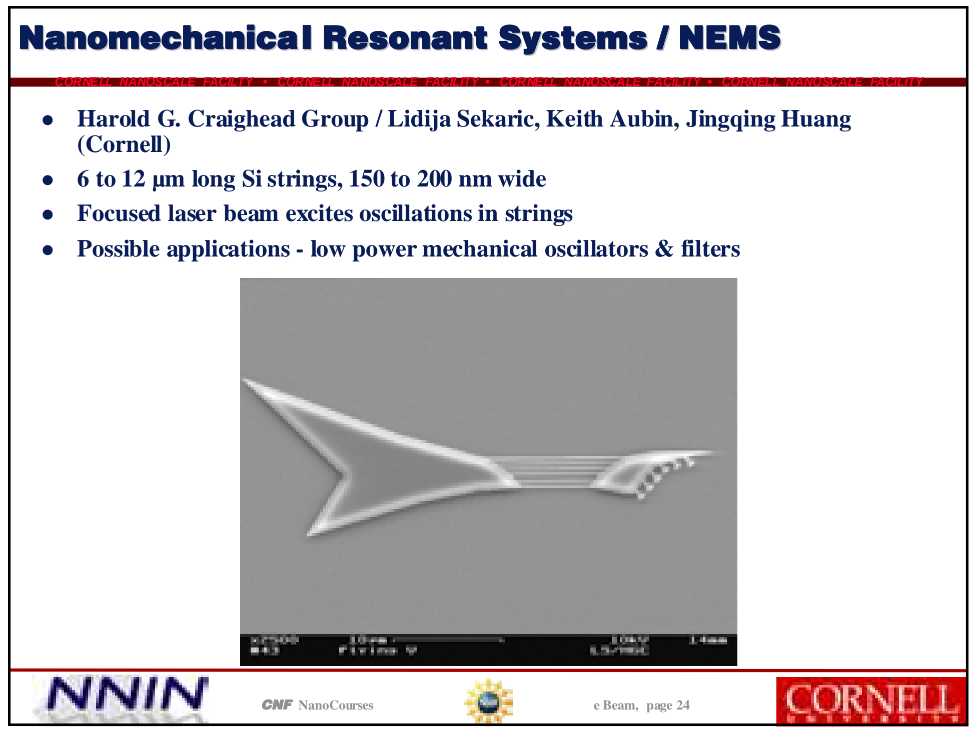
Nanomechanical Resonant Systems / NEMS
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Harold G. Craighead Group / Lidija Sekaric, Keith Aubin, Jingqing Huang (Cornell)
• 6 to 12 µm long Si strings, 150 to 200 nm wide
• Focused laser beam excites oscillations in strings
• Possible applications - low power mechanical oscillators & filters
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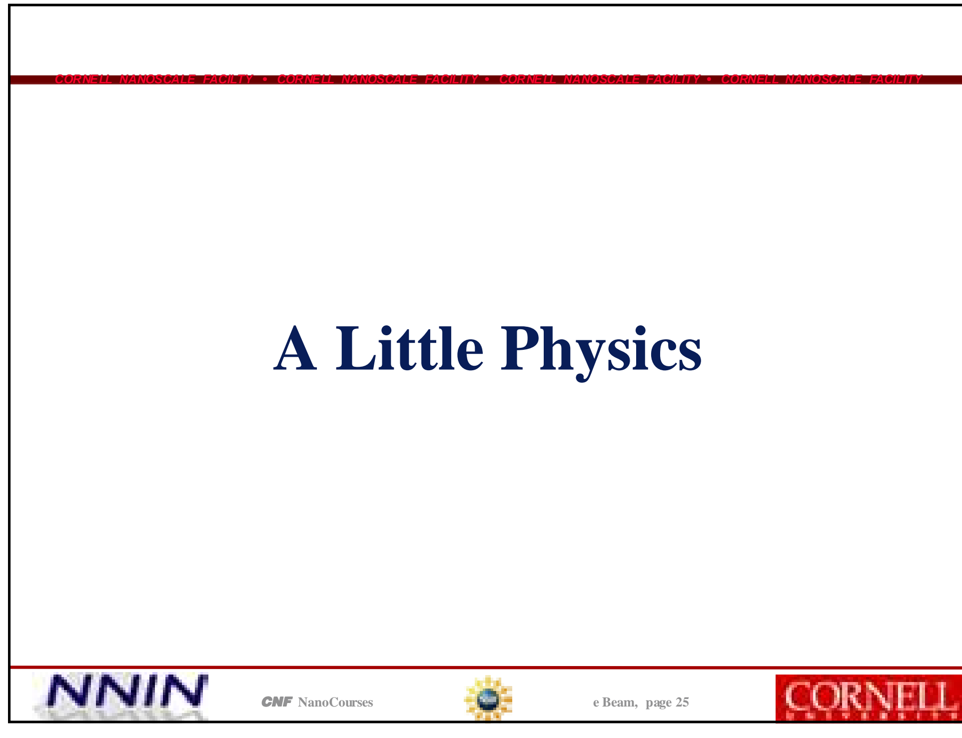
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
A Little Physics
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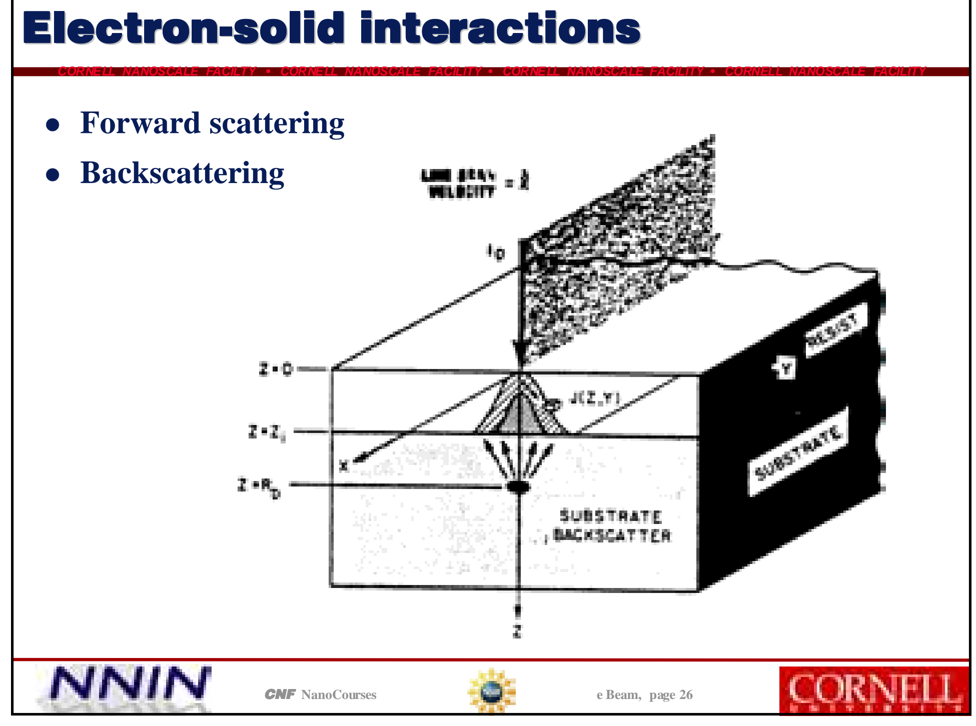
Electron-solid interactions
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Forward scattering
• Backscattering
Z = 0
J(Z,Y)
X
Y
RESIST
SUBSTRATE
SUBSTRATE BACKSCATTER
Z
NNIN
CNF NanoCourses
e Beam, page 26
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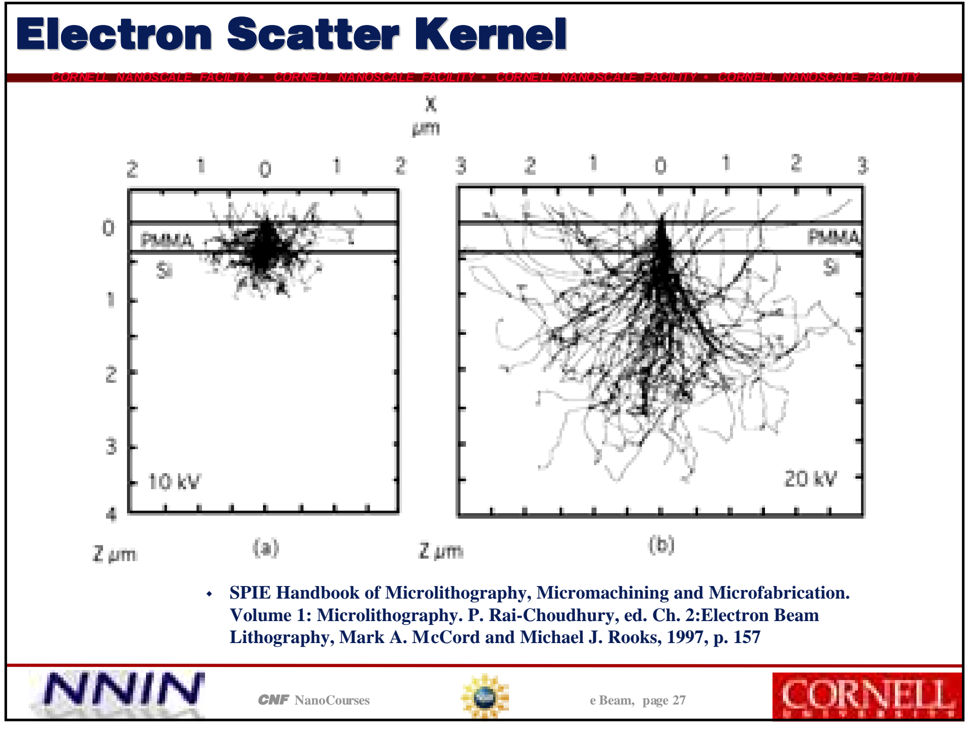
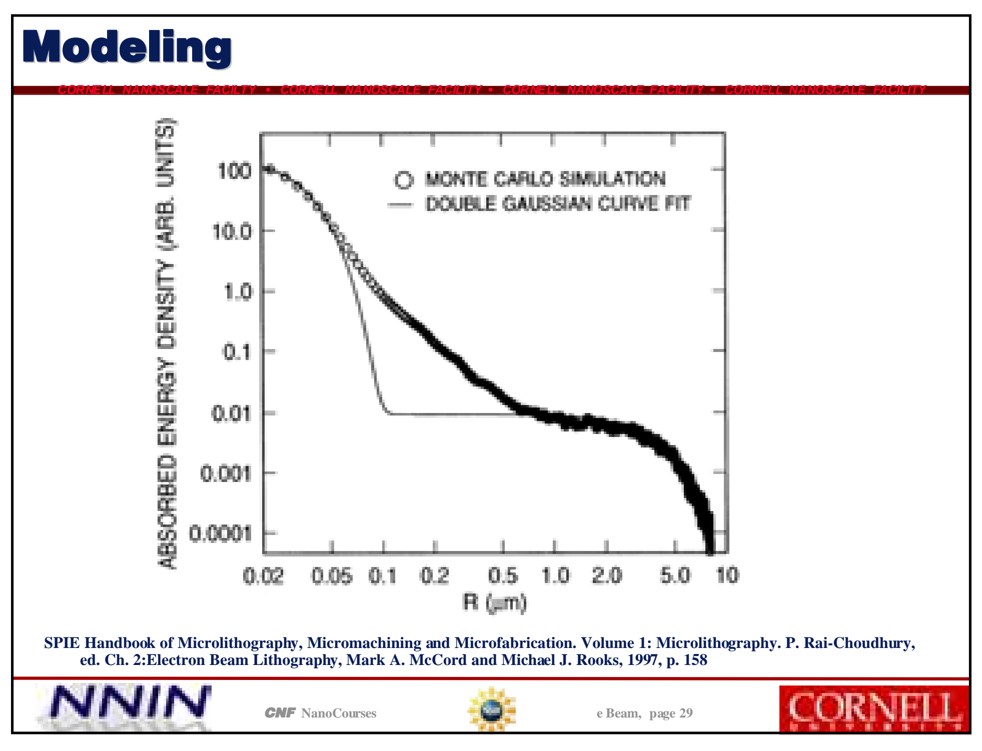
Electron Scatter Kernel



- SPIE Handbook of Microlithography, Micromachining and Microfabrication. Volume 1: Microlithography. P. Rai-Choudhury, ed. Ch. 2:Electron Beam Lithography, Mark A. McCord and Michael J. Rooks, 1997, p. 157

Secondary electrons

- Much of primary electron energy is dissipated in the form of secondary electrons with energies from 2 to 50 eV
- Responsible for the bulk of the actual resist exposure process
- Range in resist is only a few nanometers
  - Contribute little to the proximity effect
- Net result is effective widening of the beam by roughly 10 nm
- Main reason for minimum practical resolution of 20 nm in the highest resolution electron beam systems
- Contributes (along with forward scattering) to the bias that is seen in positive resist systems, where the exposed features develop larger than the size they were nominally written.


