TRANSFORMED

High Impact Technology Exchange Conference

JULY 29–30

A home developed lithography code to enhance the learning experiences in nanotechnology courses

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Presenter:

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MNT e SIG

MICRO NANO TECHNOLOGY
education
SPECIAL INTEREST GROUP

Lithography in a nutshell

- In the semiconductor world, lithography is the printing technology used to **mass-produce** chips like microprocessors, memory and flash that are at the heart of electronic devices.
- Around **30%-40% of the total cost** during IC manufacturing

Intel Transistor Leadership

2003	2005	2007	2009	2011
90 nm	65 nm	45 nm	32 nm	22 nm
Invented SiGe Strained Silicon	2nd Gen. SiGe Strained Silicon	Invented Gate-Last High-k Metal Gate	2nd Gen. Gate-Last High-k Metal Gate	First to Implement Tri-Gate

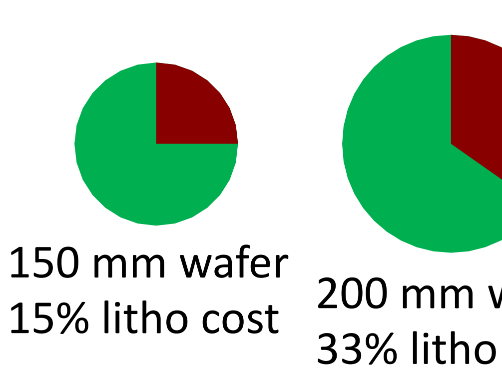
Strained Silicon
High-k Metal Gate
Tri-Gate

intel

bsn*

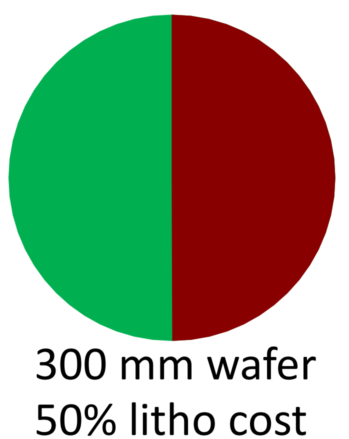
Components per chip
100000000000
10000000000
1000000000
100000000
10000000
1000000
100000
10000
1000
100
10
1
1959 1969 1979 1989 1999 2009 2019
Year
Flash
DRAM
Logic
25 µm
25 nm
feature size + die size + device cleverness

