Basics and applications in nanolithography

E-beam lithography

David López-Romero
CRESTEC-ISOM

JACA 2018

OUTLINE

- Presentation.
- E-beam lithography system basics.
- E-beam lithography technic basics.
- Parameters to be chosen.
- Application examples
- New developments in e-beam lithography

PRESENTATION

CRESTEC CORP. Establishment February10, 1995

Head Office1-9-2, Owada-machi, Hachioji-shi,

Tokyo 192-0045, Japan.

http://www.crestec8.co.jp/

david.lopezromero@crestec8.co.jp

CRESTEC-UPM agreement, technical support EU.

Beam point e-beam lithography systems:

- CABL-UH: Ultrahigh Resolution 130 kV
- CABL9000C: High Resolution 50 kV

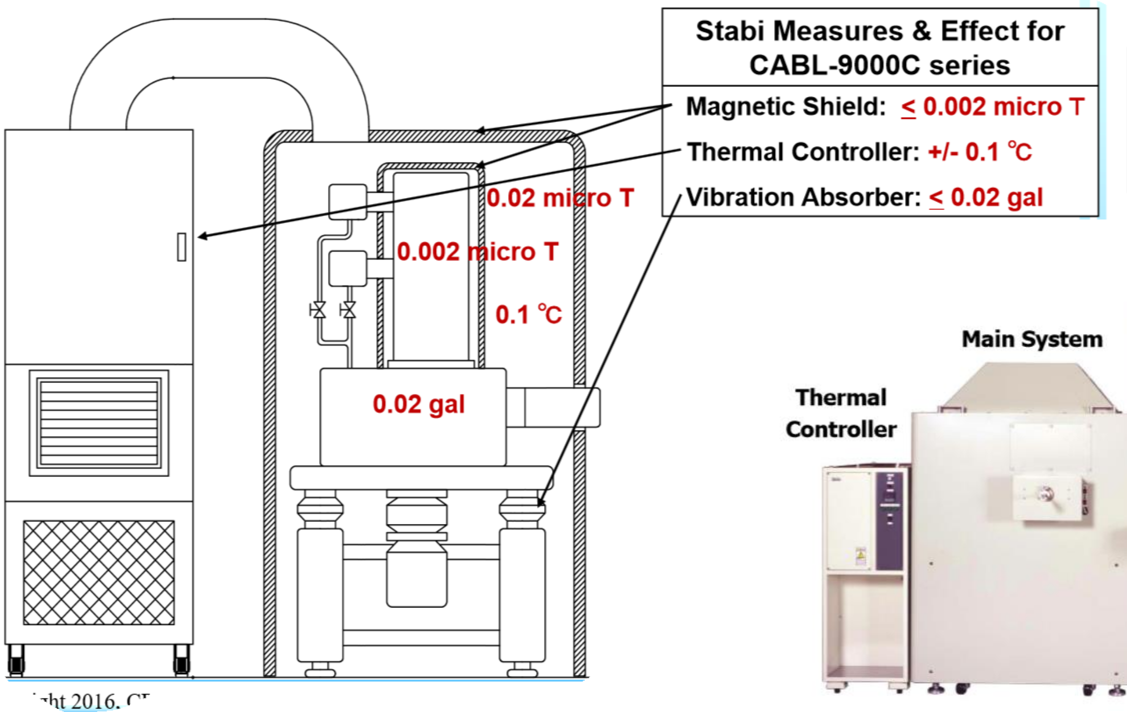
Development of new product:

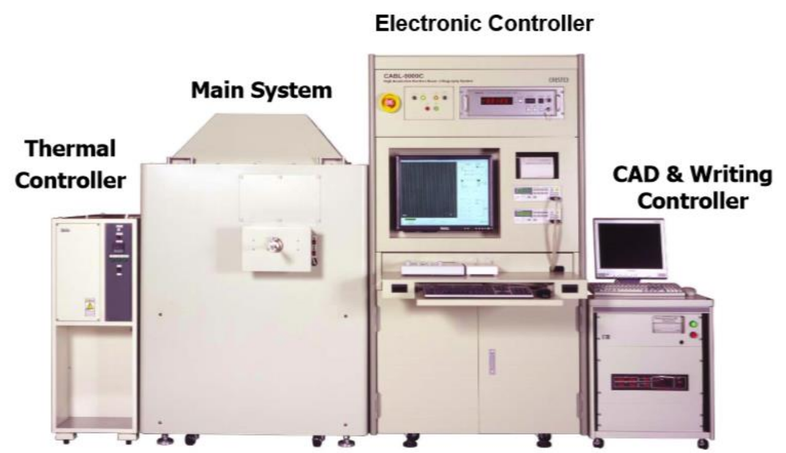
- Surface Emission EB Lithography System
- Maskless Massively Parallel EB Lithography System