Modeling
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
MONTE CARLO SIMULATION
DOUBLE GAUSSIAN CURVE FIT
ABSORBED ENERGY DENSITY (ARB. UNITS)
100
10.0
1.0
0.1
0.01
0.001
0.0001
0.02 0.05 0.1 0.2 0.5 1.0 2.0 5.0 10
R (µm)
SPIE Handbook of Microlithography, Micromachining and Microfabrication. Volume 1: Microlithography. P. Rai-Choudhury, ed. Ch. 2:Electron Beam Lithography, Mark A. McCord and Michael J. Rooks, 1997, p. 158
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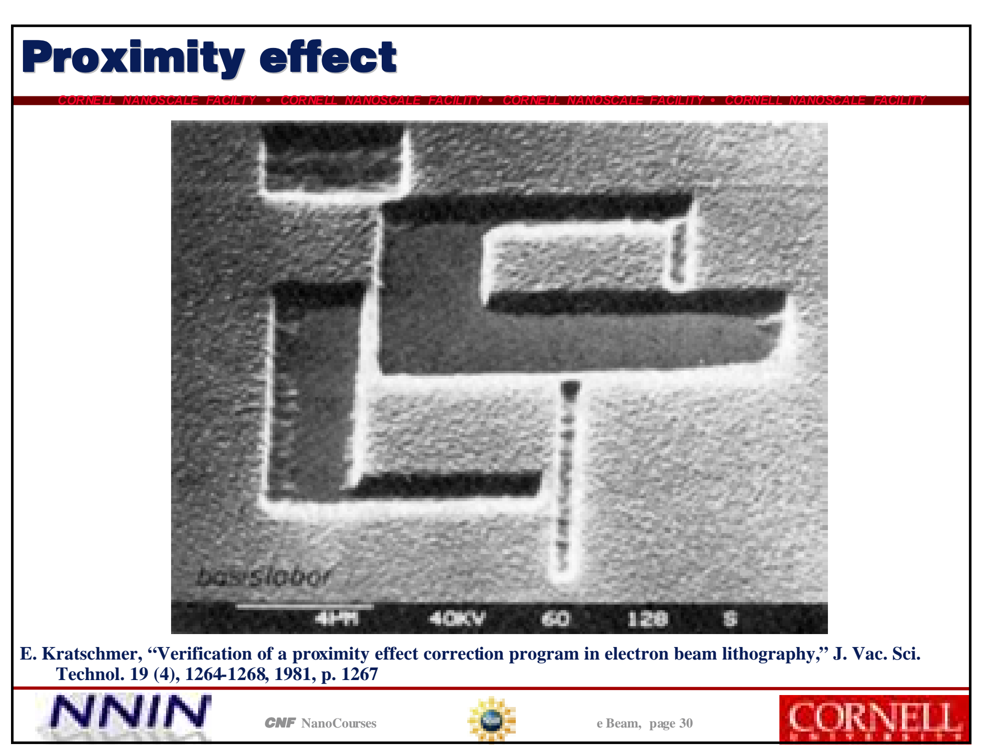
Proximity effect
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
4PM 40KV 60 128 S
E. Kratschmer, "Verification of a proximity effect correction program in electron beam lithography," J. Vac. Sci. Technol. 19 (4), 1264-1268, 1981, p. 1267
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CNF NanoCourses
e Beam, page 30
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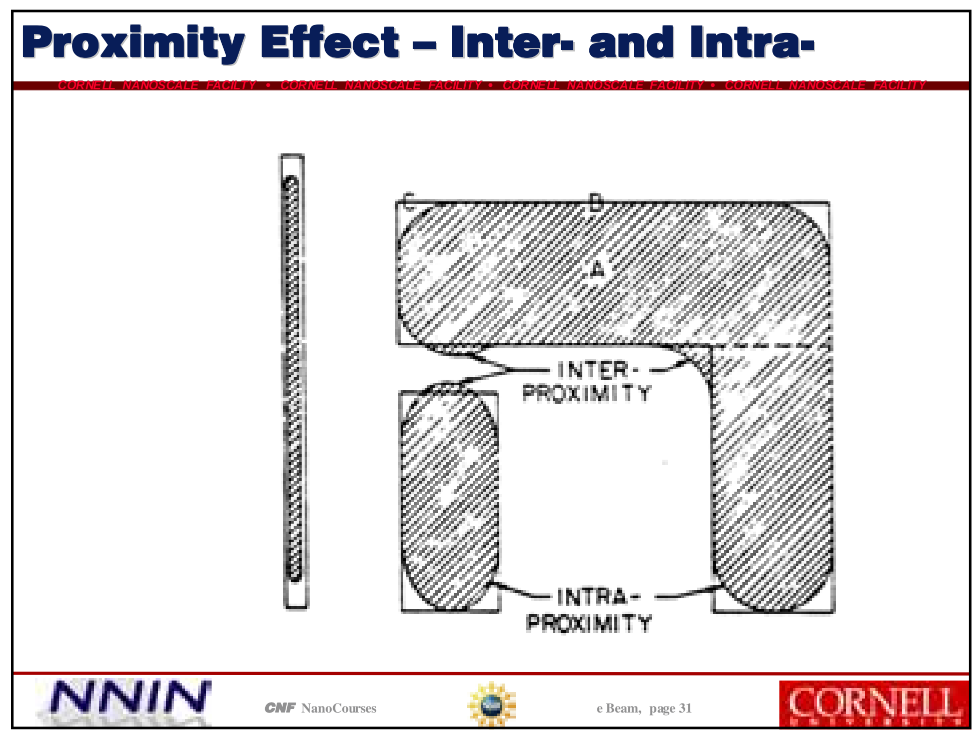
Proximity Effect – Inter- and Intra-
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
C
D
A
INTER-
PROXIMITY
INTRA-
PROXIMITY
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CNF NanoCourses
e Beam, page 31
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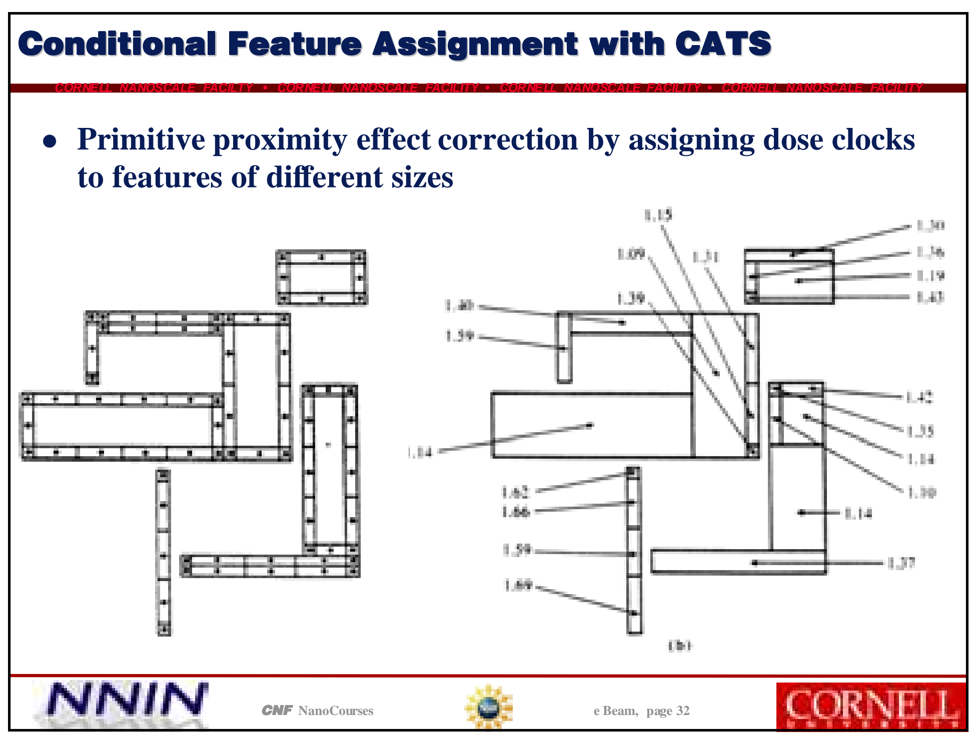
Conditional Feature Assignment with CATS
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Primitive proximity effect correction by assigning dose clocks to features of different sizes
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Using e-Beams

- in the order you would actually do things

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e-Beam Lithography Procedure

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- Design Pattern with CAD
  - Convert Pattern to Machine Format
- Choose Resist and Apply to Sample
- Expose
- Develop

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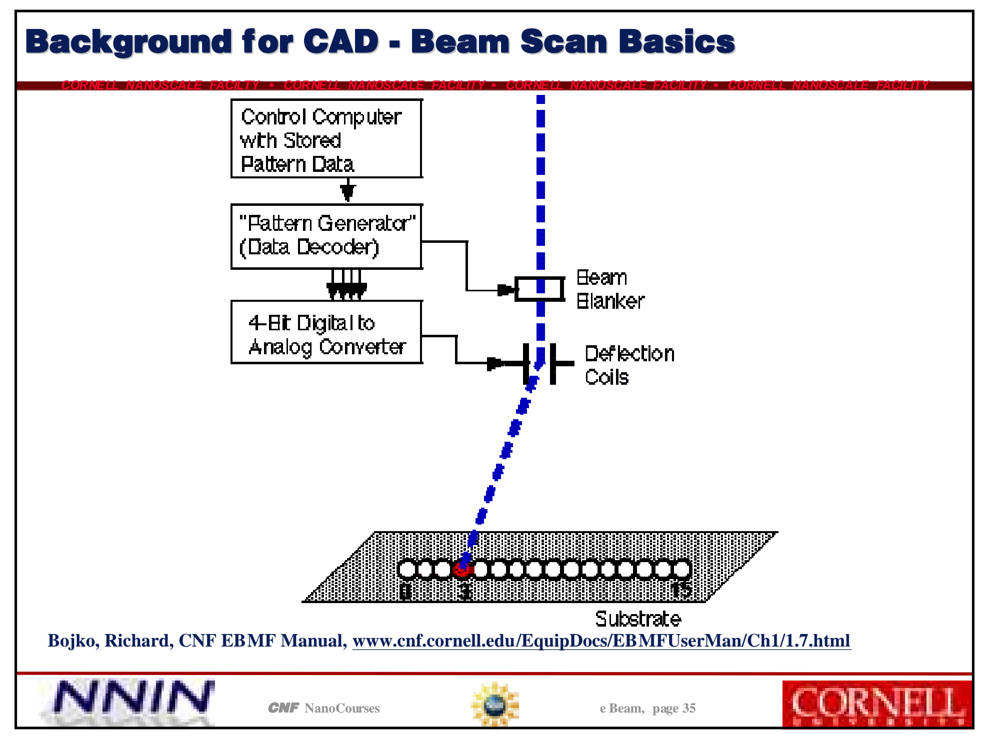
Background for CAD - Beam Scan Basics
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Control Computer with Stored Pattern Data
"Pattern Generator" (Data Decoder)
4-Bit Digital to Analog Converter
Beam Blanker
Deflection Coils
0
3
15
Substrate
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.7.html
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e Beam, page 35
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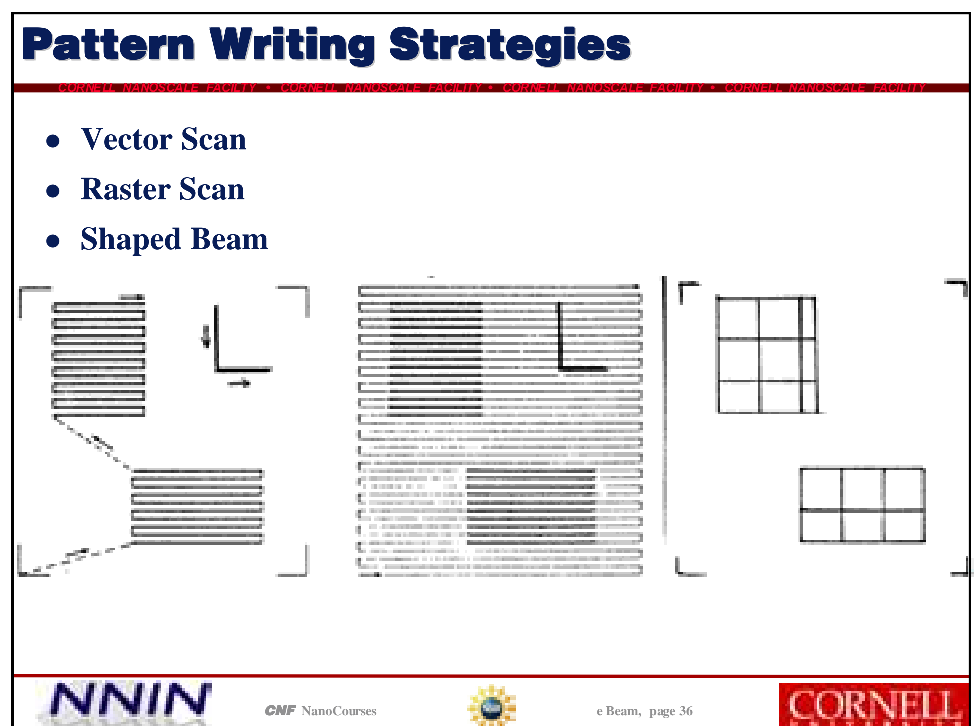
Pattern Writing Strategies
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Vector Scan
• Raster Scan
• Shaped Beam
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e Beam, page 36
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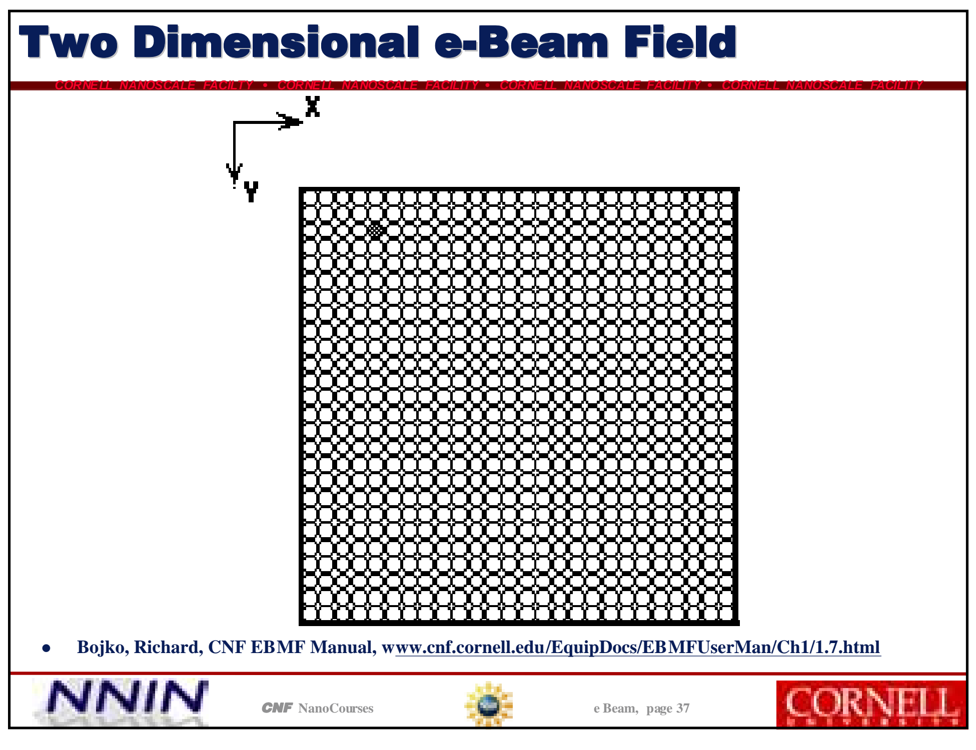
Two Dimensional e-Beam Field
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
X
Y
• Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.7.html
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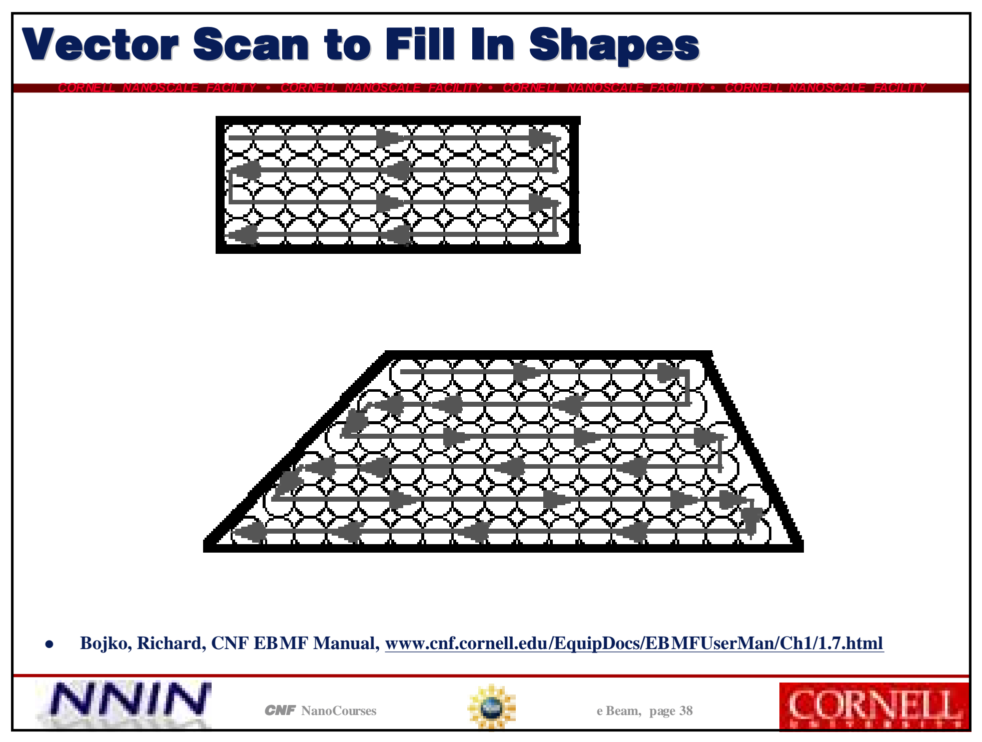
e Beam, page 37
CORNELL