Lithography in a nutshell



150 mm wafer
15% litho cost

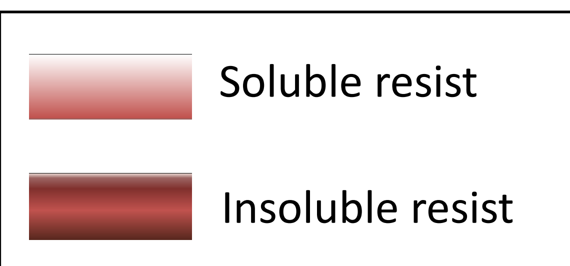
200 mm wafer
33% litho cost

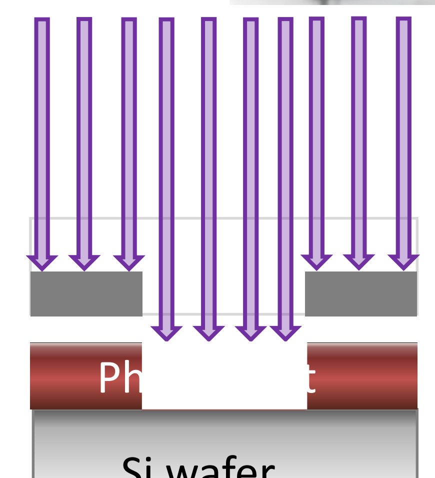


300 mm wafer
50% litho cost

75 million $$$

This was an example of positive lithography: What shows goes





Quartz Photomask

Develop soluble resist

Lithography in a nutshell

Prepare Wafer

Coat with Photoresist

Prebake

Align and Expose

Develop

Etch, Imp

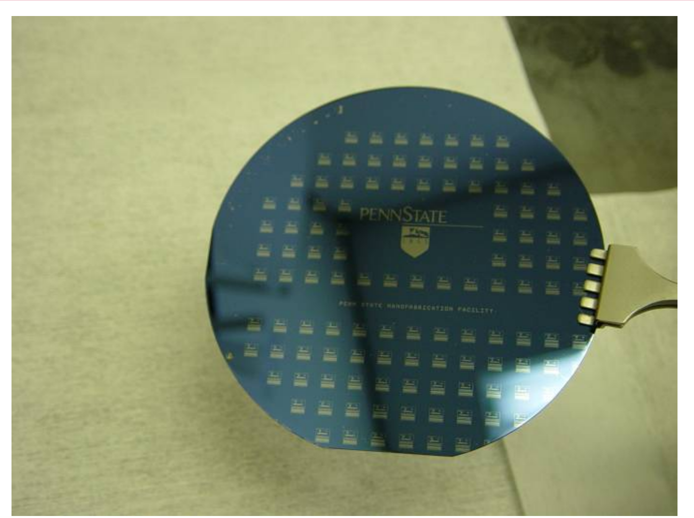
Strip Resi

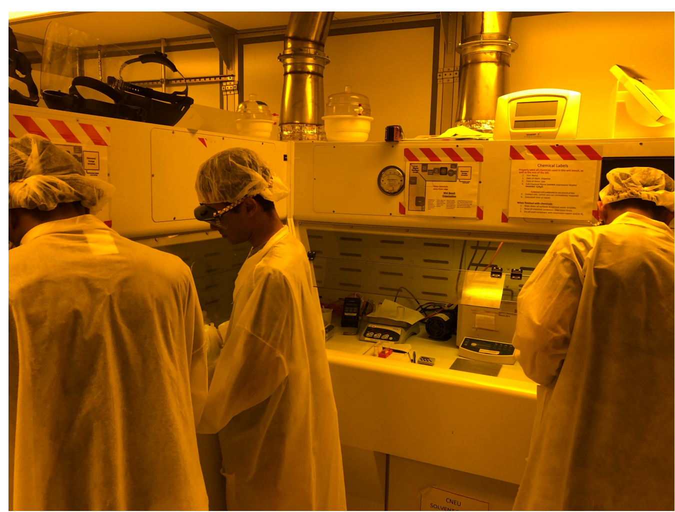
"I DON'T KNOW WHAT THIS IS, BUT YOU SHOULD SEE HOW FAST IT'S GROWING!"

© Can Stock Photo - csp1674040

Wafer Coating Prebake Expose Developing Metrology

Students at work





Students at work

light

mask

lens

Ideal light intensity

Sharp dose profile

light

Actual light intensity

“blurred” dose profile

Width

photoresist

Θ

Students at work

Positive Photoresist (Shipley 1813) results
Profilometer Scan (left) – Optical Microscope (right)