E-beam lithography system basics

- Presentation.
- E-beam lithography system basics.
- E-beam lithography technic basics.
- Parameters to be chosen.
- Application examples
- New developments in e-beam lithography

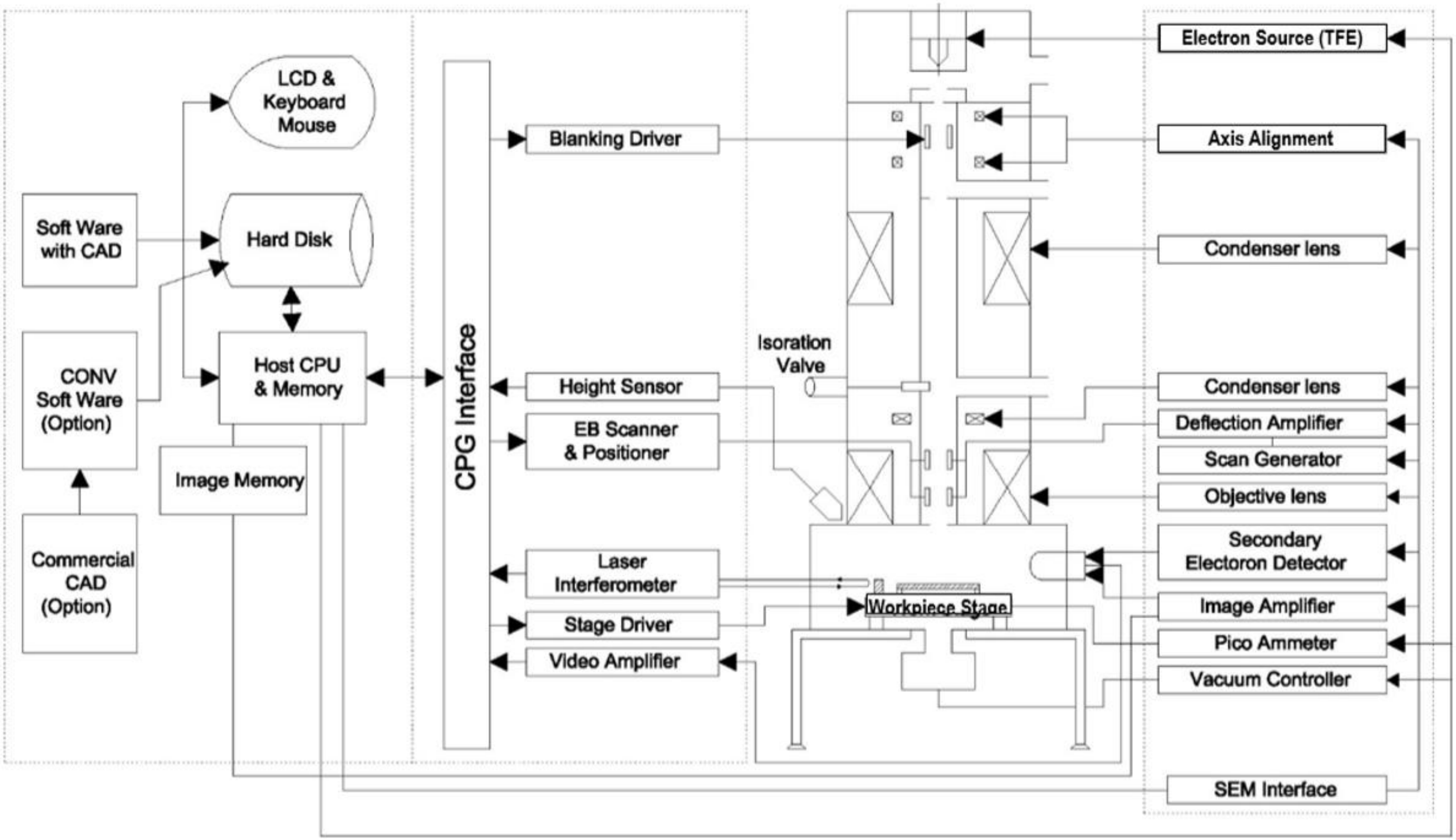
E-beam lithography system basics





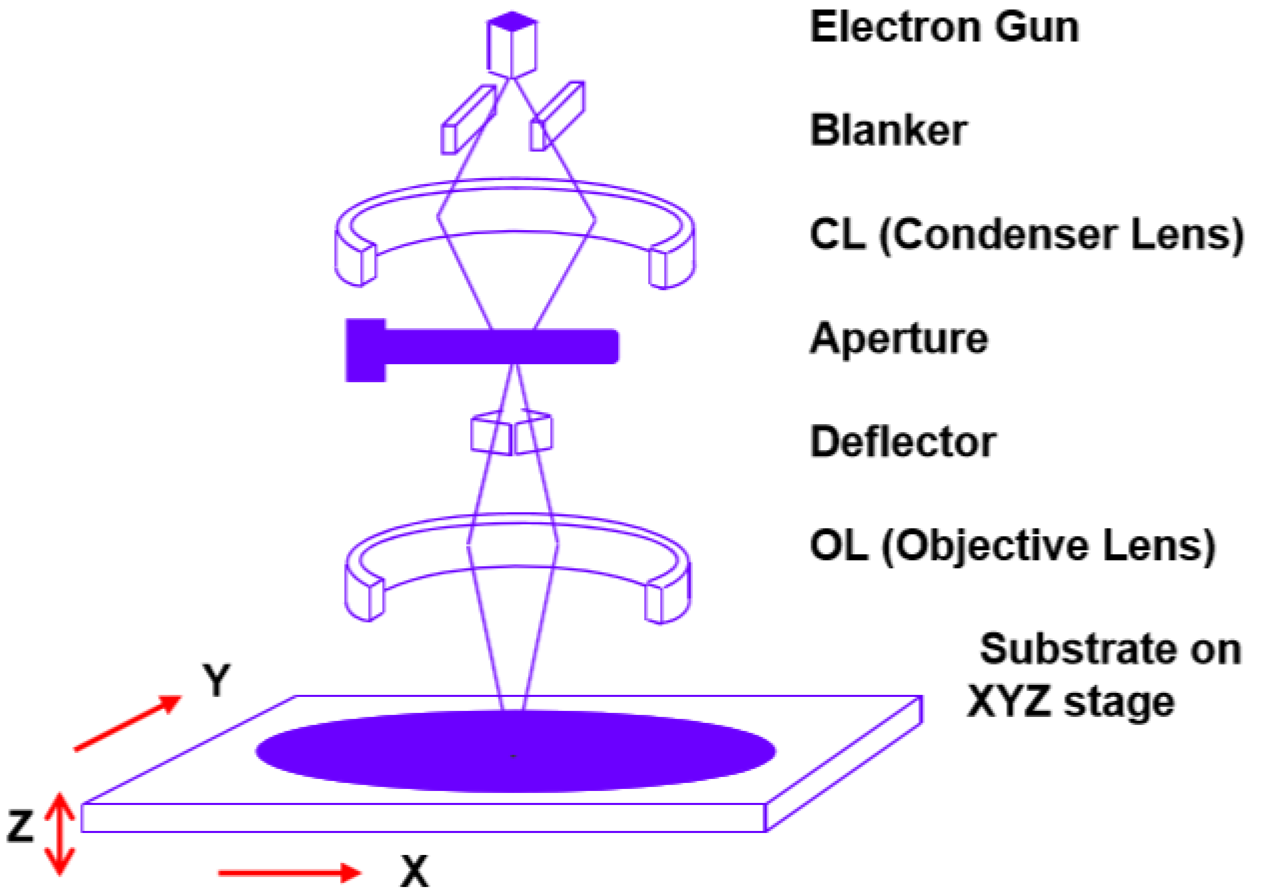
Installation and environment control

E-beam lithography system basics



