E-beam Lithography @ DTU Danchip

wordle.net

Tine Greibe, PhD
Process Engineer
DTU Danchip

Lithography team

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Tine Greibe (E-beam)

Peixiong Shi

E-beam Lithography @ DTU Danchip

PART I

How does an electron beam writer work

PART II

Proximity Effect
Charging Effect
Resist types: Positive and Negative
Heisenberg Uncertainty Principle
Temperature Issues
Exercise: calculation of beam diameter

PART III

Introduction to JEOL JBX-9500
Preparation of files
Calibration of Machine
Exercise: preparation of sdf, jdf, and v30-files

PART IV

Performance tests on JEOL JBX-9500

E-beam Lithography @ DTU Danchip

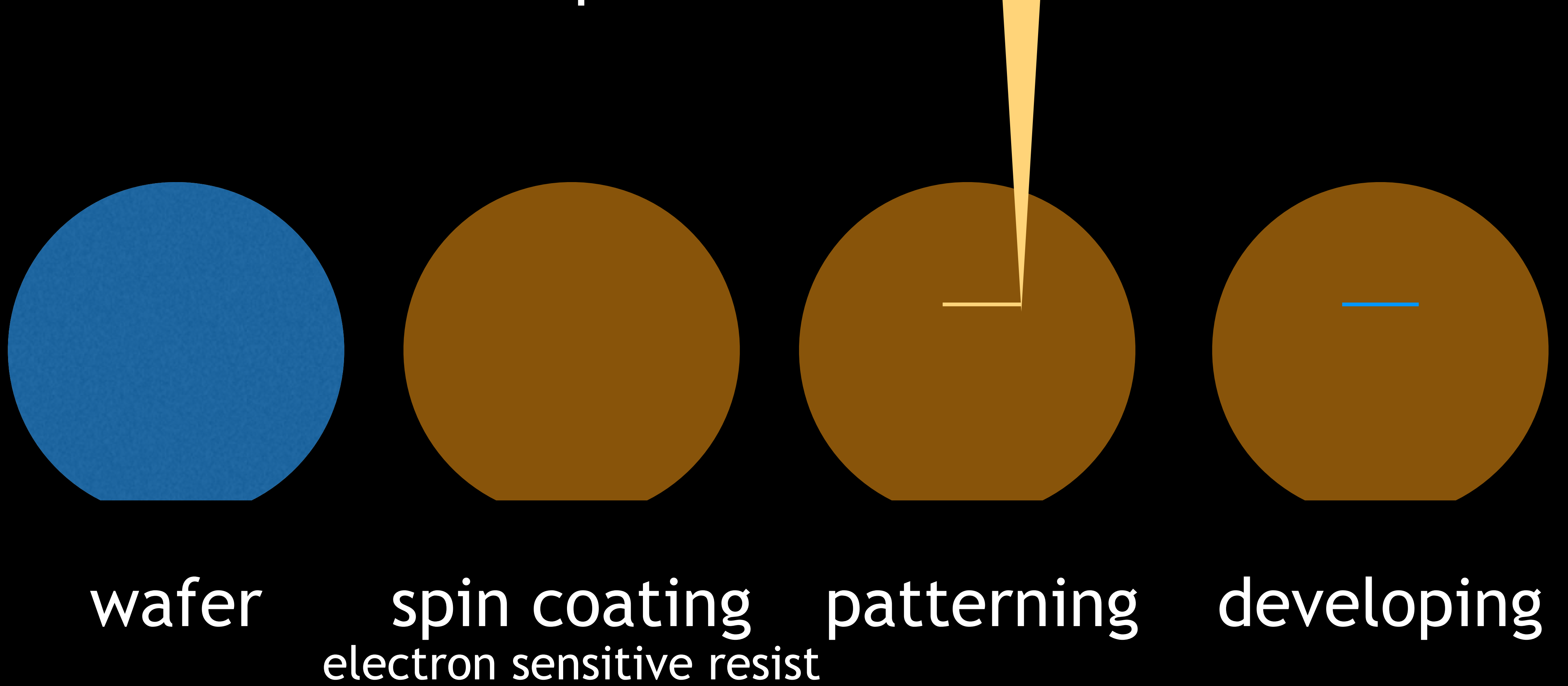
PART I

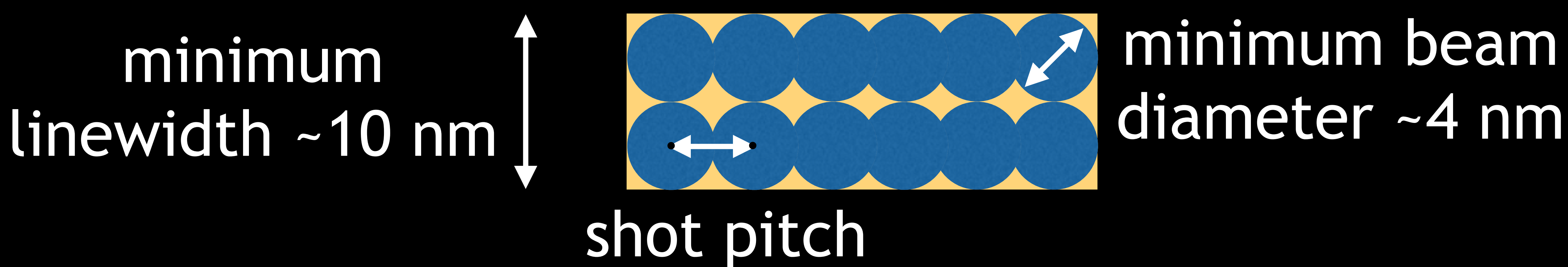
How does an electron beam writer work

DTU Danchip
National Center for Micro- and Nanofabrication

Tine Greibe

Spot electron-beam writer



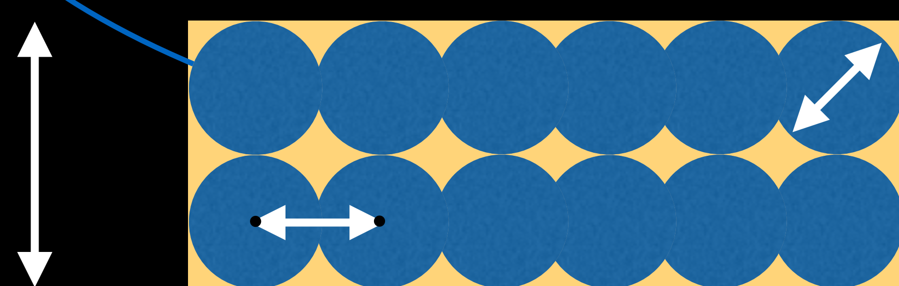


Spot electron-beam writer

Dose
(number of electrons per area) is determined by beam current and dwell time in every shot

$$Q = \frac{i\,t}{A} \qquad [Q] = \frac{\mu C}{cm^2}$$

$$f = \frac{i}{Q\,p^2} \qquad p = \text{shot pitch}$$



Spot electron-beam writer

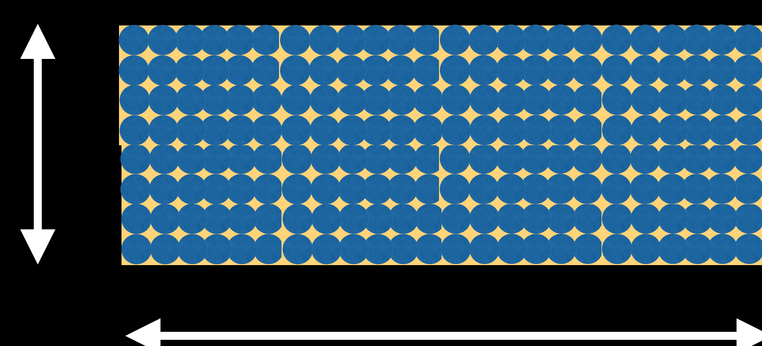
$Q = 300\ \mu C/cm^2$

$p = 5\ nm$

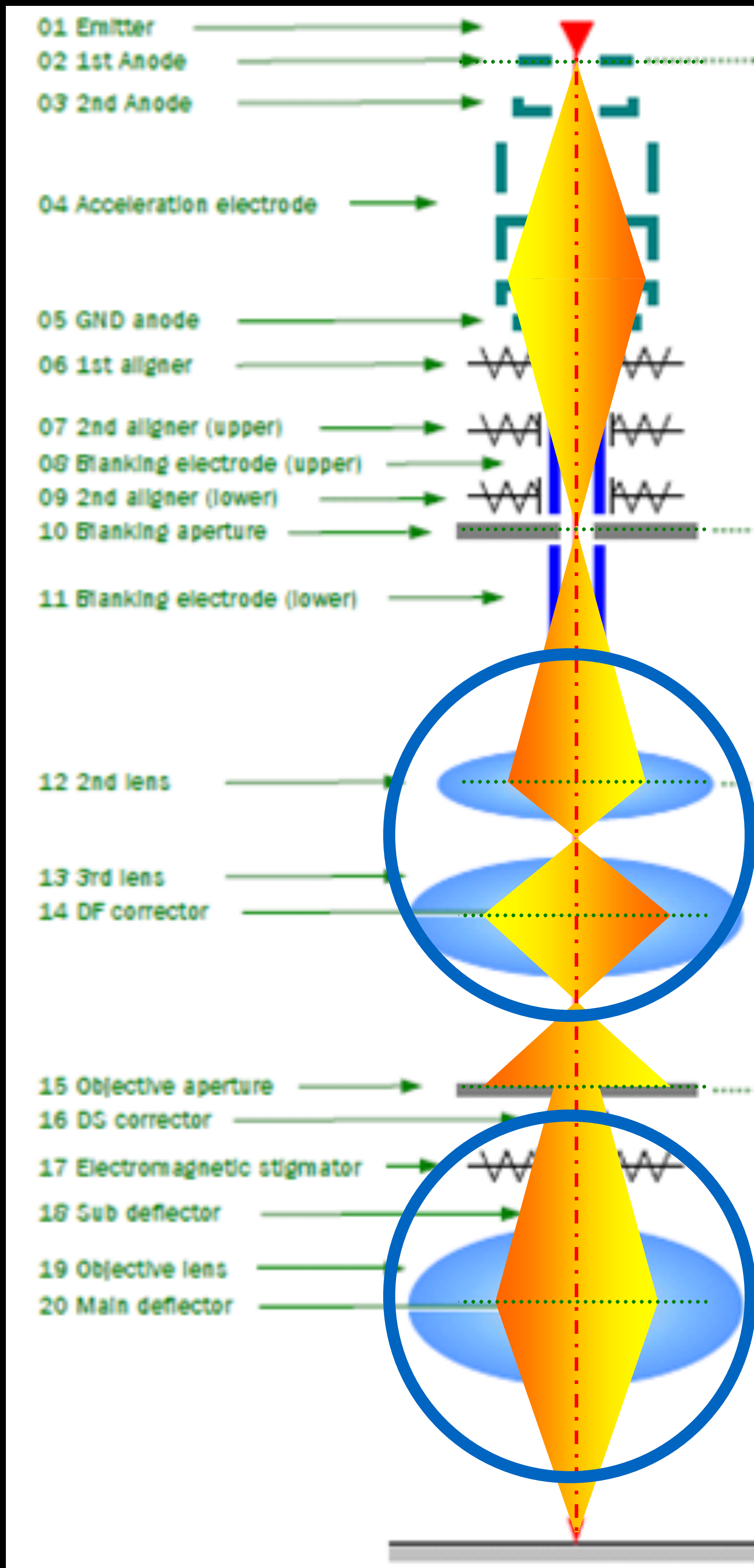
$i = 2\ nA$

$$t = \frac{Q\,A}{i} = 0.15\ s$$

$$f = \frac{i}{Q\,p^2} = 2.7\ MHz$$

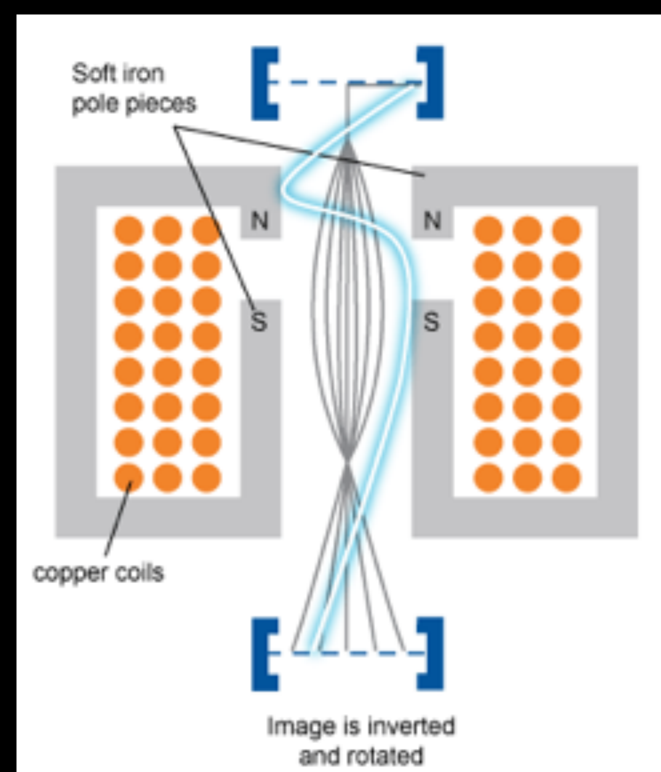


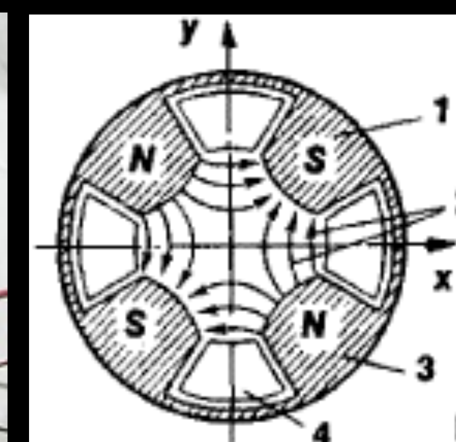
Column of e-beam writer JBX9500



Magnetic Electron Lenses

The 2nd/3rd lenses (zoom lenses) determine the beam current.
The 4th lens (objective lens) projects the beam spot to the substrate.

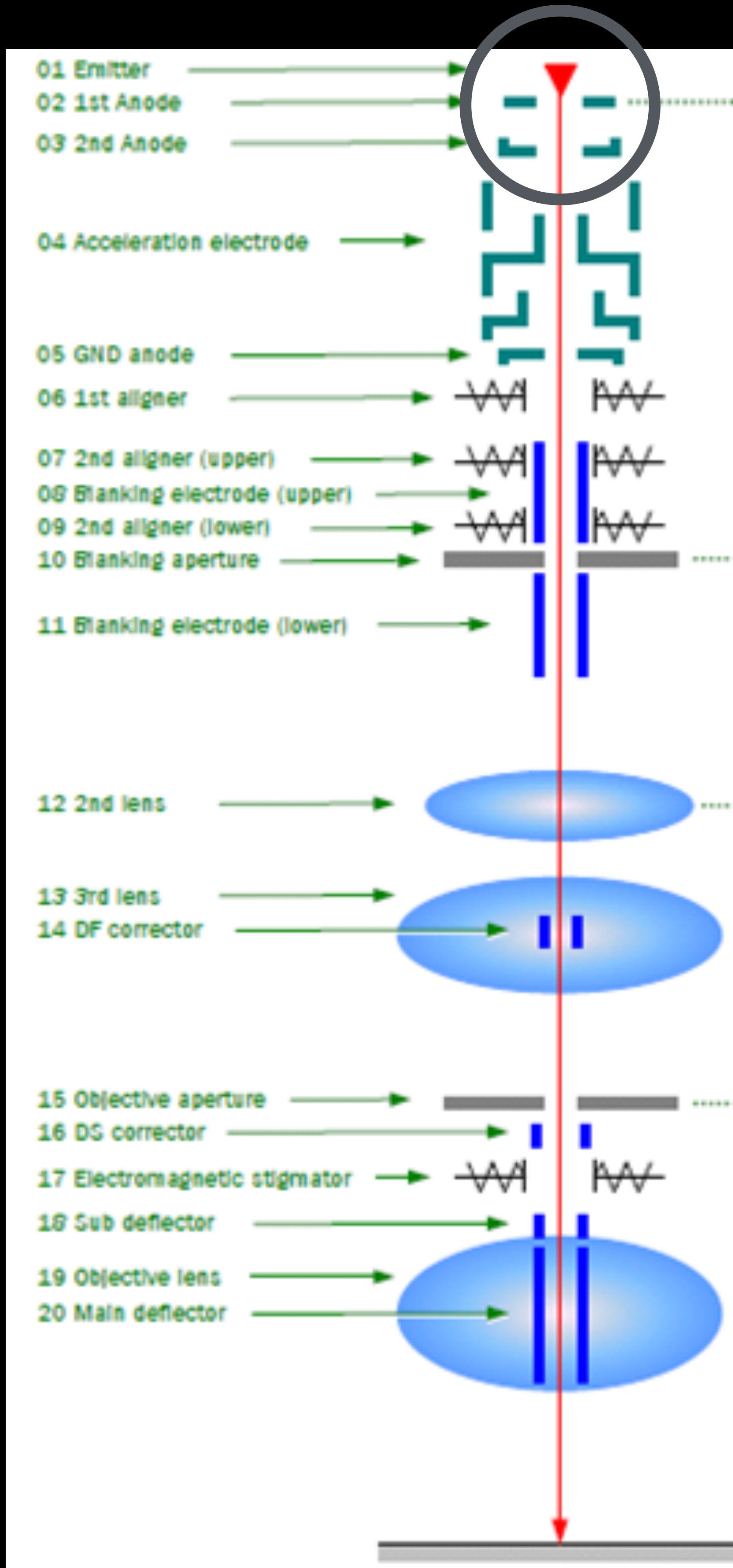




Simple magnetic lenses and quadrupole lens (right)

ammrf.org.au

Column of e-beam writer JBX9500



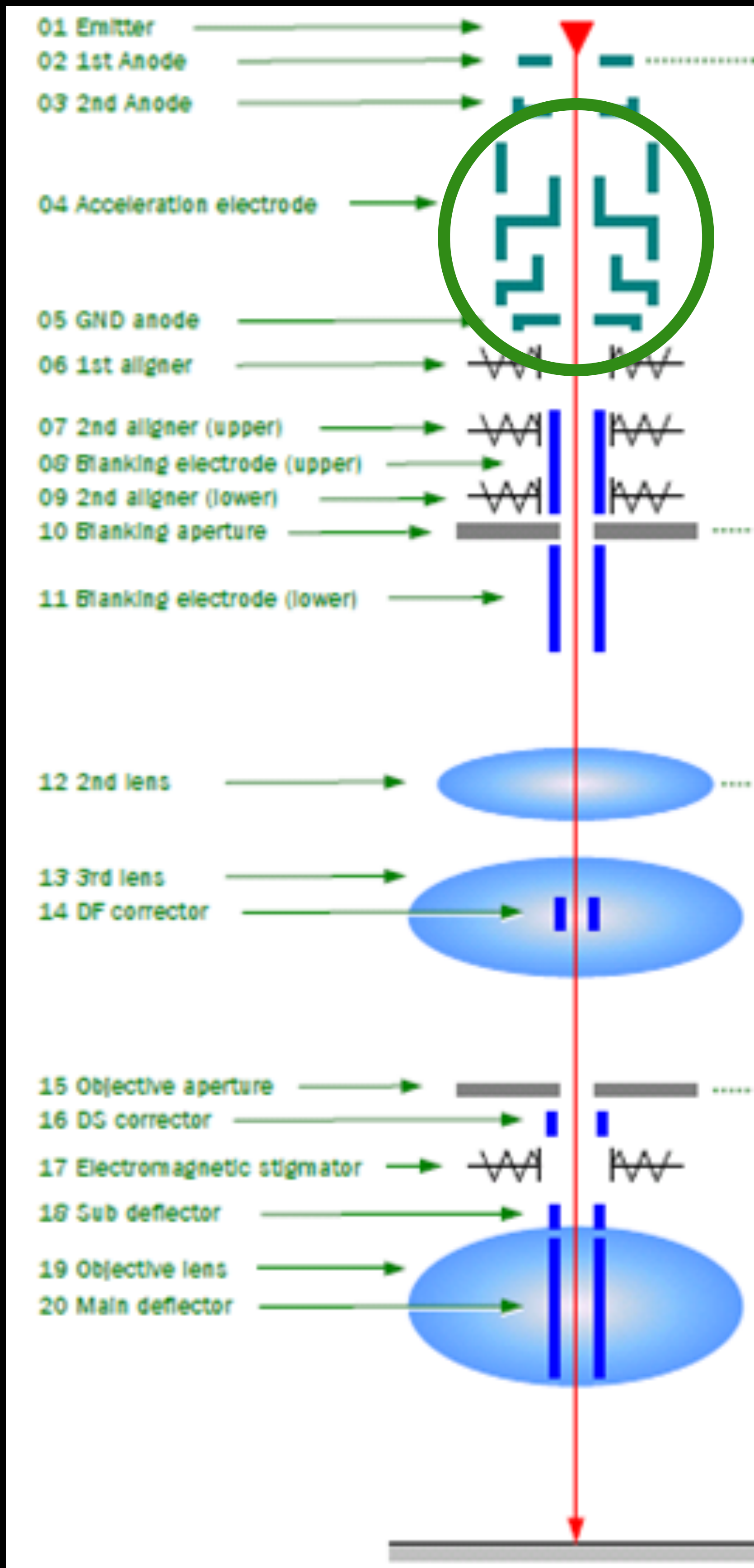
Emitter

1. thermal emission source: stable, high energy spread, dies fast
2. cold field emission source: lower energy spread, enhanced brightness, not stable (noisy - tip contamination), long term drift

	Brightness (A/cm2/sr)	Source size	energy spread (eV)	vacuum requirements (Torr)
W thermionic	~10^5	~25 µm	2-3	10^{-6}
cold field emission	~10^9	~5 nm	0.22	10^{-10}
thermal field emission	~10^8	~20 nm	0.9	10^{-9}

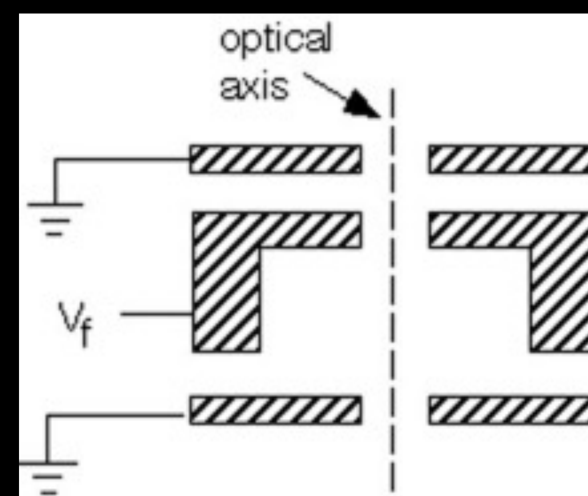
Handbook of Microlithography, Micromachining, and Microfabrication, SPIE, 1997

Column of e-beam writer JBX9500



Einzel Lens

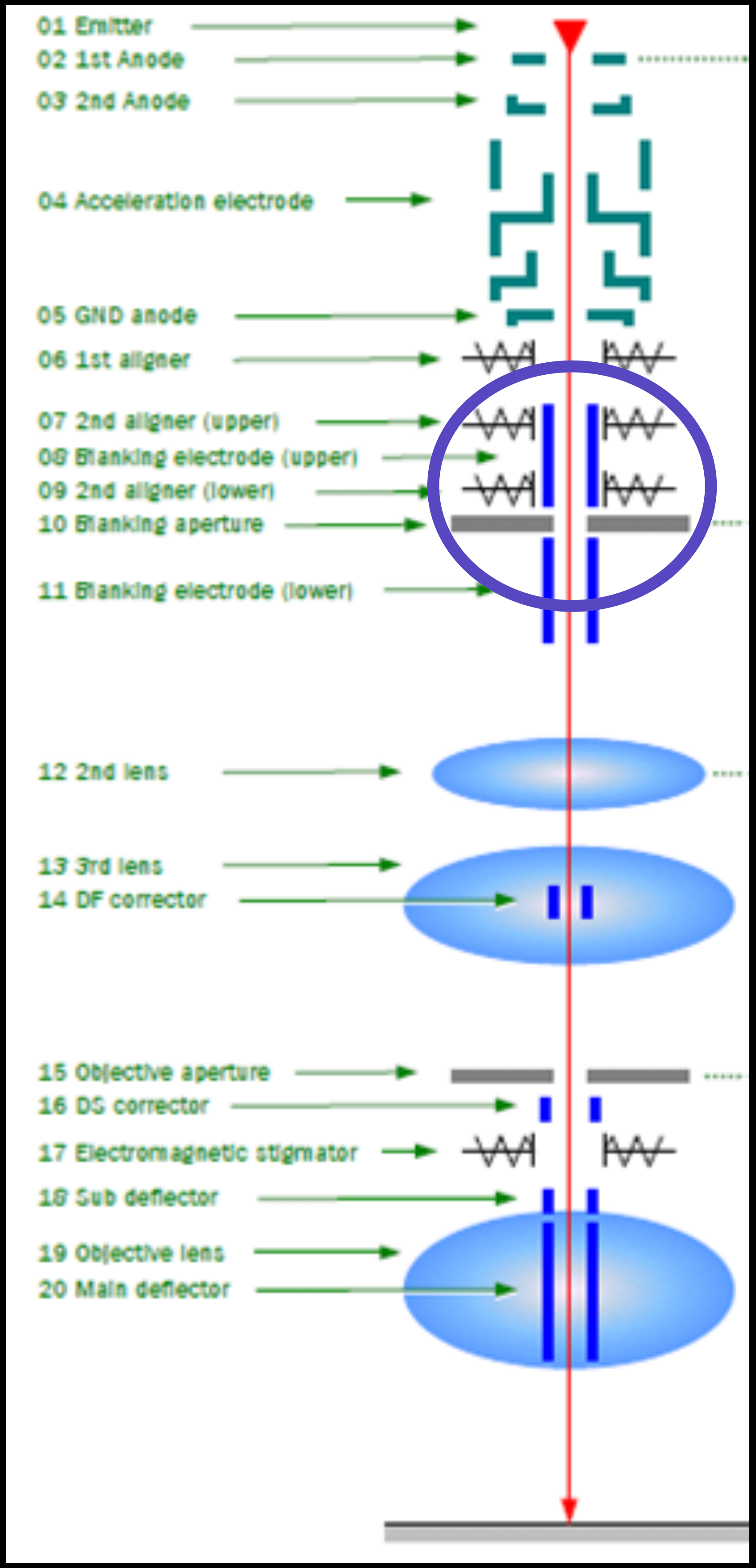
Electrostatic lens with acceleration electrode. Electrostatic lenses have worse abberations than magnetic lenses; most often found in gun region