Vector Scan to Fill In Shapes
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.7.html
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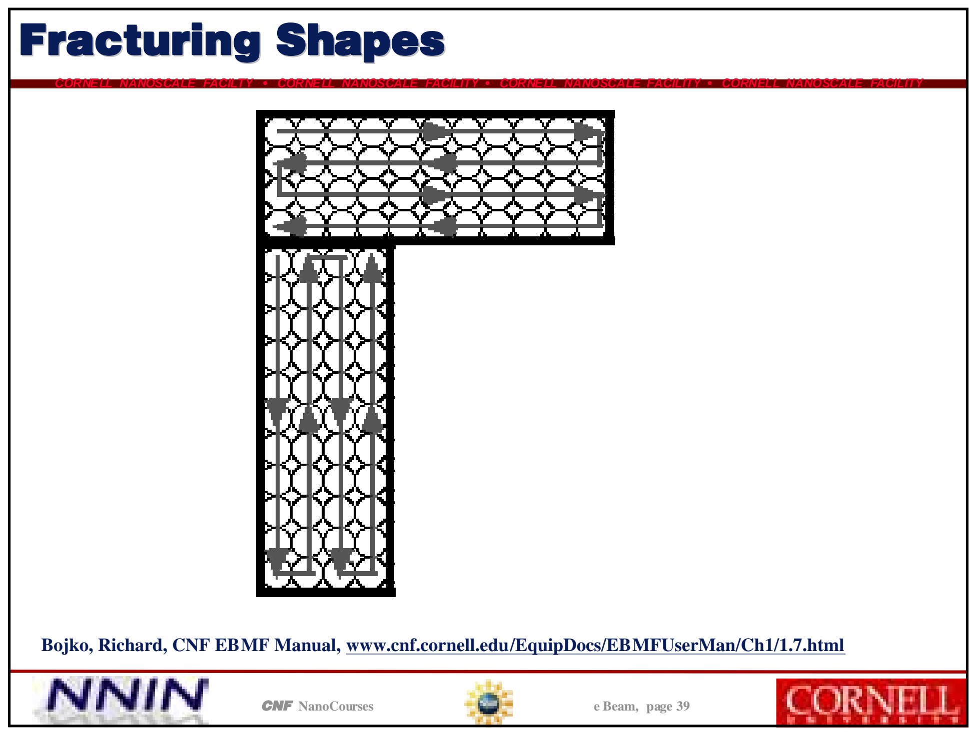
Fracturing Shapes
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.7.html
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CNF NanoCourses
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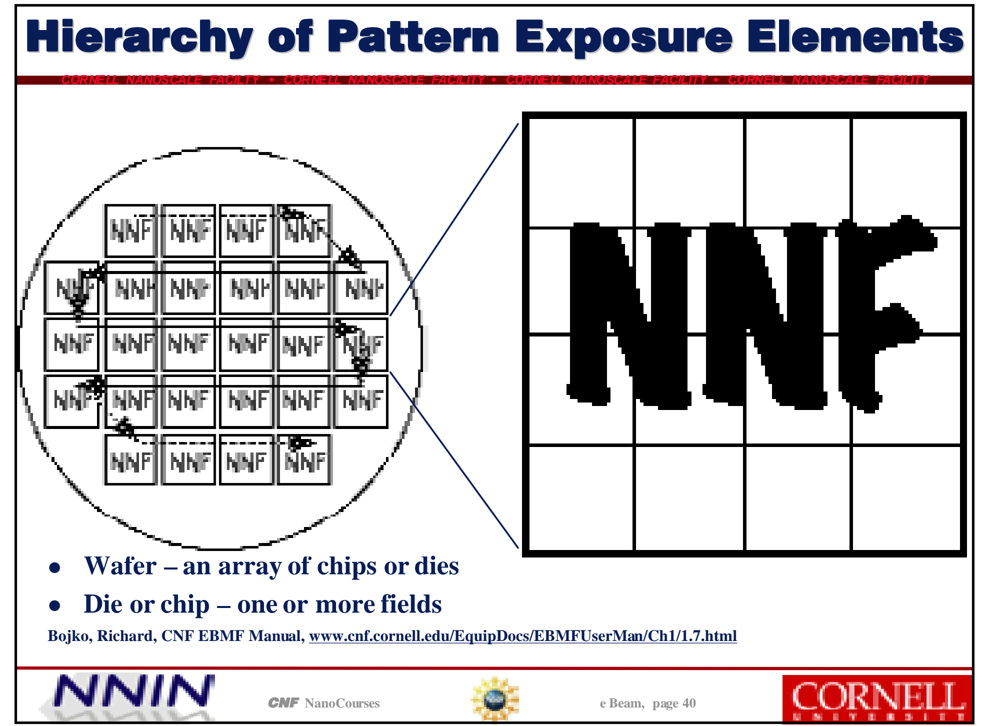
Hierarchy of Pattern Exposure Elements
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
NNF
• Wafer – an array of chips or dies
• Die or chip – one or more fields
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.7.html
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CNF NanoCourses
e Beam, page 40
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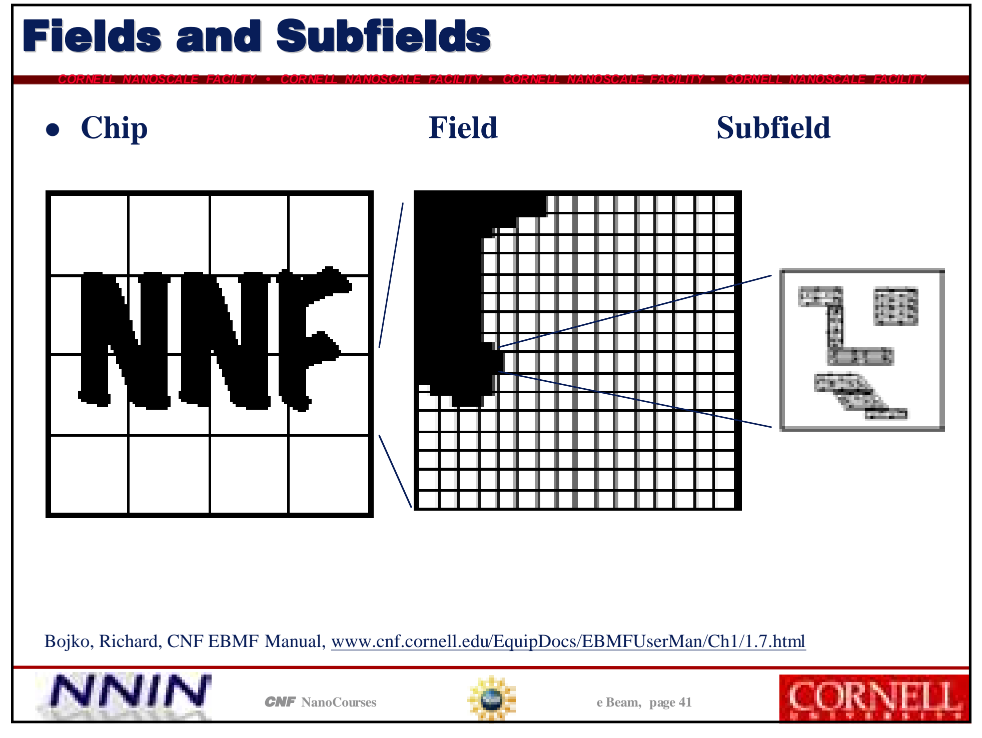
Fields and Subfields
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Chip
Field
Subfield
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.7.html
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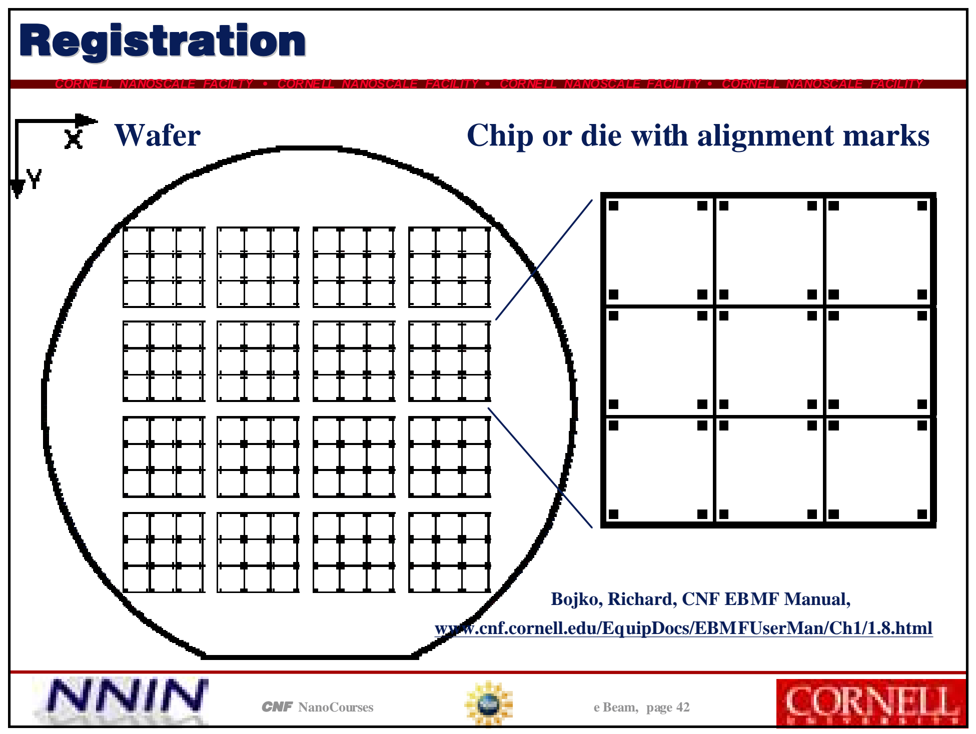
Registration
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
X
Y
Wafer
Chip or die with alignment marks
Bojko, Richard, CNF EBMF Manual,
www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch1/1.8.html
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Resolution, Current and Dose Issues

- Dose is charge/area, $\mu C/cm^2$

$$D = \frac{I \times t}{A} = \frac{I}{A \times f}$$

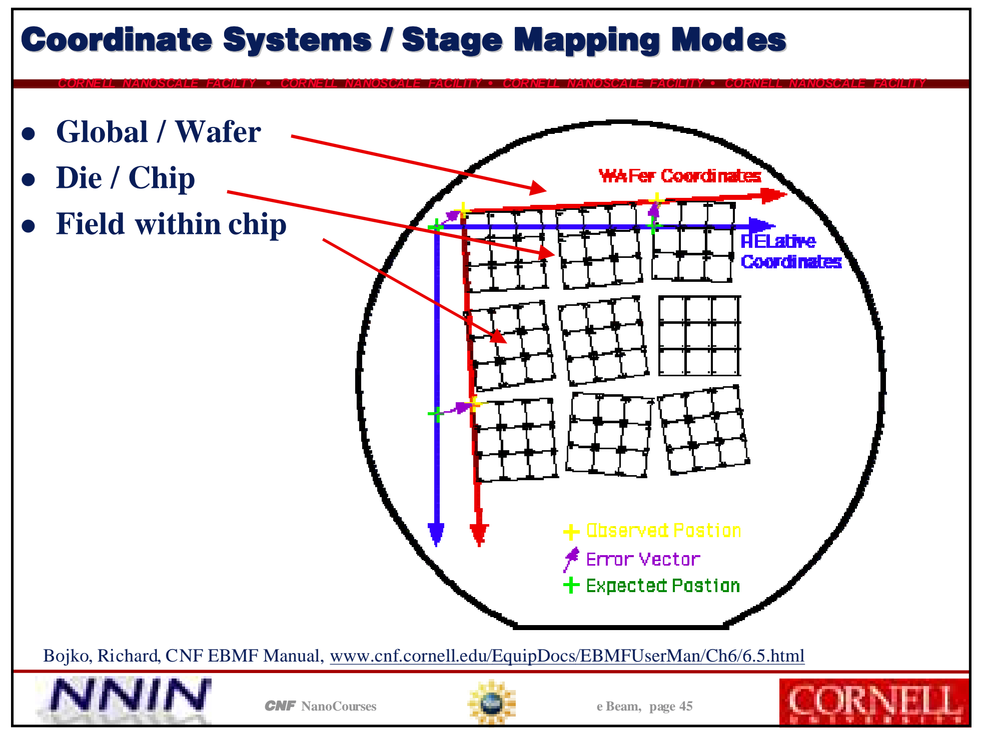
- I = current, typically 1, 2, 5, 10, 20, 50 nA
- A = area for a single beam step, e. g. 5 nm x 5 nm
- f = clock frequency
- Higher current -> faster write time, but lower resolution
- Stage moves (~ 1 s) may be major contributor to exposure time

Variable Resolution Unit (VRU) table

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- VRU is a multiple of smallest beam step size
- CFREQ command on VB6 calculates clock frequency, current, dose or exel (beam step) size
- Trade off current and beam step size to get high resolution and fast write time with less than max. clock frequency