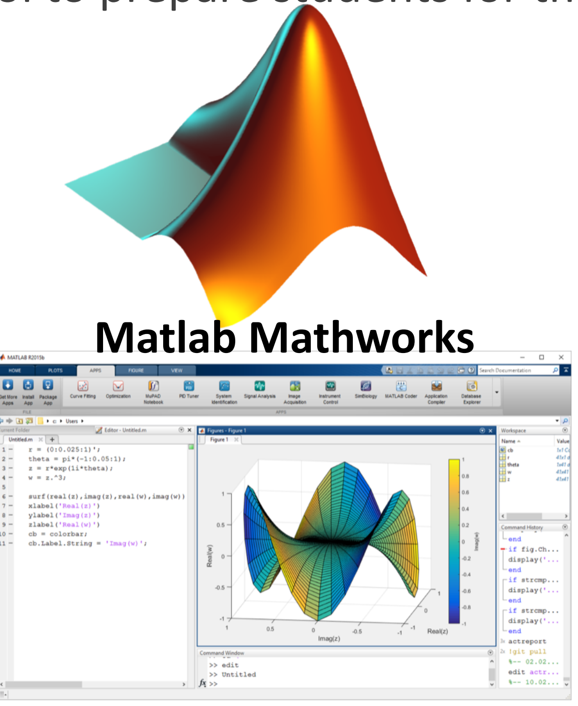
Ideal Exposure: 26 seconds

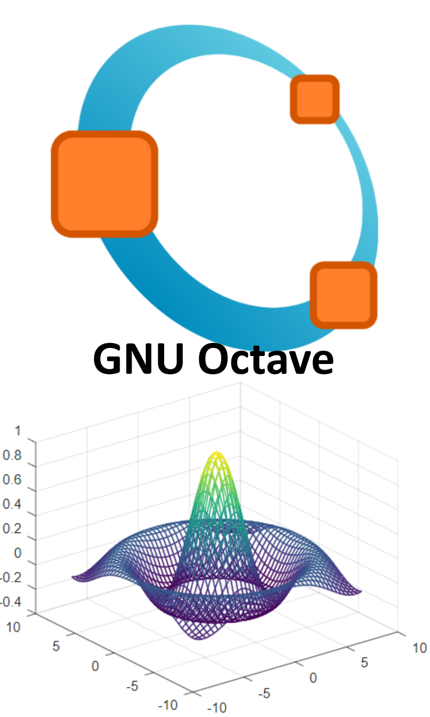
Over Exposure: 30 seconds

Over Exposure: 36 seconds

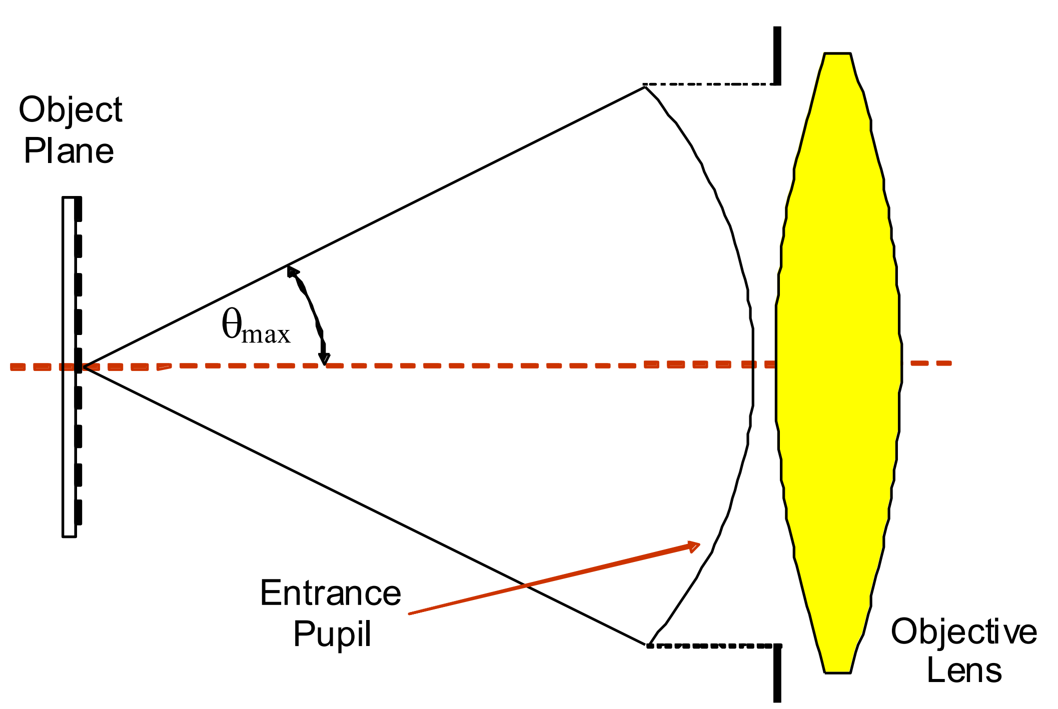
A simulation tool to mimic the process

- A free tool to teach students lithography
- A tool to allow students try different parameters, combinations **quickly and convincingly**
- A tool to allow cases that cannot be realized in the lab due to **costs**
- A tool to prepare students for the **next level**