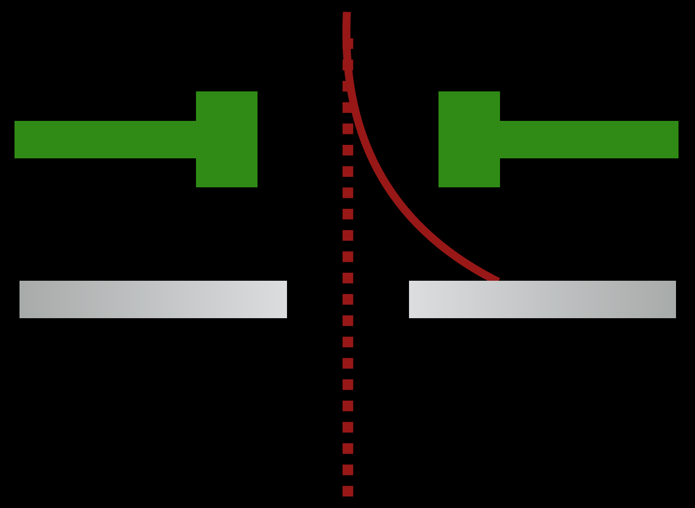
www.cnf.cornell.edu

www.physics.purdue.edu

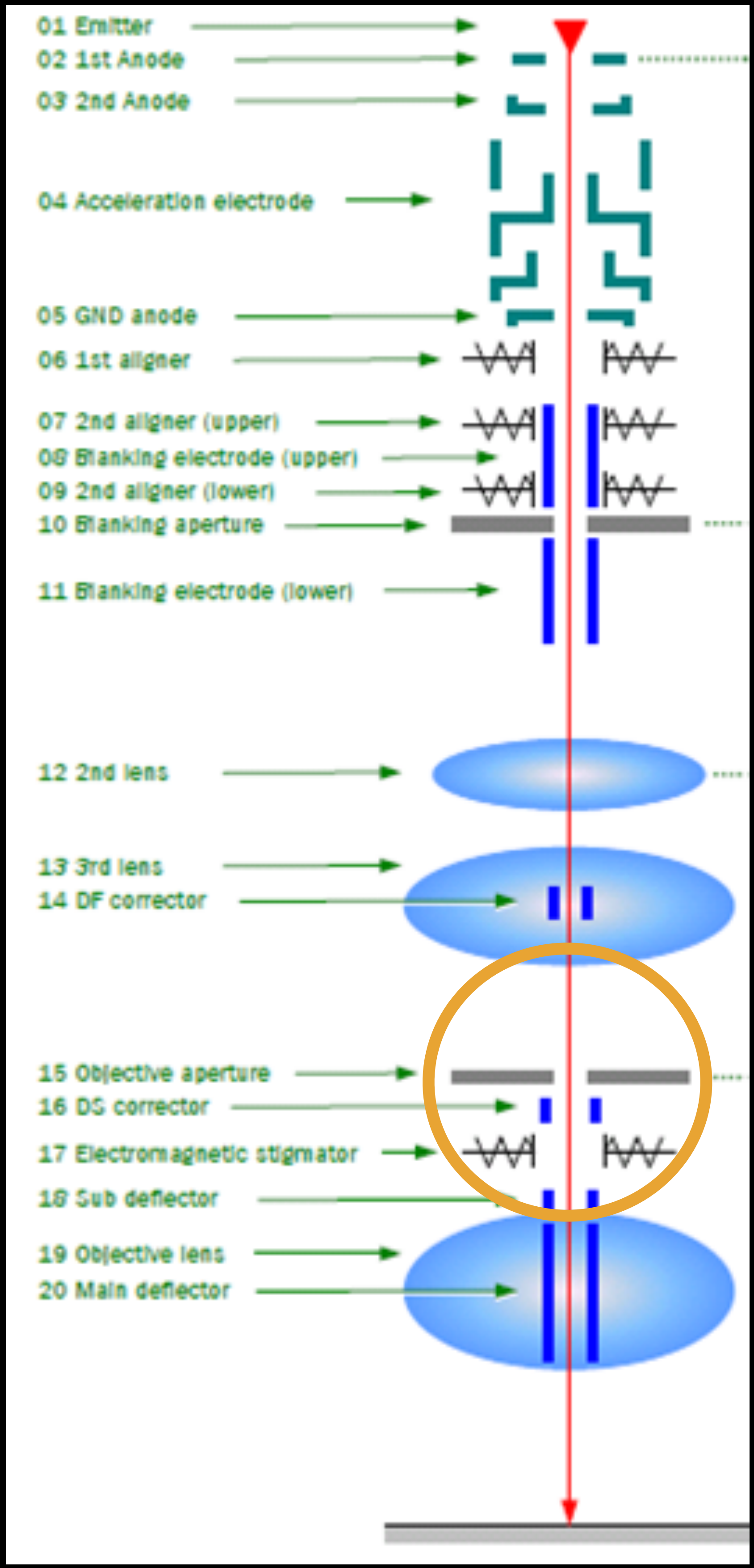
Column of e-beam writer JBX9500



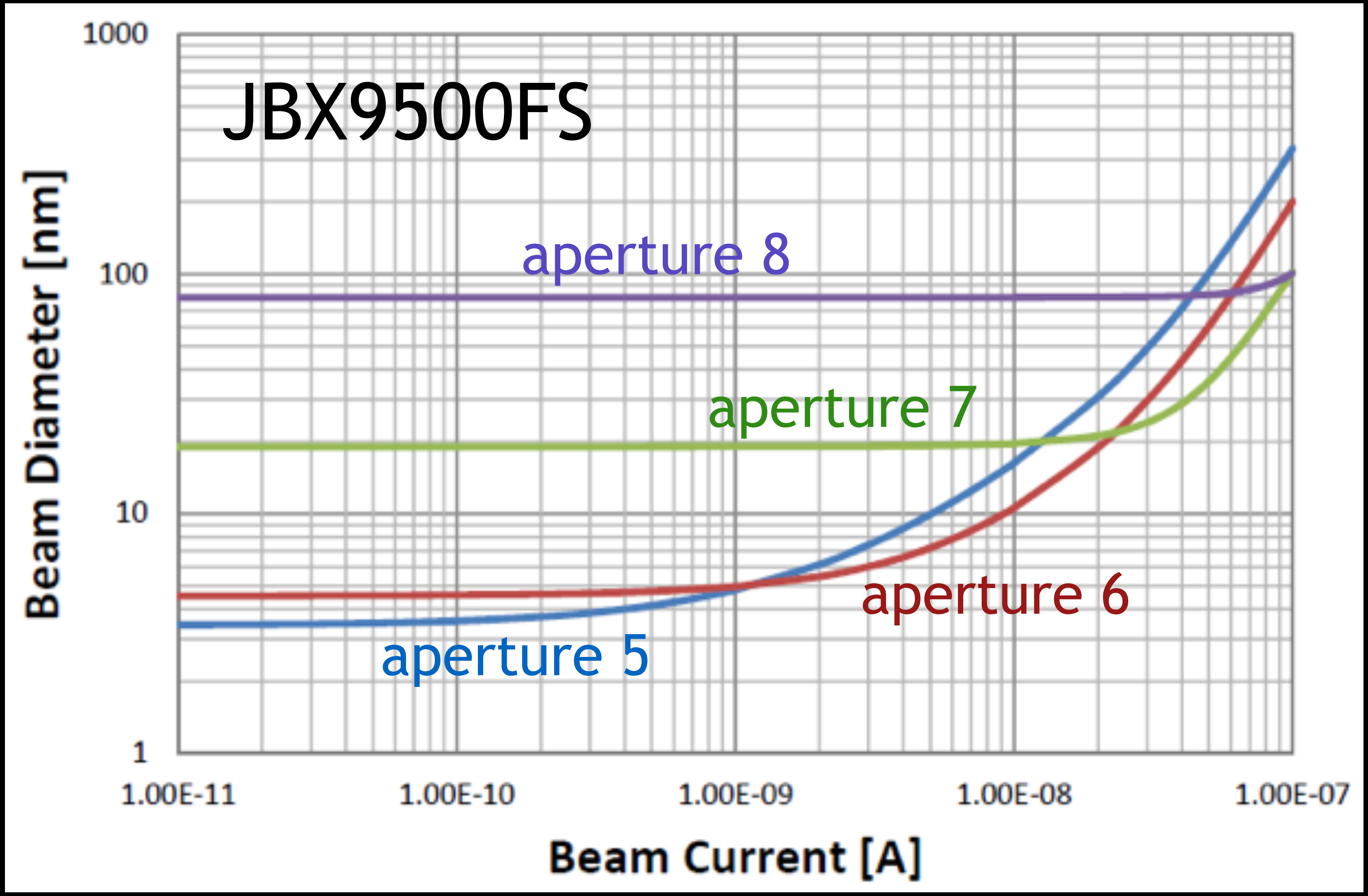
Blanking electrode and aperture



Column of e-beam writer JBX9500



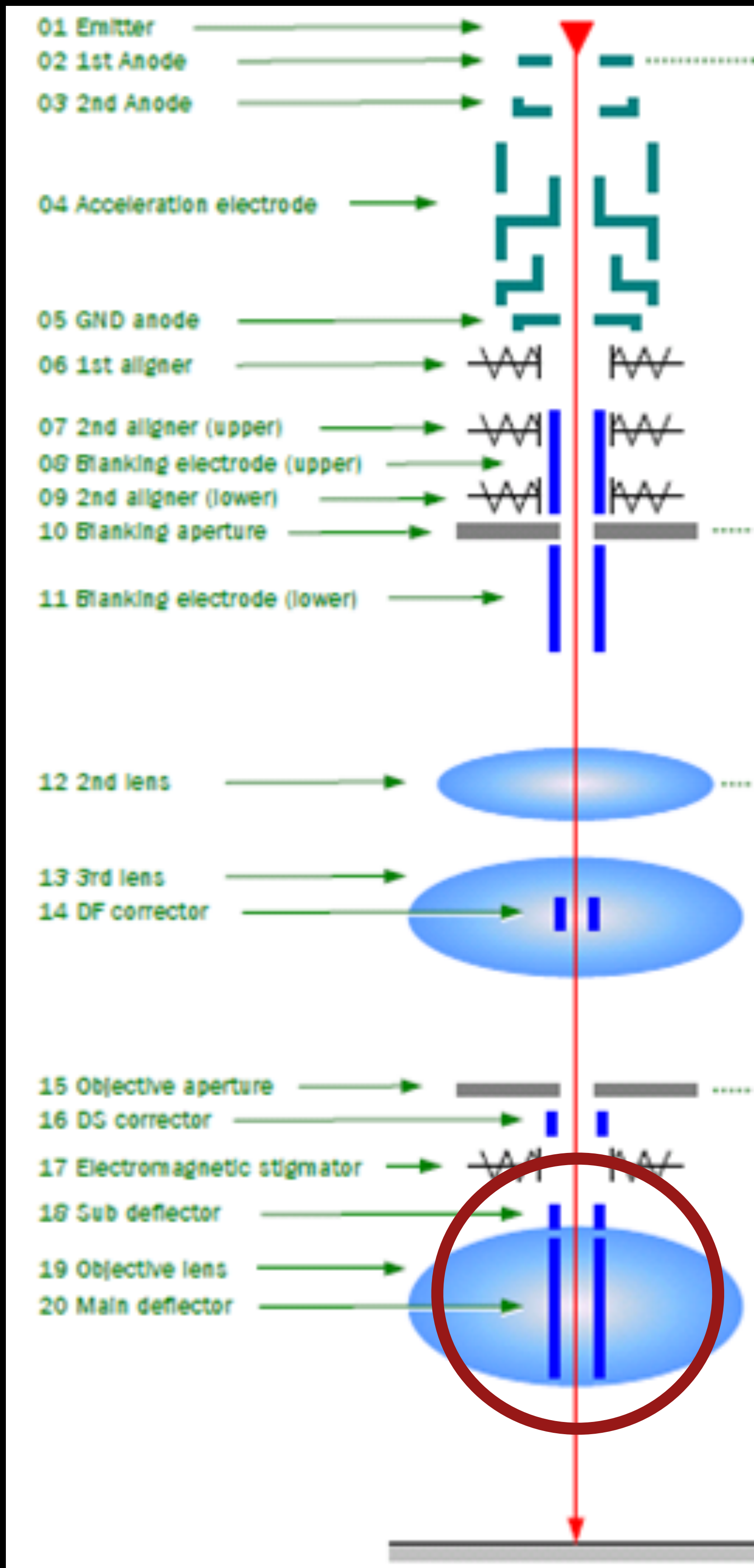
Objective aperture



condition files

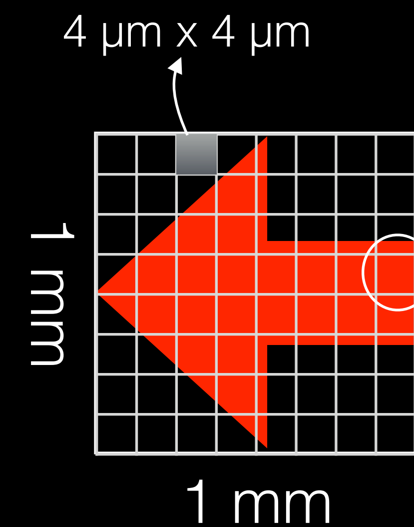
0.2nA_ap5, 2nA_ap5, 6nA_ap6, 10 nA_ap7, 20nA_ap7, 30nA_ap7, 60nA_ap7

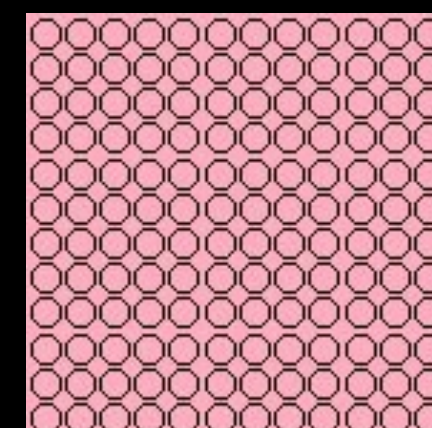
Column of e-beam writer

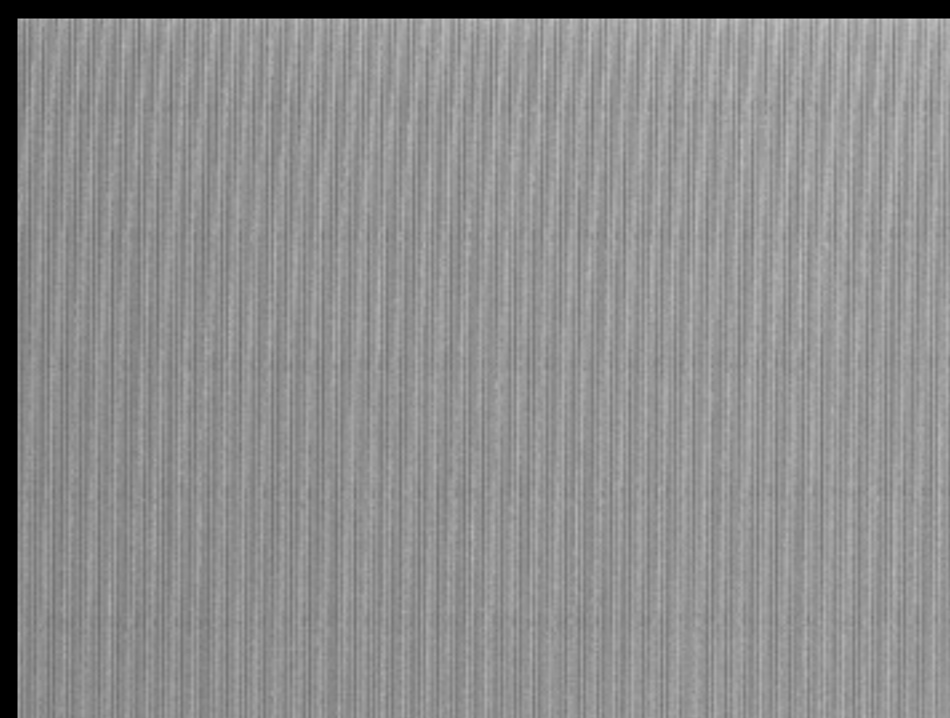


Deflectors

- secondary (sub) deflector (4 µm x 4 µm,100 MHz)
- primary deflector (1 mm x 1 mm)



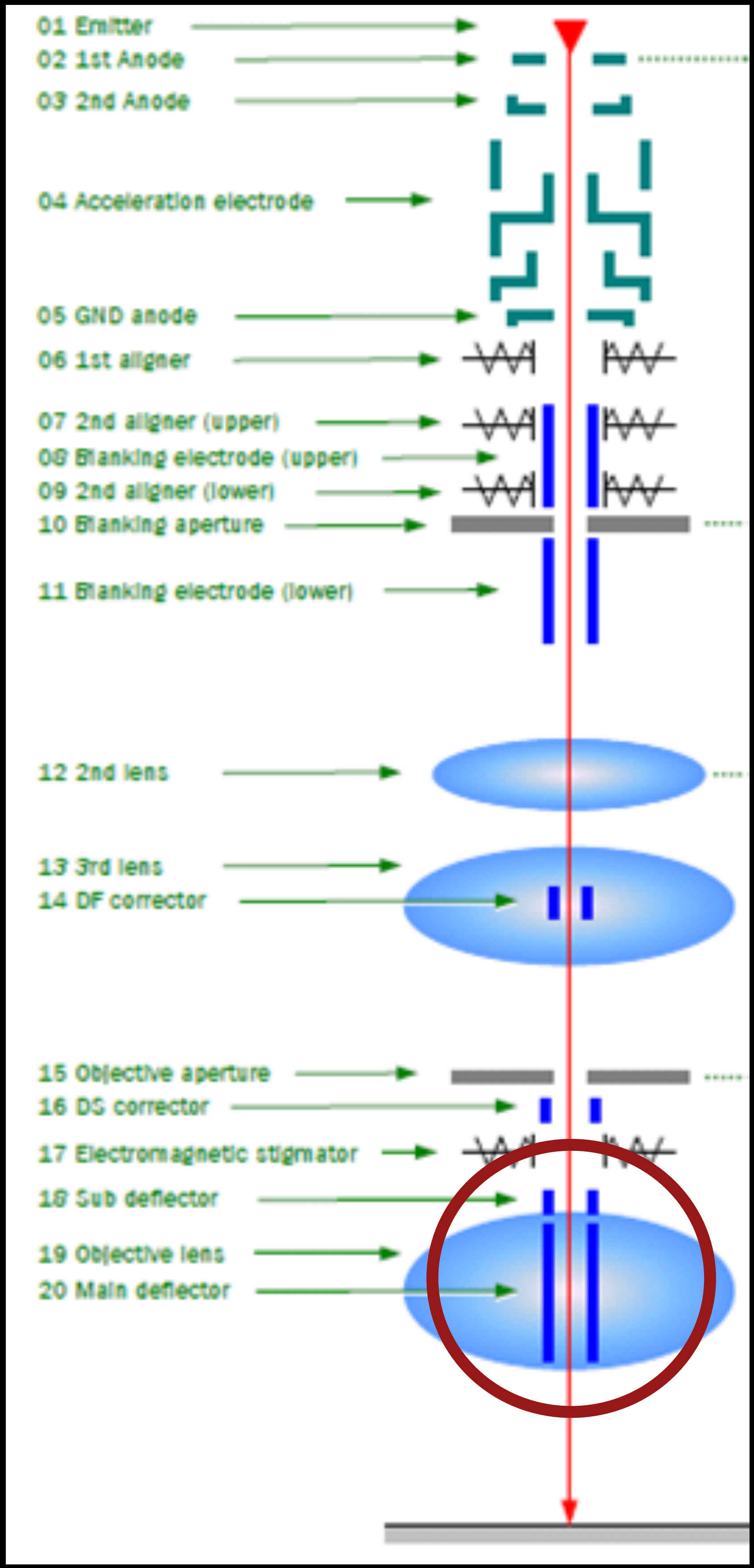


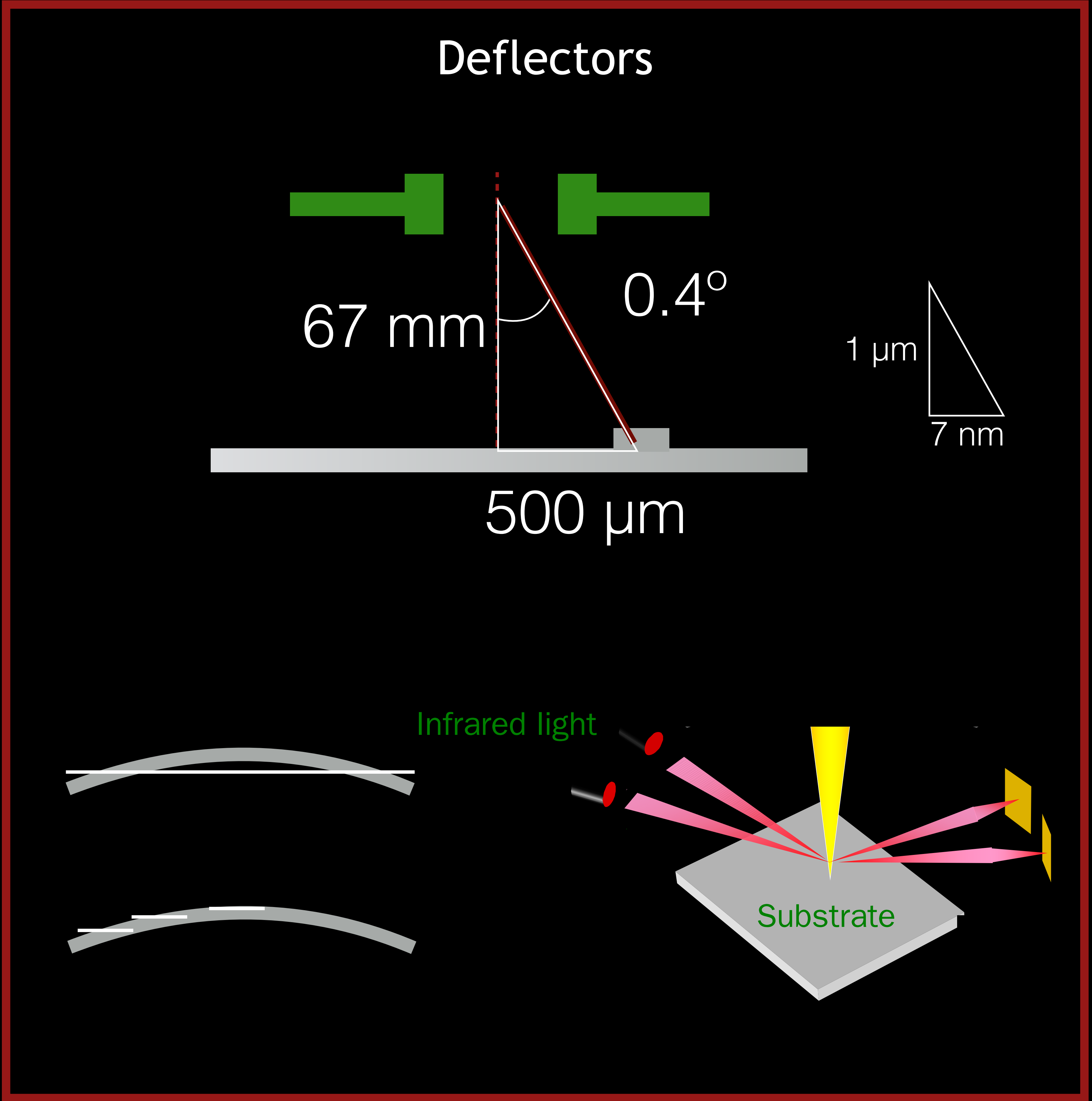


100 nm lines and spaces

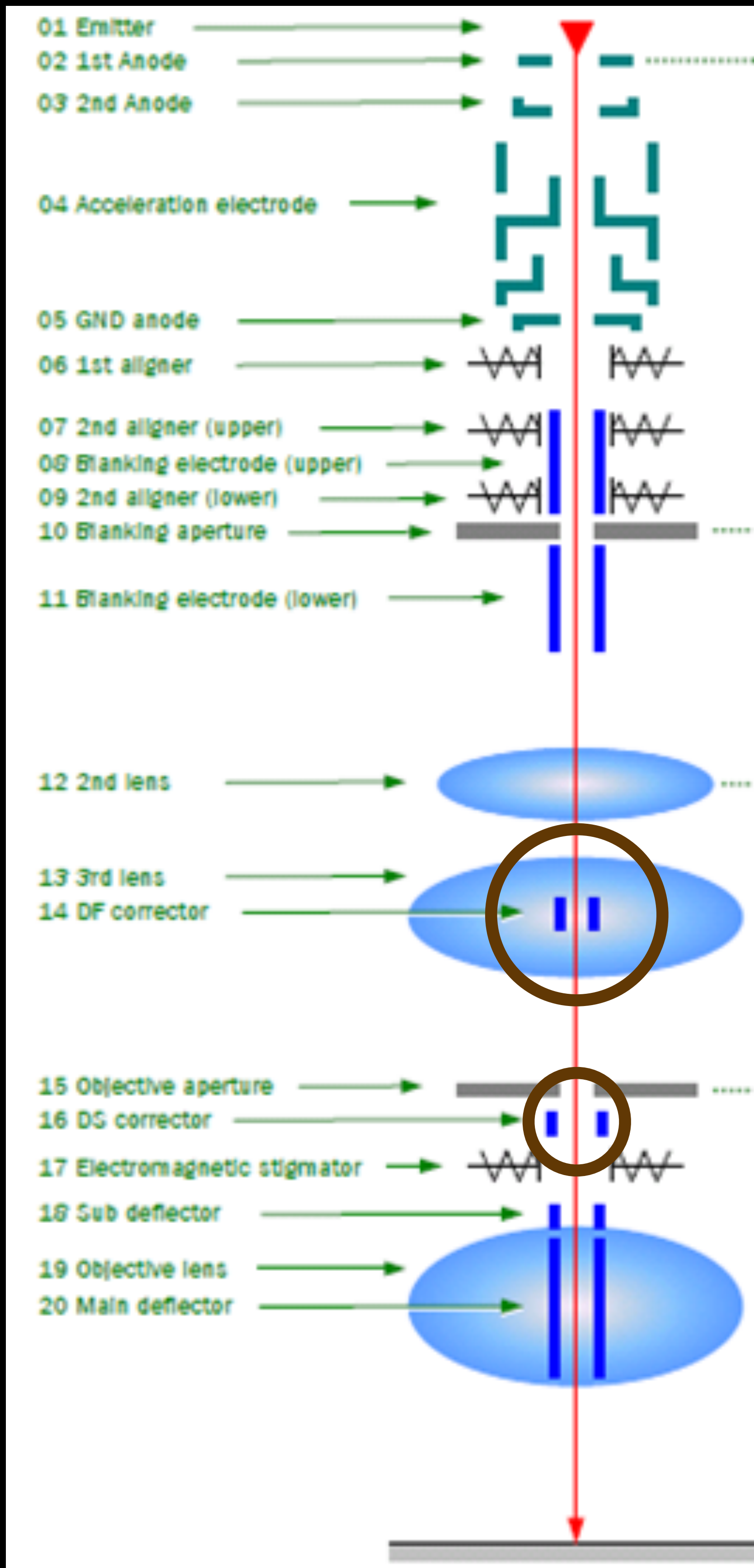
10 nA
shot pitch 6 nm
~11 ns dwell time

Column of e-beam writer

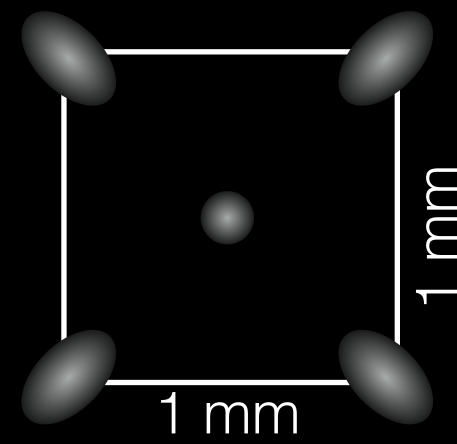




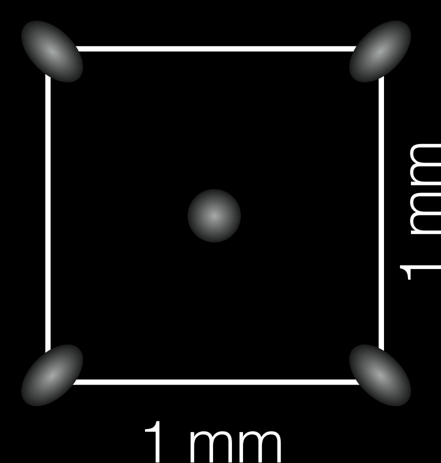
Column of e-beam writer



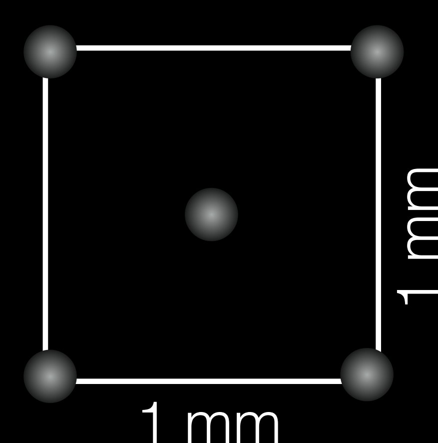
Dynamic focus and astigmatism correction



Beam shape in center of field and deflected to corners of field

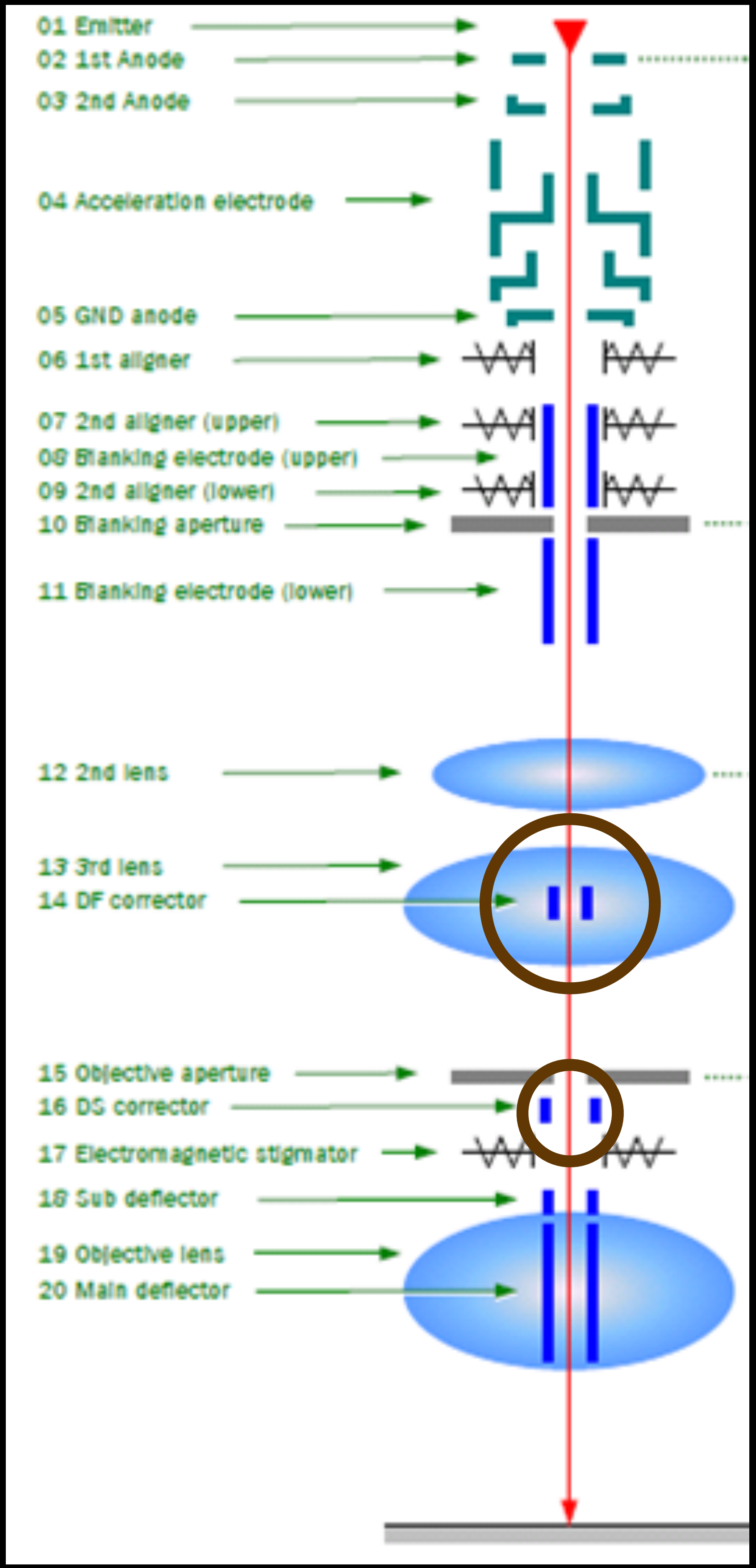


Beam shape in center of field and deflected to corners of field corrected for dynamic focus