VRU	Beam Step Size, nm	Min. Dose, uC/cm^2
1	5	160
2	10	40
4	20	10
8	40	2.5
16	80	0.63
32	160	0.16


Coordinate Systems / Stage Mapping Modes
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Global / Wafer
Die / Chip
Field within chip
WAFer Coordinates
RELative Coordinates
Observed Postion
Error Vector
Expected Postion
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.5.html
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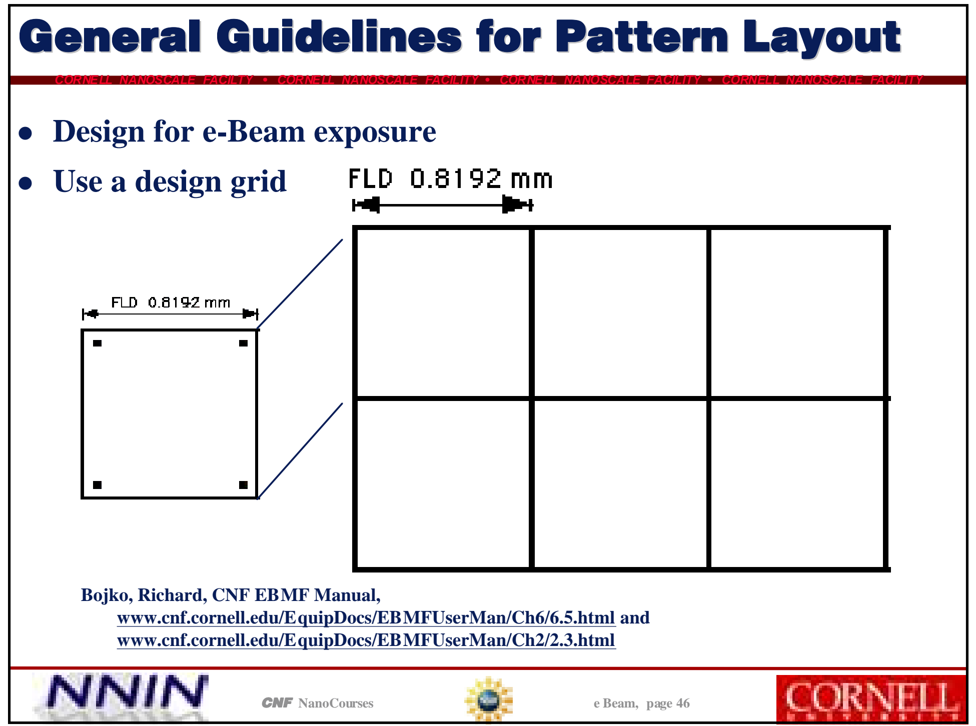
General Guidelines for Pattern Layout
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Design for e-Beam exposure
Use a design grid
FLD 0.8192 mm
FLD 0.8192 mm
Bojko, Richard, CNF EBMF Manual,
www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.5.html and
www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch2/2.3.html
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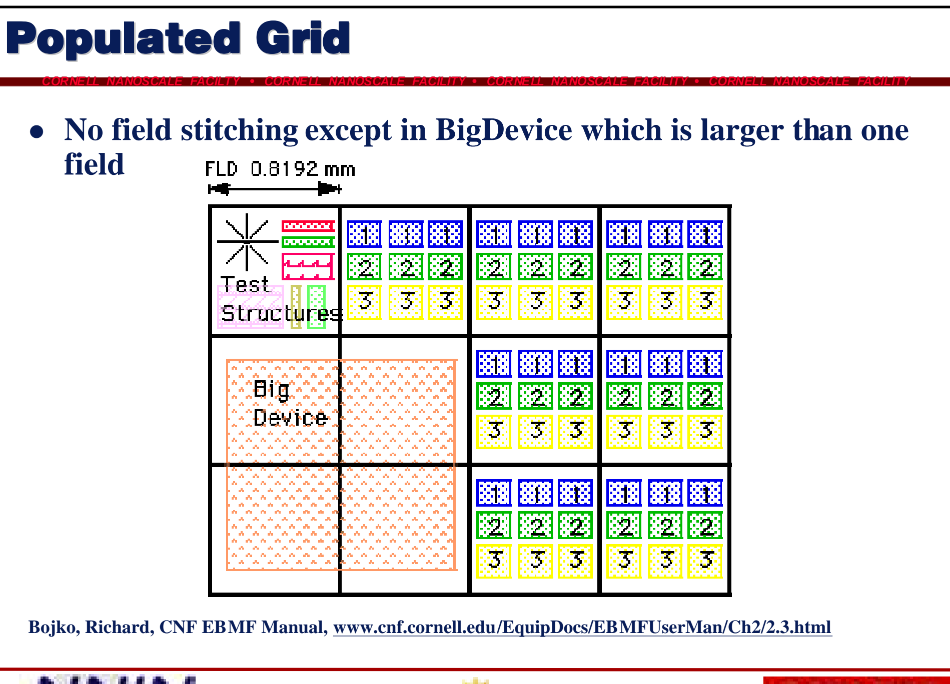
Populated Grid

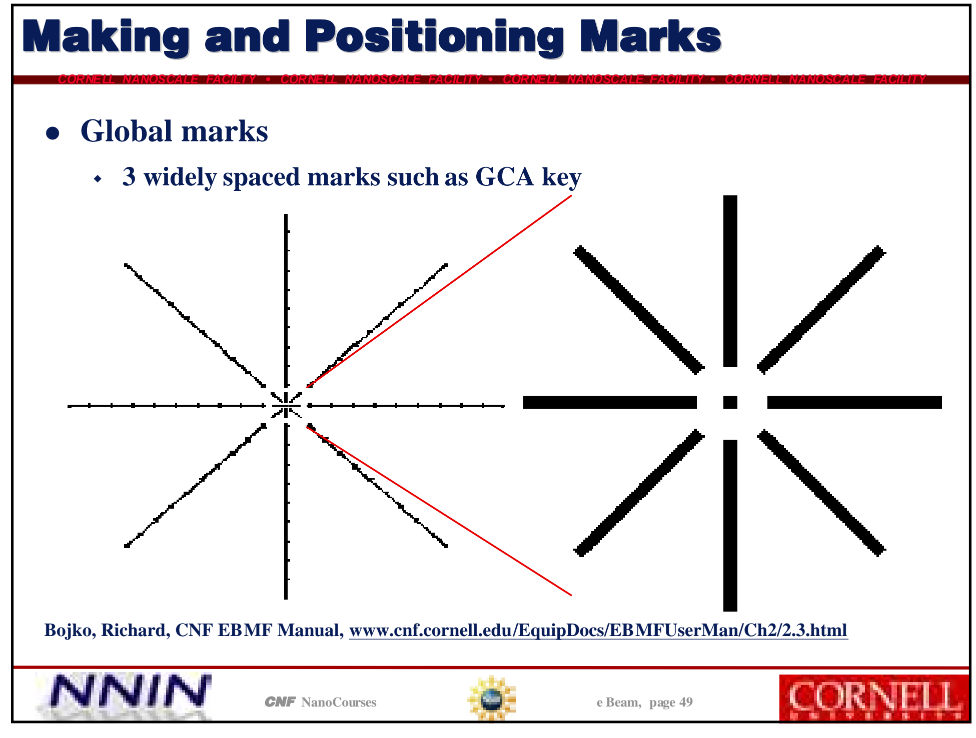
- No field stitching except in BigDevice which is larger than one field



Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch2/2.3.html

Combining e-Beam with Other Types of Lithography

- Alignment accuracy ~ 10 nm is achievable
- Techniques that make alignment marks visible (to your eye *and* to the machine) in a 100 keV scanning electron beam include
  - Specific shapes
    - Squares or octagons with 4-50 µm sides
  - Materials
    - 1 µm-deep etched pits in Si
    - 50 - 100 nm of Au, Pt, W liftoff metal (high atomic number difference between mark and substrate)
    - Al doesn't work on Si or GaAs substrates


Making and Positioning Marks
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Global marks
• 3 widely spaced marks such as GCA key
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch2/2.3.html
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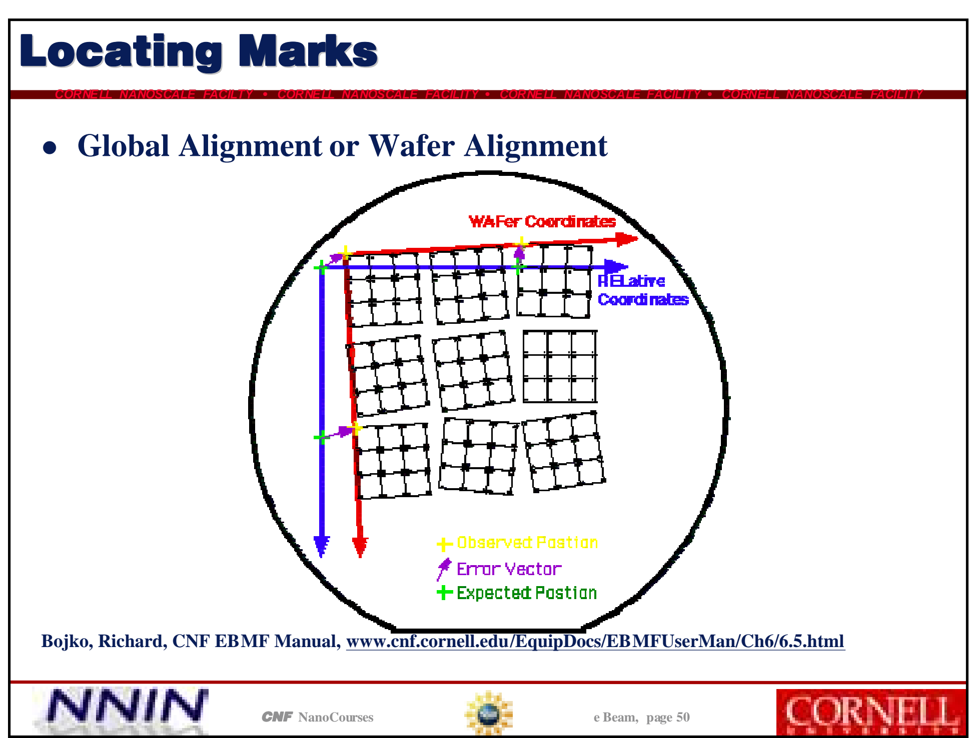
CORNELL