System block diagram

E-beam lithography system basics



EOS column

E-beam lithography system basics

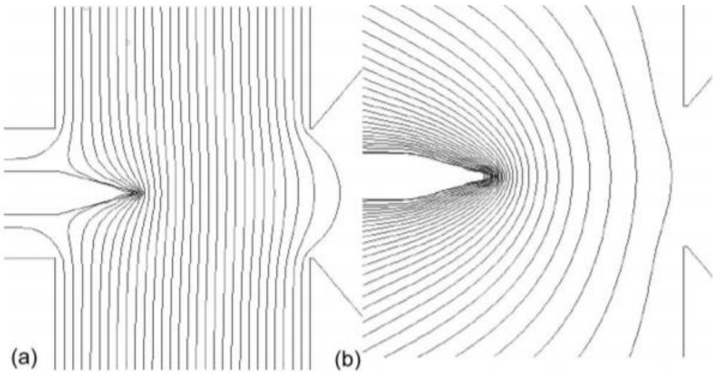
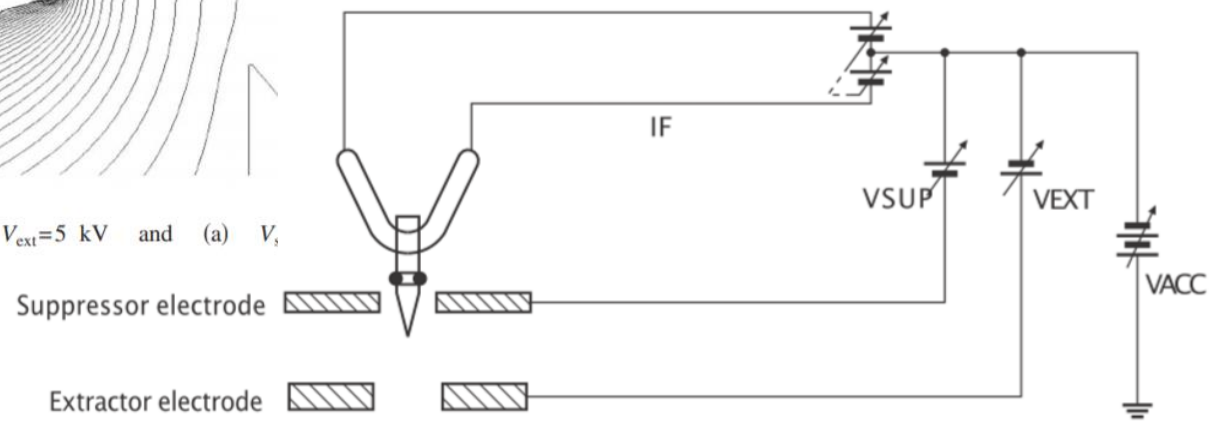
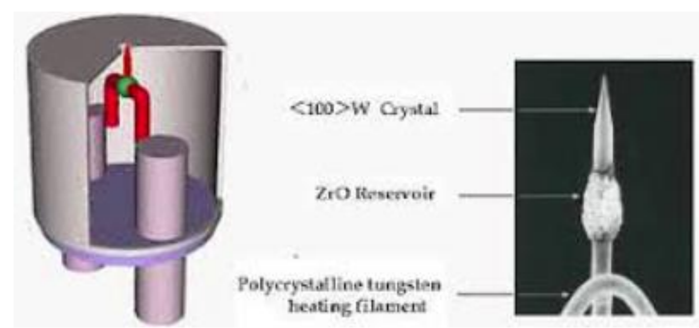


FIG. 4. Simulated field lines at V_{ext}=5 kV and (a) V, =−300 V. (b) No suppressor.



IF : Filament heating current
VSUP : Suppressor voltage
VEXT : Extractor voltage
VACC : Acceleration voltage