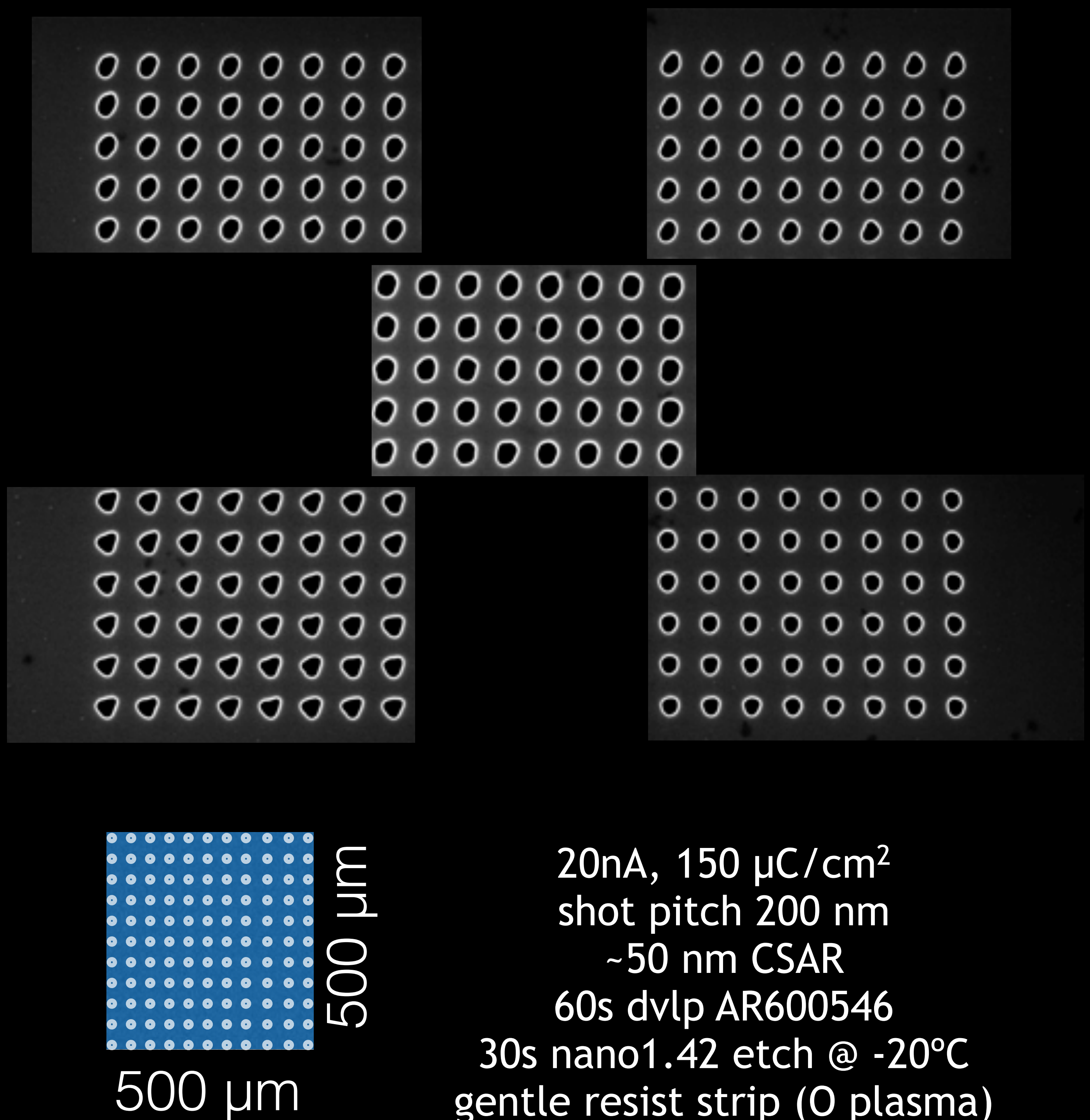


Beam shape in center of field and deflected to corners of field corrected for dynamic focus and dynamic astigmatism

Column of e-beam writer

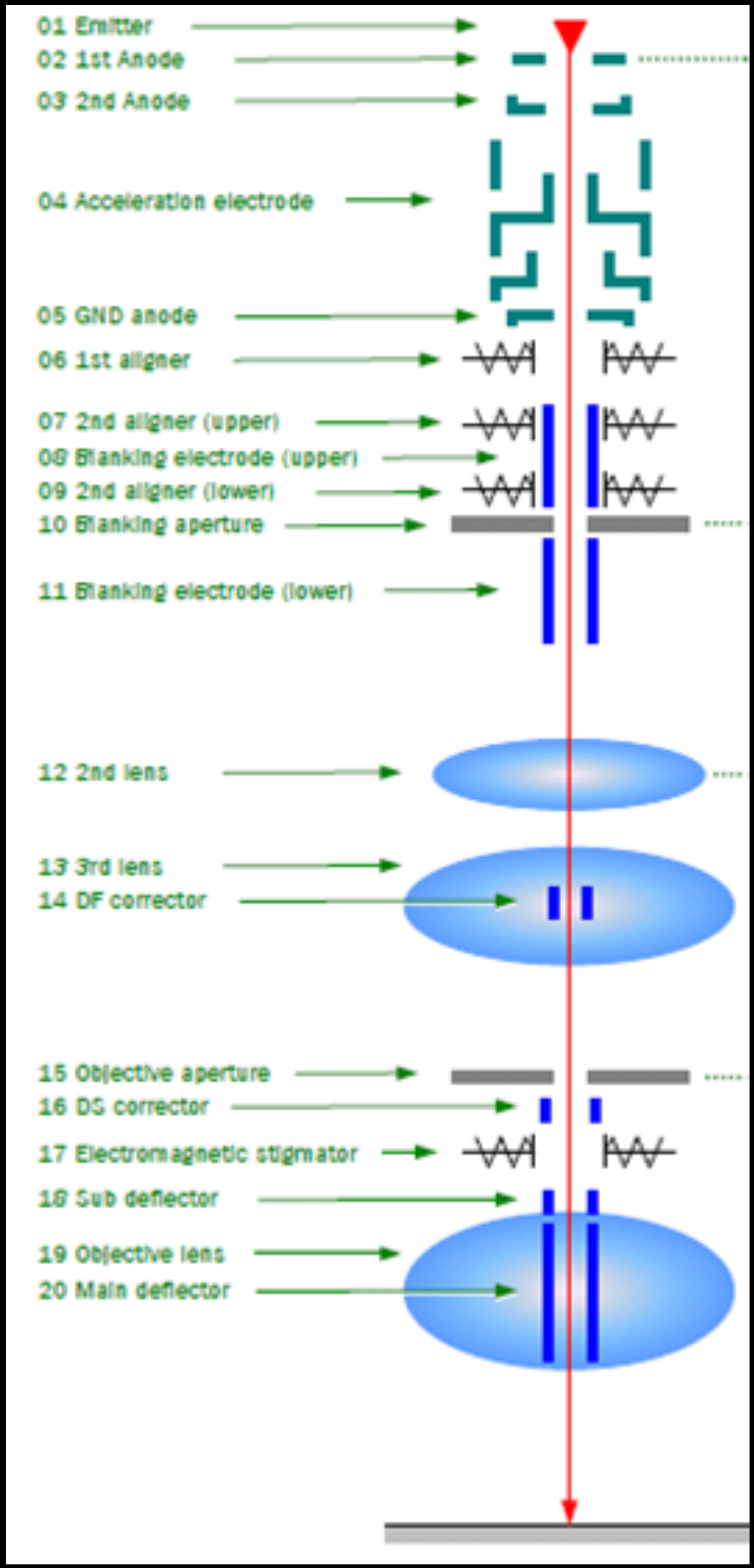


Dynamic focus and astigmatism correction



20nA, 150 µC/cm^2
shot pitch 200 nm
~50 nm CSAR
60s dvlp AR600546
30s nano1.42 etch @ -20ºC
gentle resist strip (O plasma)

Column of e-beam writer



Daily calibration routine

SFOCUS	Subprogram that adjusts the focus and astigmatism of the objective lens,and the electromagnetic stigmator (astigmatism correction) coil.
PDEFBE	Using the BE mark, PDEFBE automatically corrects the deflection gain and corrects the rotation of the main deflector.
DISTBE	Measures and corrects the deflection distortion of the electron beam in the writing field
SUBDEFBE	Corrects the deflection gain of the sub-deflector and corrects the rotation
HEIMAP	Measures the height of substrate within the specified range. Electron beam is focused to average height of substrate. This only applies to direct writing (mask writing).

E-beam Lithography @ DTU Danchip

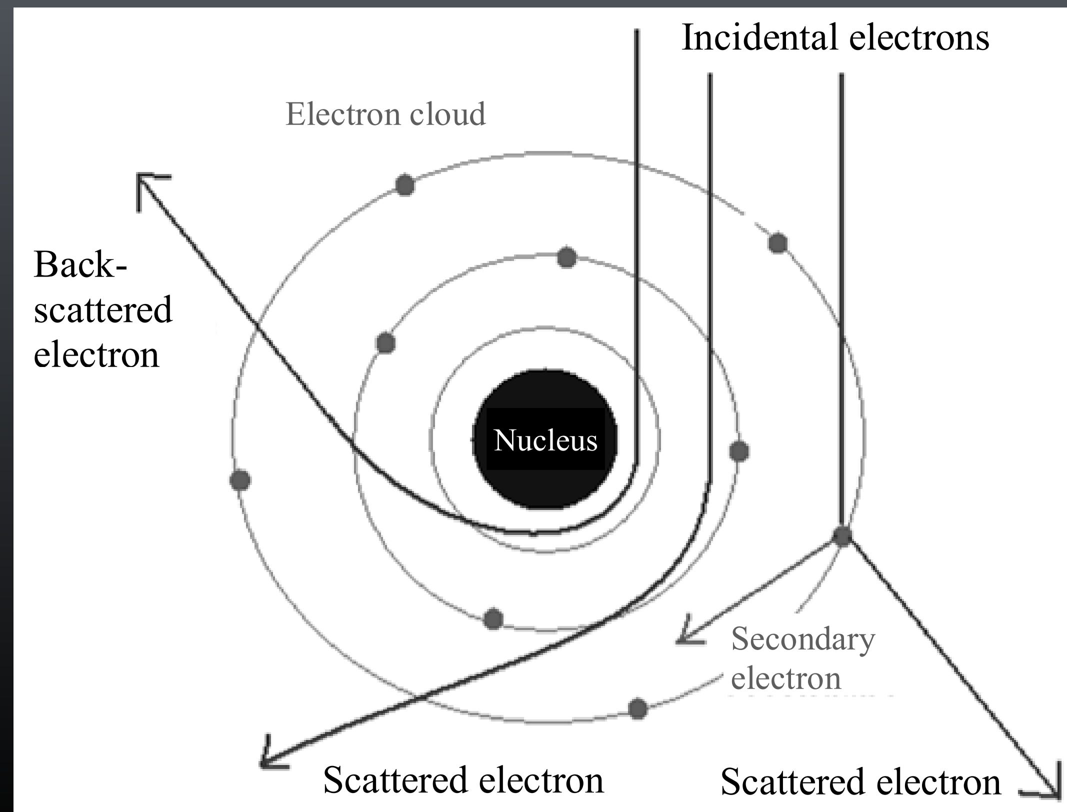
PART II

Proximity Effect
Charging Effect
Resist types: Positive and Negative
Heisenberg Uncertainty Principle
Temperature Issues
Exercise: calculation of beam diameter

DTU Danchip
National Center for Micro- and Nanofabrication
Tine Greibe

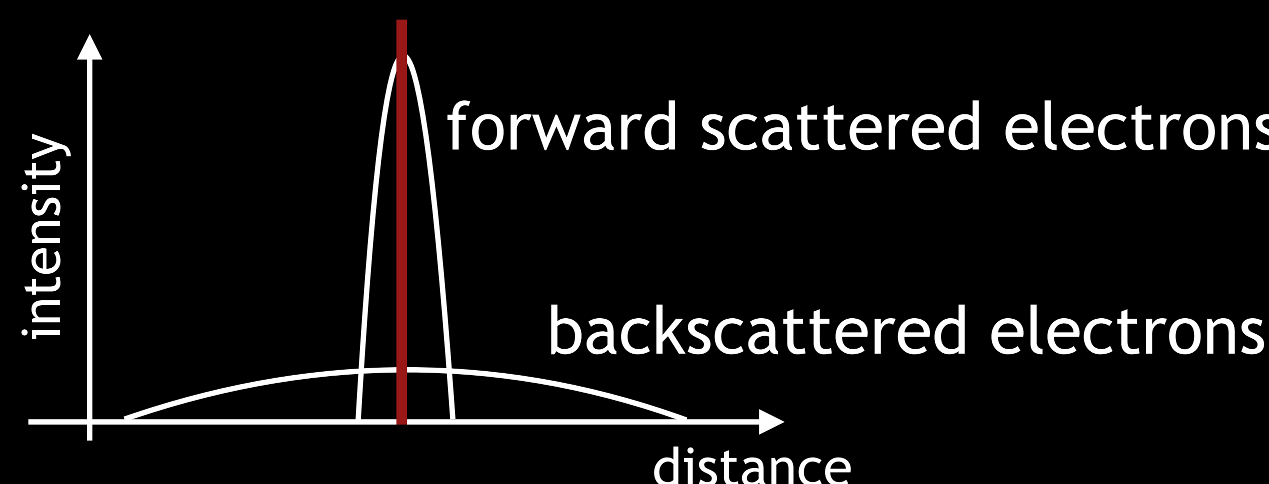
Electron-matter interaction

Backscattering
1. electron-nucleus interactions
2. electron retains (most of) its energy: elastic
3. change of travel direction

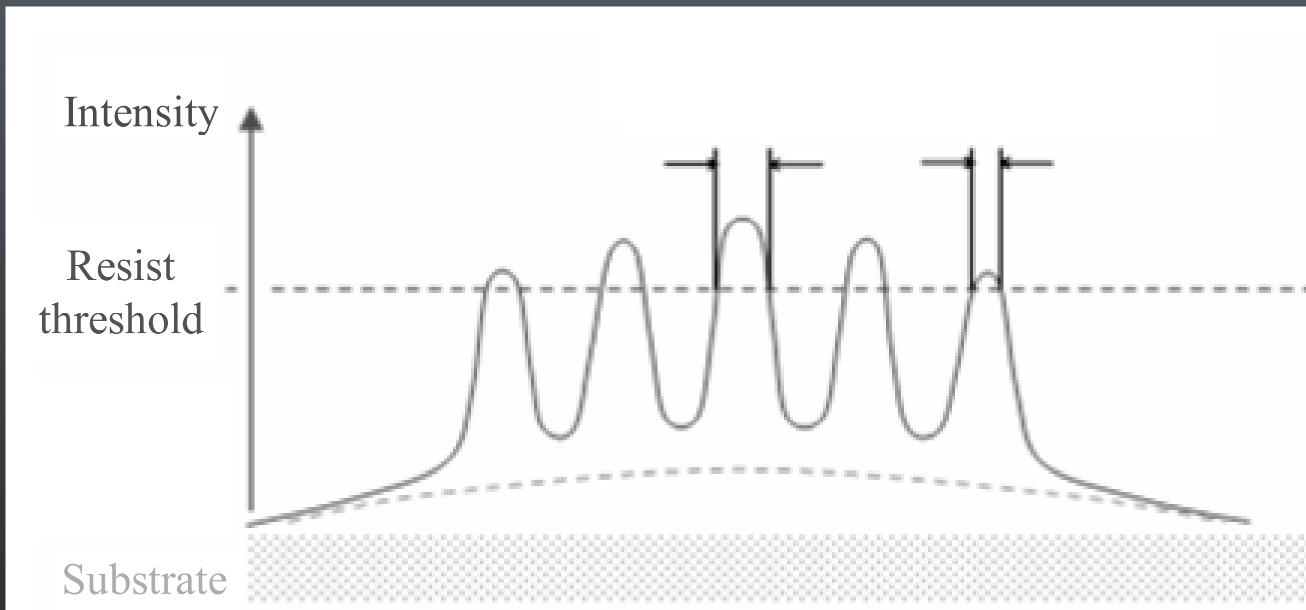


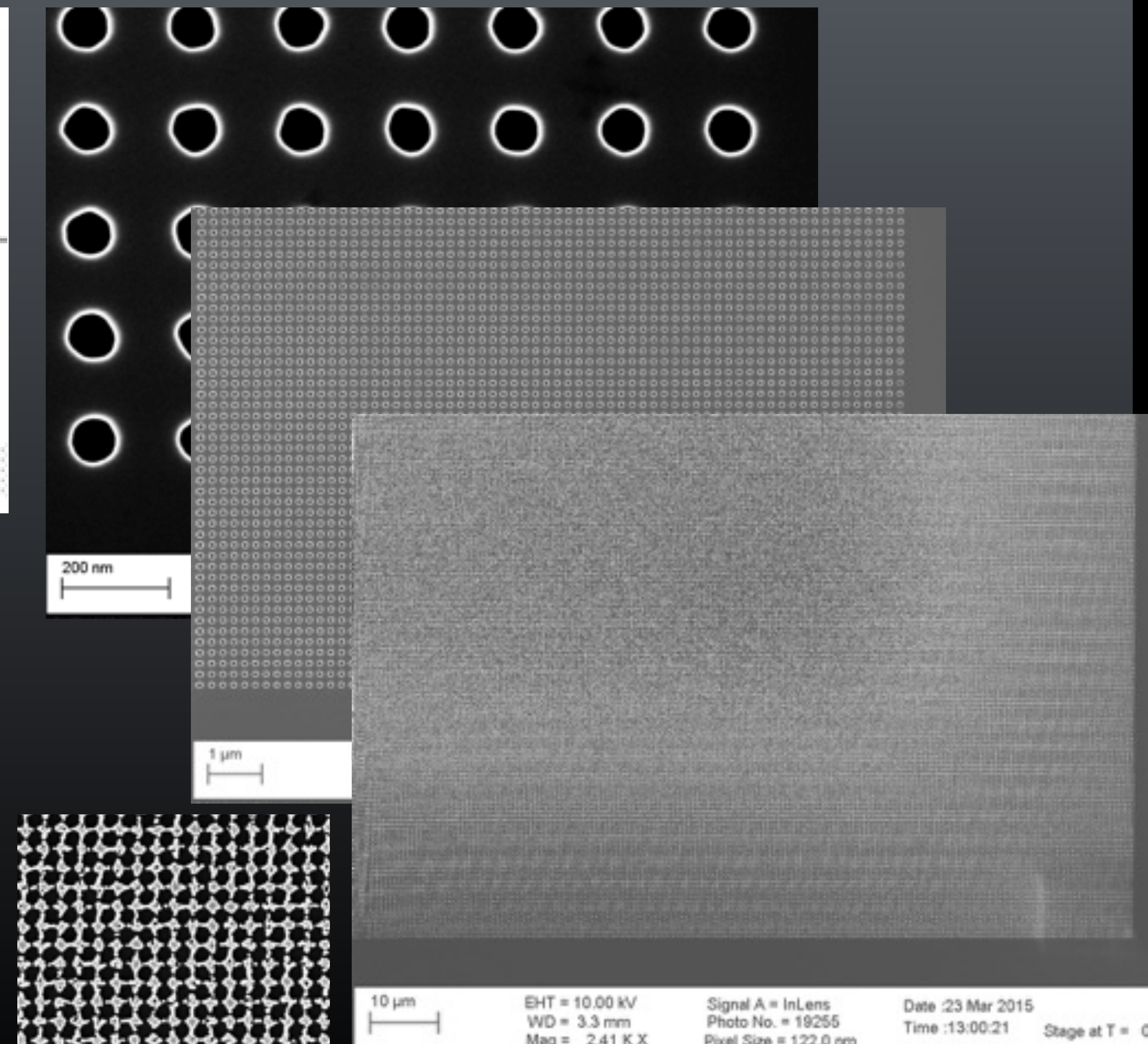
Forward scattering
1. electron-electron interactions (ionization or excitation)
2. some energy transferred: inelastic
3. causes widening of exposure regions

$$f(r) = \frac{1}{1+\eta}\left(\frac{1}{\pi\alpha^2}\exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\pi\beta^2}\exp\left(-\frac{r^2}{\beta^2}\right)\right)$$



Electron-matter interaction



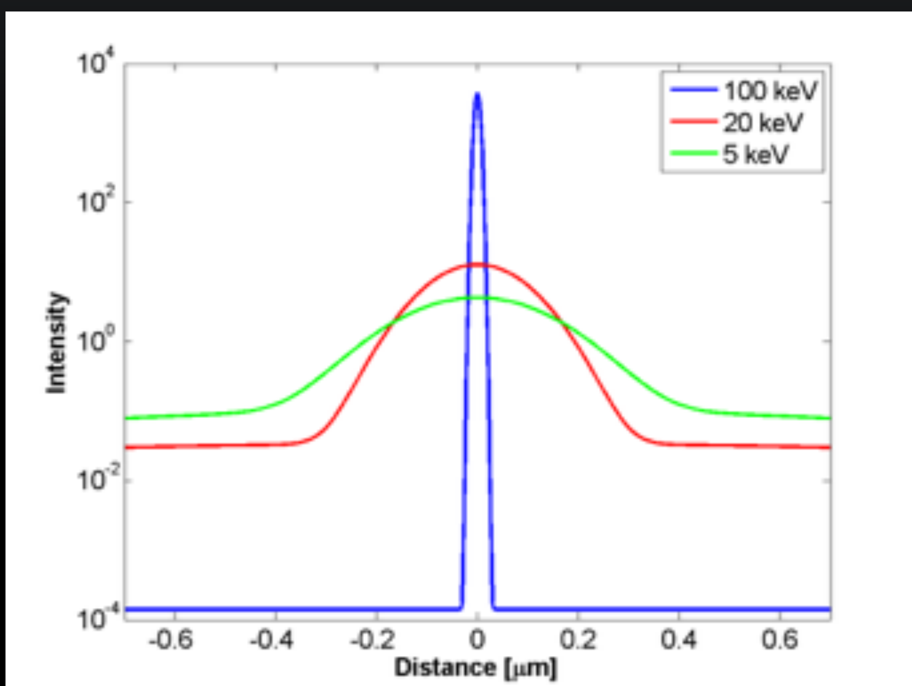


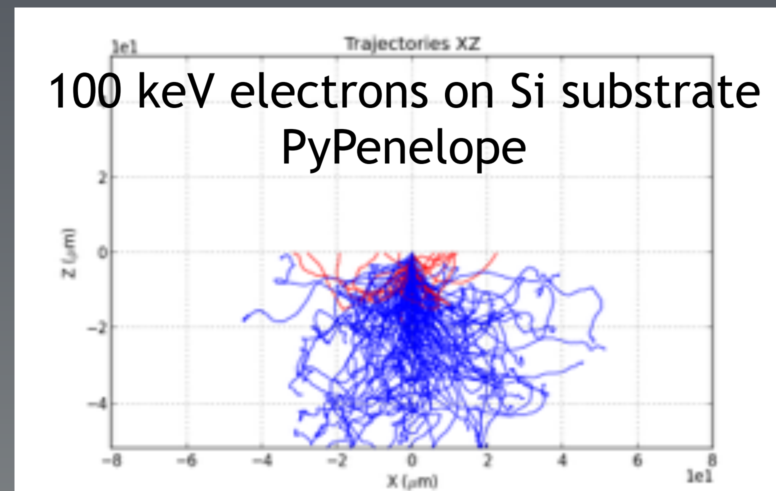
6 nA, 150 µC/cm^2
shot pitch 200 nm, ~50 nm CSAR
60 s development N50, 30s nano1.42 etch @ -20°C, gentle resist strip (O plasma)

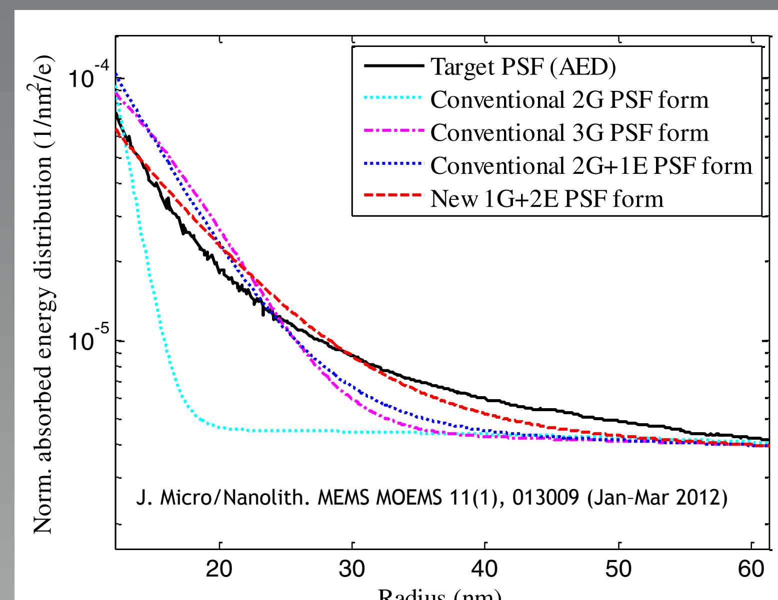
Electron-matter interaction

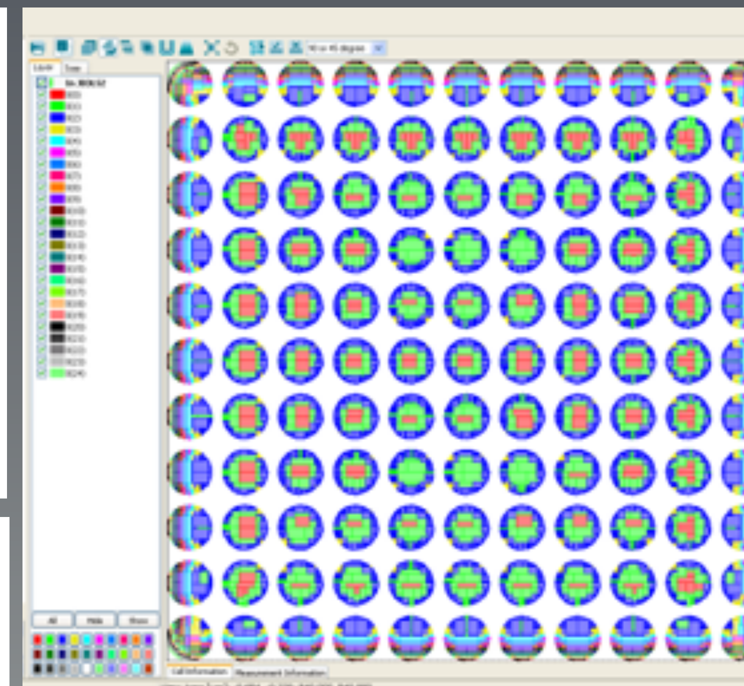
500 nm resist on Si substrate

	100 keV	20 keV	5 keV
α	0.007	0.12	1.33
β	31.2	2.0	0.18
η	0.74	0.74	0.74



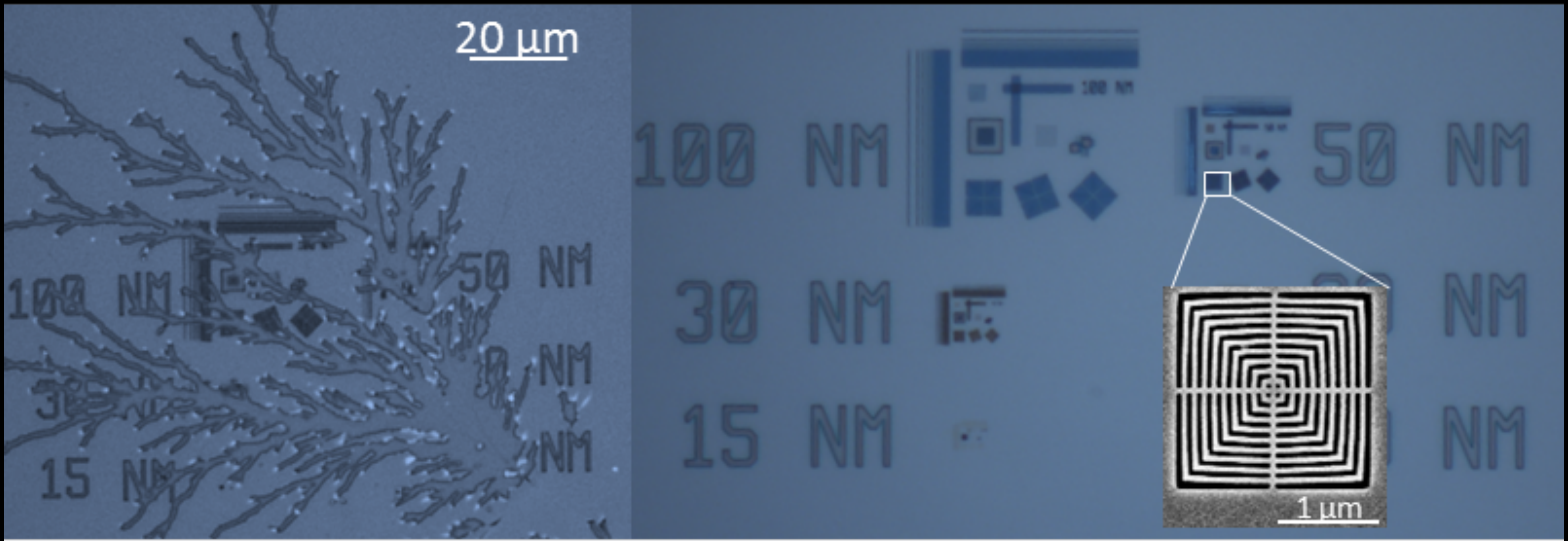






Dose modulation simulated by BEAMER software using double gaussian proximity effect

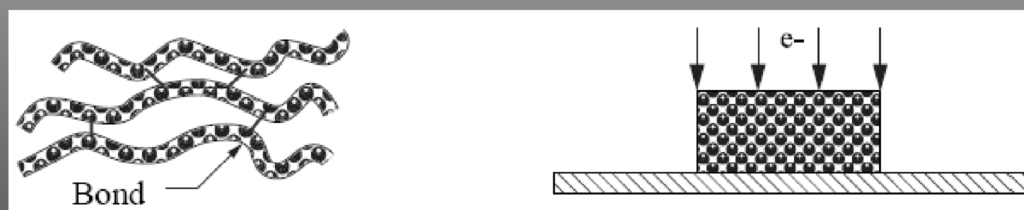
Discharging defects



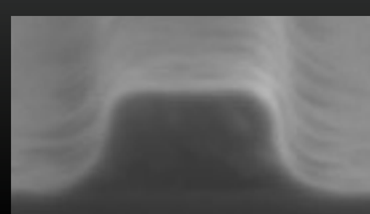
A pattern electron-beam exposed on a non-conducting substrate (borofloat glass) coated with ~150 nm AR-P 6200 CSAR leads to discharging defects in the resist (left). The same pattern is re-exposed on a similar substrate and resist, this time coated with Espacer 300 (Showa Denko) before exposure (right). SEM inspection of the latter exposure revealed no discharging effects (inset).