Locating Marks
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Global Alignment or Wafer Alignment
WAFer Coordinates
RELative Coordinates
Observed Postion
Error Vector
Expected Postion
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.5.html
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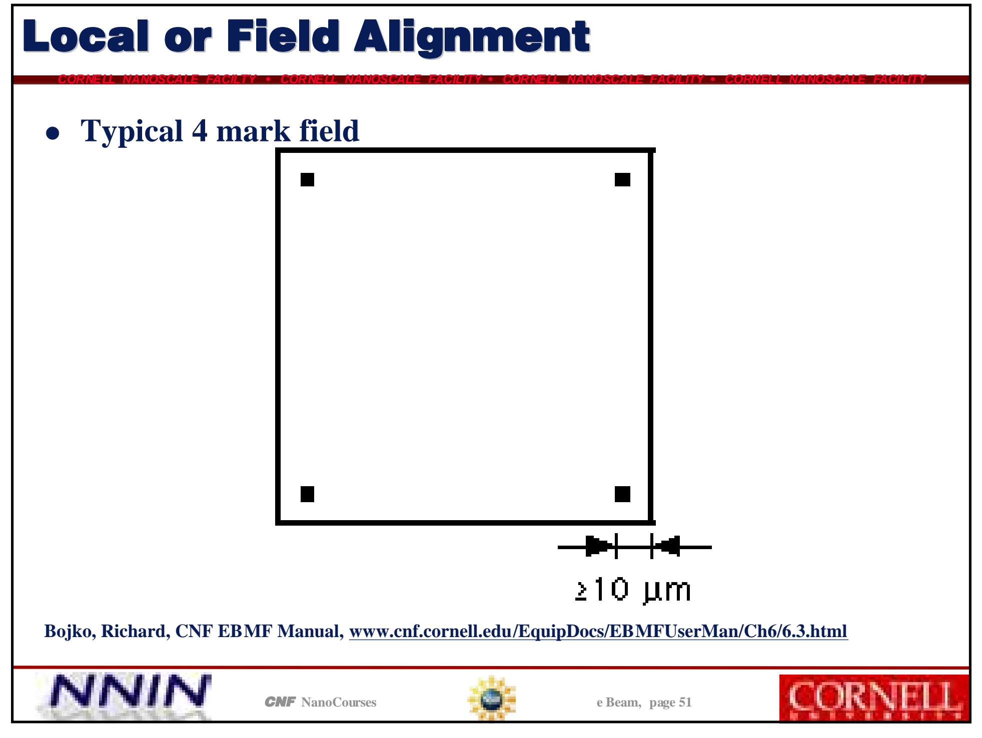
Local or Field Alignment
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Typical 4 mark field
≥10 µm
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.3.html
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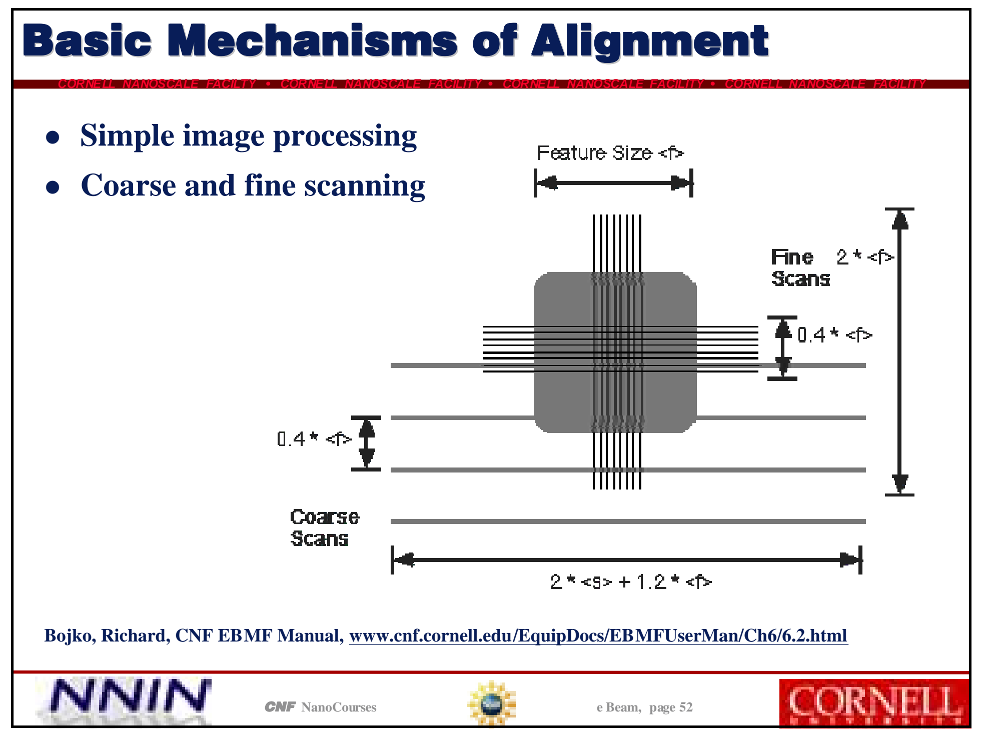
Basic Mechanisms of Alignment
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Simple image processing
• Coarse and fine scanning
Feature Size <f>
Fine Scans
2 * <f>
0.4 * <f>
0.4 * <f>
Coarse Scans
2 * <s> + 1.2 * <f>
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.2.html
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CNF NanoCourses
e Beam, page 52
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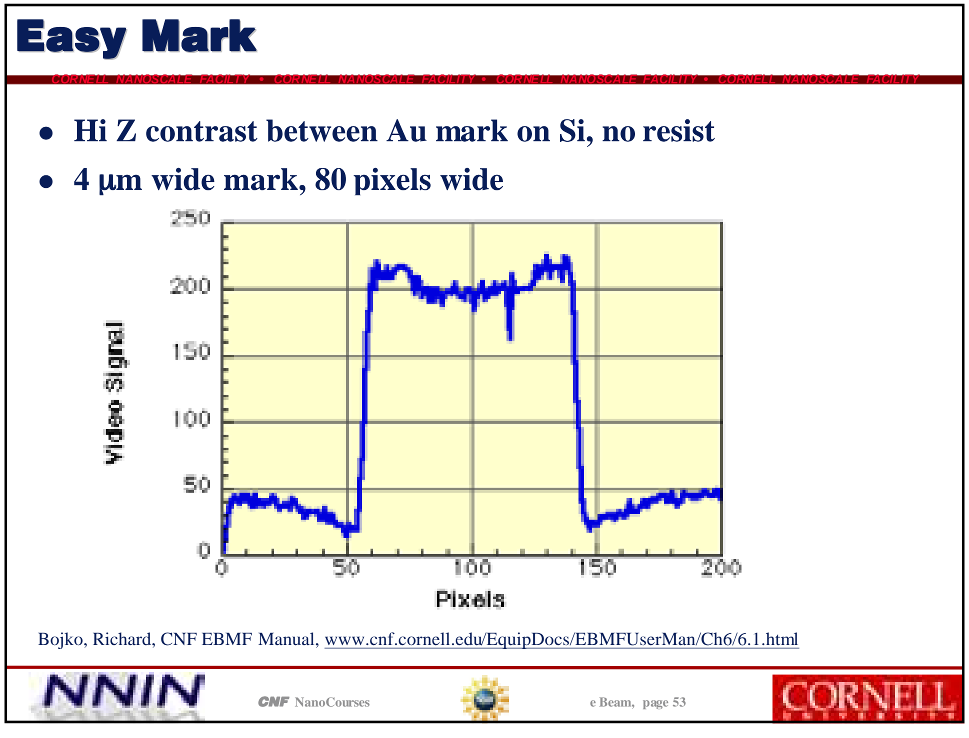
Easy Mark
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Hi Z contrast between Au mark on Si, no resist
• 4 µm wide mark, 80 pixels wide
Video Signal
250
200
150
100
50
0
0
50
100
150
200
Pixels
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.1.html
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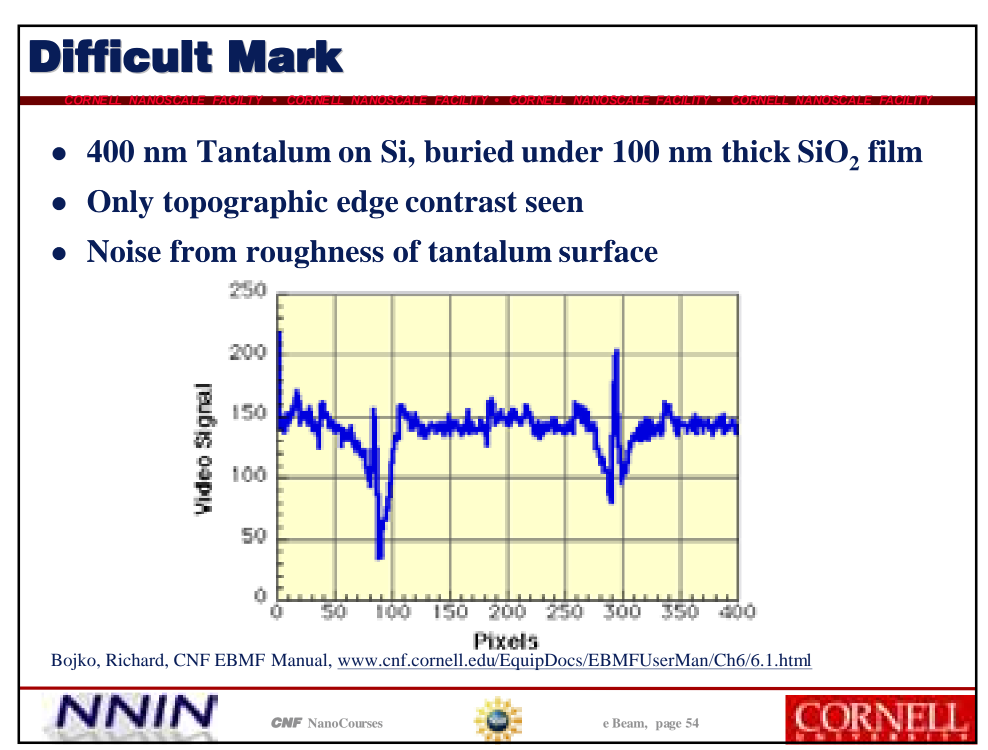
Difficult Mark
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• 400 nm Tantalum on Si, buried under 100 nm thick SiO2 film
• Only topographic edge contrast seen
• Noise from roughness of tantalum surface
Video Signal
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
Pixels
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.1.html
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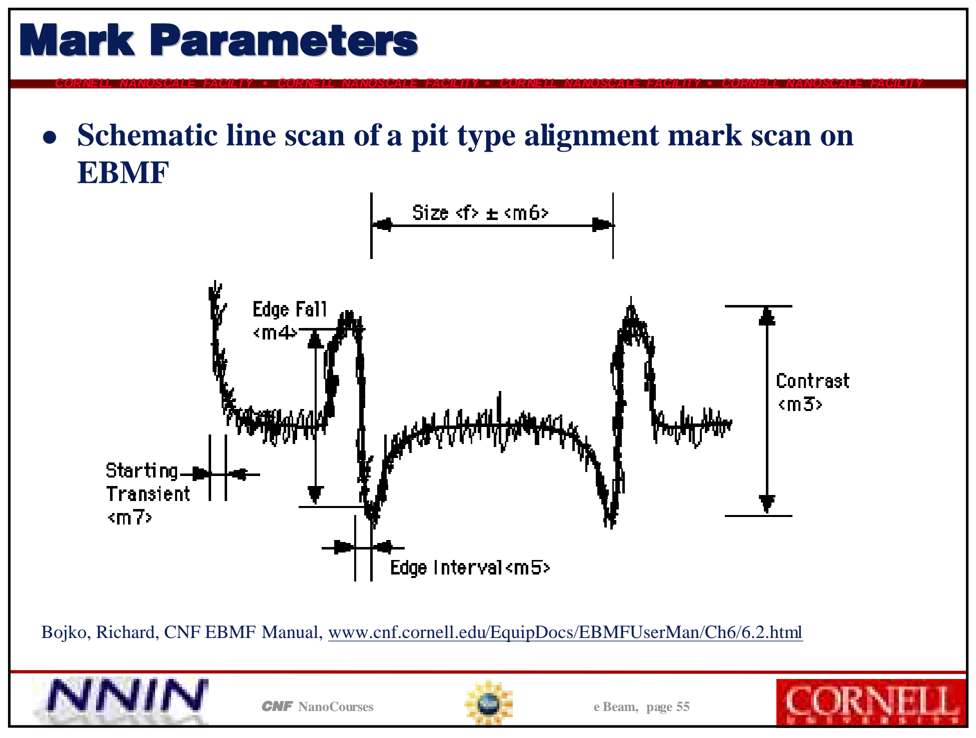
Mark Parameters
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Schematic line scan of a pit type alignment mark scan on EBMF
Size <f> ± <m6>
Edge Fall
<m4>
Contrast
<m3>
Starting
Transient
<m7>
Edge Interval <m5>
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.2.html
NNIN
CNF NanoCourses
e Beam, page 55
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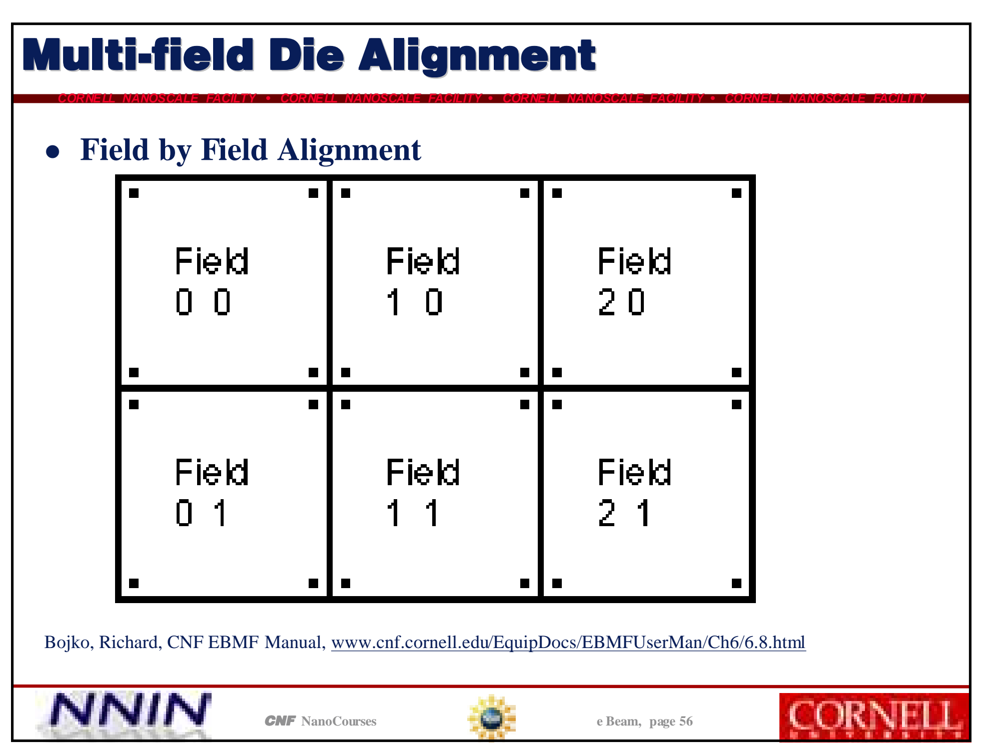
Multi-field Die Alignment
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Field by Field Alignment
Field
0 0
Field
1 0
Field
2 0
Field
0 1
Field
1 1
Field
2 1
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch6/6.8.html
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e Beam, page 56
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Resists and Processing

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- Positive resists
  - PMMA
  - Toray EBR-9
  - PBS
  - ZEP
  - Photoresists as e-beam resists
- Negative resists
  - COP
  - Shipley SAL
  - NEB-31
- Multilayer systems
  - Low/high molecular weight PMMA
  - PMMA/copolymer
  - Trilayer systems

Poly(methyl methacrylate) (PMMA)

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- The most popular e-Beam resist
- Extremely high-resolution
- Easy handling
- Excellent film characteristics
- Wide process latitude
- Usually dissolved in a solvent (e.g. anisole)
- Exposure causes scission of the polymer chains
- Solvent developer dissolves exposed (lighter molecular weight) resist

PMMA Characteristics

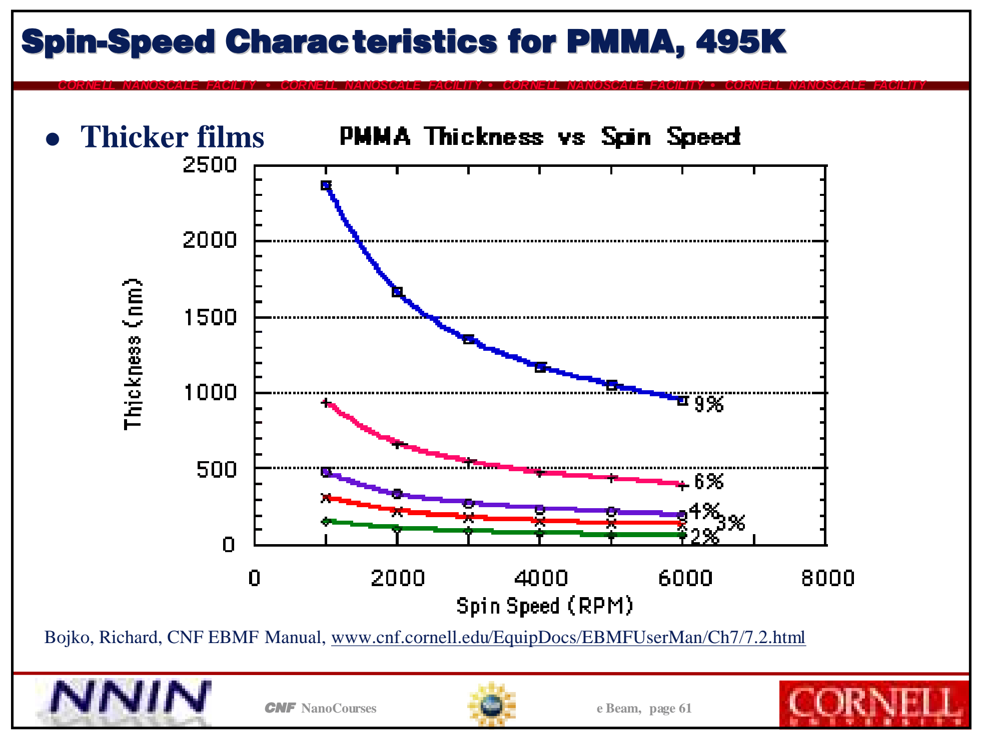
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- Positive acting
- Several viscosities available, allowing a wide range of resist thickness
- Not sensitive to white light
- Developer mixtures can be adjusted to control contrast and profile
- Appropriate processing results in undercut profile for liftoff
- Poor dry etch resistance
- No shelf life or film life issues