Temp= 1800±50 K
Vsup= -0.3 kV
Vext= 4.5 kV
Vacc=50, 100 kV

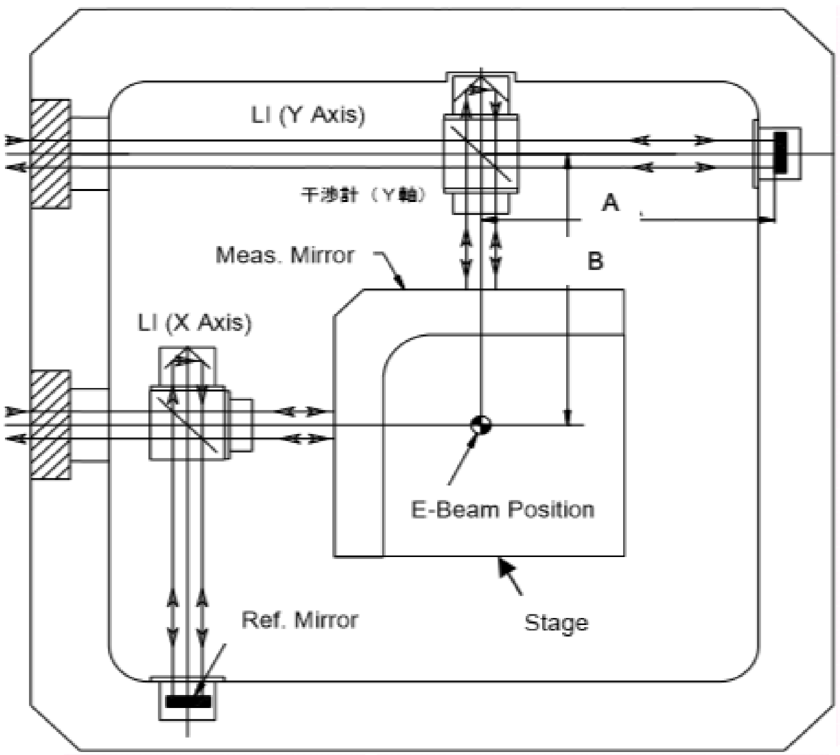
TFE Emitter

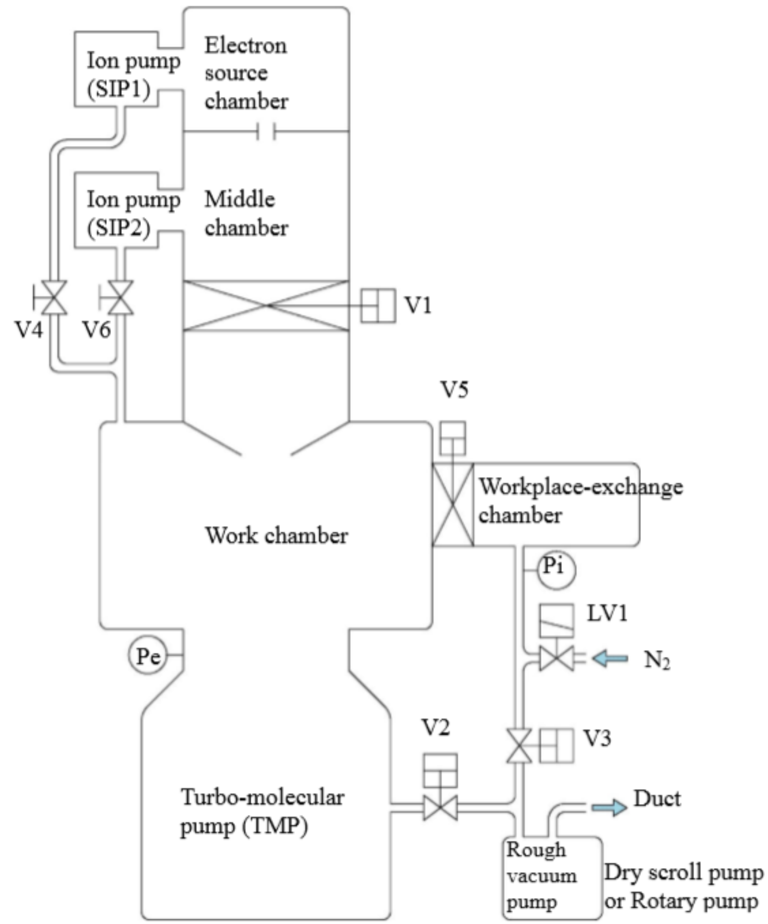
J.Vac. Sci. Technol. B 27,,6…, Nov/Dec 2009

E-beam lithography system basics

Pulse motors. (X, Y: 0.1 μm/pulse, Z: 0.01 μm/pulse)

Meas. Resolution: 0.6 nm (λ/1,024, λ = 633 nm).





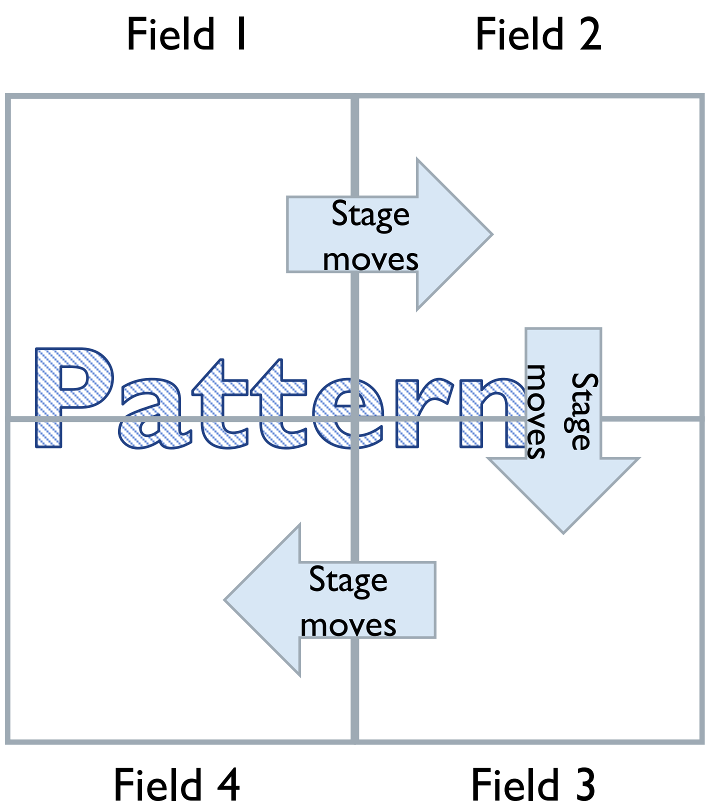
Interferometer stage and evacuation system