E-beam resist

Negative resist: crosslinking



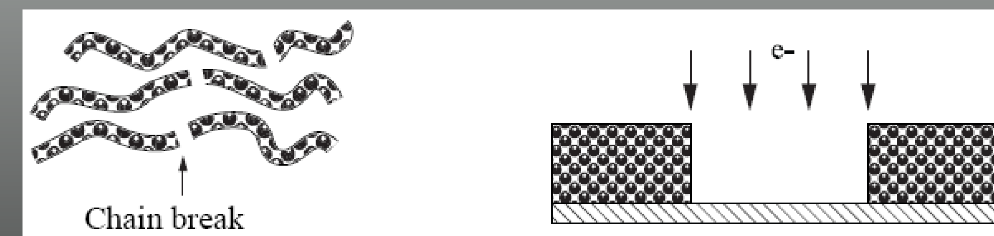
$$\frac{G(s)}{G(x)} < 4$$



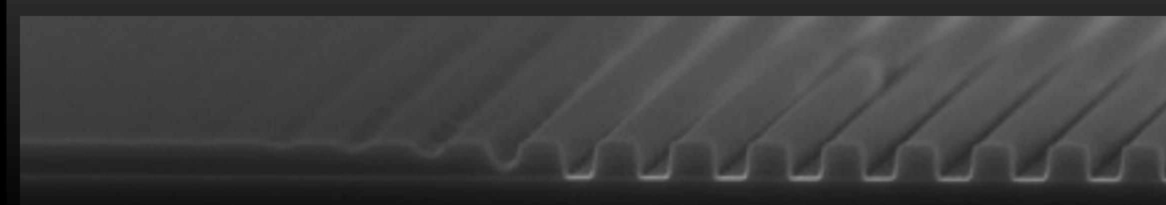
mrEBL6000.1 MicroResist

William Tiddi

Positive resist: scission



$$\frac{G(s)}{G(x)} > 4$$



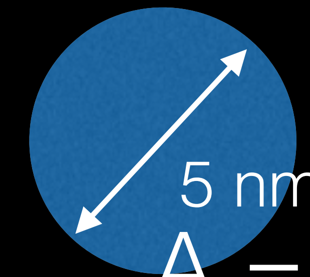
AR-P 6200 (CSAR), AllResist

G(s) - number of main scissions produced per 100 eV of energy absorbed

G(x) - number of crosslinks produced per 100 eV of energy absorbed

Contrast curves

Beam shot



$A = 19.6\ nm^2$

	mrEBL	CSAR
dose μC/cm²	**20**	**300**
electrons/ nm²	**1.25**	**18.75**
electrons/ beam shot	**25**	**368**
P(m-1)	**~ 8%**	**~ 2%**

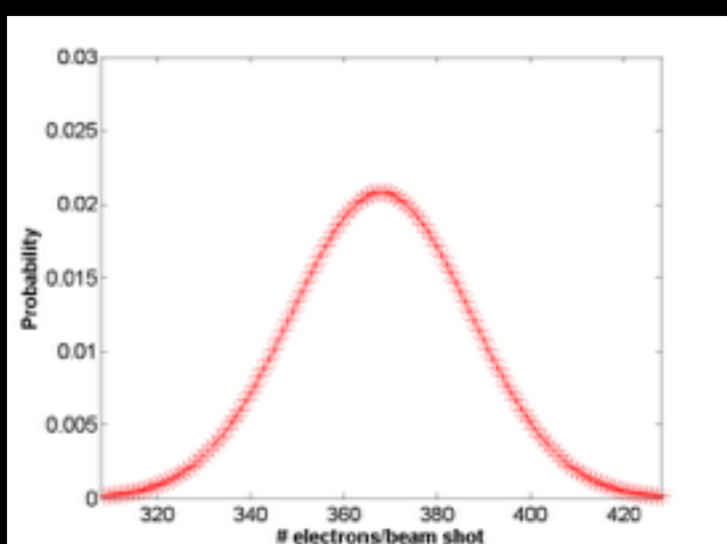
Poisson distributed

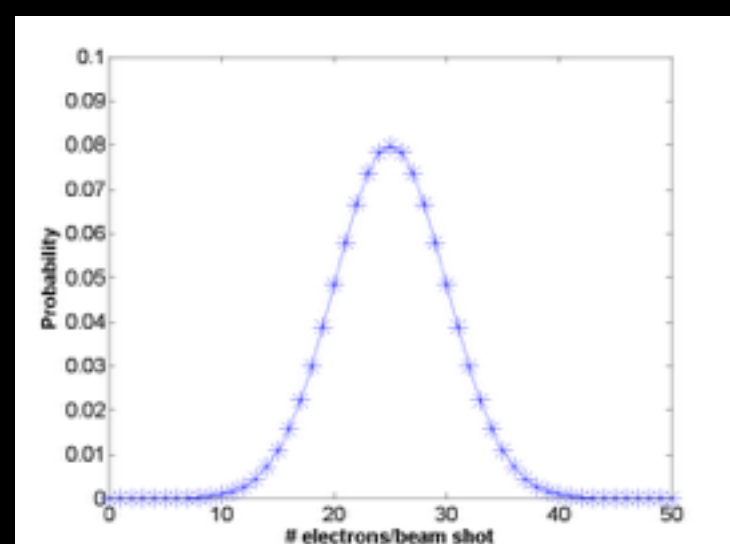
Normal distributed for large m

$$P_n = \frac{m^n}{n!}\, e^{-m}$$

m = expected

n = true

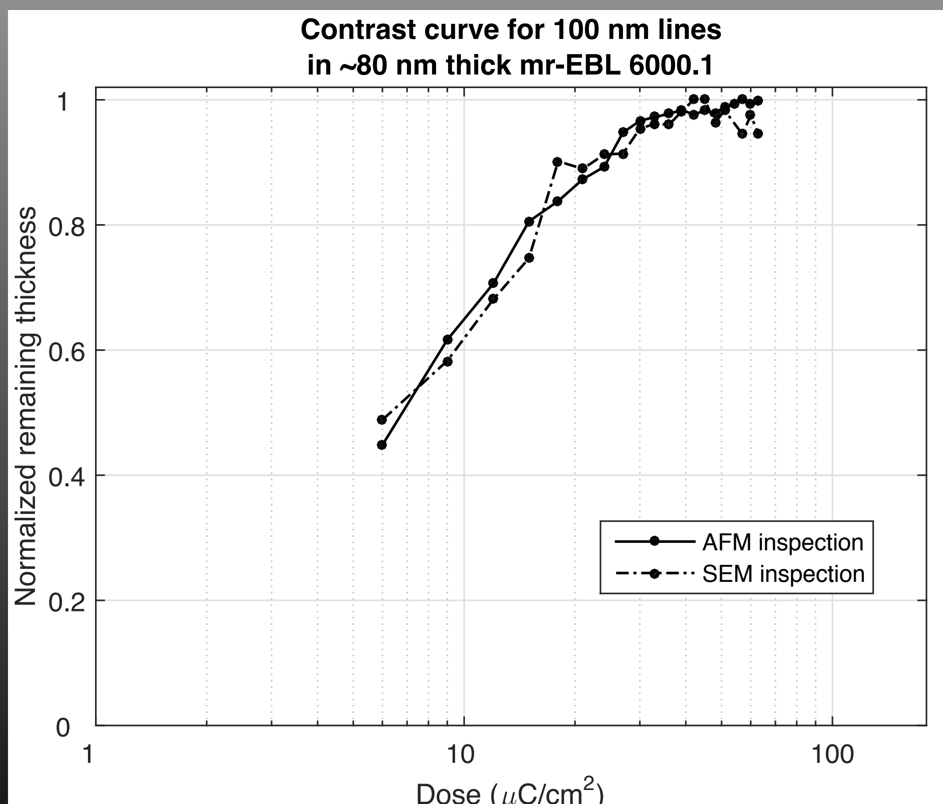


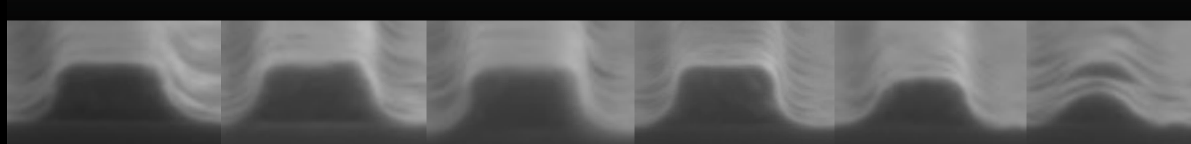


Resolution and sensitivity walk hand in hand

Contrast curves

mrEBL6000.1

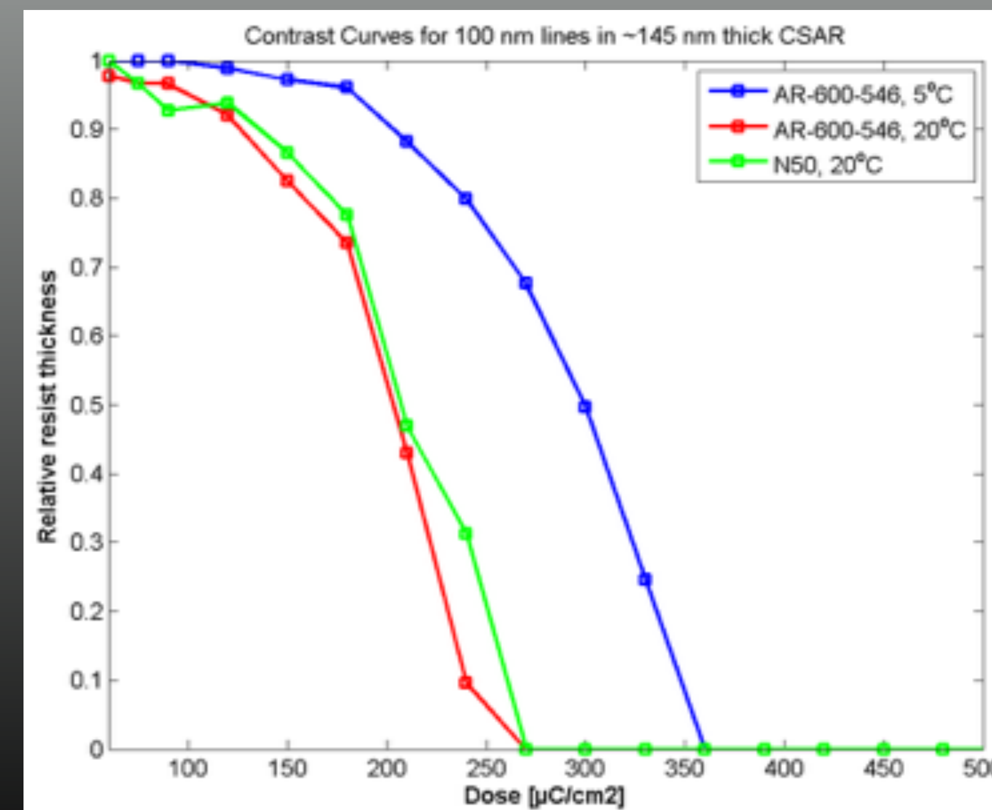


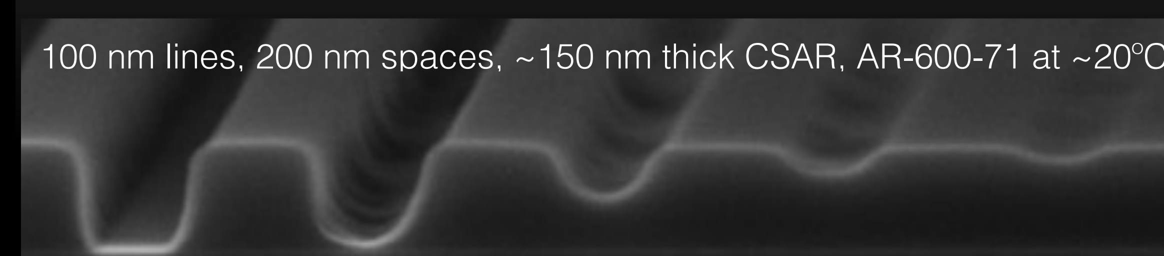


100 nm lines. ~80 nm thick mrEBL. mrDEV at ~20°C

William Tiddi, Graph and SEM pictures

AR-P 6200 (CSAR)

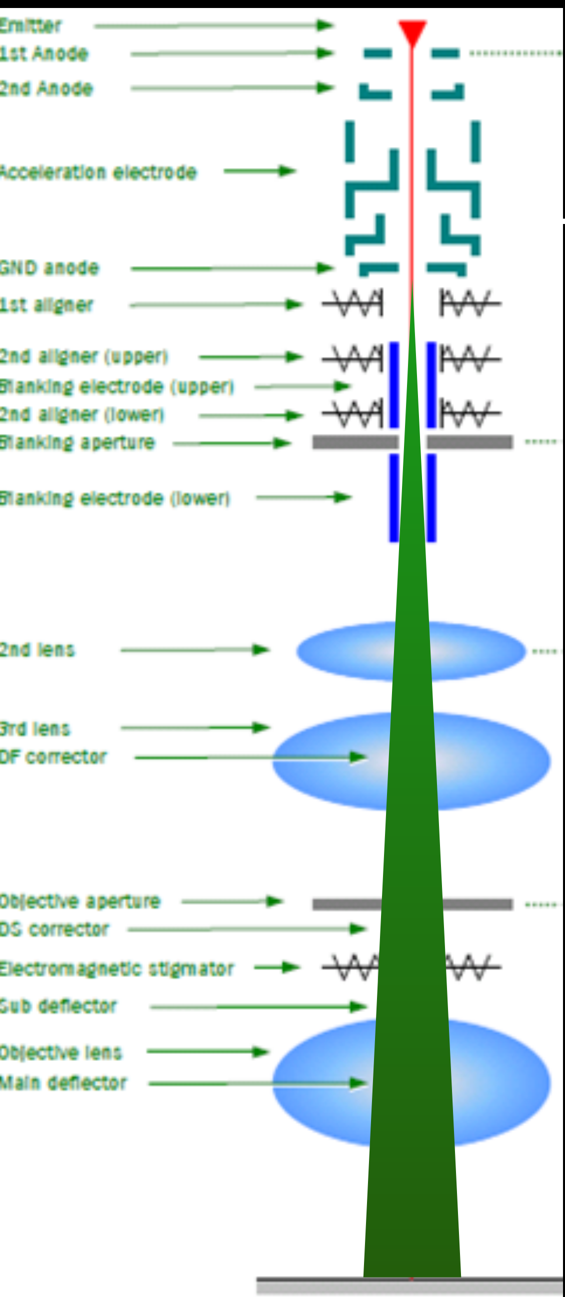




270 µC/cm^2 240 µC/cm^2 210 µC/cm^2 180 µC/cm^2 150 µC/cm^2

AFM: Berit Geilman Herstrøm, DTU Danchip (2015)

Fundamental quantum mechanical limit of electrons

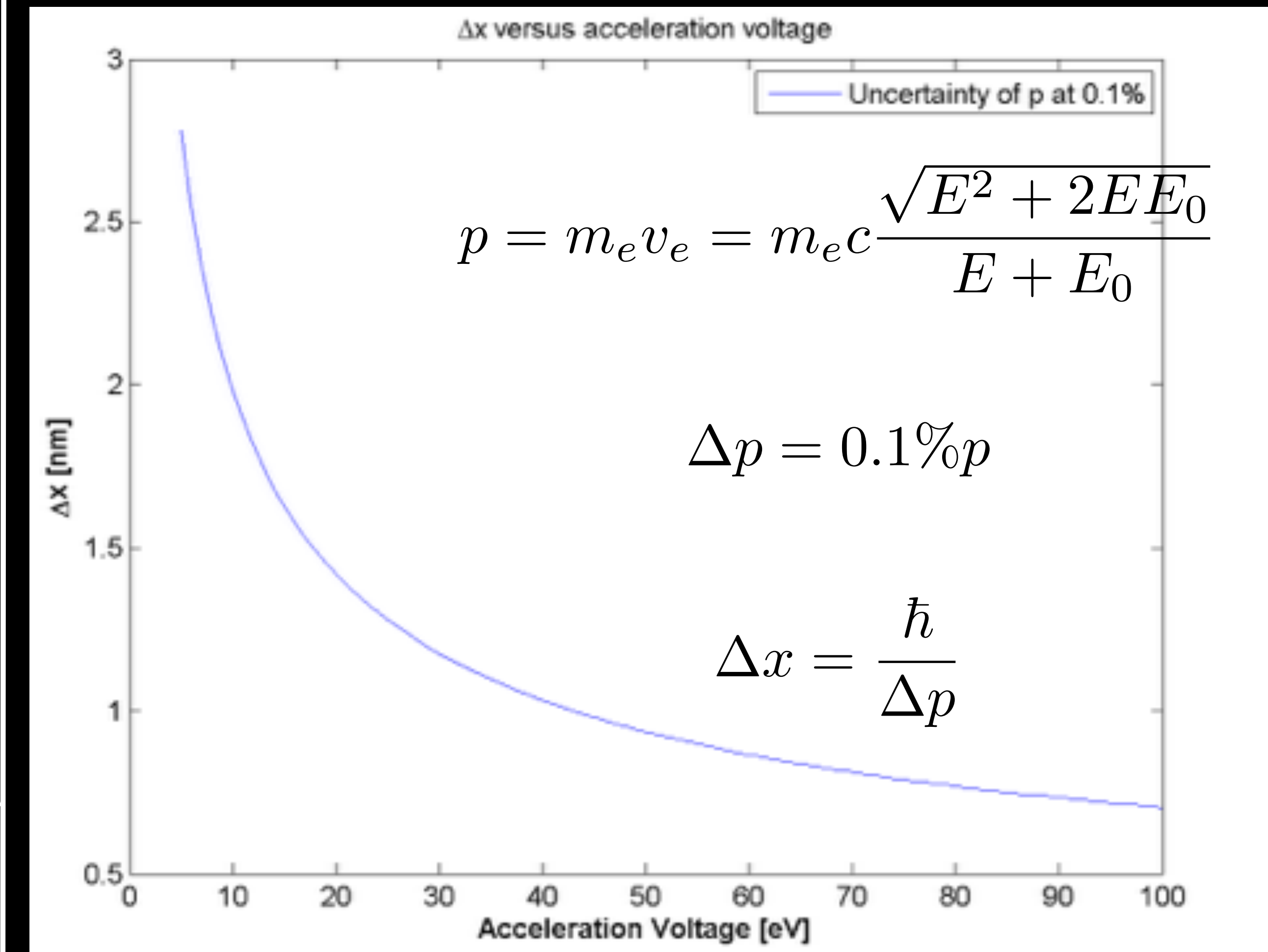


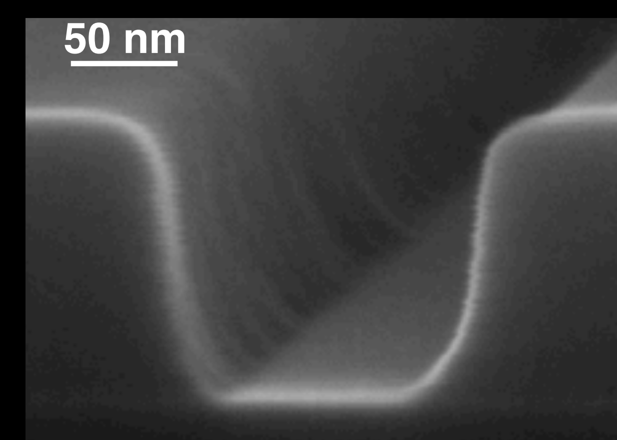
Δx

Heisenberg uncertainty principle

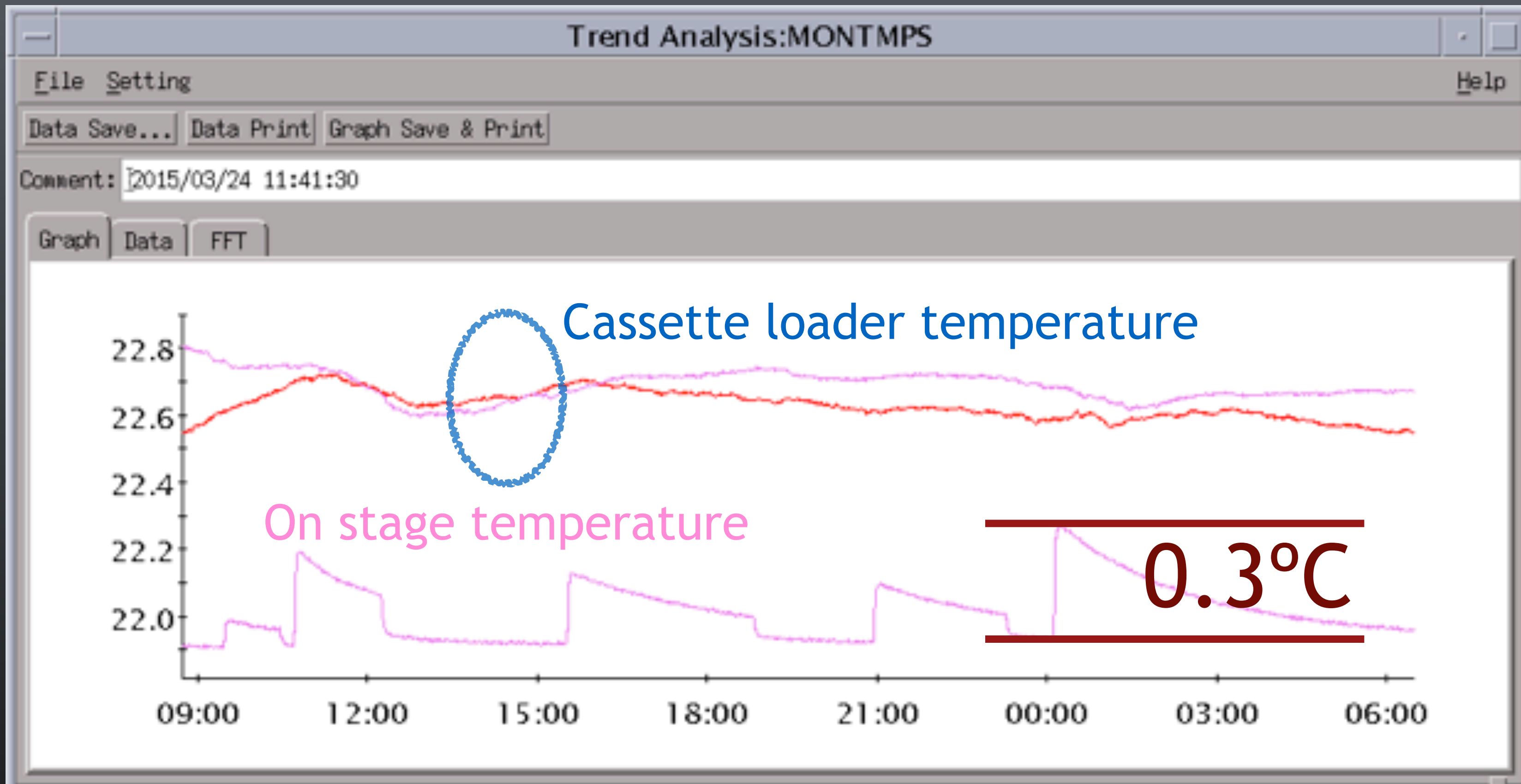
$\Delta x \, \Delta p \geq \hbar$

$\downarrow \Delta p$

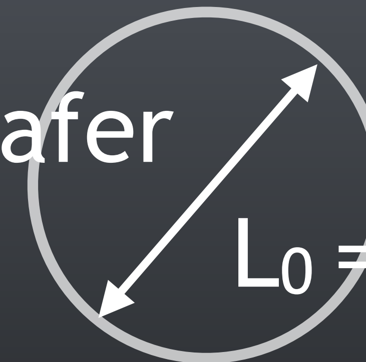




Hands-on the JBX9500



$\Delta L = L_0 \alpha \Delta t$



4” wafer

L_0 = 100 mm

cassette

L_0 = 35 mm

	α (10^{-6}/K)	ΔL (4” wafer)	ΔL (cassette)
Al	23.1	693 nm	2426 nm
Ti	8.6	258 nm	903 nm
Si	2.56	77 nm	

Theoretical limit of beam diameter of an electro-optical system

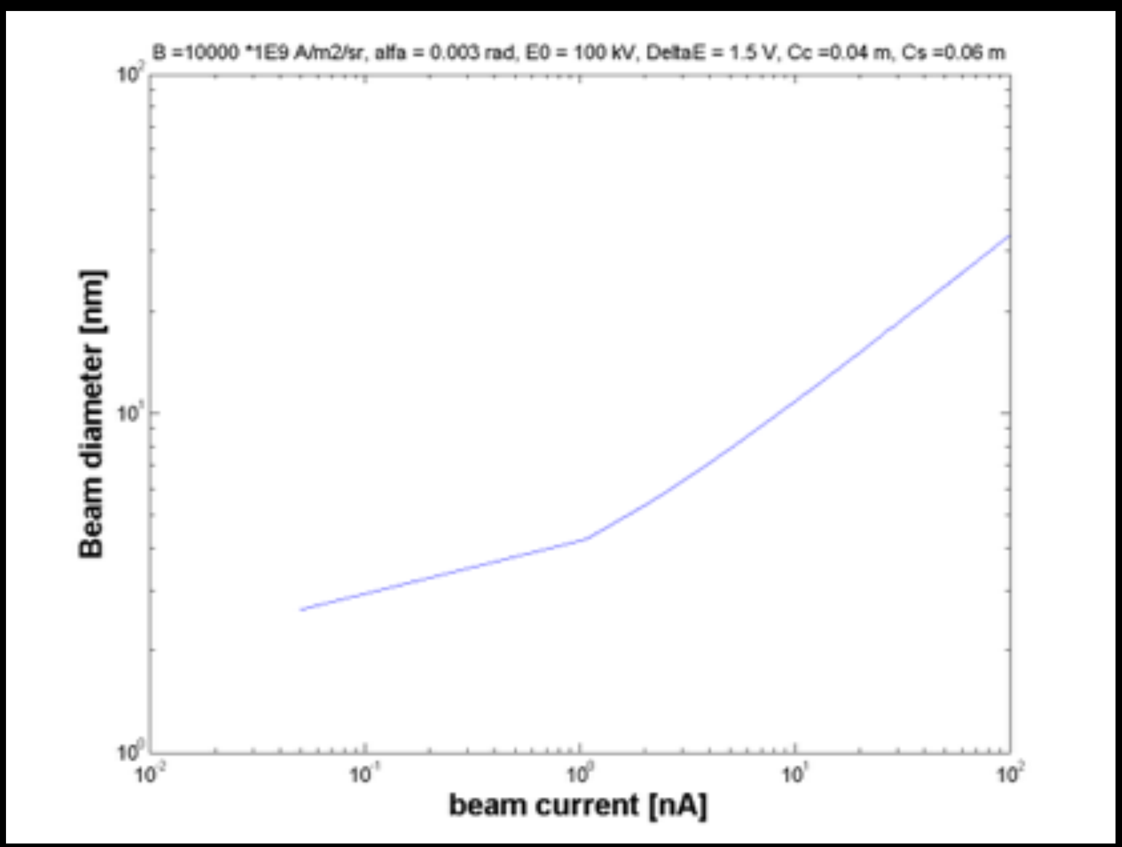
$$d^2 = \left[\frac{i}{B} + (1.22\lambda)^2\right]\frac{1}{\alpha^2} + \left(C_c\frac{\Delta E}{E_0}\right)^2\alpha^2 + (0.5C_s)^2\alpha^6$$