PMMA Basic Processing

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- Surface Preparation
  - In general, no surface preparation (aside from normal cleaning) is necessary. Excellent adhesion to most surfaces
- Spin
  - Speed 1000-5000 rpm, 60 sec. (100-1000 nm)
- Pre-bake
  - 170 deg C oven, 1 hr. Non-critical. Must be 150 < T < 200 degrees, for at least 30 minutes. May also be hot-plate baked
- Expose
  - Dose around 100 $\mu C/cm^2$ at 20 kV


Spin-Speed Characteristics for PMMA, 495K
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Thicker films
PMMA Thickness vs Spin Speed
Thickness (nm)
Spin Speed (RPM)
2500
2000
1500
1000
500
0
0
2000
4000
6000
8000
9%
6%
4%
3%
2%
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch7/7.2.html
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CNF NanoCourses
e Beam, page 61
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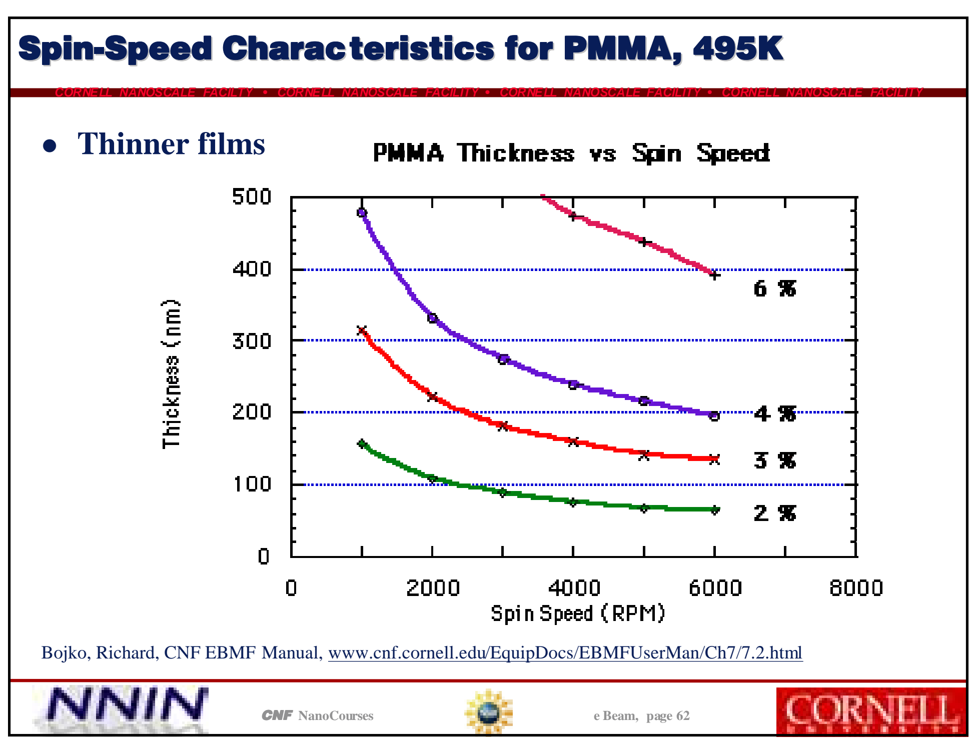
Spin-Speed Characteristics for PMMA, 495K
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Thinner films
PMMA Thickness vs Spin Speed
Thickness (nm)
Spin Speed (RPM)
500
400
300
200
100
0
0
2000
4000
6000
8000
6 %
4 %
3 %
2 %
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch7/7.2.html
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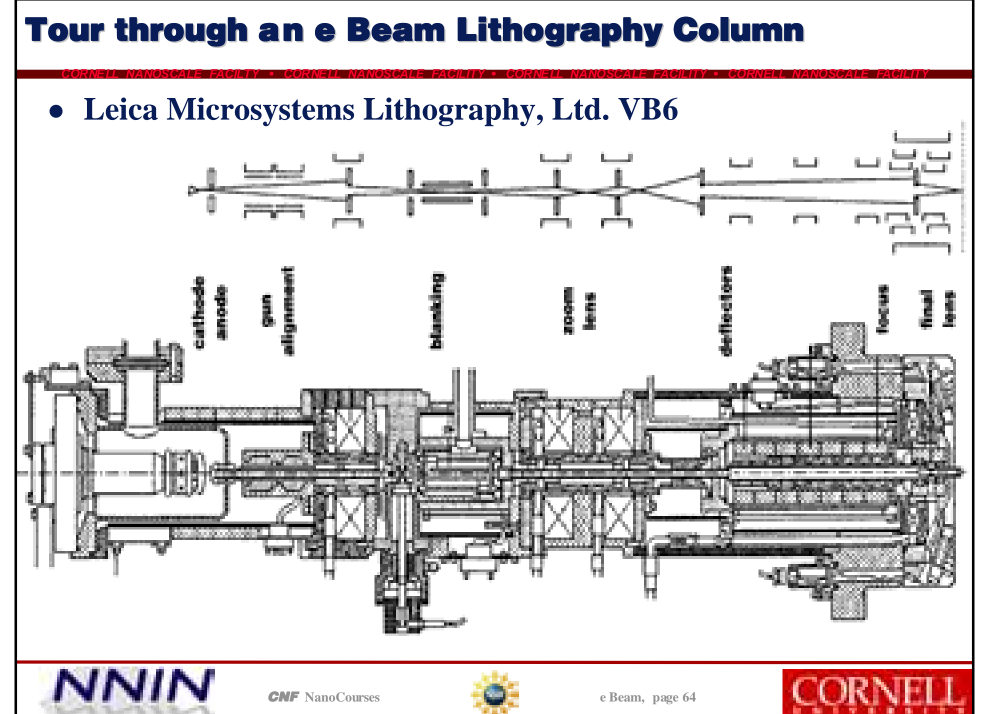
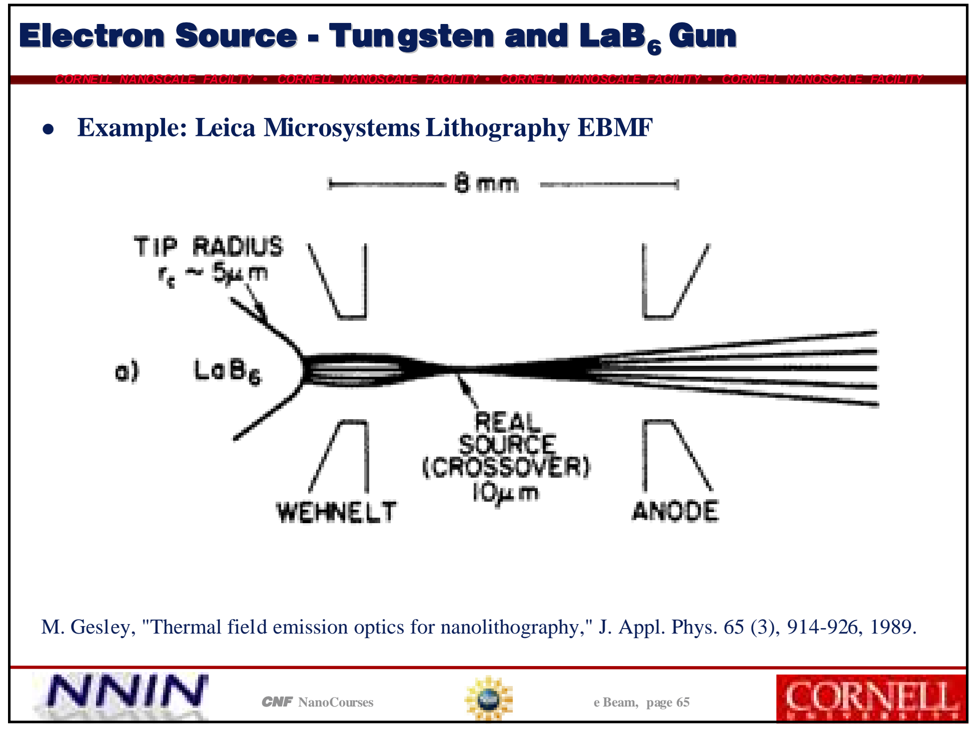
P(MMA-MAA) Copolymer Resist

- Higher sensitivity than PMMA
  - Can be exposed at a lower dose
  - Faster
  - Less contrast
- Most useful in Bi-level resists with PMMA, to produce undercut profiles useful in liftoff processing
- Characteristics
  - Positive acting
  - Several viscosities available, allowing a wide range of resist thickness
  - Not sensitive to white light
  - Developer mixtures can be adjusted to control contrast and profile
  - Poor dry etch resistance
  - No shelf life or film life issues

Tour through an e Beam Lithography Column

- **Leica Microsystems Lithography, Ltd. VB6**




Electron Source - Tungsten and LaB_6 Gun
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Example: Leica Microsystems Lithography EBMF
8 mm
TIP RADIUS
$r_t \sim 5\mu m$
a)
LaB_6
WEHNELT
REAL
SOURCE
(CROSSOVER)
$10\mu m$
ANODE
M. Gesley, "Thermal field emission optics for nanolithography," J. Appl. Phys. 65 (3), 914-926, 1989.
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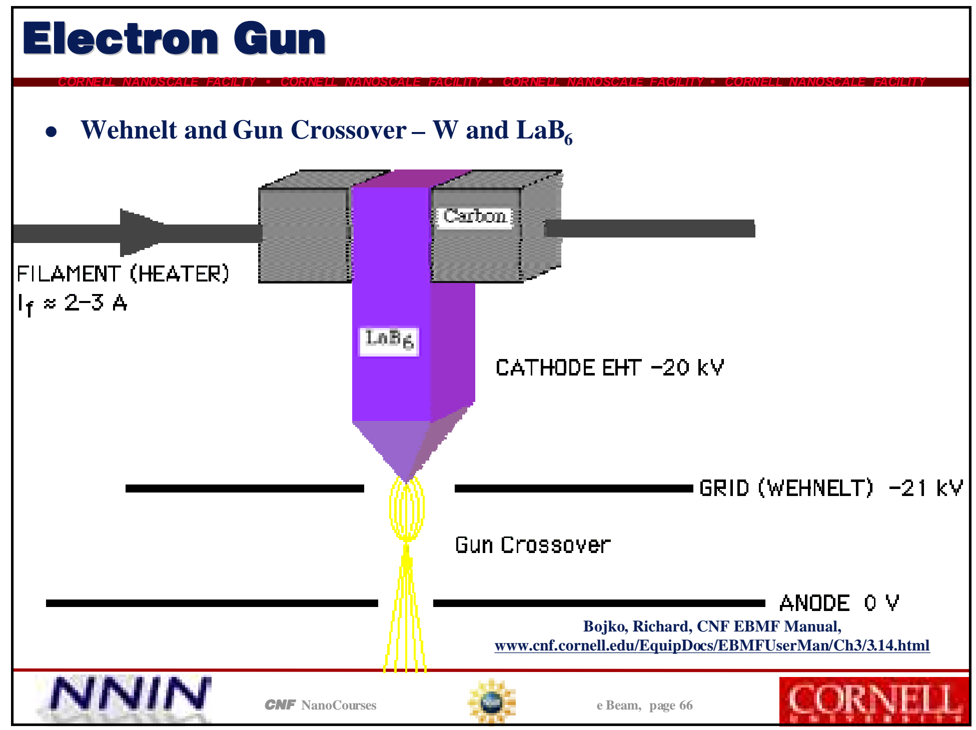
Electron Gun
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Wehnelt and Gun Crossover – W and LaB_6
Carbon
FILAMENT (HEATER)
$I_f \approx 2\text{-}3$ A
LaB_6
CATHODE EHT -20 kV
GRID (WEHNELT) -21 kV
Gun Crossover
ANODE 0 V
Bojko, Richard, CNF EBMF Manual,
www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.14.html
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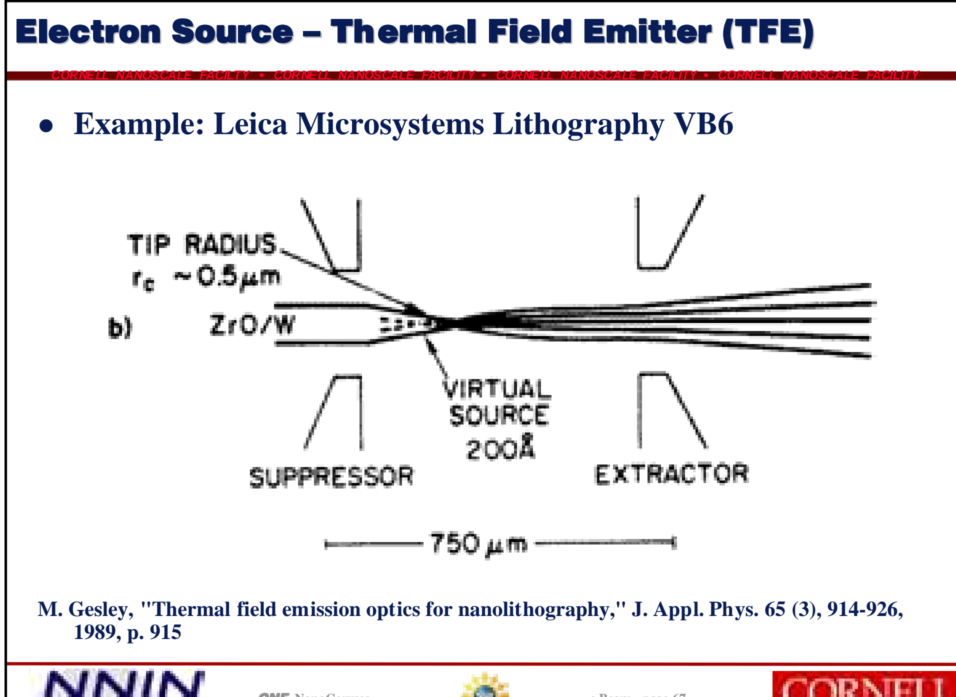


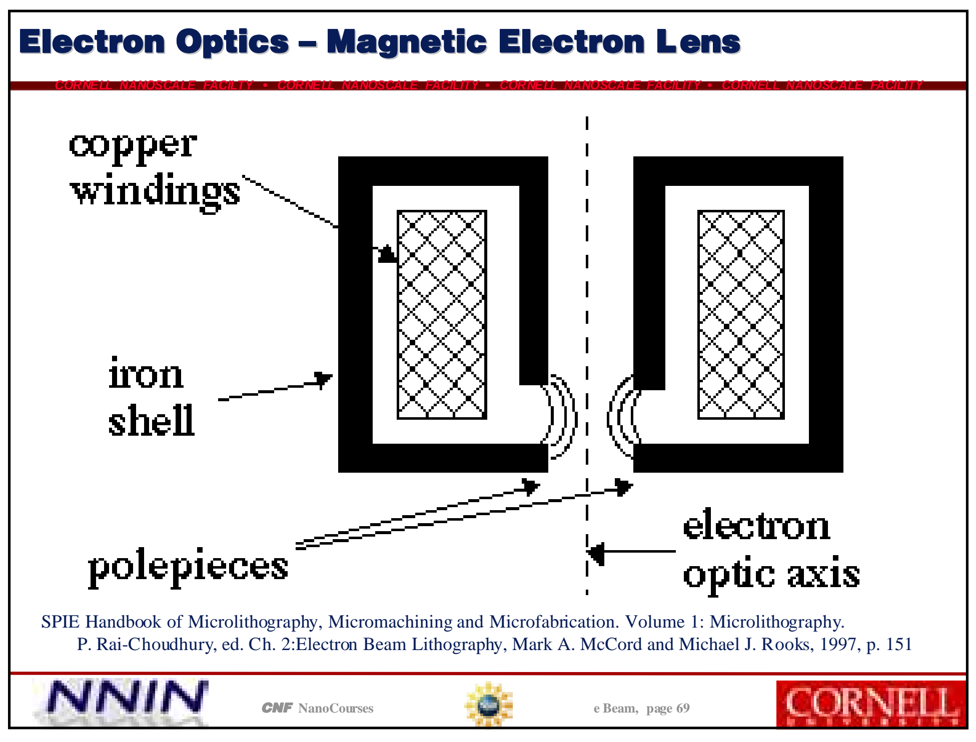
Comparison of Electron Sources

Comparison of Electron Sources at 20 kV

Source	Brightness	Lifetime	Source size	Energy spread ΔE	Beam current Stability	References
Tungsten						
hairpin	10^5 A/cm²sr	40–100 h	30–100 μm	1–3 eV	1%	a,b
LaB_6	10^6	200–1000	5–50 μm	1–2	1%	b,c
Field Emission						
Cold	10^8	>1000	<5 nm	0.3	5%	d,e
Thermal	10^8	>1000	<5 nm	1	5%	e
Schottky	10^8	>1000	15–30 nm	0.3–1.0	2%	e

[a] Haine and Cosslett (1961).
[b] Troyon (1987).
[c] Broers (1974).
[d] Crewe et al. (1971).
[e] Tuggle et al. (1985).