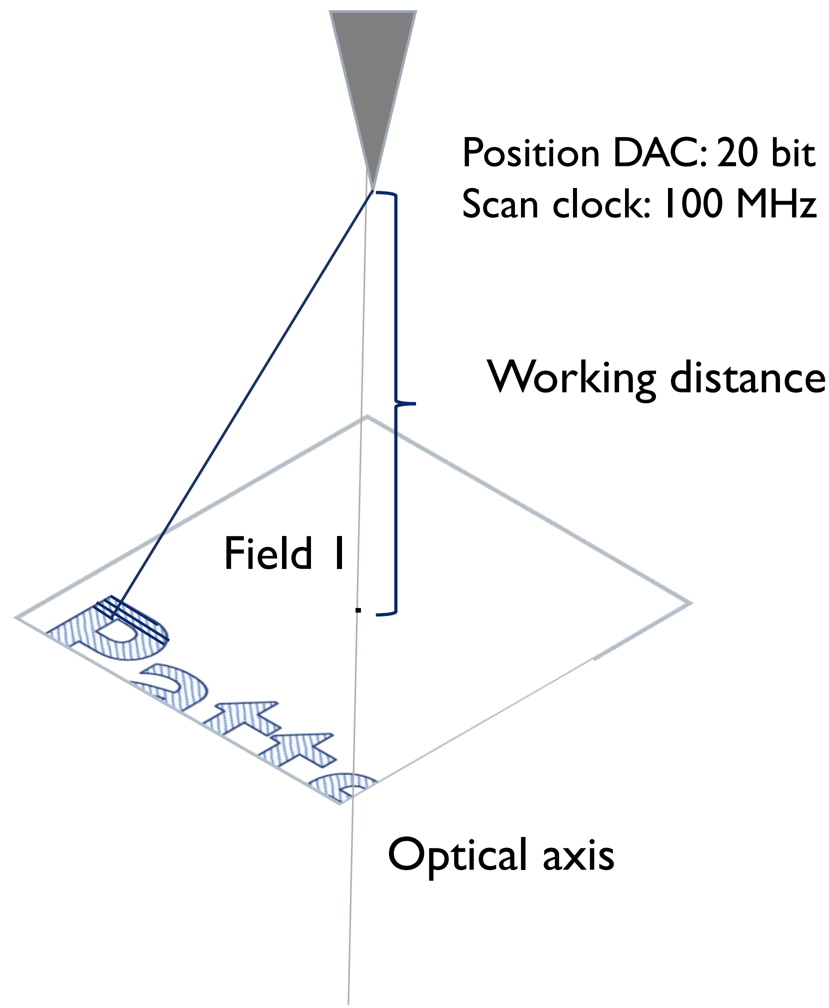
E-beam lithography technic basics

- Presentation.
- E-beam lithography system basics.
- E-beam lithography technic basics.
- Parameters to be chosen.
- Application examples
- New developments in e-beam lithography

E-beam lithography technic basics

How does the system expose?