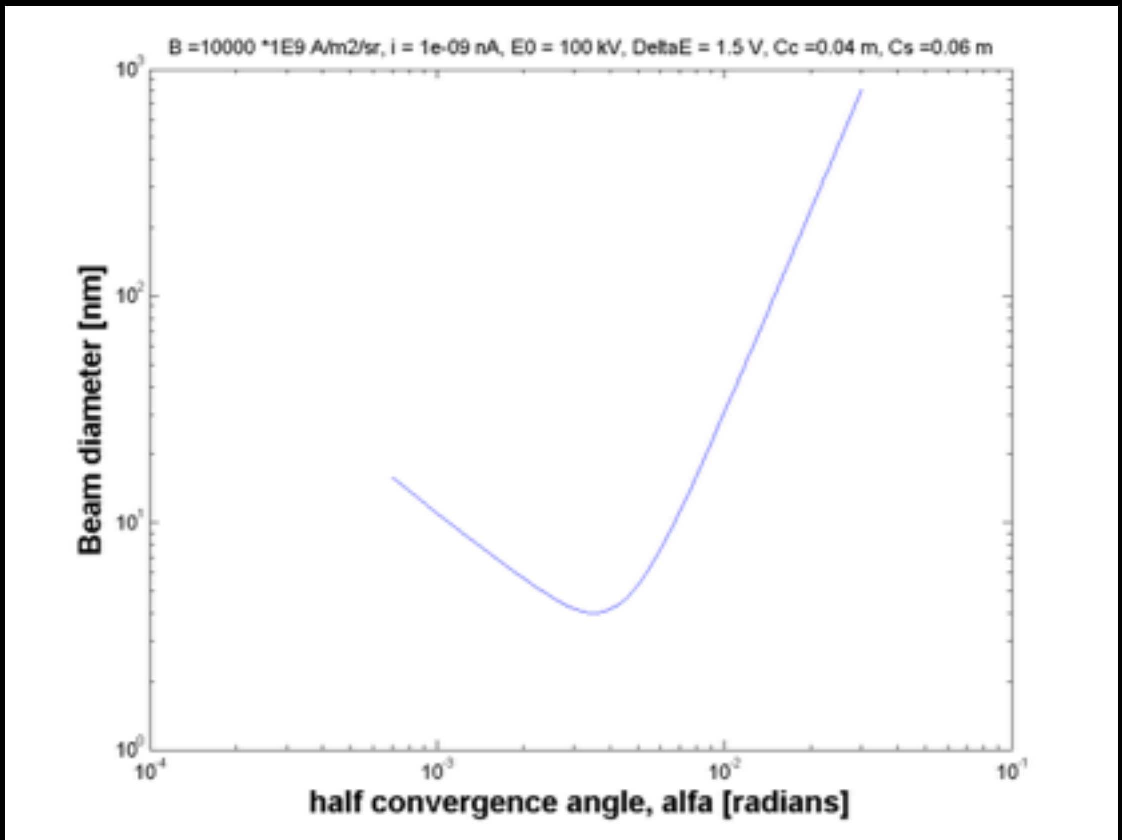
Parameter		value
beam current	i [A]	1E-09
Brightness	B [A/cm^2/sr]	1E+09
Average energy of electrons	E_0 [keV]	100
Energy spread of electrons	ΔE [eV]	1.5
de Broglie wavelength	λ [pm]	3.88
convergence half-angle	α [radians]	2E-03
Chromatic aberration coefficient of final lens	Cc [mm]	40
Spherical aberration coefficient of final lens	Cs [mm]	60

Optimizing electron beam lithography in the nanometer range, Vladimir Zlobin,13 April 2006, SPIE Newsroom

Theoretical limit of beam diameter of an electro-optical system

$$d^2 = \left[\frac{i}{B} + (1.22\lambda)^2\right]\frac{1}{\alpha^2} + \left(C_c\frac{\Delta E}{E_0}\right)^2\alpha^2 + (0.5C_s)^2\alpha^6$$





Optimizing electron beam lithography in the nanometer range, Vladimir Zlobin,13 April 2006, SPIE Newsroom

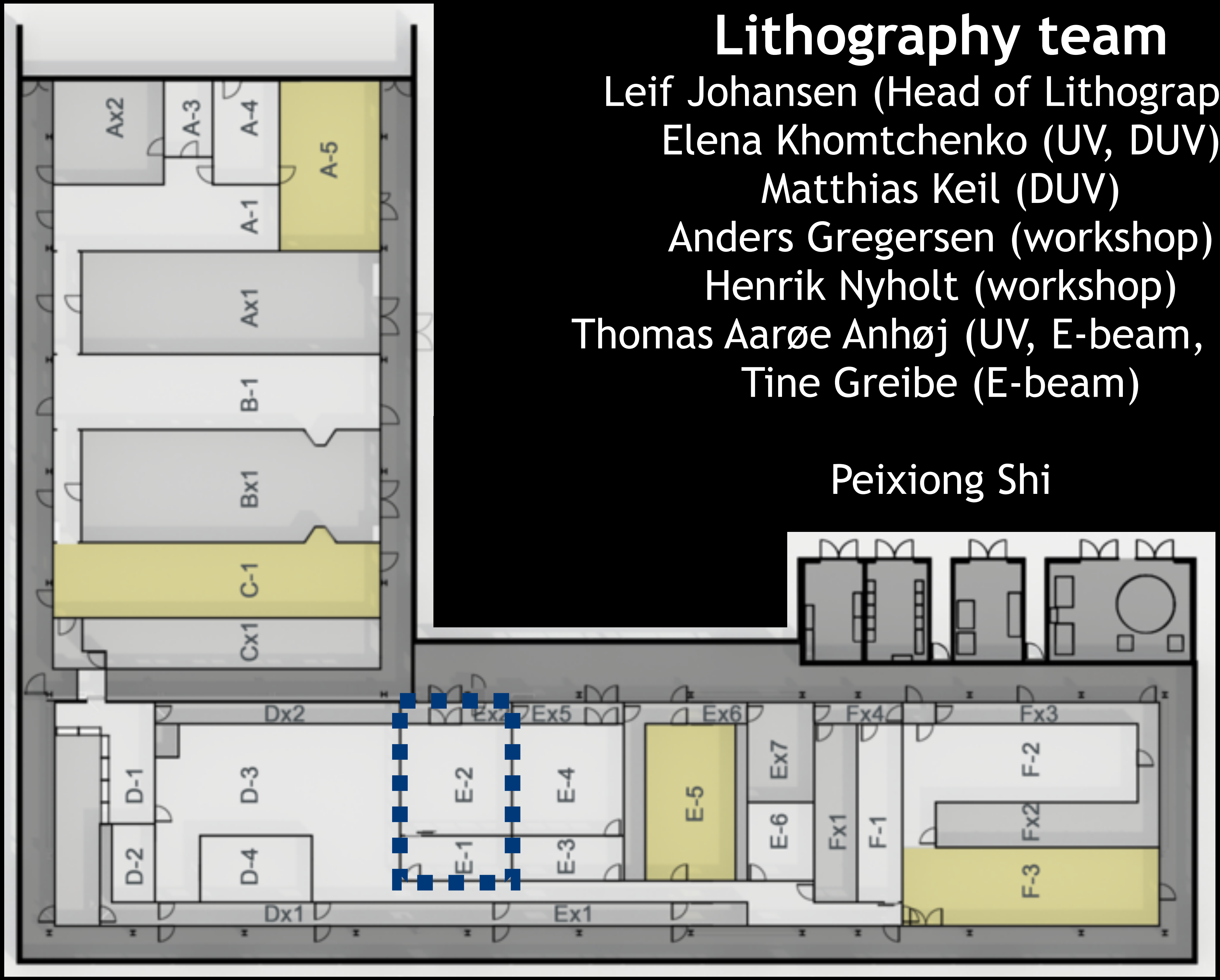
E-beam Lithography @ DTU Danchip

PART III

Introduction to JEOL JBX-9500
Preparation of files
Calibration of Machine before exposure
Exercise: preparation of sdf, jdf, and v30-files

DTU Danchip
National Center for Micro- and Nanofabrication
Tine Greibe

E-beam Lithography @ DTU Danchip

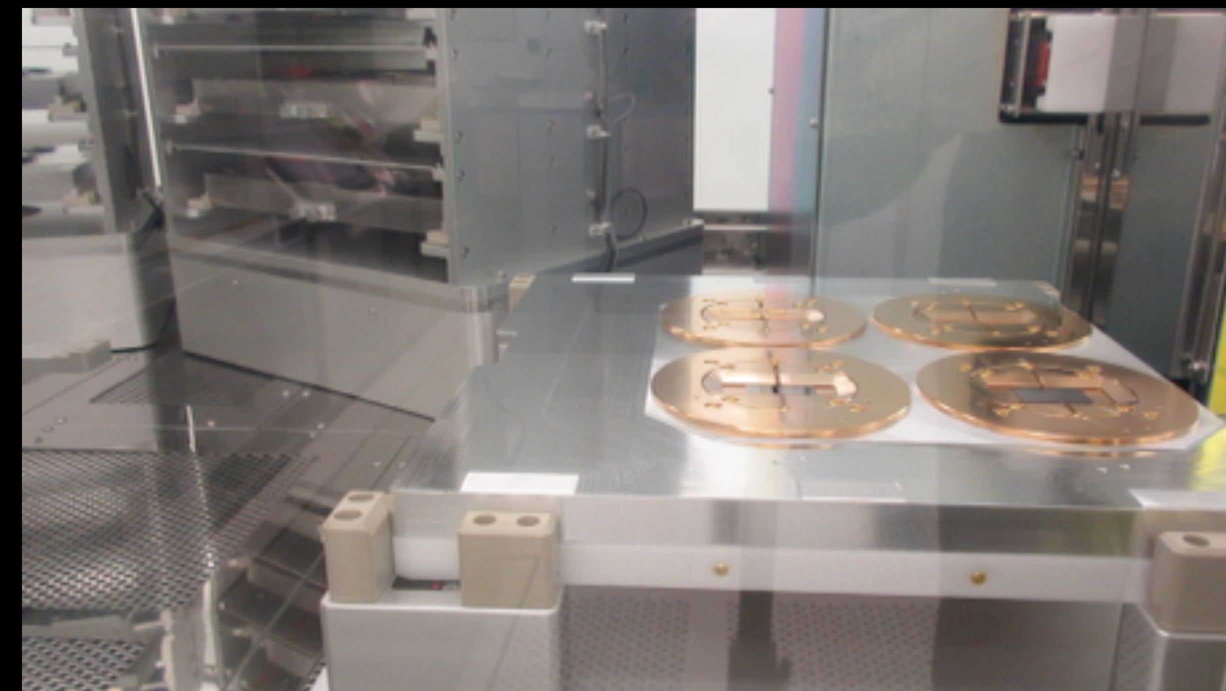


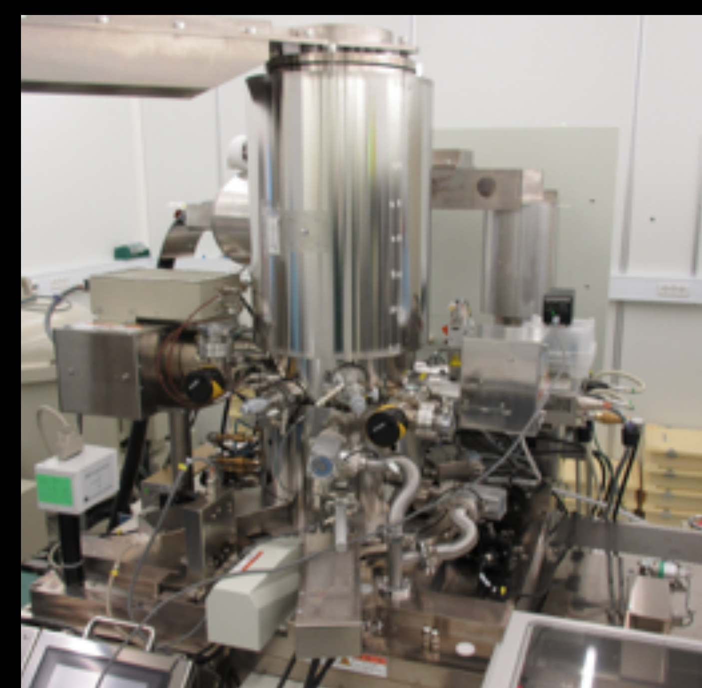
Lithography team

Leif Johansen (Head of Lithography)
Elena Khomtchenko (UV, DUV)
Matthias Keil (DUV)
Anders Gregersen (workshop)
Henrik Nyholt (workshop)
Thomas Aarøe Anhøj (UV, E-beam, DUV)
Tine Greibe (E-beam)

Peixiong Shi

E-beam Lithography @ DTU Danchip



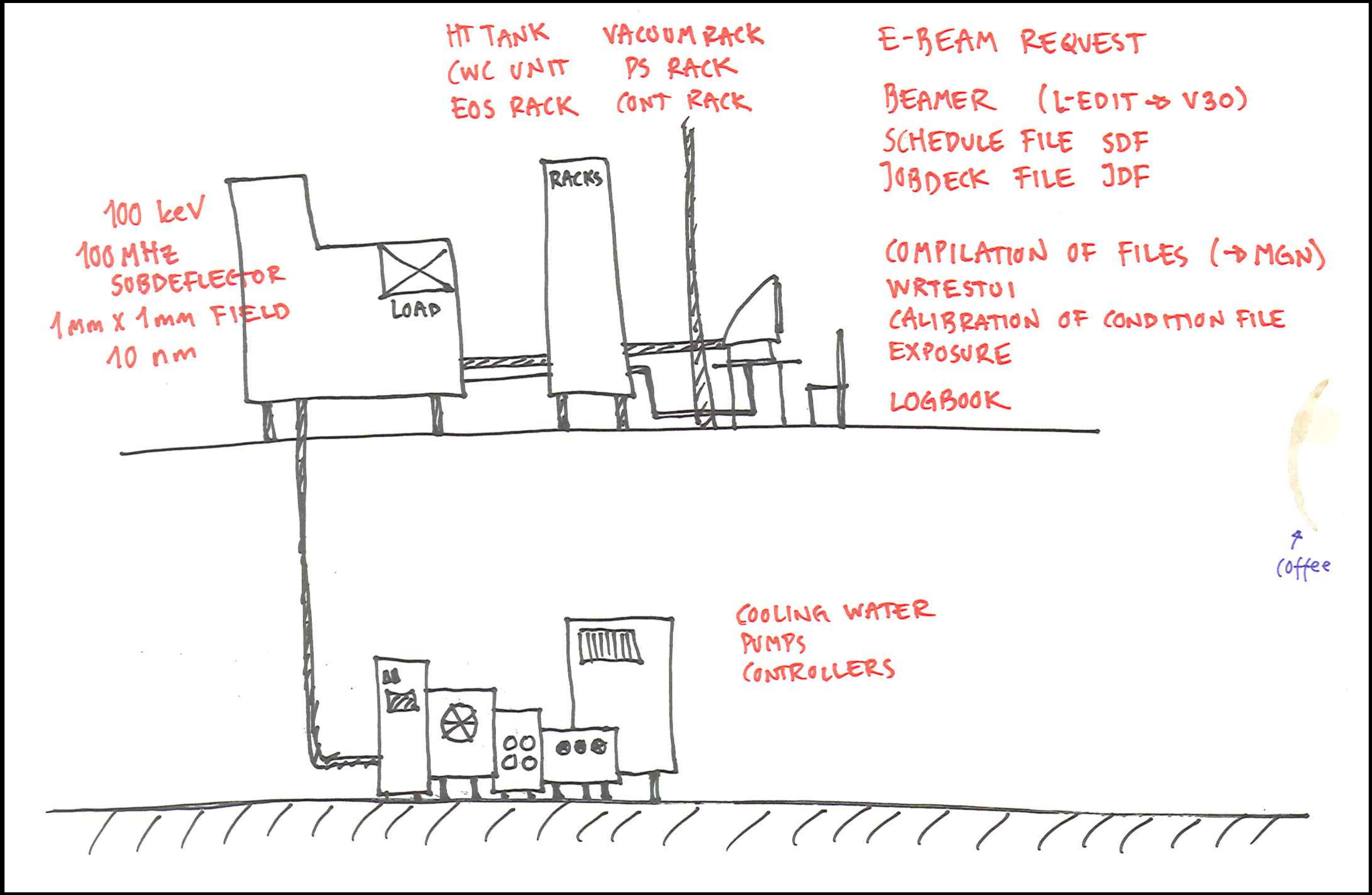


JEOL JBX-9500FS: Installed 2012
ISO 4 (class 10) cleanroom
Temperature drift control 0.05 K/h
Screened from magnetic noise (0.05 μT)

E-beam Lithography @ DTU Danchip

(1) On weak ground (on reclaimed land, near the edge of a lake or river, near the sea shore, etc.)
(2) Within 50 m of a motorway
(3) Within 100 m of a railway
(4) Within 15 m of an elevator
(5) Within 10 m of an electrical machine of 10 kW or more
(6) Within 10 m of a large transformer of 10 kVA or more
(7) Within 3 m of indoor wiring rated at 100 A or more
(8) Within 20 m of high-voltage wiring in a factory
(9) Within 30 m of an electric-power substation
(10) Within 150 m of high-voltage transmission lines
(11) Within 1 km of a transmitter antenna
(12) Within 2 m of a personal computer or other computer
(13) Where a high-power transceiver or wireless telephone is being used
(14) A very acoustically noisy place

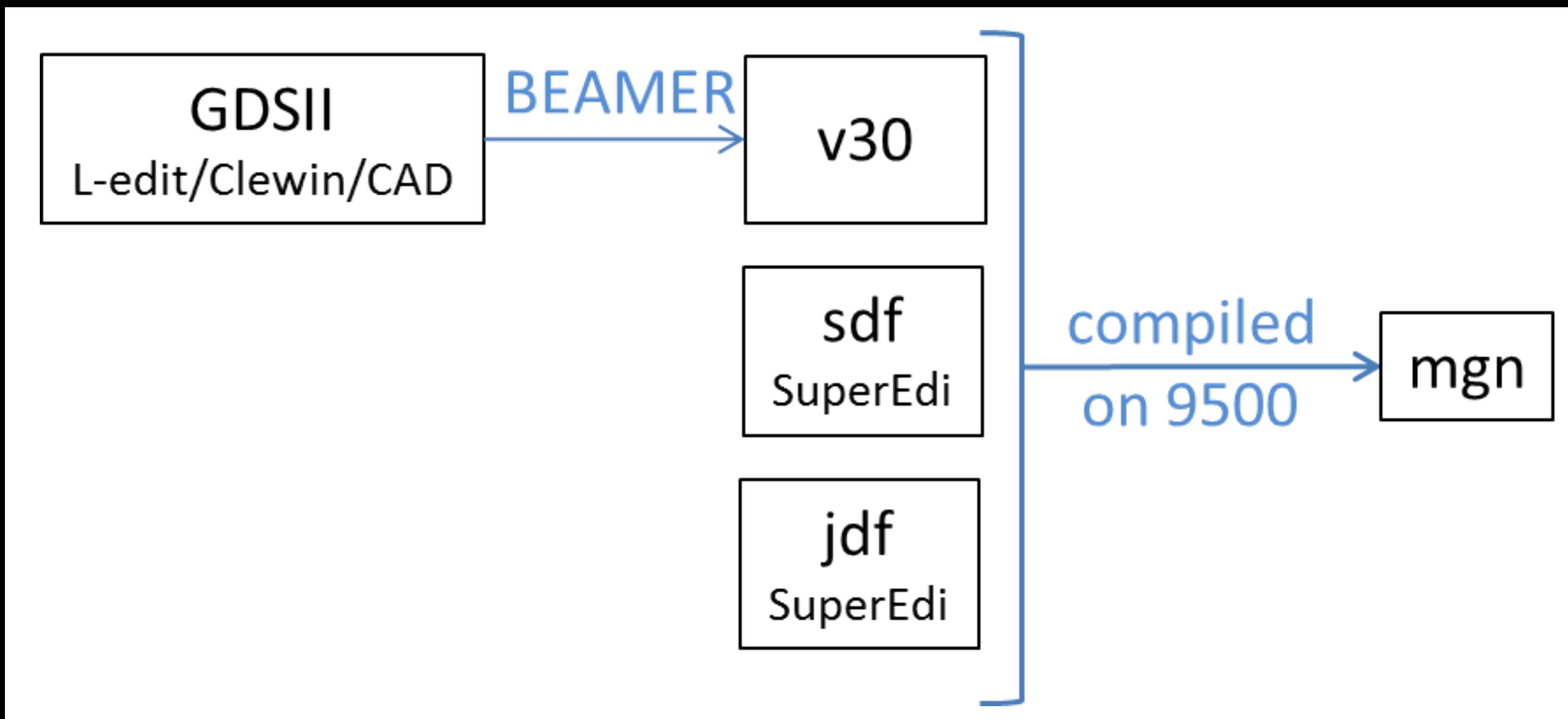
E-beam Lithography @ DTU Danchip



Procedure

1. File preparation: sdf-file, jdf-file and GDS-file
2. Converting of GDS to v30
3. Compiling of files
4. Load of substrate
5. Calibration of column
6. Exposure

File preparation: sdf-file, jdf-file and GDS-file



Creation of sdf- and jdf-file

SuperEdi - [QC12W1003.sdf]

M:\E-beam\sdf jdf templates\QC12W1003.sdf

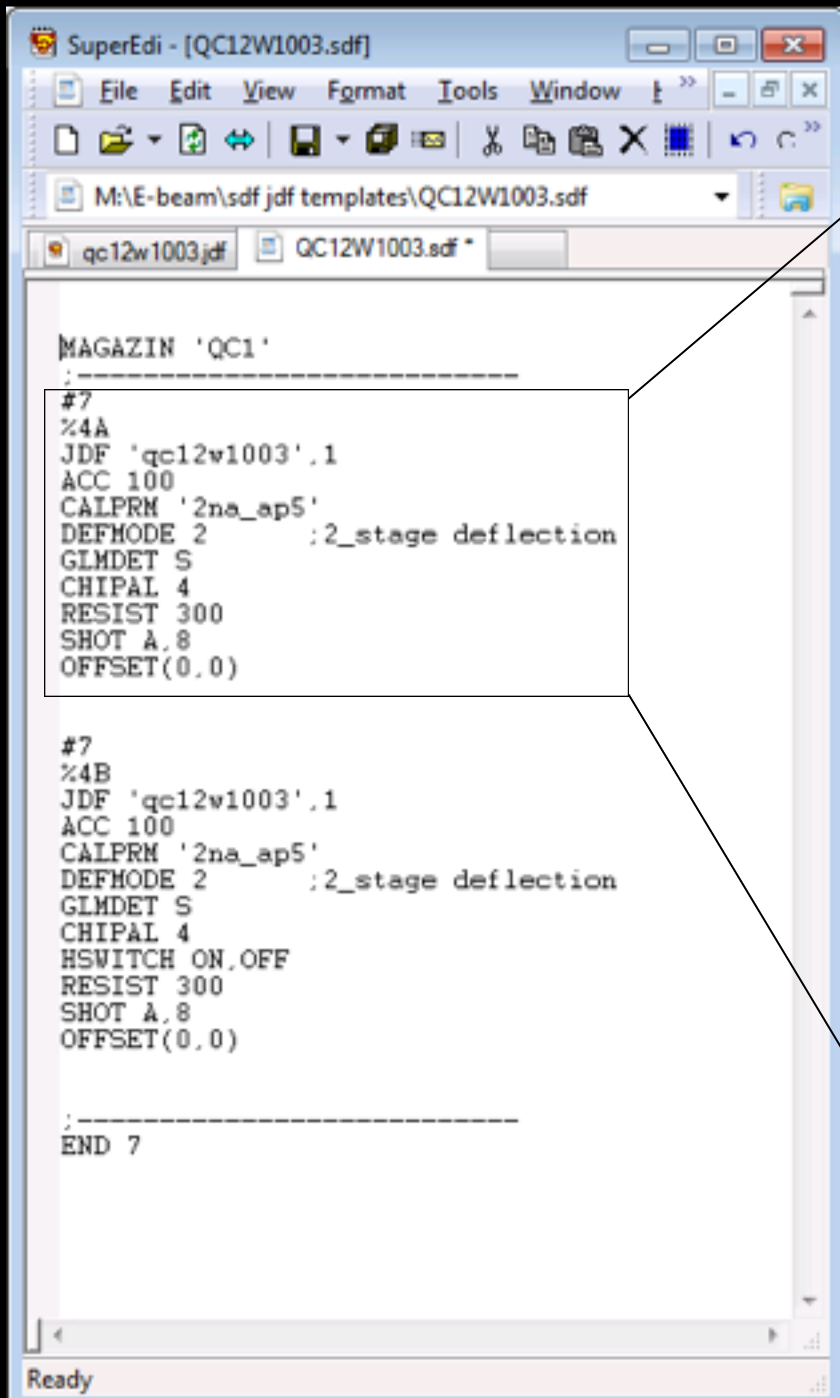
```
MAGAZIN 'QC1'
;---------------------------
#7
%4A
JDF 'qc12w1003',1
ACC 100
CALPRM '2na_ap5'
DEFMODE 2      ;2_stage deflection
GLMDET S
CHIPAL 4
RESIST 300
SHOT A,8
OFFSET(0,0)


#7
%4B
JDF 'qc12w1003',1
ACC 100
CALPRM '2na_ap5'
DEFMODE 2      ;2_stage deflection
GLMDET S
CHIPAL 4
HSWITCH ON,OFF
RESIST 300
SHOT A,8
OFFSET(0,0)


;---------------------------
END 7
```

SuperEdi - [qc12w1003.jdf]

M:\E-beam\sdf jdf templates\qc12w1003.jdf

```
JOB/W     'QC12',4   ; 4inch wafer

GLMPOS    P=(-35000,0),Q=(35000,0)

PATH FT01

ARRAY    (-10000,3,10000)/(10000,3,10000)
    ASSIGN  A(1) -> (*,*)
AEND

1: ARRAY     (-1000,3,1000)/(1000,3,1000)
    CHMPOS M1=(-750,750),M2=(750,750),M3=(750,-750),M4=(-750,-750)
     CHMARK 4.0,100.0
    ASSIGN  P(1) -> (*,*)
   AEND

PEND

LAYER    1

        P(1)   'TIGRE_L1CM4.v30'
        STDCUR  2.2    ; 2 nA

END
```

Creation of sdf- and jdf-file

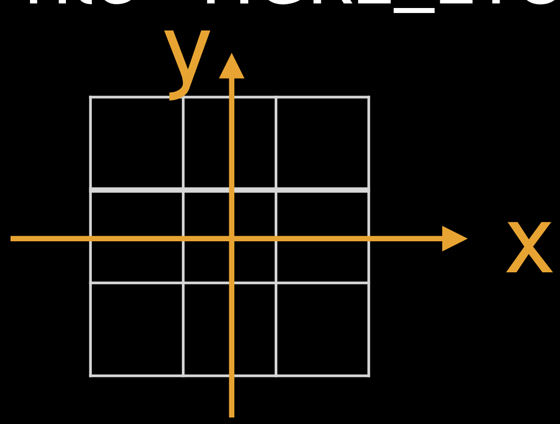


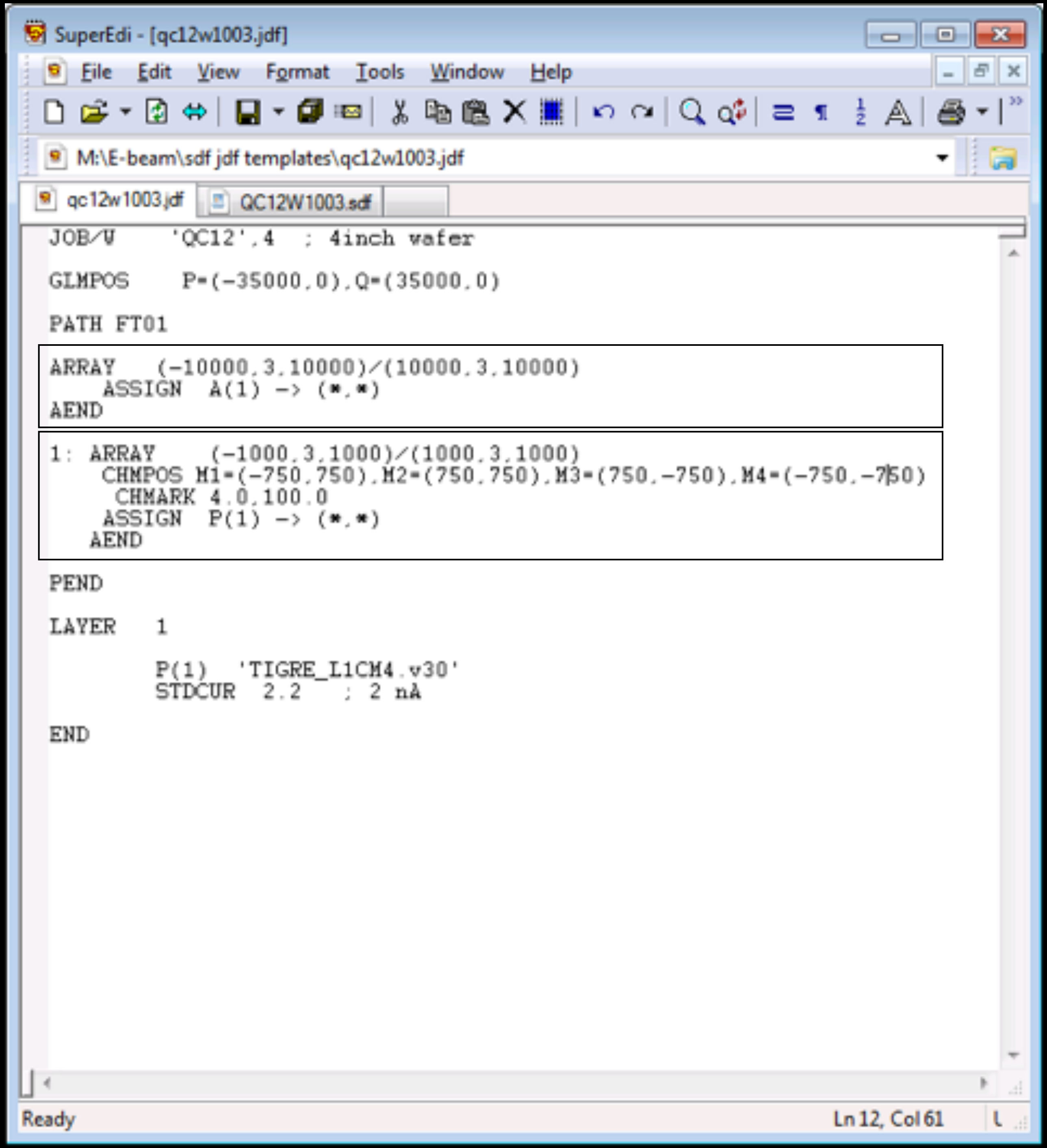
#7	*cassette #7*
%4A	*wafer position 4A*
JDF ‘qc12w1003’,1	*jdf file, layer 1*
ACC 100	*acceleration voltage*
CALPRM ‘2nA_ap5’	*condition file; 2 nA*
DEFMODE 2	*2 deflectors in use*
GLMDET S	*global mark detection*
CHIPAL 4	*chip mark detection*
RESIST 300	*dose in units*
SHOT A,8	*shot pitch 4 nm*
OFFSET (0,0)	*pattern offset*