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al., Plenum Press)


Electron Optics – Magnetic Electron Lens
copper windings
iron shell
polepieces
electron optic axis
SPIE Handbook of Microlithography, Micromachining and Microfabrication. Volume 1: Microlithography.
P. Rai-Choudhury, ed. Ch. 2:Electron Beam Lithography, Mark A. McCord and Michael J. Rooks, 1997, p. 151
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e Beam, page 69
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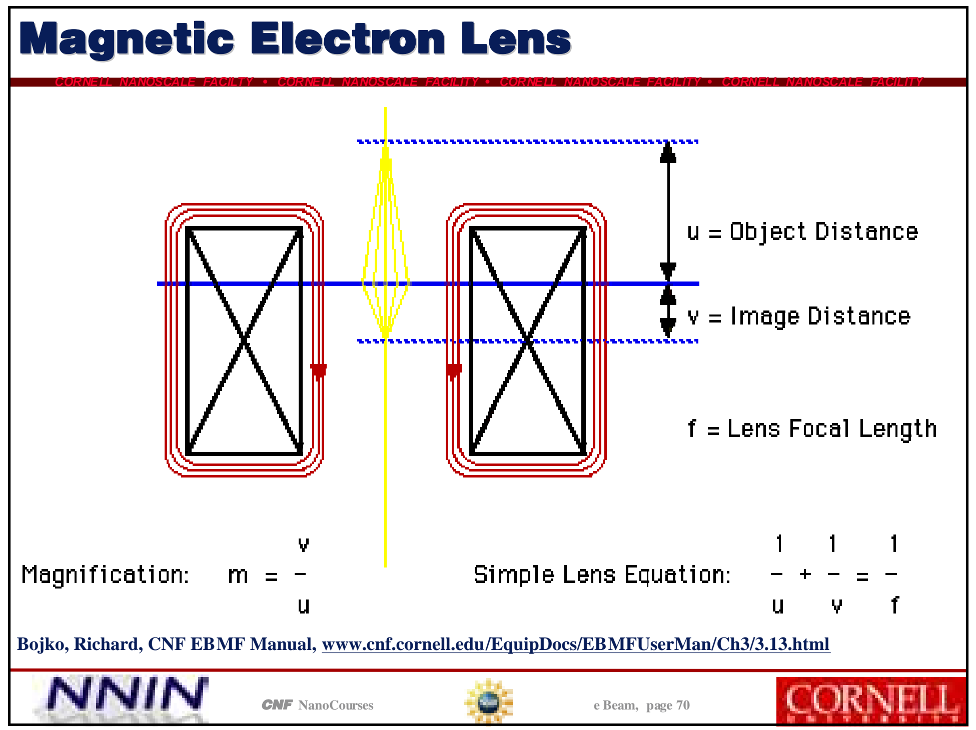
Magnetic Electron Lens
u = Object Distance
v = Image Distance
f = Lens Focal Length
Magnification: m = v/u
Simple Lens Equation: 1/u + 1/v = 1/f
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.13.html
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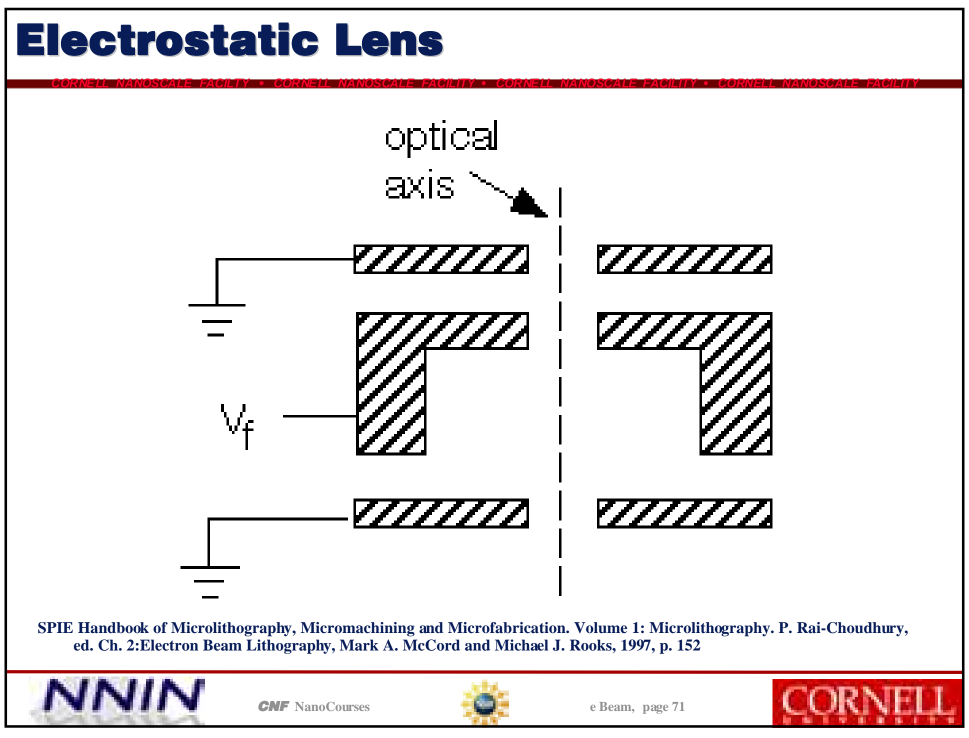


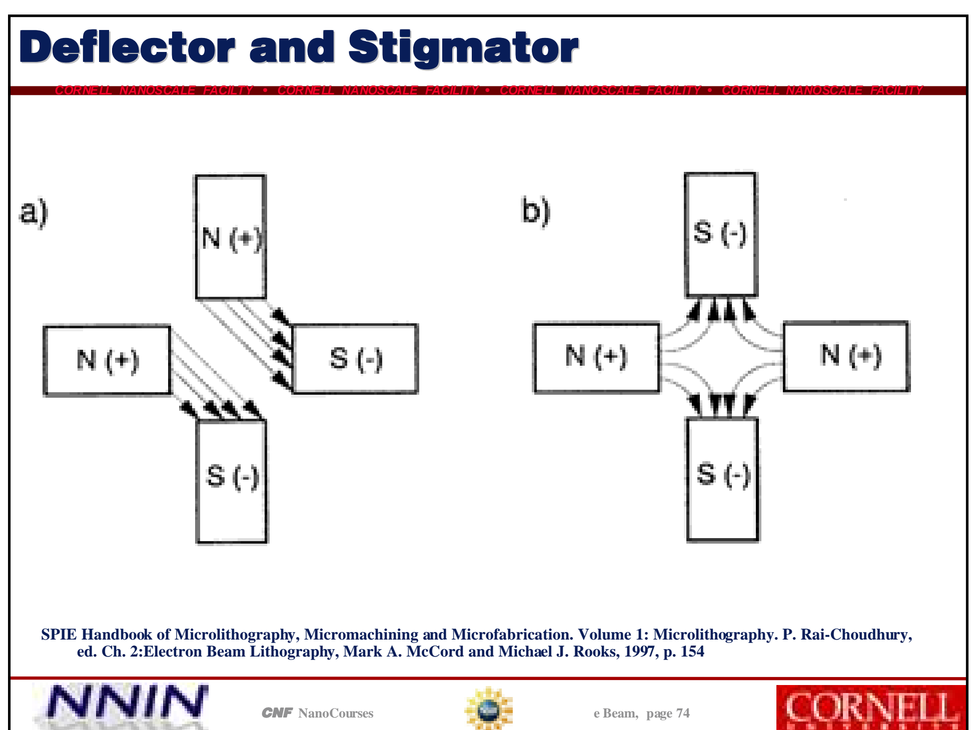
Other Electron Optical Elements

- Beam blanking
- Stigmators
- Electron beam deflection
- Apertures

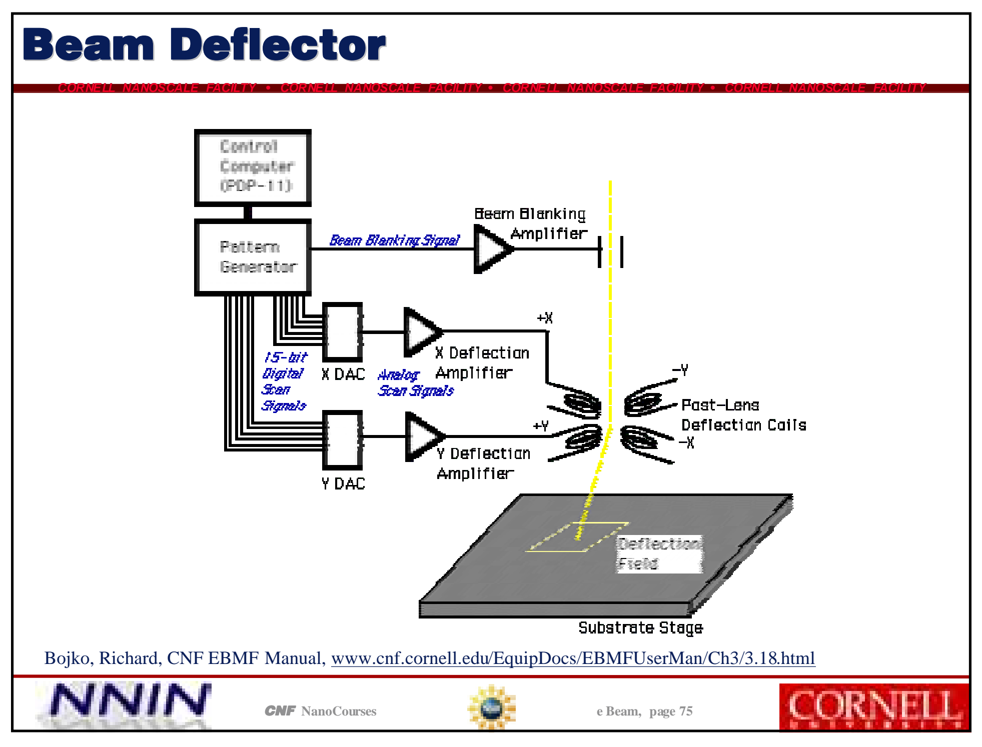
Beam Blanking

- Turning the beam on and off
- Usually accomplished with a pair of plates set up as an electrostatic deflector
- One or both of the plates are connected to a blanking amplifier with a fast response time
- Voltage applied across plates sweeps beam off axis until it is intercepted by a downstream aperture
- *Conjugate blanking*
  - Beam at target does not move while the blanking plates are activated
  - Prevents leaving streaks in the resist as beam is blanked
  - Blanking plates are centered at an intermediate focal point, or crossover

Deflector and Stigmator



SPIE Handbook of Microlithography, Micromachining and Microfabrication. Volume 1: Microlithography. P. Rai-Choudhury, ed. Ch. 2:Electron Beam Lithography, Mark A. McCord and Michael J. Rooks, 1997, p. 154