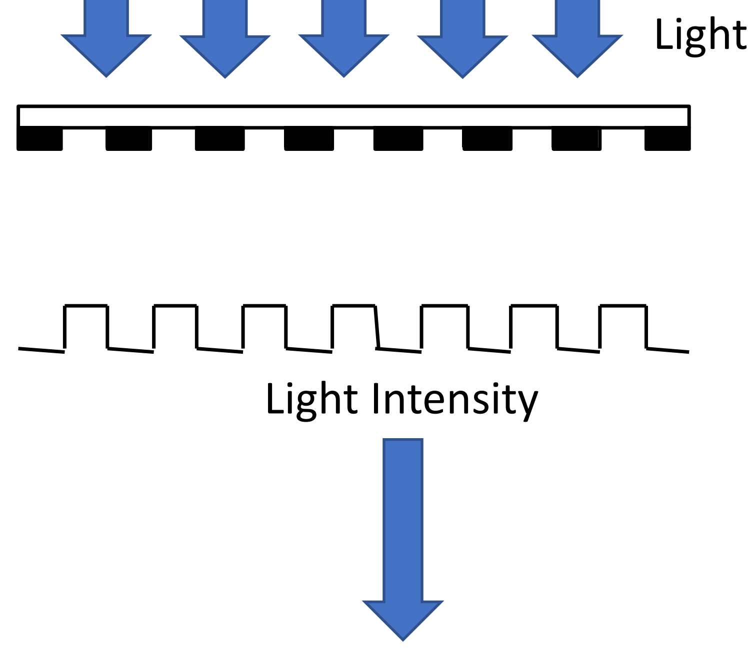




A simulation tool to mimic the process



One dimensional mask under projection lithography



Positive Resist: Inverse of Light Intensity Distribution

A simulation tool to mimic the process

Dx: aperture

Dx=a*q

a: Period

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =1;      %period on the mask (u
        q              =0.5;     %portion of the peri
        Dx             =q*a;     %aperture size (um)
        %lithography tool/settings parameters
        defocus        =0;       %defocus (um)
        immersion      =0;       %dry (enter 0), imme
        lambda         =0.436;   %exposure wavelength
44 -    NA             =0.50;    %numerical aperture
45 -    Lamp_intensity=10;       %exposure lamp/laser
46      %expo
47 -    exp_t                    e time in se
48      %resist parameters
49 -    C              =0.25;    %Dill parameter of t
50 -    poly_chain     =16;      %number of deblockin
51 -    r_max          =100;     %max development rat
52 -    r_min          =0.1;     %min development rat
53      %development parameters
```

Name	Value
a	1
C	0.2500
defocus	0
Dx	0.5000
E_x	
exp_tin	
Exposure_Dose	250
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	2095
index3	2329
j	250
k	251
lambda	0.4360
Lamp_intensity	10
m	2

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

Figure 3

Pattern width=523nm
and slope=57degrees
rough slope=88degrees

Pattern Profile

Resist thickness (μm)

x (μm)

A simulation tool to mimic the process

MATLAB R2016a

Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysis.m

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a             =1;    %period on the mask (u
38 -    q             =0.5;   %portion of the peri
39 -    Dx            =q*a;   %aperture size (um)
40      %lithography tool/settings parameters
        defocus       =0;     %defocus (um)
        immersion     =0;     %dry (enter 0), imme
        lambda        =0.436; %exposure wavelength
        NA            =0.50;  %numerical aperture
        Lamp_intensity=10;    %exposure lamp/laser
        %exposure parameters
```

λ: Exposure Wavelength

NA: Numerical Aperture

Figure 3

Pattern width=523nm
and slope=57degrees
rough slope=88degrees

Pattern Profile

Workspace	
exp_time	25
Exposure_Dose	250
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	2095
index3	2329
j	250
k	251
lambda	0.4360
Lamp_intensity	10
m	2

Future technology
Current technology
Ultra-Hi Voltage Mercury-vapor lamp
SOR
Excimer Laser
Xe, Sn, or Li 13.5nm
unknown 71nm
Ar2 126nm
F2 157nm
ArF 193nm
KrF 248nm
i-line 365nm
h-line 405nm
g-line 436nm
X-ray
10nm
100nm
400nm
750nm
Extreme Ultra Violet (10-121nm)
Ultraviolet rays
Visible spectrum rays

A simulation tool to mimic the process

History of optics in lithography: Lenses Get Larger, wavelength shrink => NA ↑, λ ↓

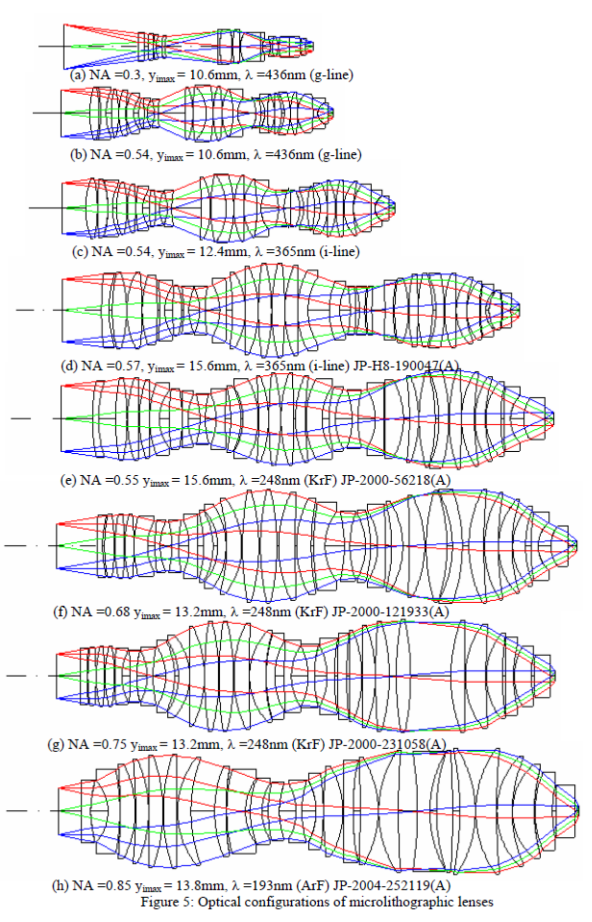
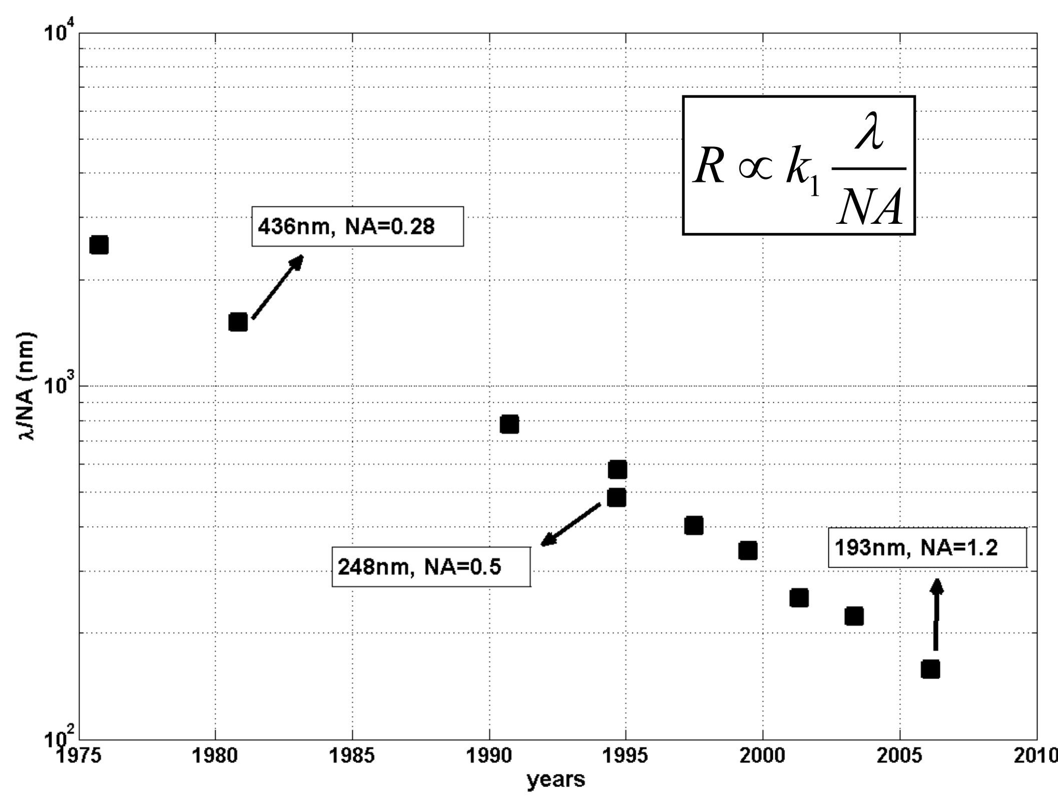