Creation of sdf- and jdf-file

Array of 3x3 chips, pitch 10000, center of upper left at (-1000,1000), each chip patterned with ARRAY 1

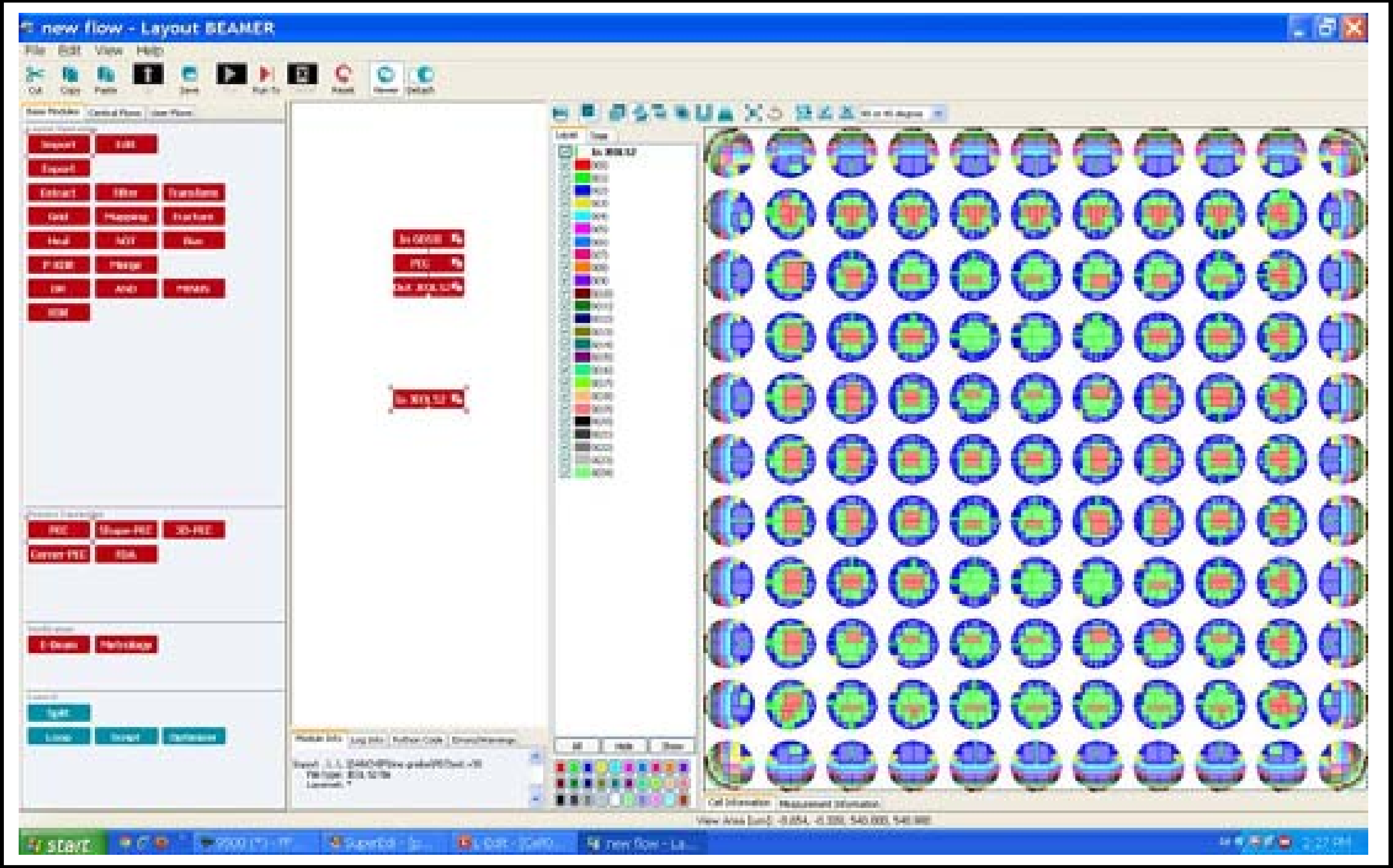
ARRAY 1: Array of 3x3 chips, pitch 1000, center of upper left at (-1000,1000), each chip patterned with v30-file ‘TIGRE_L1CM4.v30’

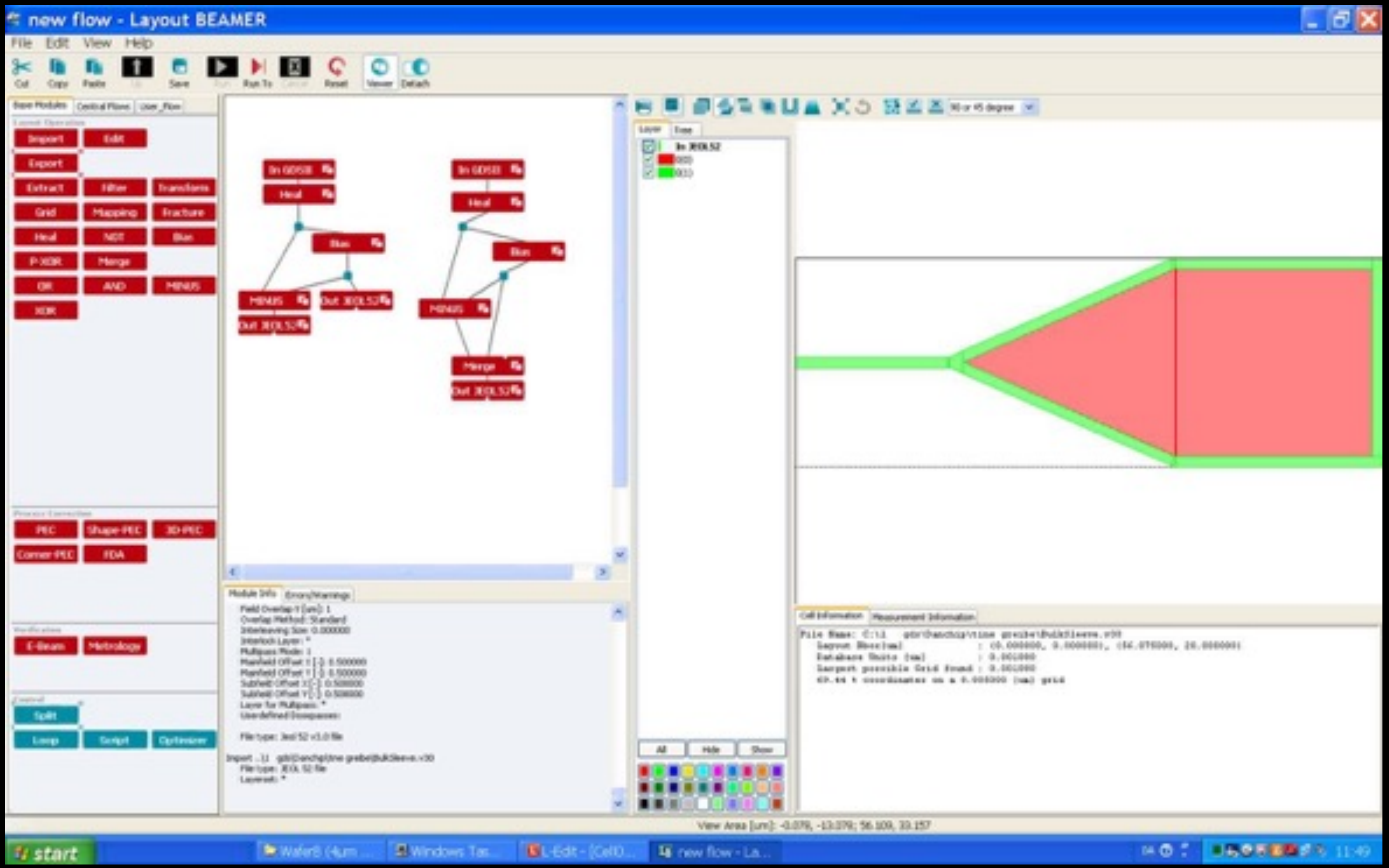


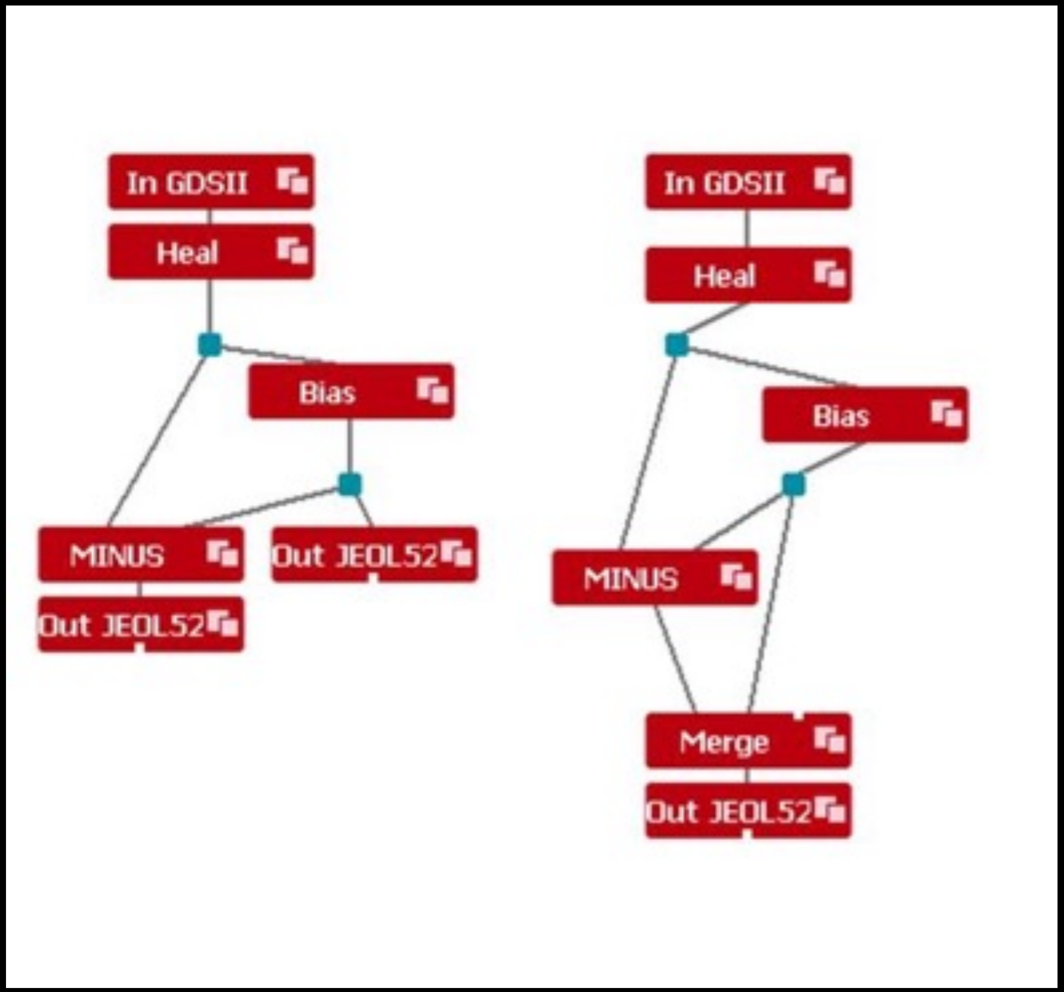



```
JOB/W     'QC12',4   ; 4inch wafer

GLMPOS     P=(-35000,0),Q=(35000,0)

PATH FT01

ARRAY    (-10000,3,10000)/(10000,3,10000)
    ASSIGN  A(1) -> (*,*)
AEND

1: ARRAY     (-1000,3,1000)/(1000,3,1000)
    CHMPOS M1=(-750,750),M2=(750,750),M3=(750,-750),M4=(-750,-750)
     CHMARK 4.0,100.0
    ASSIGN  P(1) -> (*,*)
   AEND

PEND

LAYER    1

        P(1)   'TIGRE_L1CM4.v30'
        STDCUR  2.2    ; 2 nA

END
```

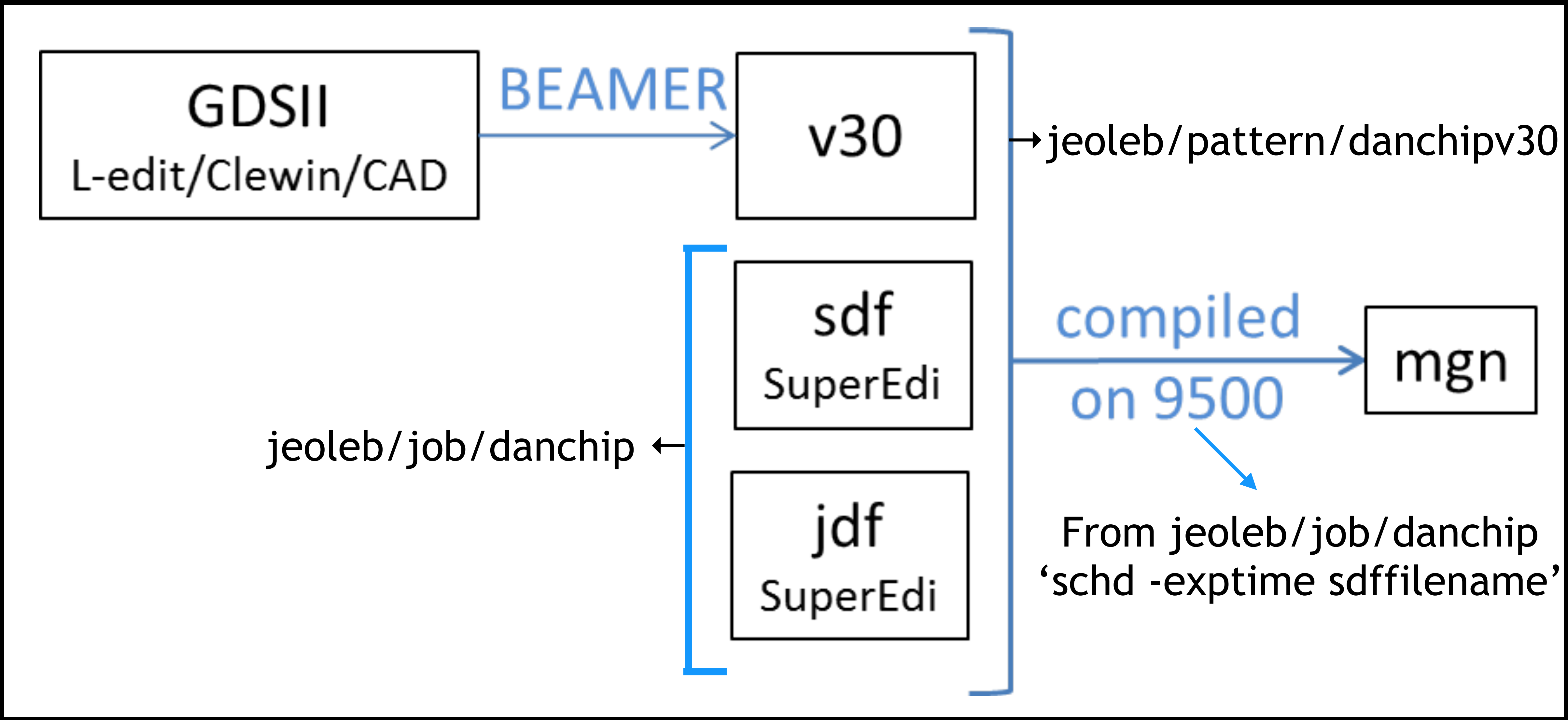
Converting of GDS to v30: BEAMER




new flow - Layout BEAMER
File Edit View Help

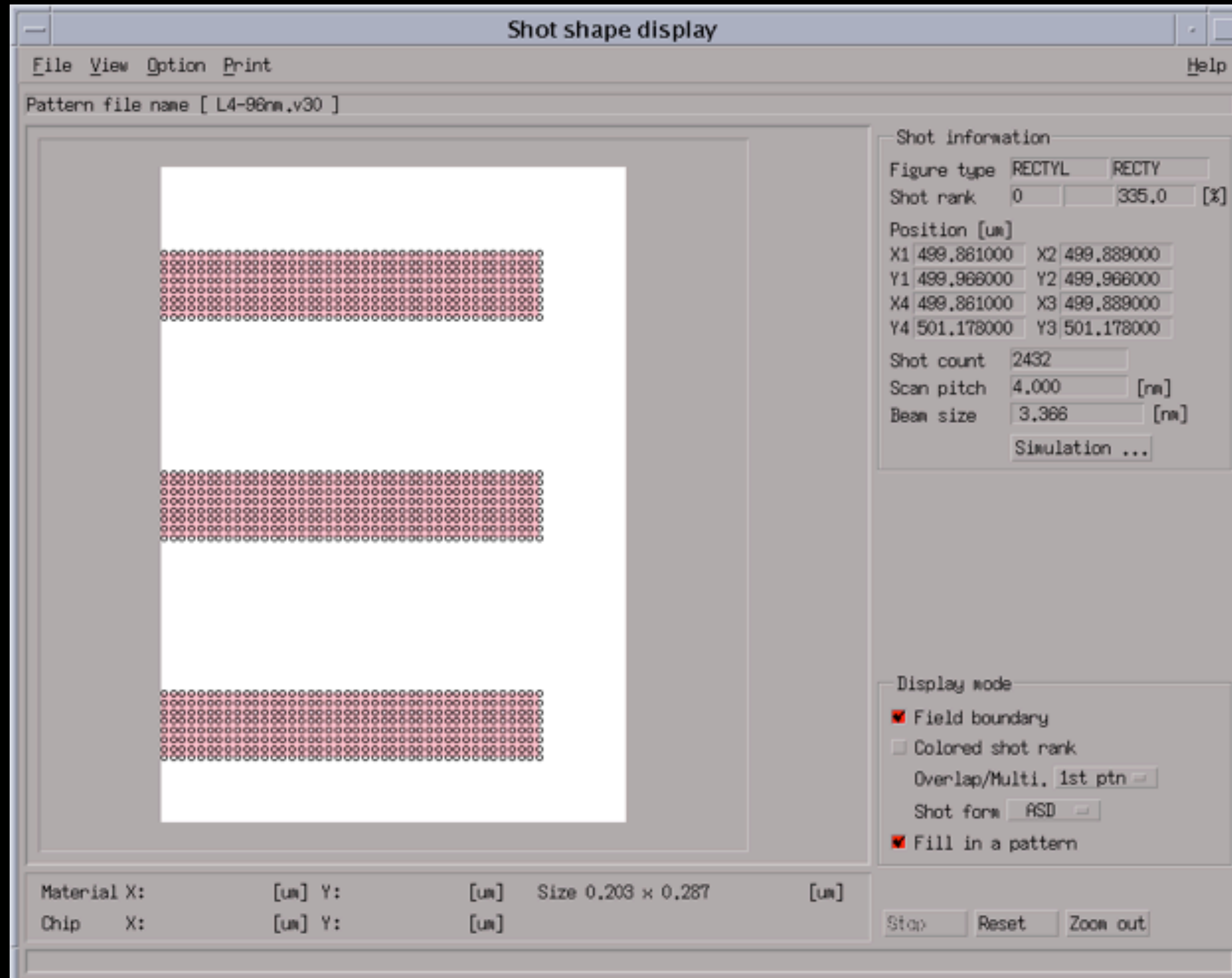

In GDSII
Heal
Bias
MINUS
Out JEOL52
Out JEOL52
In GDSII
Heal
Bias
MINUS
Merge
Out JEOL52

Compiling of files

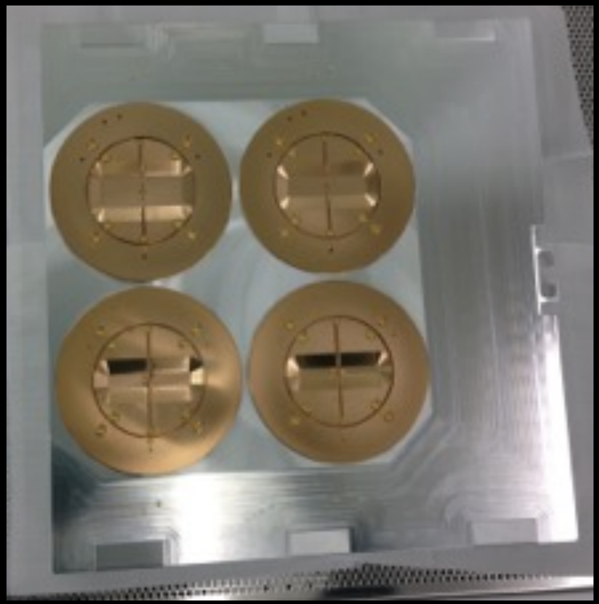


Compiling of files

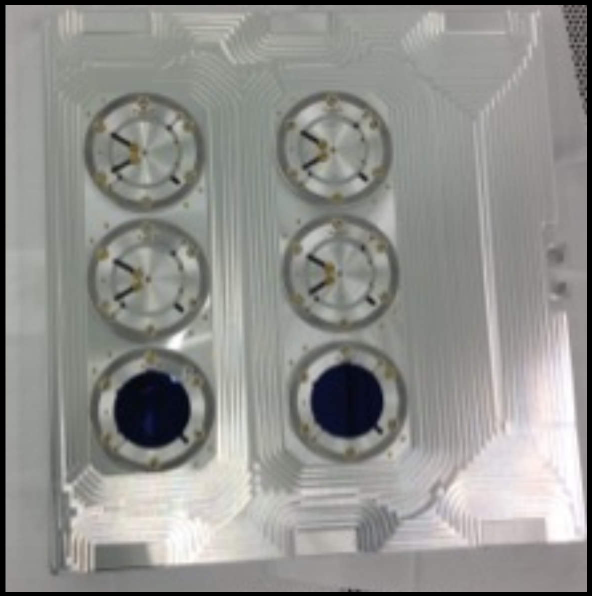
Check magazine-file with ACHK



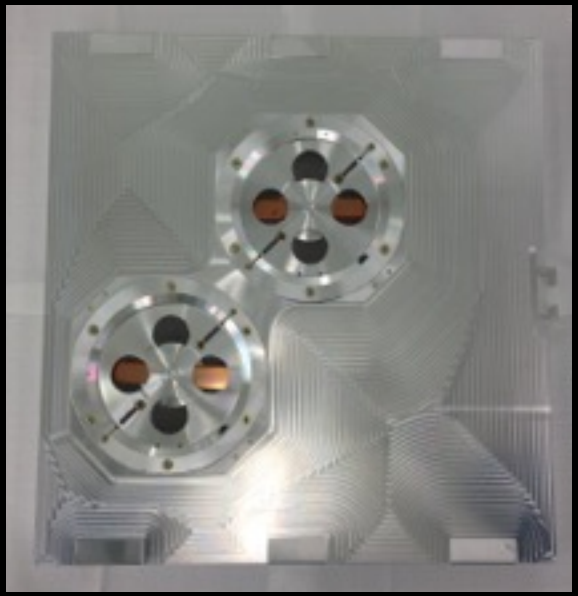
Load of substrates



chip cassette (3”)



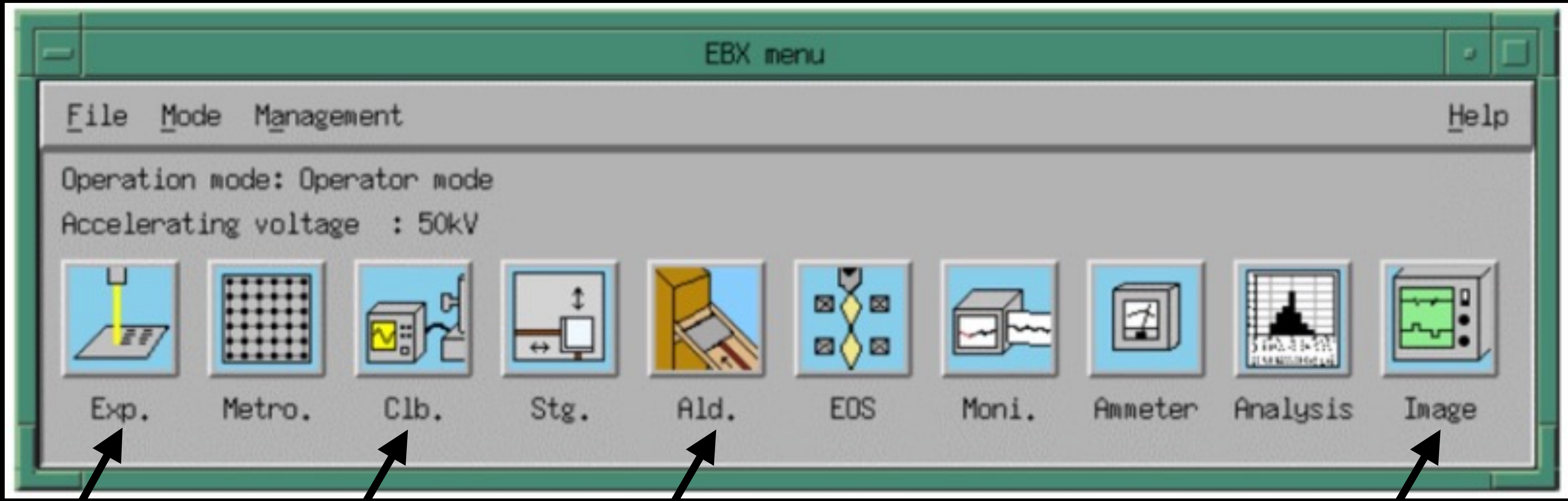
2” cassette



4” cassette

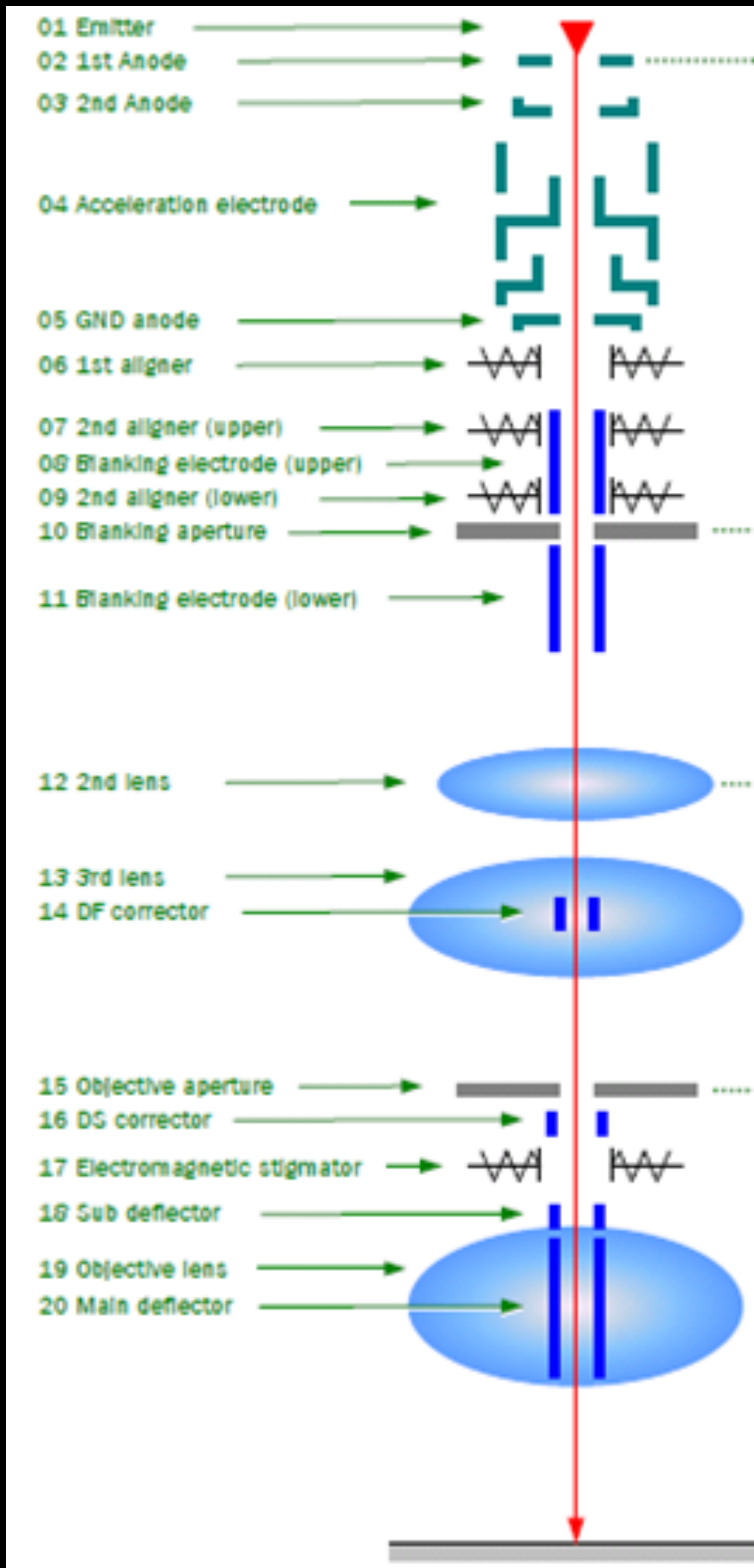
Only authorized DTU Danchip staff are allowed to load cassettes