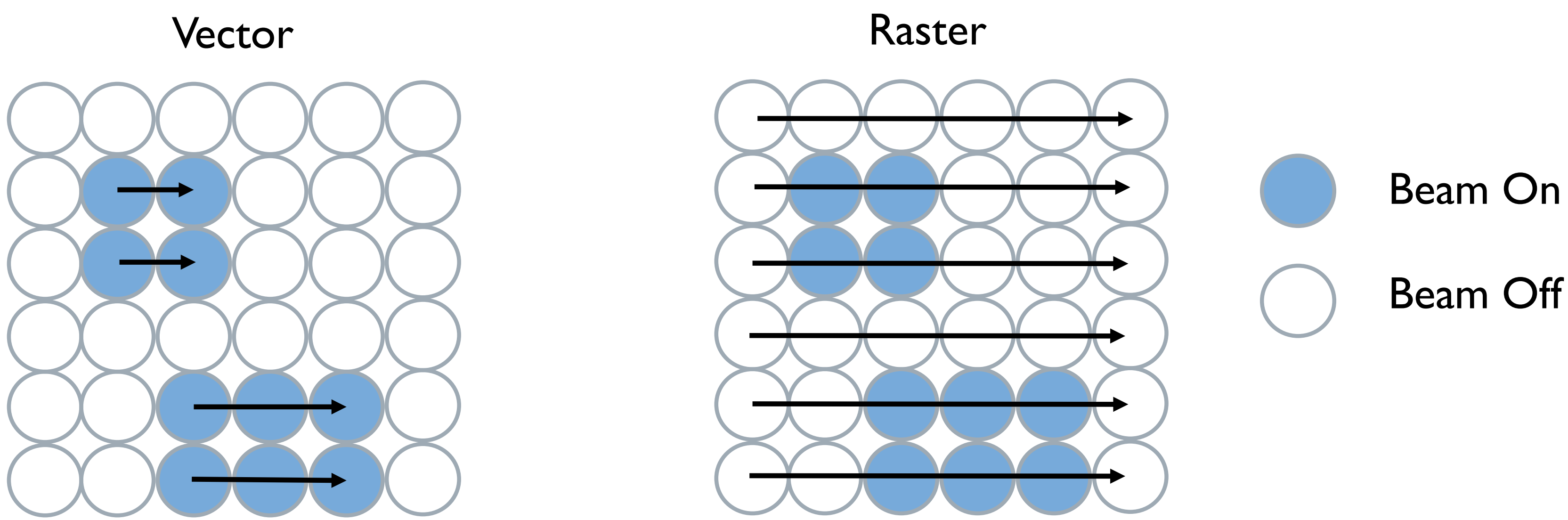




E-beam lithography technic basics

Vector & raster scans :

In vector mode the beam is deflected only over the entities to be exposed. In raster scan the beam scans at constant speed, while turning on/off the beam according to the presence absence of pattern.



E-beam lithography technic basics

Pros and cons of e-beam lithography:

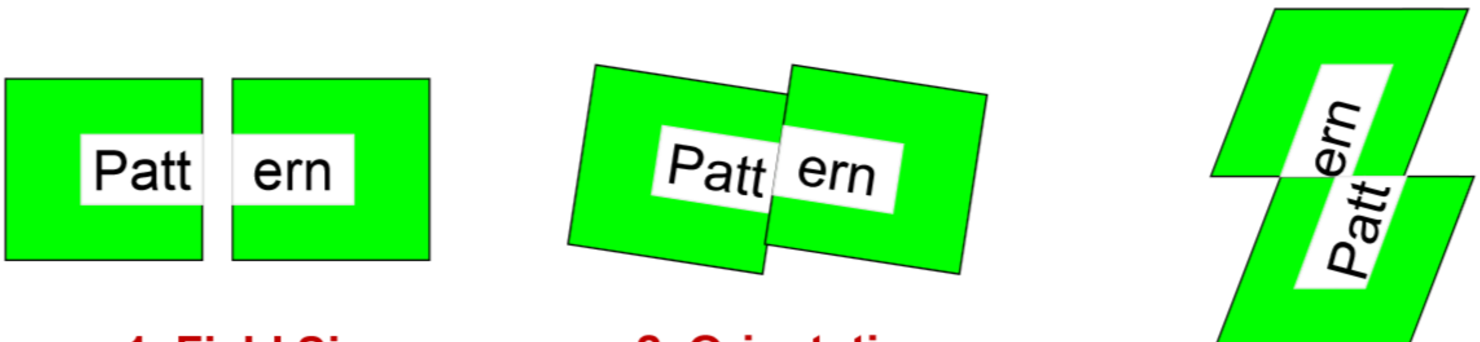
* Resolution ≤ 10 nm
  ⇨ Spot size ≤ 5 nm.
  ⇨ λe(50 keV)=5.5 pm.
* Mask less lithography

* Pixel by pixel exposure