Figure 5: Optical configurations of microlithographic lenses



A simulation tool to mimic the process

λ: 432nm

NA: 0.5

1µm Mask

0.5µm Apertures

RESOLVED!

MATLAB R2016a — Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysis.m

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =1;     %period on the mask (u
38 -    q              =0.5;   %portion of the peri
39 -    Dx             =q*a;   %aperture size (um)
40      %lithography tool/settings parameters
        defocus        =0;     %defocus (um)
        immersion      =0;     %dry (enter 0), imme
        lambda         =0.436; %exposure wavelength
        NA             =0.50;  %numerical aperture
        Lamp_intensity=10;     %exposure lamp/laser
        %exposure parameters
        exp_time       =25;    %exposure time in se
        %resist parameters
        C              =0.25;  %Dill parameter of t
        poly_chain     =16;    %number of deblockin
        r_max          =100;   %max development rat
        r_min          =0.1;   %min development rat
53      %development parameters
```

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

Figure 3

Pattern width=523nm
and slope=57degrees
rough slope=88degrees

Legend: Pattern Profile

y-axis: Resist thickness (µm) — 0, -0.5, -1

x-axis: x (µm) — -0.5, 0, 0.5

A simulation tool to mimic the process

MATLAB R2016a

Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysis.m

```
35    %General Parameters%
36    %geometry/mask parameters
37 -  a             =0.6;   %period on the mask (um)
```

light

λ: 432nm

NA: 0.5

0.6µm Mask

0.3µm Apertures

NOT RESOLVED!

YOU SHALL NOT **Resolve!**

Command Window

```
Index exceeds matrix dimensions.

Error in litho_analysis (line 110)
        z(i,ii)=median(diff(x))/3*(totall+r_x(i+1)/sqrt(r_x0^2-r_x(i+1)^2)+r_x(ii)/sqrt(r_x0^2-r_x(ii)^2));
```

A simulation tool to mimic the process

MATLAB R2016a

Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysis.m

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =0.6;   %period on the mask (
38 -    q              =0.5;   %portion of the perio
39 -    Dx             =q*a;   %aperture size (um)
40      %lithography tool/settings parameters
        defocus        =0;     %defocus (um)
        immersion      =0;     %dry (enter 0), immer
        lambda         =0.193; %exposure wavelength
        NA             =0.50;  %numerical aperture o
        Lamp_intensity=10;     %exposure lamp/laser
        %exposure parameters
        exp_time       =25;    %exposure time in sec
        %resist parameters
        C              =0.25;  %Dill parameter of th
        poly_chain     =16;    %number of deblocking
        r_max          =100;   %max development rate
        r_min          =0.1;   %min development rate
53      %development parameters
```

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

λ: 193nm

NA: 0.5

0.6µm Mask

0.3µm Apertures

RESOLVED!

Pattern width=308nm and slope=59degrees rough slope=89degrees

Pattern Profile

Resist thickness (µm)

x (µm)

A simulation tool to mimic the process

λ: 193nm

NA: 0.5

0.3µm Mask

0.15µm Apertures

NOT RESOLVED!