Calibration of column



Exposure Calibration Load Image

Column of e-beam writer

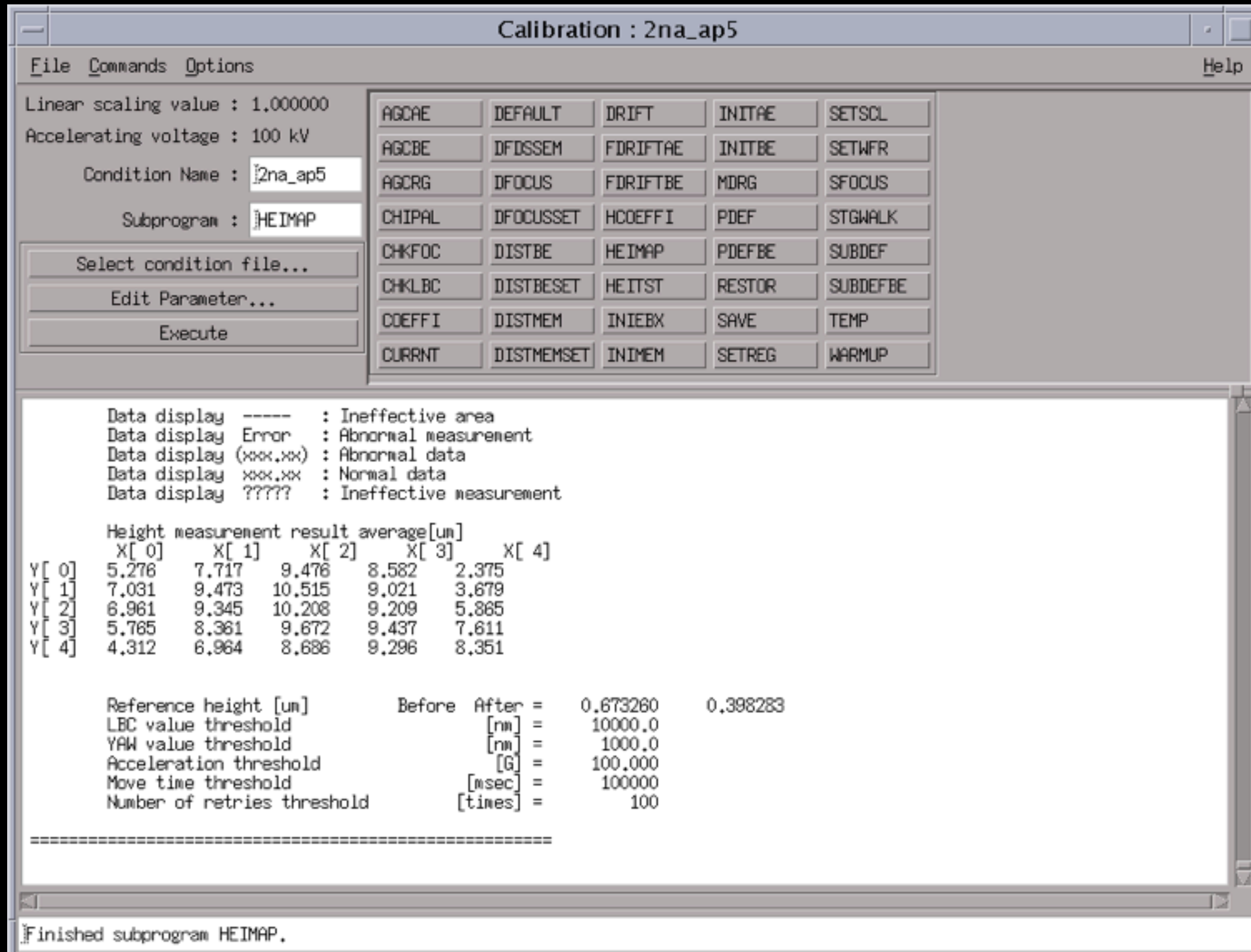


Daily calibration routine

SFOCUS	Subprogram that adjusts the focus and astigmatism of the objective lens,and the electromagnetic stigmator (astigmatism correction) coil.
PDEFBE	Using the BE mark, PDEFBE automatically corrects the deflection gain and corrects the rotation of the main deflector.
DISTBE	Measures and corrects the deflection distortion of the electron beam in the writing field
SUBDEFBE	Corrects the deflection gain of the sub-deflector and corrects the rotation
HEIMAP	Measures the height of substrate within the specified range. Electron beam is focused to average height of substrate. This only applies to direct writing (mask writing).

Calibration of condition file

SFOCUS
PDEFBE
DISTBE
SUBDEFBE
HEIMAP



Creation of sdf- and jdf-file

SuperEdi - [QC12W1003.sdf]

M:\E-beam\sdf jdf templates\QC12W1003.sdf

```
MAGAZIN 'QC1'
;---------------------------
#7
%4A
JDF 'qc12w1003',1
ACC 100
CALPRM '2na_ap5'
DEFMODE 2        ;2_stage deflection
GLMDET S
CHIPAL 4
RESIST 300
SHOT A,8
OFFSET(0,0)


#7
%4B
JDF 'qc12w1003',1
ACC 100
CALPRM '2na_ap5'
DEFMODE 2        ;2_stage deflection
GLMDET S
CHIPAL 4
HSWITCH ON,OFF
RESIST 300
SHOT A,8
OFFSET(0,0)


;---------------------------
END 7
```

SuperEdi - [qc12w1003.jdf]

M:\E-beam\sdf jdf templates\qc12w1003.jdf

```
JOB/W     'QC12',4   ; 4inch wafer

GLMPOS    P=(-35000,0),Q=(35000,0)

PATH FT01

ARRAY    (-10000,3,10000)/(10000,3,10000)
    ASSIGN  A(1) -> (*,*)
AEND

1: ARRAY     (-1000,3,1000)/(1000,3,1000)
    CHMPOS M1=(-750,750),M2=(750,750),M3=(750,-750),M4=(-750,-750)
     CHMARK 4.0,100.0
    ASSIGN  P(1) -> (*,*)
   AEND

PEND

LAYER   1

        P(1)   'TIGRE_L1CM4.v30'
        STDCUR  2.2    ; 2 nA

END
```

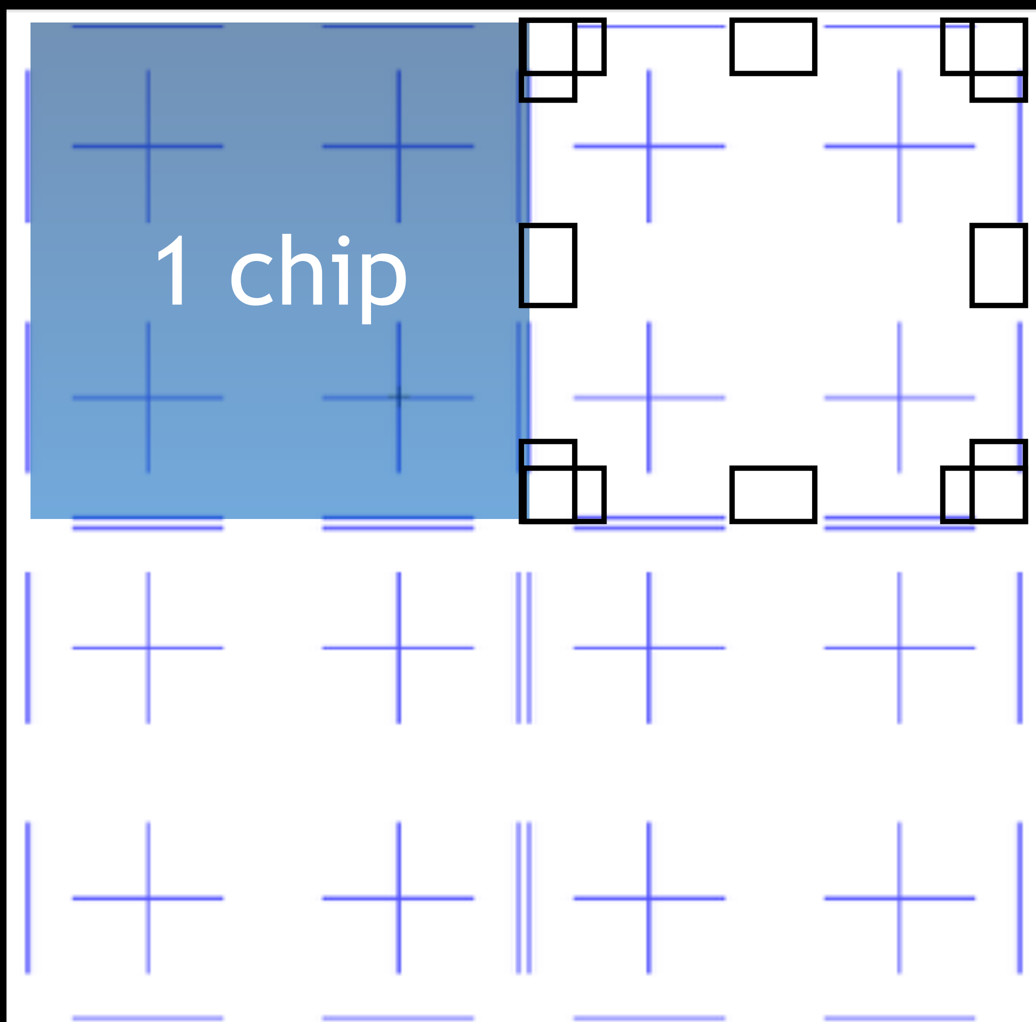
http://labmanager.dtu.dk/function.phpmodule=Machine&view=view&mach=292

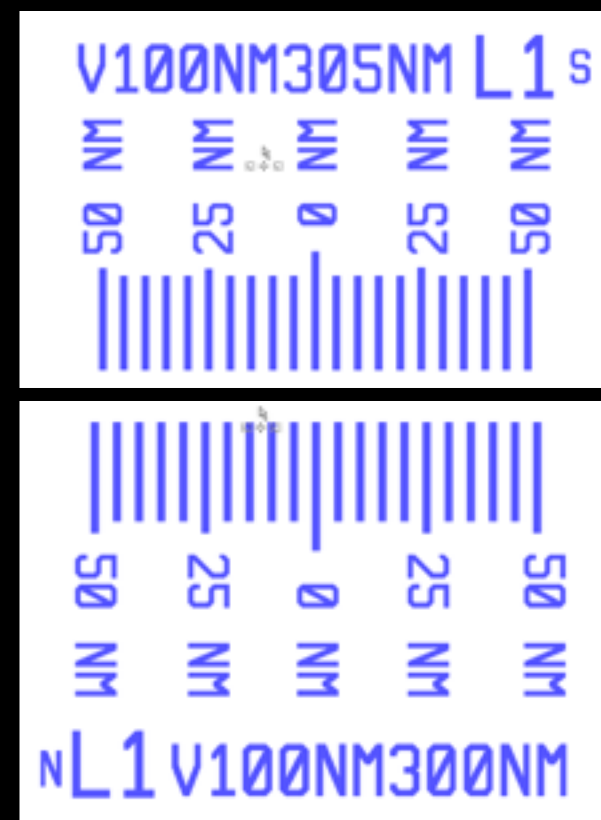
E-beam Lithography @ DTU Danchip

PART IV

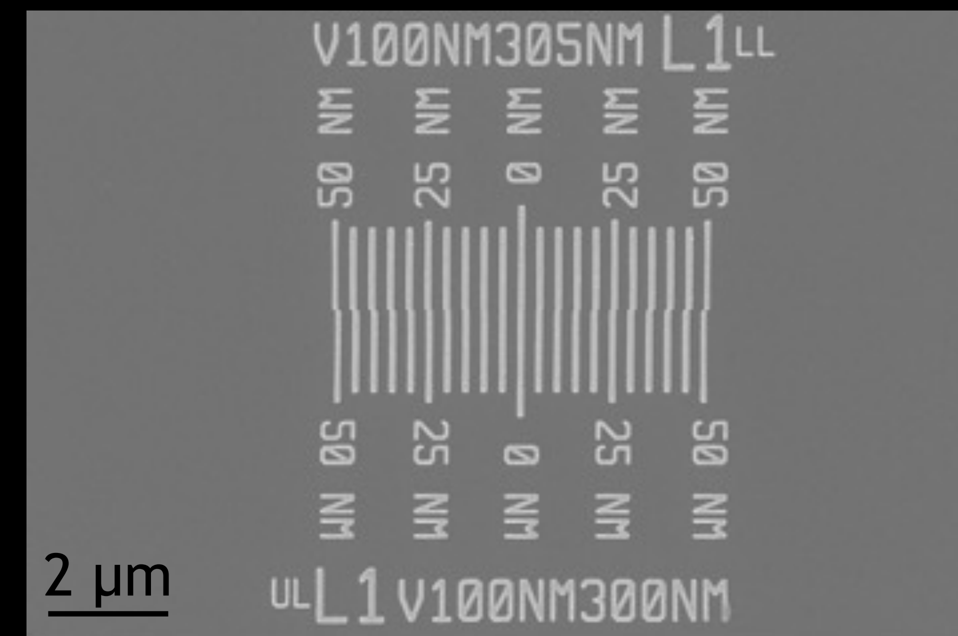
Performance tests on JEOL JBX-9500

Hands-on JEOL JBX9500
Stitching accuracy: field to field



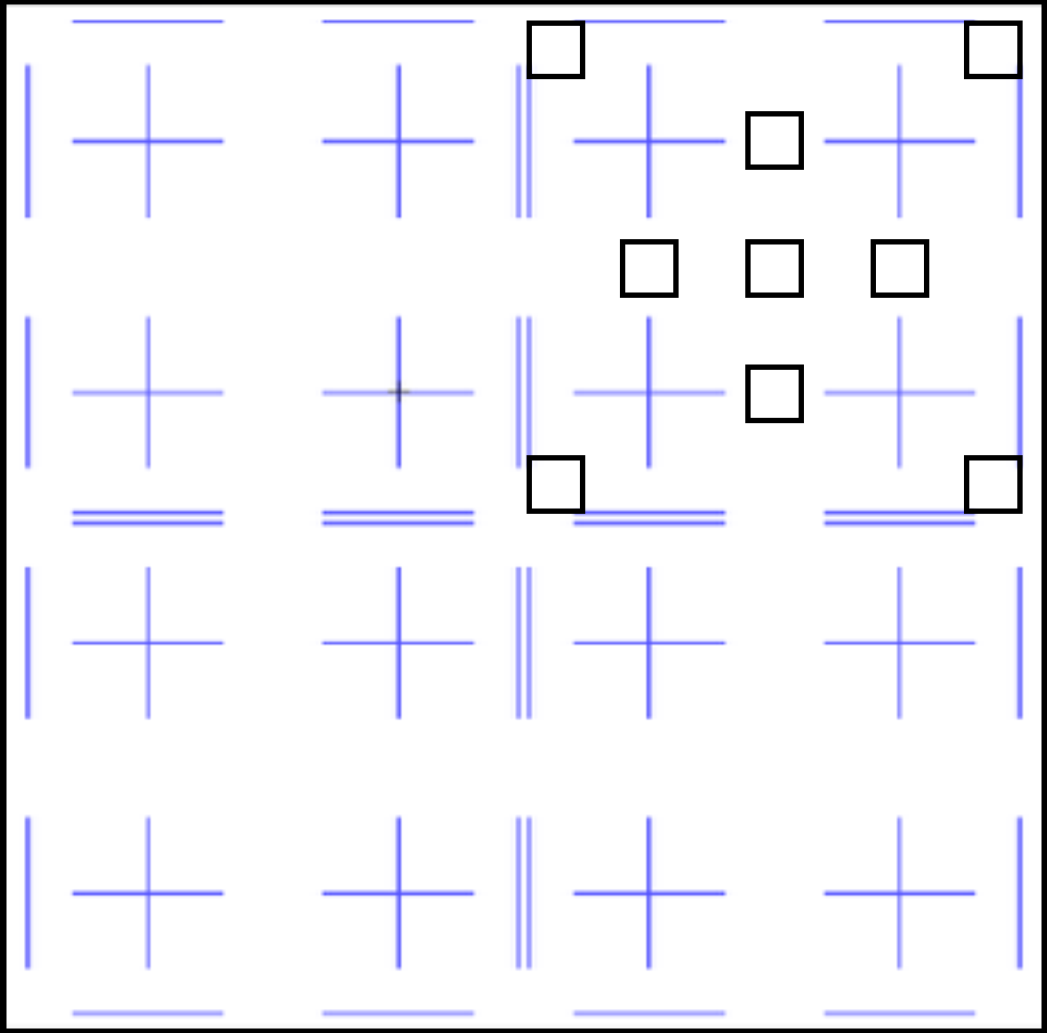


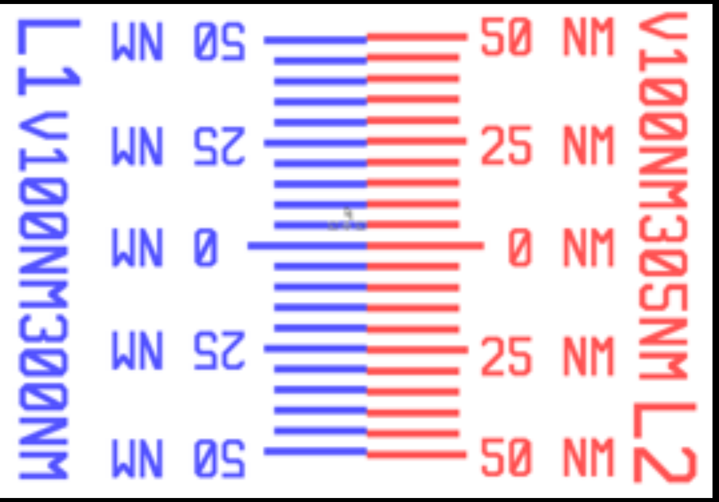
~150 nm CSAR, 2 nA,
5/15 nm Ti/Au, lift-off:
4s ultrasonic, AR 600-71

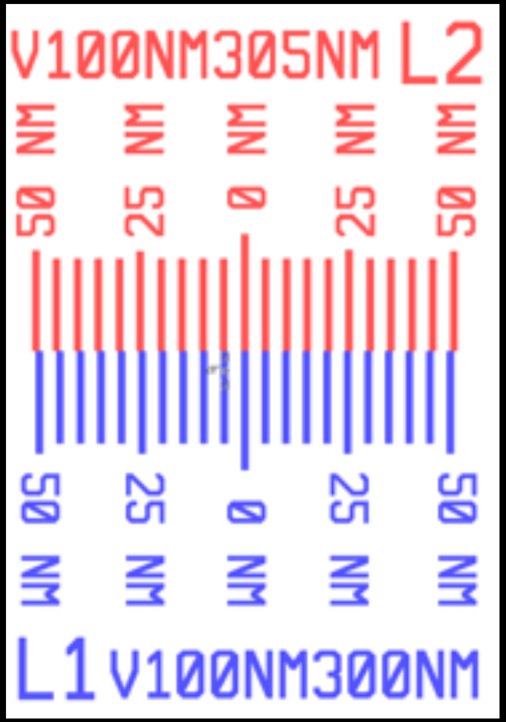


X direction 6 ± 2 nm
Y direction 13 ± 3 nm

Hands-on JEOL JBX9500
Stitching accuracy: overlay accuracy



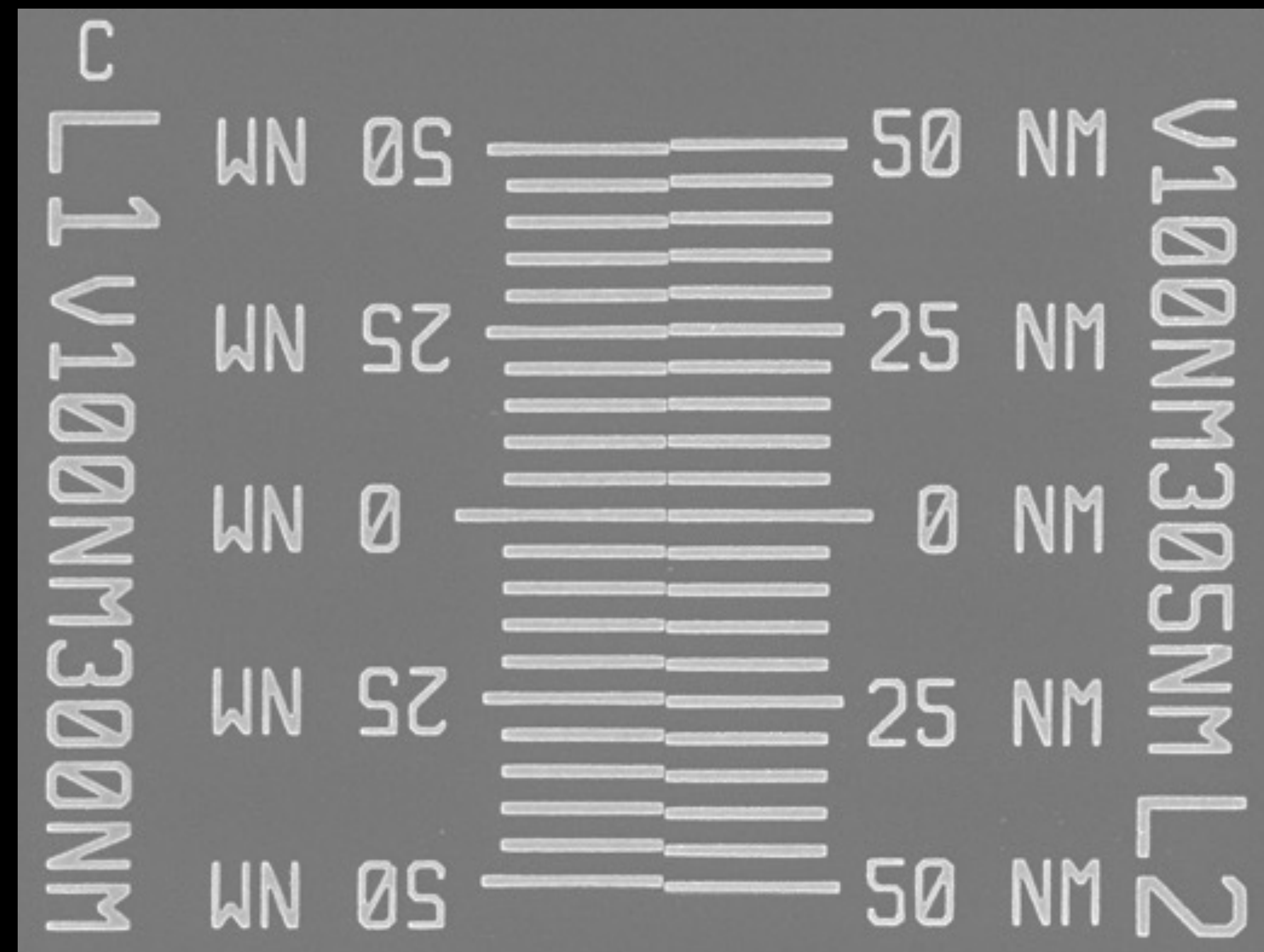




~150 nm CSAR, 2 nA
5/15 nm Ti/Au
lift-off: 4s ultrasonic, AR 600-71
Layer 2 stitched to Layer 1 via 2 global marks and chip marks

Hands-on JEOL JBX9500
Stitching accuracy: overlay accuracy

X direction 5 ± 3 nm
Y direction 3 ± 2 nm



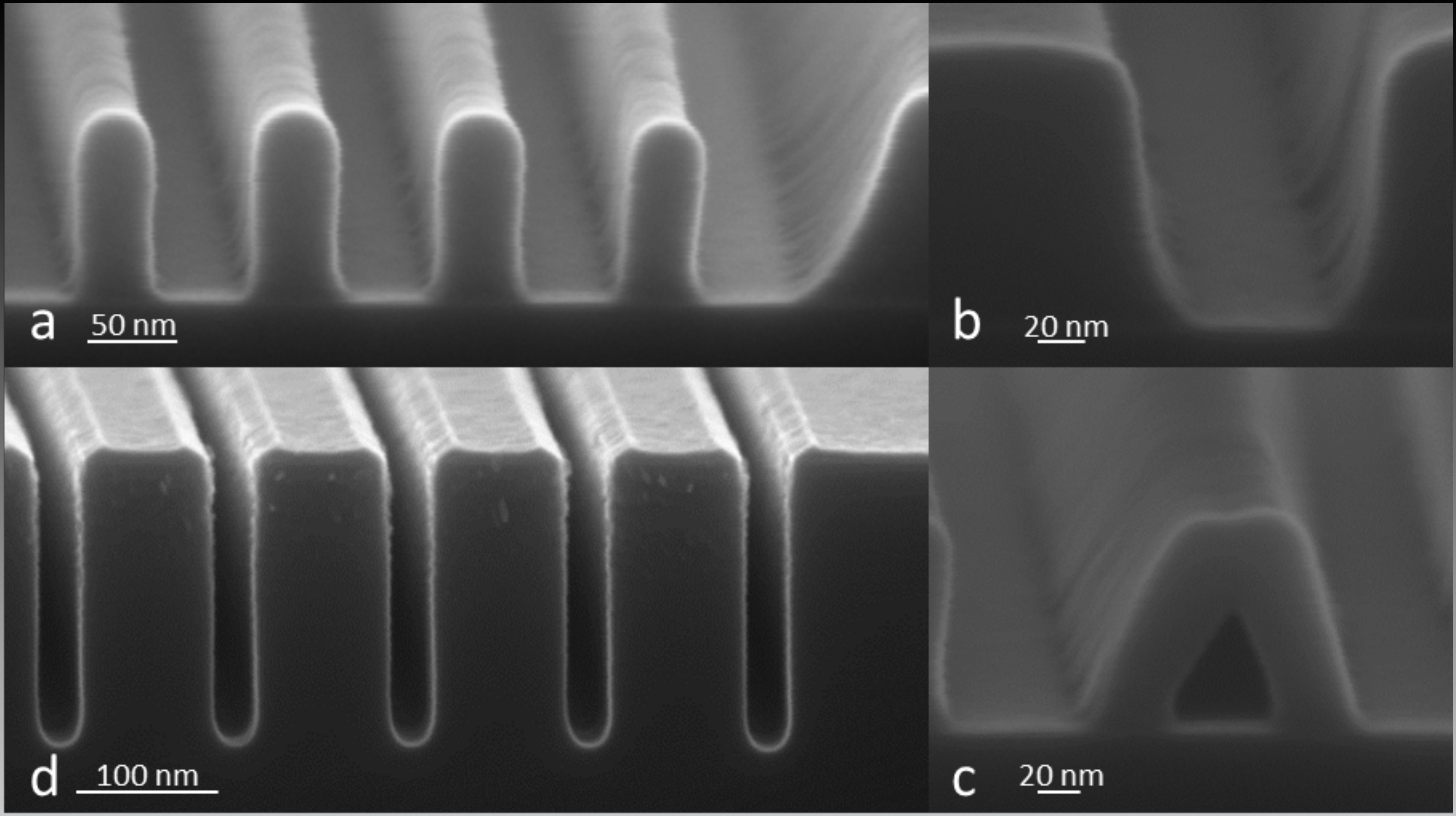
DTU Danchip
National Center for Micro- and Nanofabrication
Tine Greibe