* Stitching accuracy
  ⇨ low throughput
* Aberrations ⇨ distortion & Stig.
* Proximity effect (PE) and charging effect.
* Beam stability.

How do manufactures overcome stitching, aberrations and PE to get theoretical resolution?

E-beam lithography technic basics

Stitching accuracy



1. Field Size 2. Orientation 3. Right Angle

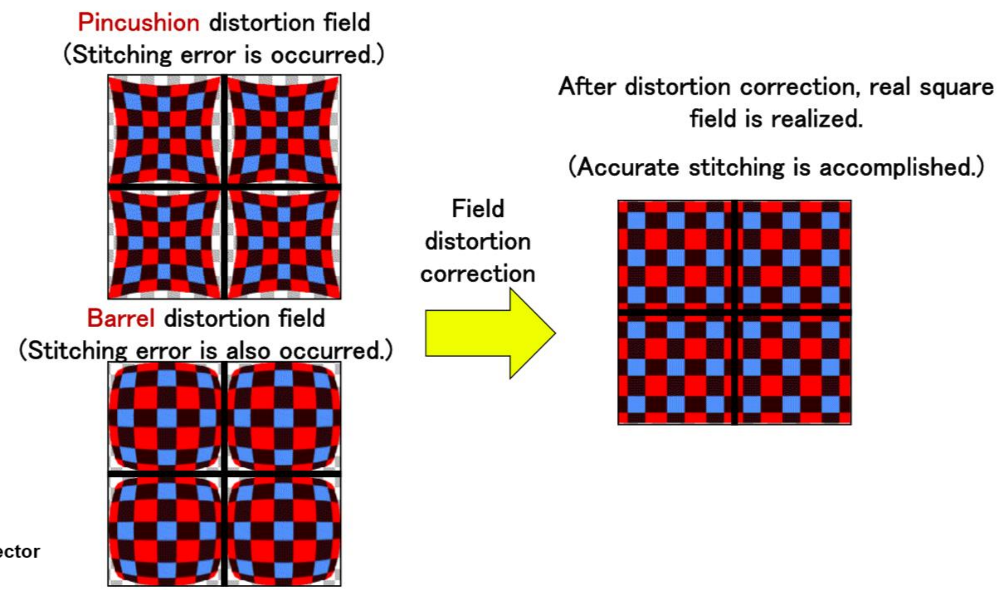
Three main factor are corrected electronically via electrostatic deflectors. Field size, rotation and right angle are adjusted using internal marks.