YOU SHALL NOT **Resolve!**

```
Index exceeds matrix dimensions.

Error in litho_analysis (line 110)
        z(i,ii)=median(diff(x))/3*(totall+r_x(i+1)/sqrt(r_x0^2-r_x(i+1)^2)+r_x(ii)/sqrt(r_x0^2-r_x(ii)^2));
```

A simulation tool to mimic the process

λ: 193nm

NA: 0.96

0.3µm Mask

0.15µm Apertures

RESOLVED!

```
defocus         =0;      %defocus (um)
immersion       =0;      %dry (enter 0), imm
lambda          =0.193;  %exposure wavelengt
NA              =0.96;   %numerical aperture
Lamp_intensity=10;       %exposure lamp/lase
%exposure parameters
exp_time        =25;     %exposure time in s
%resist parameters
C               =0.25;   %Dill parameter of
poly_chain      =16;     %number of deblocki
r_max           =100;    %max development ra
r_min           =0.1;    %min development ra
%development parameters
```

Figure 3: Pattern width=150nm and slope=60degrees rough slope=89degrees

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

A simulation tool to mimic the process

λ: 193nm
NA: 0.96
0.3µm Mask
0.015µm Apertures (q=0.05)
Underexposed!

```
%geometry/mask parameters
a              =0.3;   %period on the mas
q              =0.05;  %portion of the p
Dx             =q*a;   %aperture size (um
%lithography tool/settings parameters
defocus        =0;     %defocus (um)
immersion      =0;     %dry (enter 0), im
lambda         =0.193; %exposure waveleng
NA             =0.96;  %numerical apertur
Lamp_intensity=10;     %exposure lamp/las
%exposure parameters
exp_time       =25;    %exposure time in
%resist parameters
C              =0.25;  %Dill parameter
poly_chain     =16;    %number of debl
```

Name	Value
a	0.3000
C	0.2500
defocus	0
Dx	0.0150
E_x	2x251 double
exp_time	25
Exposure_Dose	250
i	249
I_x	1x251 double

Pattern width=0nm
and slope=45degrees
rough slope=NaNdegrees

Pattern Profile

YOU SHALL NOT PASS!

Large Opening

Small Opening

A simulation tool to mimic the process

λ: 13nm (Extreme UV)

NA: 0.96

0.3µm Mask

0.015µm Apertures (q=0.05)

Resolved!

Pattern width=14nm
and slope=65degrees
rough slope=89degrees

Pattern Profile

CPU ROADMAP

SUSTAINED HIGH-PERFORMANCE LEADERSHIP

14nm / 12nm	7nm	7nm	5nm
"ZEN"	"ZEN 2"	"ZEN 3"	"ZEN 4"

2017 — 2022

A simulation tool to mimic the process

λ: 193nm
NA: 0.96
0.3µm Mask
0.15µm Apertures
t=2 second exposure
Underexposed!

MATLAB R2016a

PUBLISH VIEW

Breakpoints | Run | Run and Advance | Run Section | Advance | Run and Time

EDIT BREAKPOINTS RUN

submission3

Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysi

litho_analysis.m

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =0.3;   %period on the m
38 -    q              =0.5;   %portion of the
39 -    Dx             =q*a;   %aperture size (
40      %lithography tool/settings parameters
41 -    defocus        =0;     %defocus (um)
42 -    immersion      =0;     %dry (enter 0),
43 -    lambda         =0.193; %exposure wavele
44 -    NA             =0.96;  %numerical apert
45 -    Lamp_intensity=10;     %exposure lamp/l
46      %exposure parameters
47 -    exp_time       =2;    %exposure time in
48      %resist parameters
49 -    C              =0.25;  %Dill parameter
50 -    poly_chain     =16;    %number of deblo
51 -    r_max          =100;   %max development
52 -    r_min          =0.1;   %min development
53      %development parameters
```

Figure 3

File Edit View Insert Tools Desktop Window Help

Pattern width=0nm
and slope=53degrees
rough slope=87degrees

Pattern Profile

Resist thickness (μm)

x (μm)

0, -0.5, -1

-0.15, -0.1, -0.05, 0, 0.05, 0.1

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

litho_analysis.m (Script)

Workspace

Name	Value
a	0.3000
C	0.2500
defocus	0
Dx	0.1500
E_x	2x251 double
exp_time	2
Exposure_Dose	20
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	1
index3	560
j	250
k	251
lambda	0.1930
Lamp_intensity	10
m	2

script Ln 47 Col 17

A simulation tool to mimic the process

λ: 193nm
NA: 0.96
0.3μm Mask
0.15μm Apertures
t=6 second exposure
Underexposed!

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =0.3;   %period on the
38 -    q              =0.5;   %portion of the
39 -    Dx             =q*a;   %aperture size
40      %lithography tool/settings parameters
41 -    defocus        =0;     %defocus (um)
42 -    immersion      =0;     %dry (enter 0),
43 -    lambda         =0.193; %exposure wavel
44 -    NA             =0.96;  %numerical aper
45 -    Lamp_intensity=10;     %exposure lamp
46      %exposure parameters
47 -    exp_time       =6;    %exposure time i
48      %resist parameters
49 -    C              =0.25;  %Dill paramete
50 -    poly_chain     =16;    %number of debl
51 -    r_max          =100;   %max developmen
52 -    r_min          =0.1;   %min developmen
53      %development parameters
```