E-beam Resist

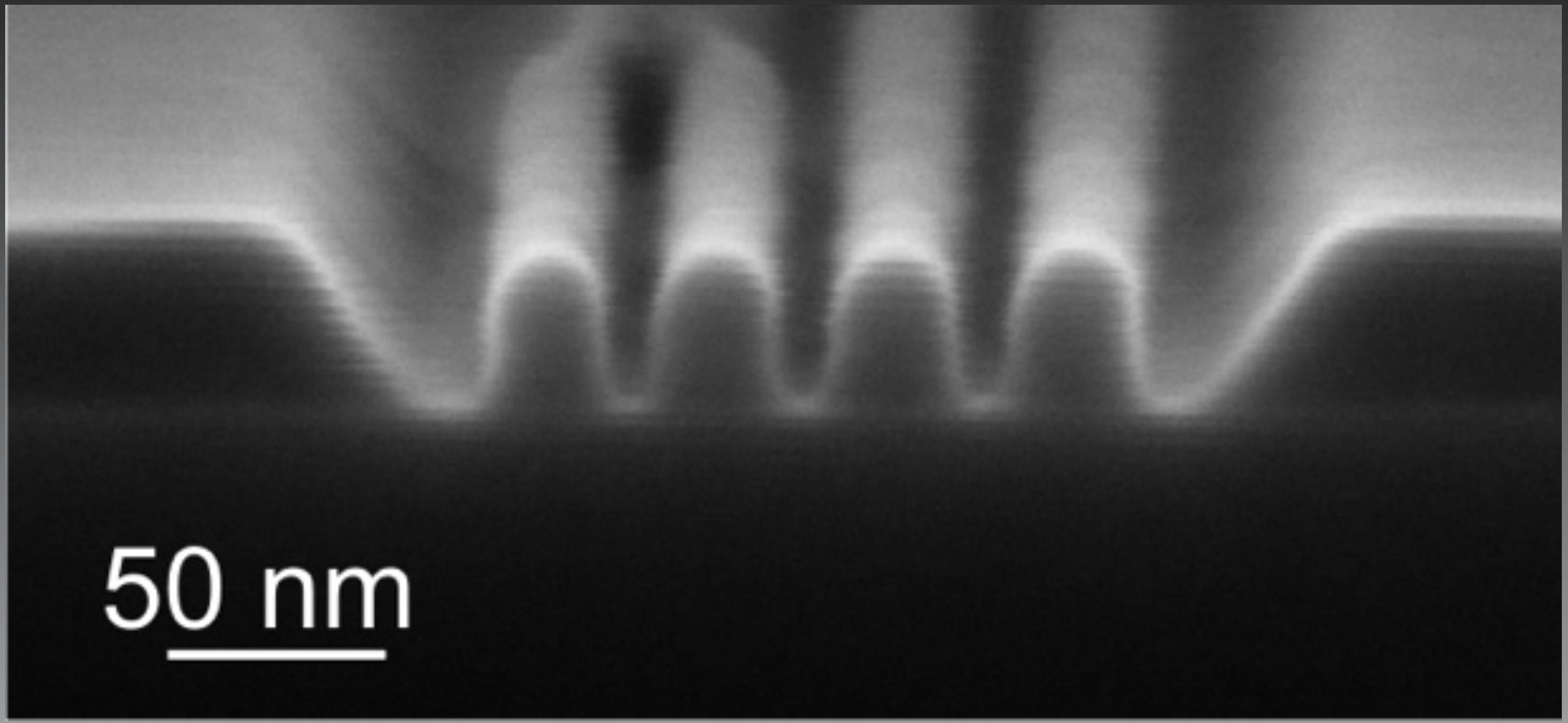
Positive-tone e-beam resist	Negative-tone e-beam resist
CSAR	**mrEBL6000**
ZEP520A	**AR-N 7520**
PMMA	**HSQ**

http://labadviser.danchip.dtu.dk/index.php/Specific_Process_Knowledge/Lithography/EBeamLithography#E-beam_resists_and_Process_Flows

AR-P 6200 (CSAR) - standard positive resist @ DTU Danchip

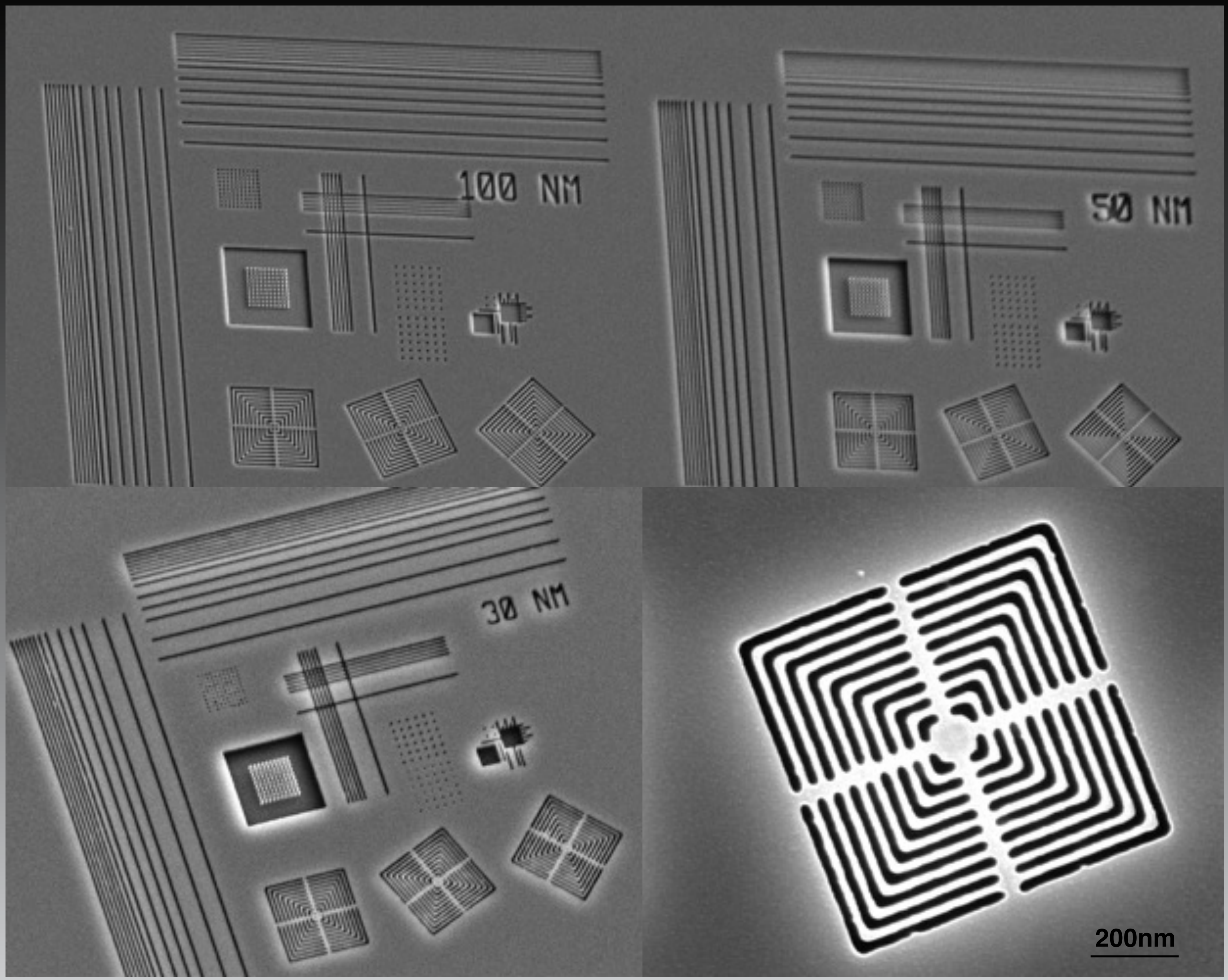


AR-P 6200 (CSAR) - standard positive resist @ DTU Danchip



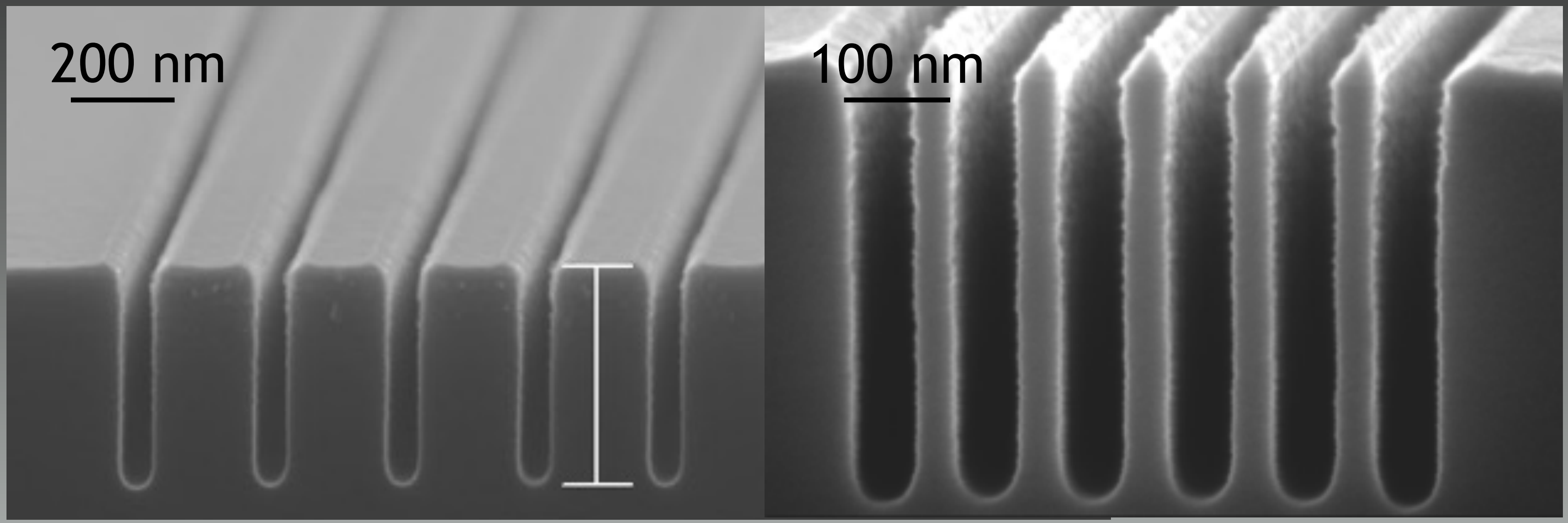
~12 nm lines in ~50 nm thick CSAR resist
0.2 nA, dose 2200 μC/cm^2

AR-P 6200 (CSAR) - standard positive resist @ DTU Danchip

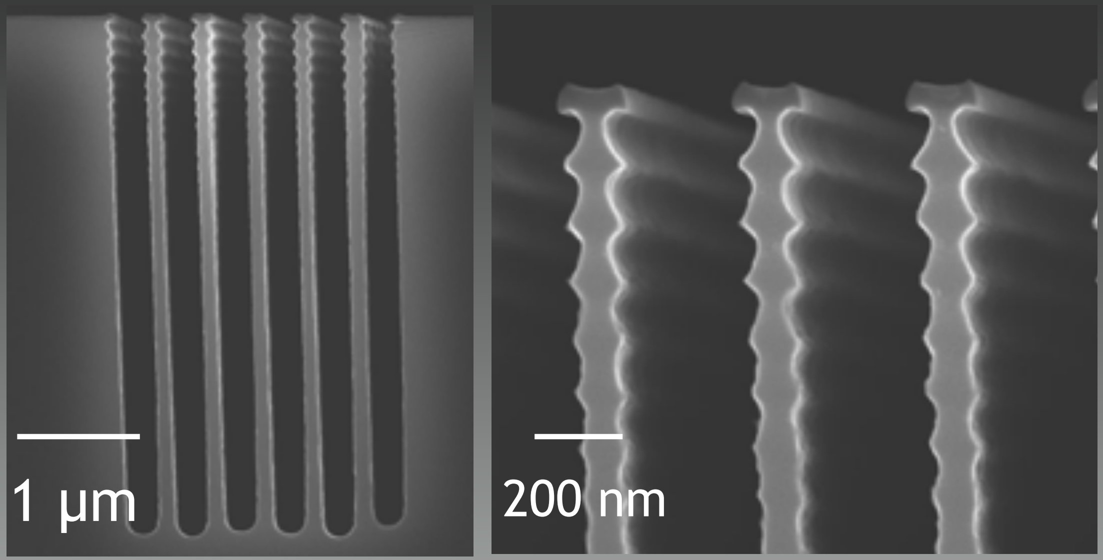


~ 50 nm CSAR
exposed at 0.2 nA
dose ~300 µC/cm2
50 sec C_4F_8/SF_6 etch
at -20 ºC (DRIE)

Etch of nano structures (CSAR)



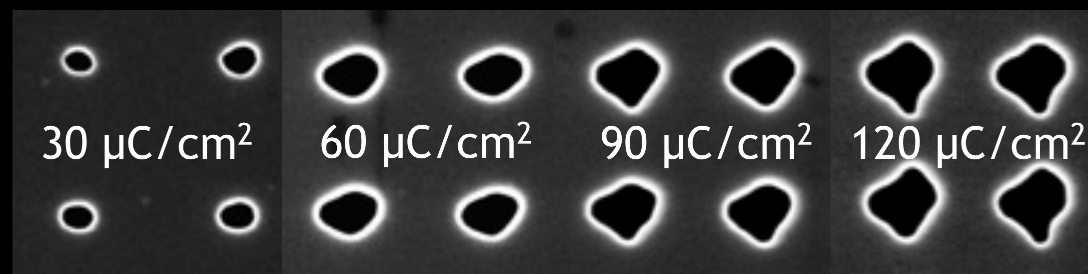
2:30 min C_4F_8/SF_6 continous etch at -20 ºC (DRIE)
selectivity CSAR:Si is ~1:3



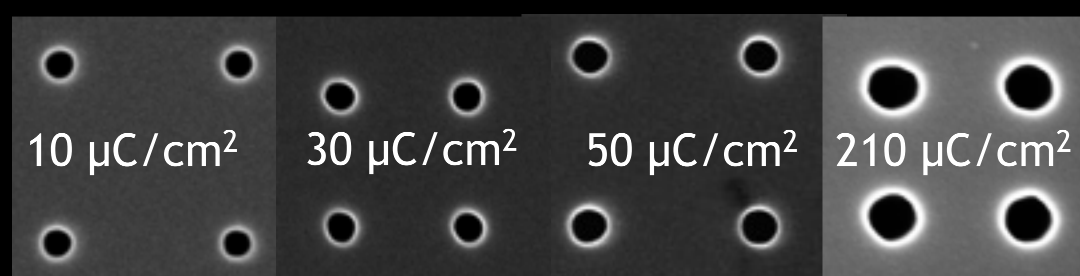
6 min C_4F_8/SF_6 Bosch etch at -20 ºC (DRIE)
selectivity CSAR:Si is ~1:38

Hands-on JEOL JBX9500

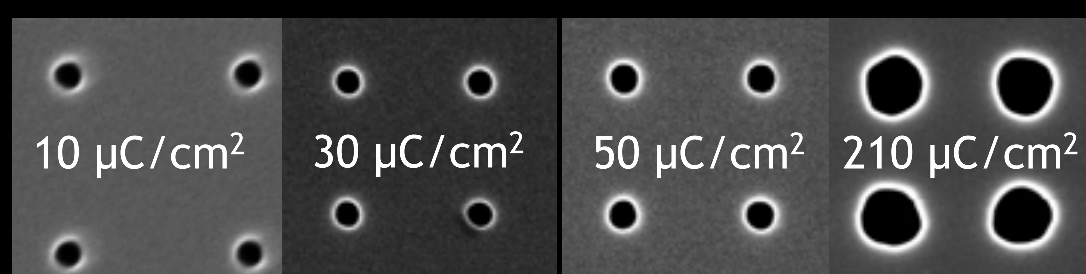
60 nA

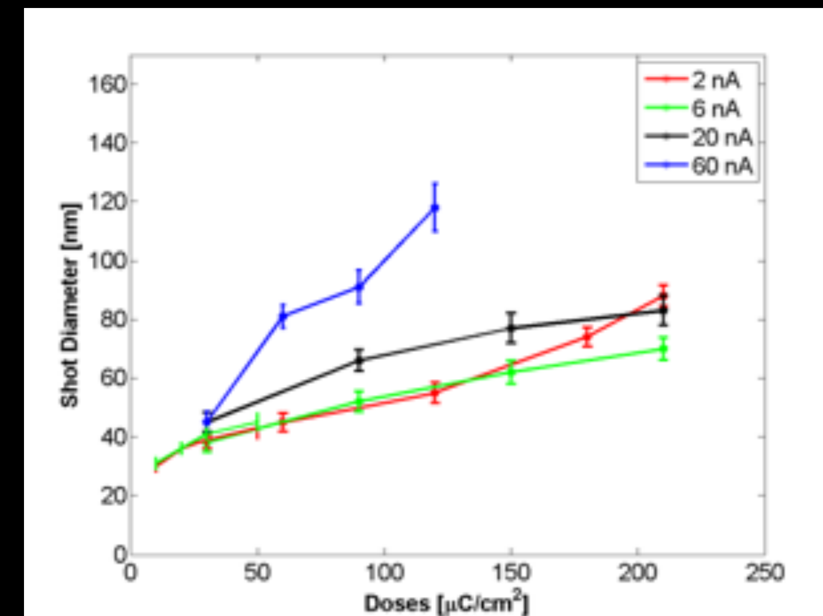


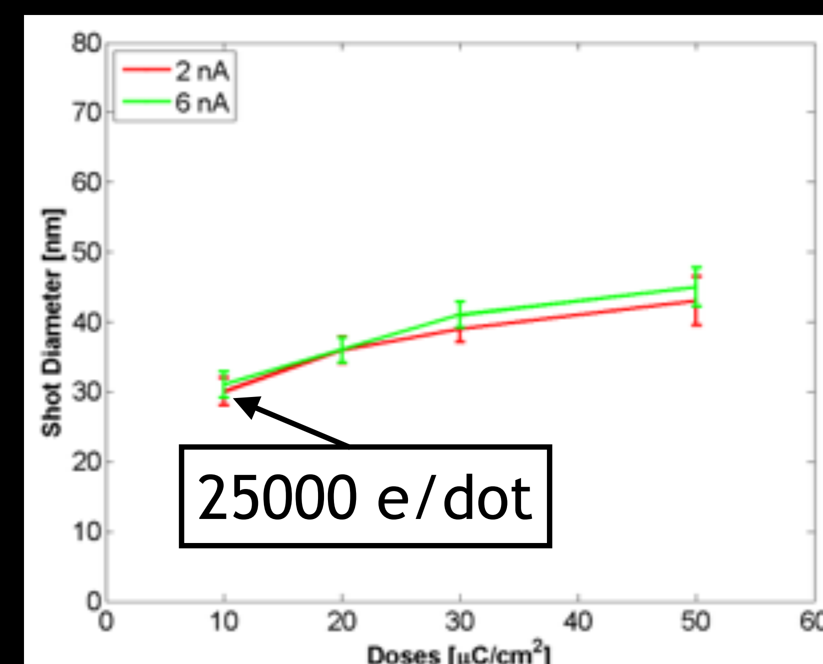
6 nA



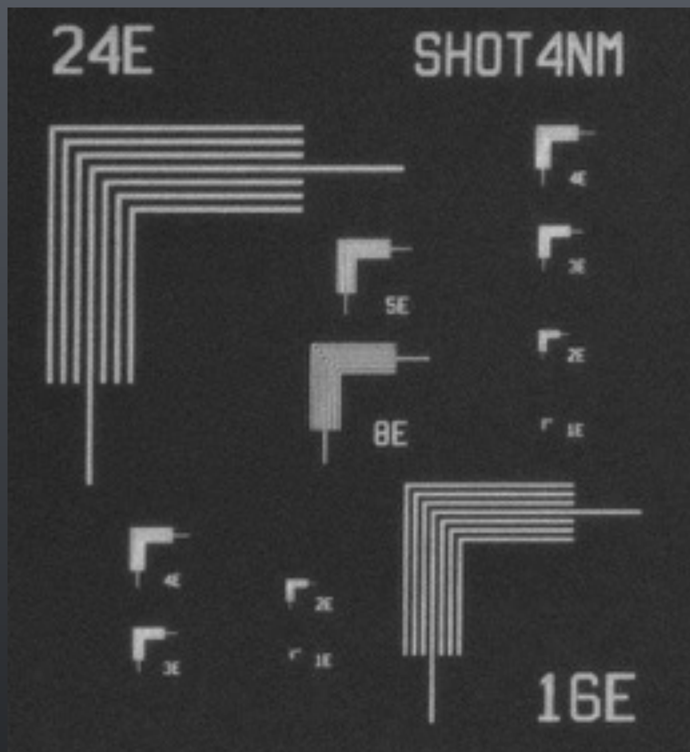
2 nA

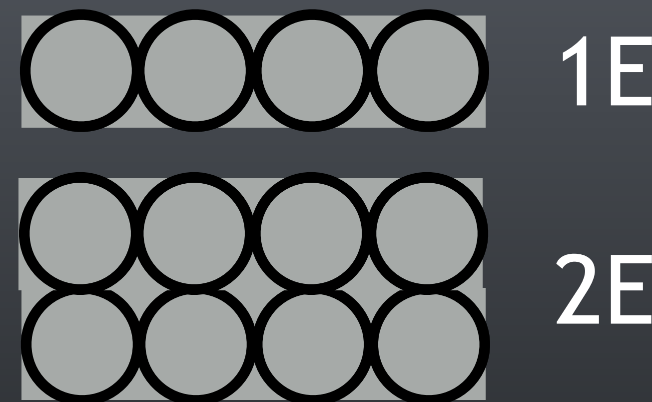






Excel patterns



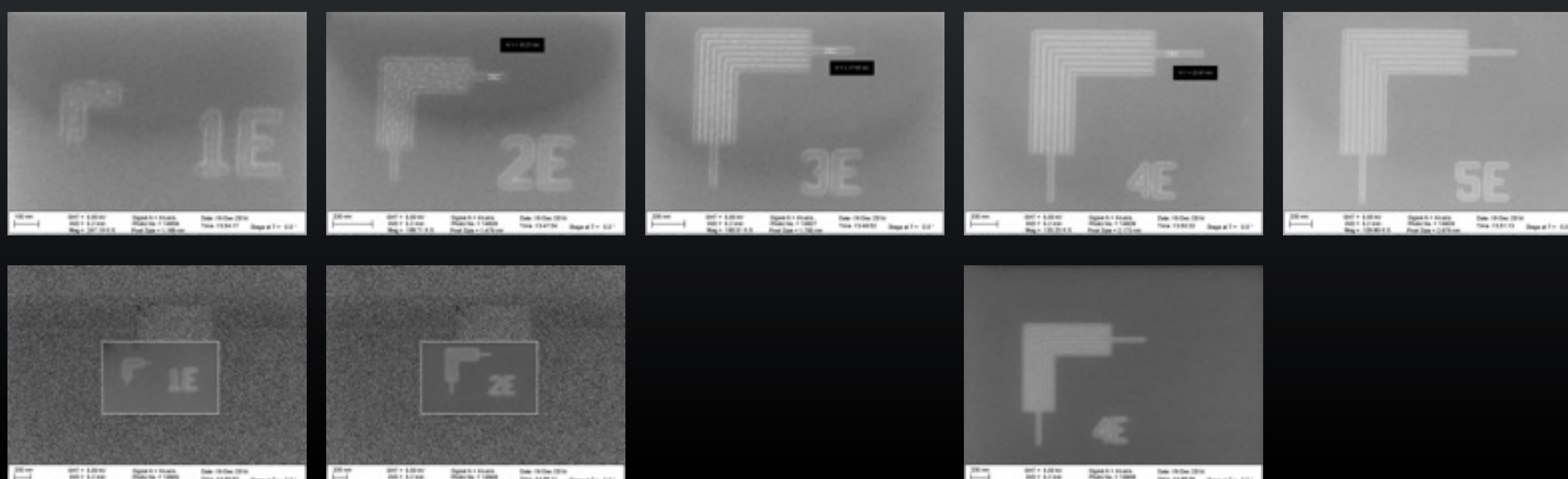


15 nm CSAR, 0.2 nA, developed with room temperature developer and refrigerated developer (AR 600 546)

Room temperature development

500 µC/cm²

850 µC/cm²

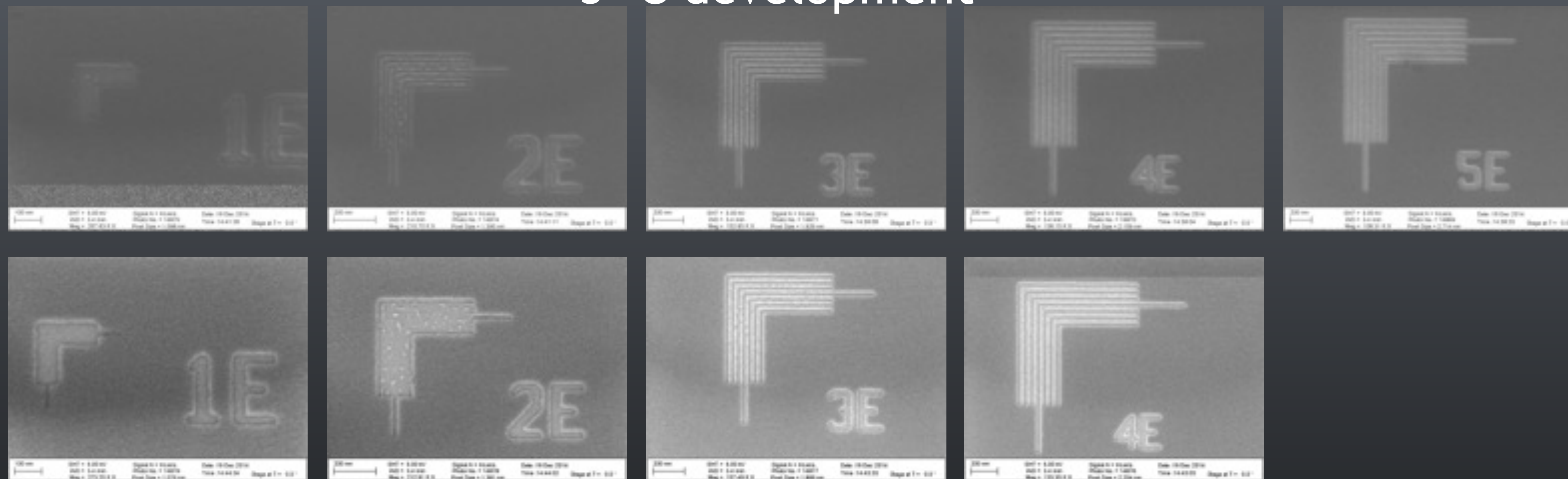


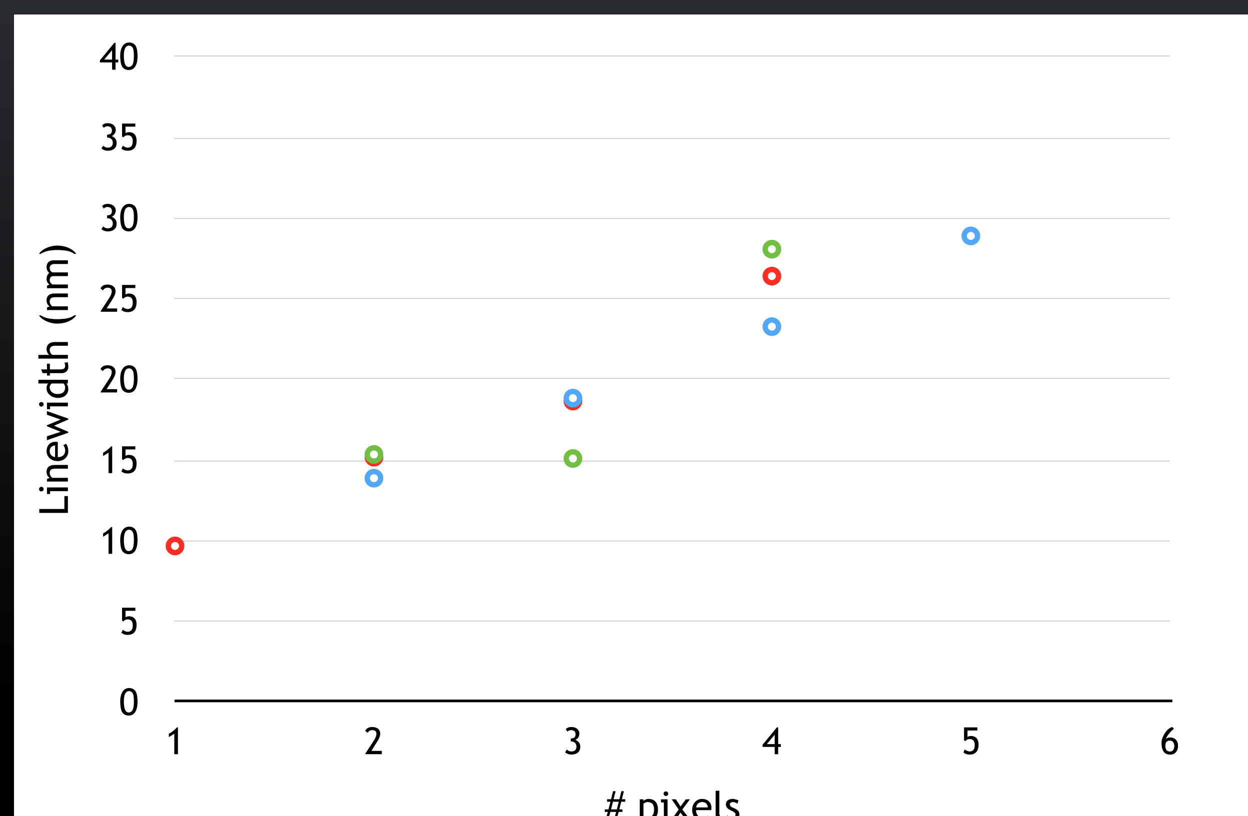
Excel patterns

~5 °C development

600 μC/cm^2

850 μC/cm^2





Literature & references

Lithography, Michael Wang (Editor), INTECH 2010

SPIE Handbook of Microlithography, Micromachining and Microfabrication, Volume 1: Micro-lithography, Section 2.3 Electron-Solid Interactions

Lithography, Stefan Landis (Editor), Wiley 2010

ammrf.org.au

cnf.cornell.edu

JEOL

Optimizing electron beam lithography in the nanometer range, Vladimir Zlobin,13 April 2006, SPIE Newsroom