Beam Deflector
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Control Computer (PDP-11)
Pattern Generator
Beam Blanking Signal
Beam Blanking Amplifier
15-bit Digital Scan Signals
X DAC
Analog Scan Signals
X Deflection Amplifier
+X
-Y
Post-Lens Deflection Coils
+Y
-X
Y DAC
Y Deflection Amplifier
Deflection Field
Substrate Stage
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.18.html
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e Beam, page 75
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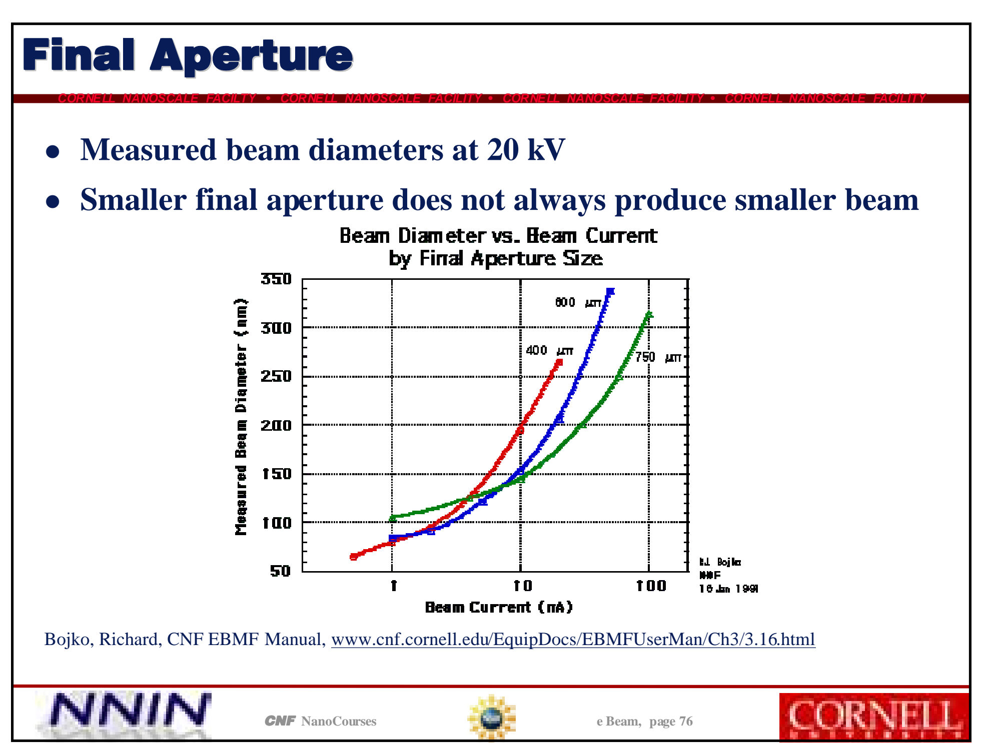
Final Aperture
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Measured beam diameters at 20 kV
• Smaller final aperture does not always produce smaller beam
Beam Diameter vs. Beam Current by Final Aperture Size
Measured Beam Diameter (nm)
350
300
250
200
150
100
50
1
10
100
Beam Current (nA)
400 µm
600 µm
750 µm
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.16.html
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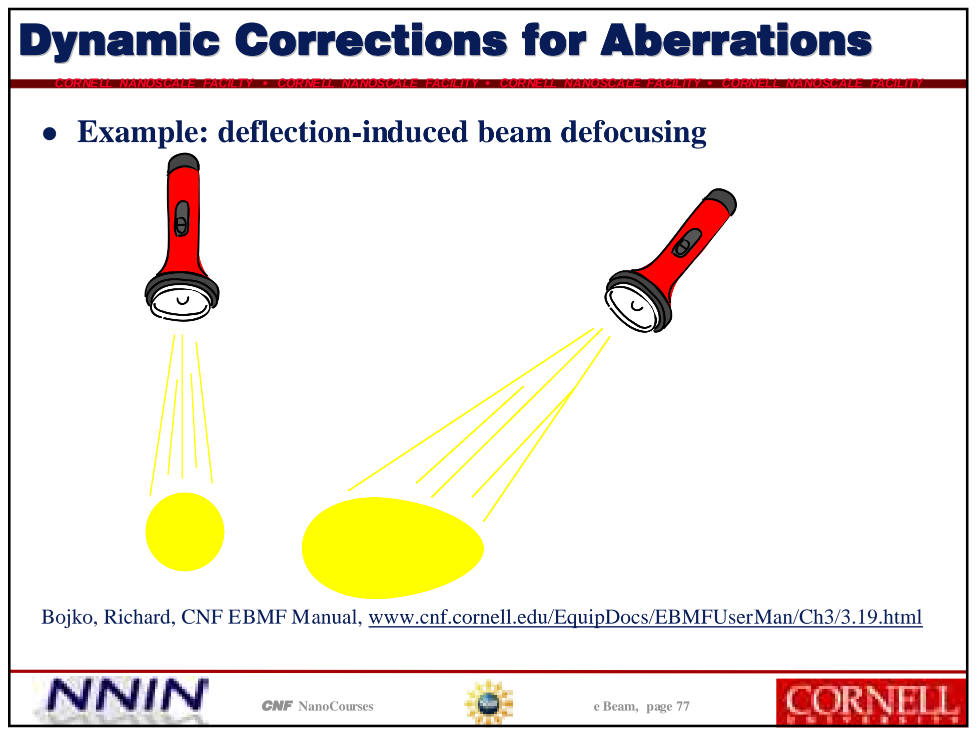
Dynamic Corrections for Aberrations
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Example: deflection-induced beam defocusing
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.19.html
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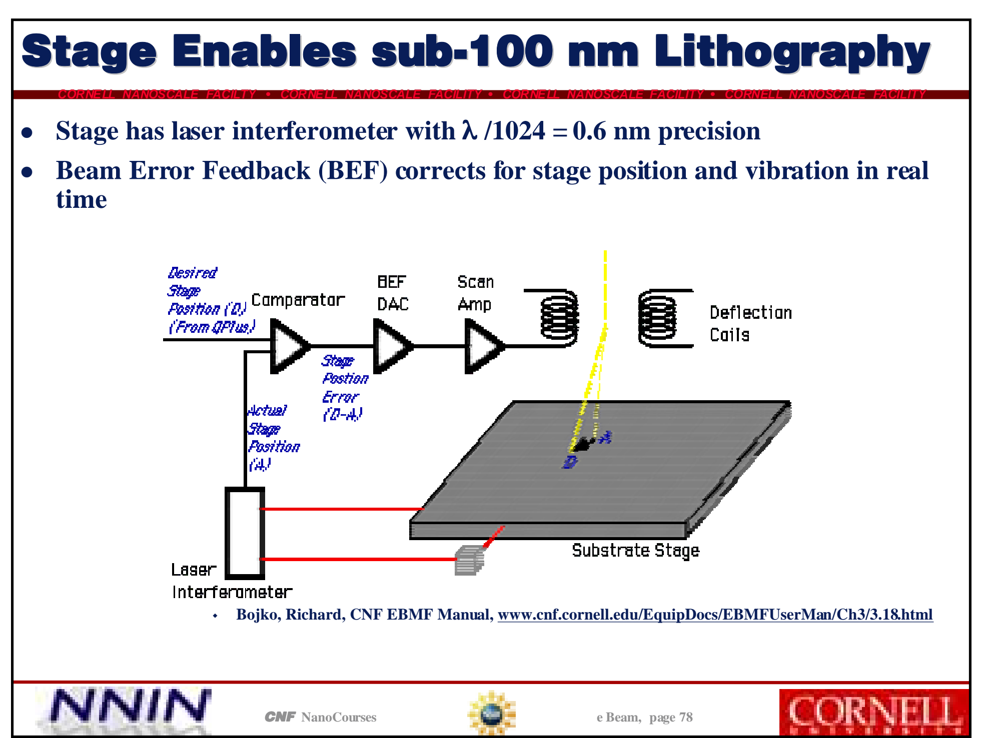
Stage Enables sub-100 nm Lithography
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
• Stage has laser interferometer with λ /1024 = 0.6 nm precision
• Beam Error Feedback (BEF) corrects for stage position and vibration in real time
Desired Stage Position (D) (From QPlus)
Comparator
BEF DAC
Scan Amp
Deflection Coils
Stage Postion Error (D-A)
Actual Stage Position (A)
Substrate Stage
Laser Interferometer
• Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.18.html
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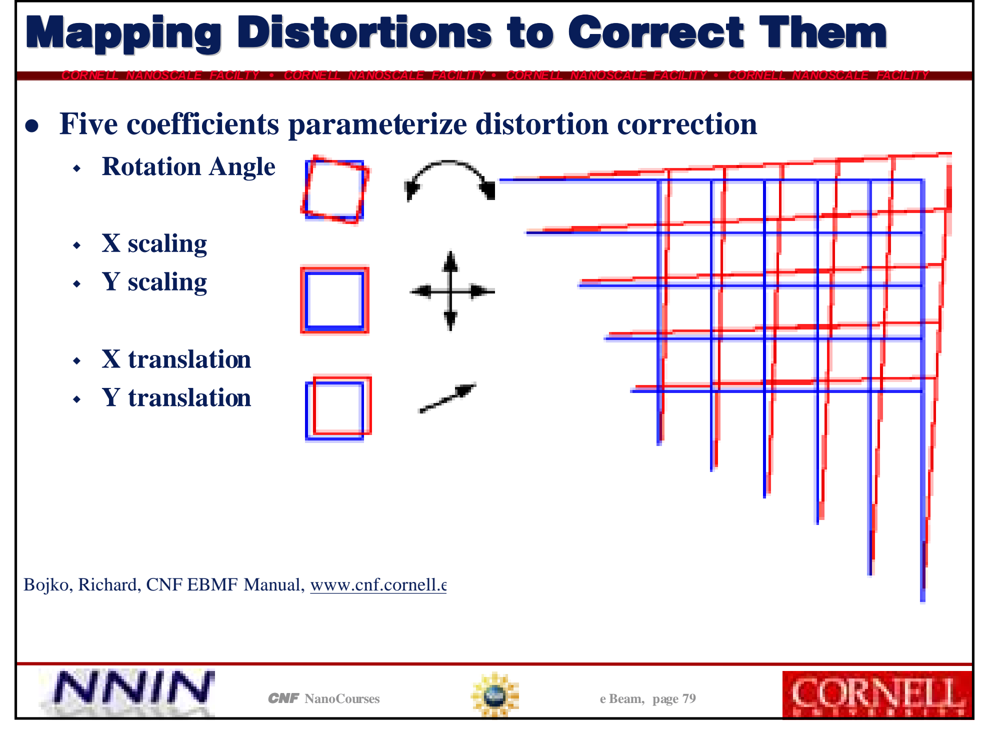
Mapping Distortions to Correct Them
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
Five coefficients parameterize distortion correction
Rotation Angle
X scaling
Y scaling
X translation
Y translation
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.e
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CNF NanoCourses
e Beam, page 79
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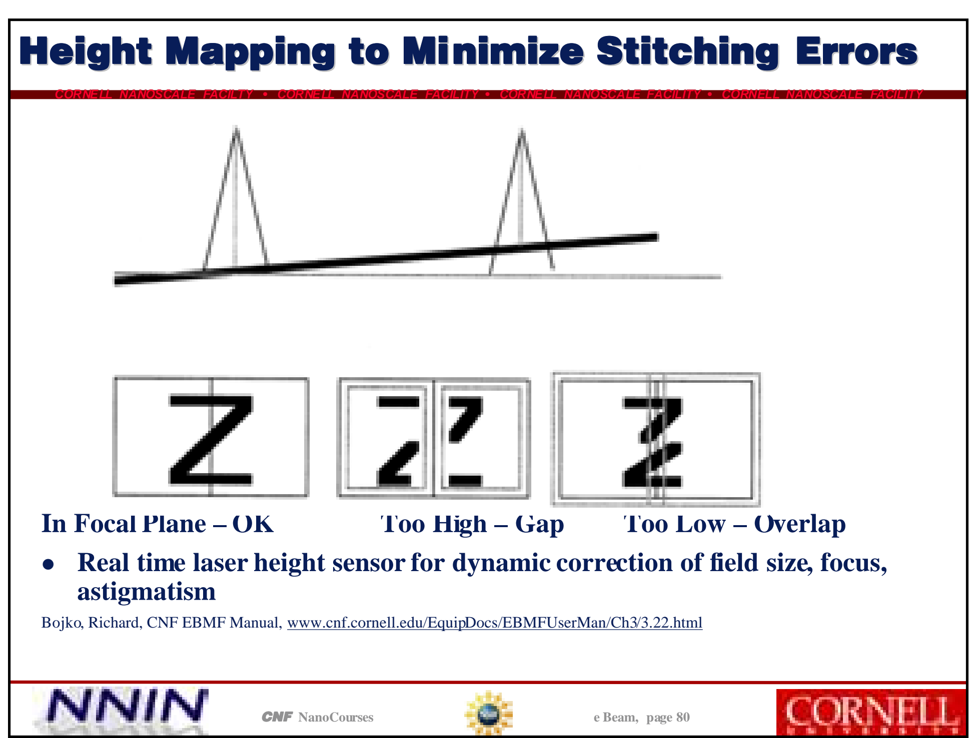
Height Mapping to Minimize Stitching Errors
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY
In Focal Plane – OK
Too High – Gap
Too Low – Overlap
Real time laser height sensor for dynamic correction of field size, focus, astigmatism
Bojko, Richard, CNF EBMF Manual, www.cnf.cornell.edu/EquipDocs/EBMFUserMan/Ch3/3.22.html
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Typical Exposure Sequence

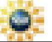
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- Ready the airlock for venting
- Vent the airlock
- Load the wafer into a chuck
- Load the chuck into the airlock
- Pump the airlock back to vacuum
- Load and settle the chuck on the exposure stage
- Set up the machine operating parameters
- Run your exposure job file
- Unload chuck
- Remove the chuck from the airlock

PMMA Basic Processing – post exposure

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- Develop
  - 1:1 MIBK:IPA, 1-2 minutes
- Rinse with IPA
- Dry by spinning or dry N_2
- Post-Bake not normally necessary
- Light Descum
- Stripping
  - Acetone will strip PMMA
  - NMP (Remover 1165)
  - Strong bases (KOH)
  - Acid normally hostile to organics, such as NanoStrip
  - Oxygen plasmas etch PMMA very well

CNF NanoCourses


CNF e-Beam Systems

CNF has 3 complementary systems

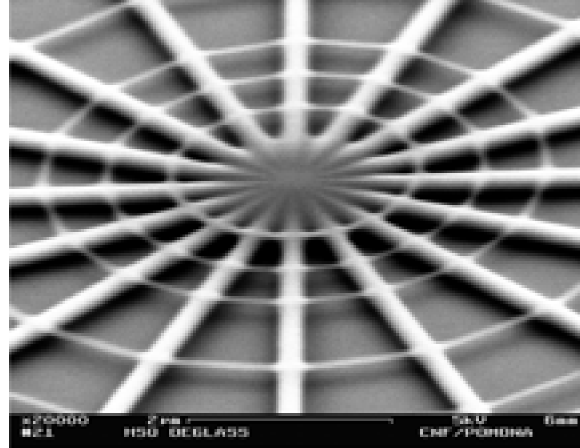
CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

1. Nabity Nanometer Pattern Generation System (NPGS) on LEO SEM
2. Leica VB6 HR
3. JEOL 9300FS

Nabity Nanometer Pattern Generation System (NPGS)

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- PC-based pattern generator
- Interfaced to a LEO 982 scanning electron microscope
- 1 to 30 keV



David Tanenbaum
(Pomona College)

Leica VB6-HR

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- For features from above 1 µm to below 30 nm
- Thermal Field Emission electron source running at 100 kV provides high brightness and small source size
- Minimum feature sizes < 30 nm are possible
- Field sizes up to 655 µm
- Beam currents as high as 50 nA
- Flexible job control language

JEOL 9300FS

CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY • CORNELL NANOSCALE FACILITY

- General purpose high-resolution electron-beam lithography
- Thermal Field Emitter electron source at 100 kV
- Beam spot size 4 nm
- Repeatable minimum resolution < 20 nm
- Pixel step 1 nm
- Placement and automated alignment accuracies of 20 nm over a 0.5 mm field
- Max 25 MHz clock, 20-bit pattern generator
- Wafers and masks up to 12 inches
- Upgrades to 50 MHz clock and 1 mm field size in future

References and Acknowledgements

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