Name	Value
a	0.3000
C	0.2500
defocus	0
Dx	0.1500
E_x	2x251 double
exp_time	6
Exposure_Dose	60
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	1030
index3	1520
j	250
k	251
lambda	0.1930
Lamp_intensity	10
m	2

Pattern width=77nm
and slope=61degrees
rough slope=89degrees

Pattern Profile

Resist thickness (μm): 0, -0.5, -1
x (μm): -0.15, -0.1, -0.05, 0, 0.05, 0.1

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

A simulation tool to mimic the process

λ: 193nm
NA: 0.96
0.3μm Mask
0.15μm Apertures
t=16 second exposure
Underexposed!

MATLAB R2016a

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =0.3;   %period on the m
38 -    q              =0.5;   %portion of the
39 -    Dx             =q*a;   %aperture size (
40      %lithography tool/settings parameters
41 -    defocus        =0;     %defocus (um)
42 -    immersion      =0;     %dry (enter 0),
43 -    lambda         =0.193; %exposure wavele
44 -    NA             =0.96;  %numerical apert
45 -    Lamp_intensity=10;     %exposure lamp/l
46      %exposure parameters
47 -    exp_time       =16;    %exposure time i
48      %resist parameters
49 -    C              =0.25;  %Dill parameter
50 -    poly_chain     =16;    %number of deblo
51 -    r_max          =100;   %max development
52 -    r_min          =0.1;   %min development
53      %development parameters
```

Workspace

Name	Value
a	0.3000
C	0.2500
defocus	0
Dx	0.1500
E_x	2x251 double
exp_time	16
Exposure_Dose	160
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	1777
index3	2035
j	250
k	251
lambda	0.1930
Lamp_intensity	10
m	2

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

Figure 3

Pattern width=133nm
and slope=63degrees
rough slope=89degrees

Pattern Profile

Resist thickness (μm): 0, -0.5, -1
x (μm): -0.15, -0.1, -0.05, 0, 0.05, 0.1

A simulation tool to mimic the process

λ: 193nm
NA: 0.96
0.3µm Mask
0.15µm Apertures
t=25 second exposure
Ideal!

MATLAB R2016a

PUBLISH VIEW

Breakpoints | Run | Run and Advance | Run Section | Advance | Run and Time

EDIT BREAKPOINTS RUN

submission3

Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysis.m

litho_analysis.m

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =0.3;   %period on the mask
38 -    q              =0.5;   %portion of the per
39 -    Dx             =q*a;   %aperture size (um)
40      %lithography tool/settings parameters
41 -    defocus        =0;     %defocus (um)
42 -    immersion      =0;     %dry (enter 0), imm
43 -    lambda         =0.193; %exposure wavelengt
44 -    NA             =0.96;  %numerical aperture
45 -    Lamp_intensity=10;     %exposure lamp/lase
46      %exposure parameters
47 -    exp_time       =25;    %exposure time in s
48      %resist parameters
49 -    C              =0.25;  %Dill parameter of
50 -    poly_chain     =16;    %number of deblocki
51 -    r_max          =100;   %max development ra
52 -    r_min          =0.1;   %min development ra
53      %development parameters
```

litho_analysis.m (Script)

Workspace

Name	Value
a	0.3000
C	0.2500
defocus	0
Dx	0.1500
E_x	2x251 double
exp_time	25
Exposure_Dose	250
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	2006
index3	2211
j	250
k	251
lambda	0.1930
Lamp_intensity	10
m	2

Figure 3

File Edit View Insert Tools Desktop Window Help

Pattern width=150nm
and slope=60degrees
rough slope=89degrees

Pattern Profile

Resist thickness (μm)

x (μm)

0, -0.5, -1

-0.15, -0.1, -0.05, 0, 0.05, 0.1

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

script Ln 44 Col 20

A simulation tool to mimic the process

λ: 193nm
NA: 0.96
0.3μm Mask
0.15μm Apertures
t=30 second exposure
Overexposed!

MATLAB R2016a

Editor - D:\IMAC_HOME_6_11_20\HITEC\submission3\litho_analysis.m

litho_analysis.m

```
35      %General Parameters%
36      %geometry/mask parameters
37 -    a              =0.3;   %period on the mask
38 -    q              =0.5;   %portion of the per
39 -    Dx             =q*a;   %aperture size (um)
40      %lithography tool/settings parameters
41 -    defocus        =0;     %defocus (um)
42 -    immersion      =0;     %dry (enter 0), imm
43 -    lambda         =0.193; %exposure wavelengt
44 -    NA             =0.96;  %numerical aperture
45 -    Lamp_intensity=10;     %exposure lamp/lase
46      %exposure parameters
47 -    exp_time       =30;    %exposure time in s
48      %resist parameters
49 -    C              =0.25;  %Dill parameter of
50 -    poly_chain     =16;    %number of deblocki
51 -    r_max          =100;   %max development ra
52 -    r_min          =0.1;   %min development ra
53      %development parameters
```

Workspace

Name	Value
a	0.3000
C	0.2500
defocus	0
Dx	0.1500
E_x	2x251 double
exp_time	30
Exposure_Dose	300
i	249
I_x	1x251 double
ignore_dev	10
ii	251
iii	[]
immersion	0
index	1x250 double
index2	2088
index3	2274
j	250
k	251
lambda	0.1930
Lamp_intensity	10
m	2

Command Window

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

Figure 3

Pattern width=156nm
and slope=52degrees
rough slope=89degrees

Pattern Profile

Resist thickness (μm): 0, -0.5, -1

x (μm): -0.15, -0.1, -0.05, 0, 0.05, 0.1

A simulation tool to mimic the process

λ: 193nm

NA: 0.96

0.3µm Mask

0.15µm Apertures

t=40 second exposure

Overexposed!

```
%General Parameters%
%geometry/mask parameters
a             =0.3;    %period on the m
q             =0.5;    %portion of the
Dx            =q*a;    %aperture size (
%lithography tool/settings parameters
defocus       =0;      %defocus (um)
immersion     =0;      %dry (enter 0),
lambda        =0.193;  %exposure wavele
NA            =0.96;   %numerical apert
Lamp_intensity=10;     %exposure lamp/l
%exposure parameters
exp_time      =40;     %exposure time i
%resist parameters
C             =0.25;   %Dill parameter
poly_chain    =16;     %number of deblo
r_max         =100;    %max development
r_min         =0.1;    %min development
%development parameters
```

Pattern width=165nm
and slope=56degrees
rough slope=89degrees

Pattern Profile

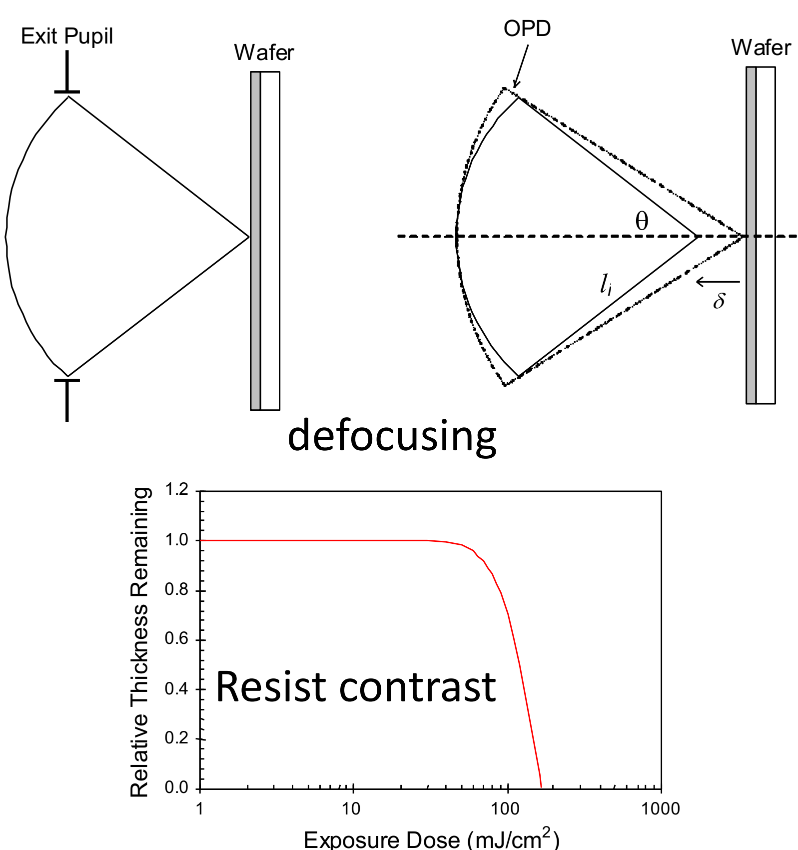
Resist thickness (µm): 0, -0.5, -1

x (µm): -0.15, -0.1, -0.05, 0, 0.05, 0.1

```
Current plot held
Current plot held
Current plot held
Current plot held
Current plot held
>>
```

Other Possibilities

- Immersion Lithography, defocusing (Depth of Focus) study
- Resist Chemistry (Dill Parameter C – exposure kinetics)
- Resist Chemistry – Resist Contrast
- Development time



References

- Matlab: https://www.mathworks.com/products/matlab.html
- Octave: https://www.gnu.org/software/octave/
- Matlab Code: https://psu.box.com/s/ss2nfg68xbk1zegz0ln1asoz8nov3b4v
- Chris Mack’s Page: http://www.lithoguru.com/
- Fundamental Principles of Optical Lithography: https://www.wiley.com/WileyCDA/WileyTitle/productCd-0470727306,descCd-buy.html