E-beam lithography technic basics

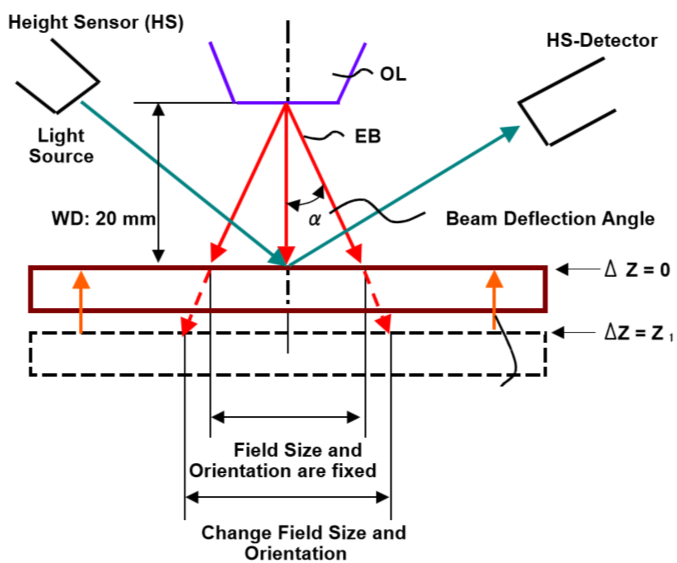
Stitching accuracy

The Other Error Factors

4. Field Distortion
5. Beam Position Drift
6. Surface Height of Wafer
7. Local Field Rotation due to Stage Position Shift



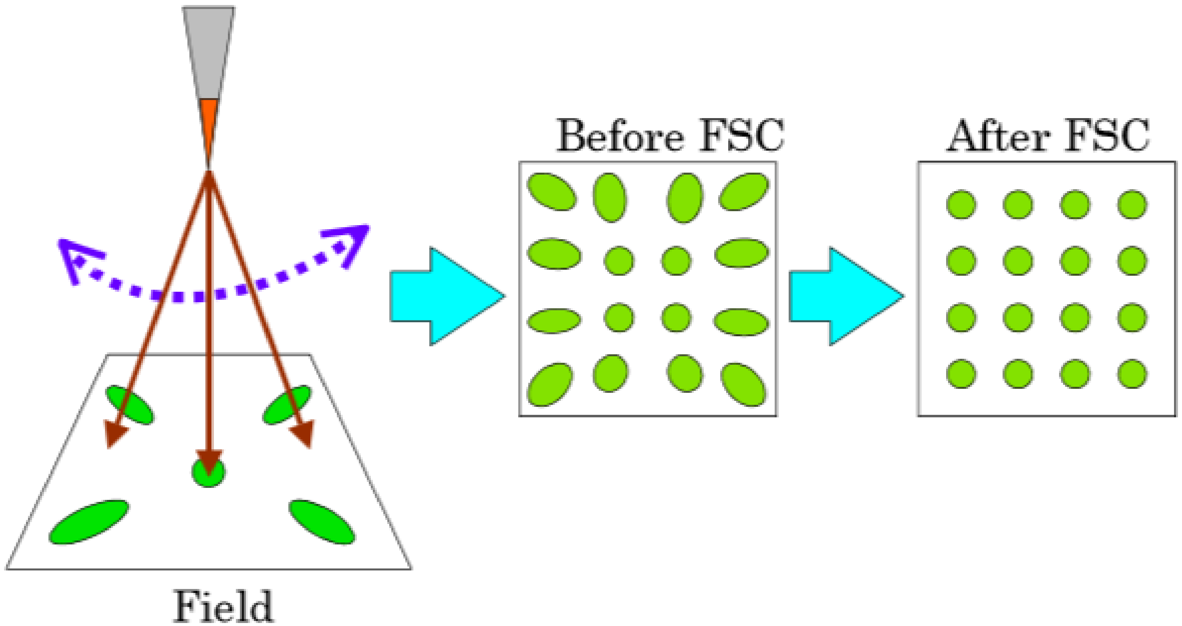
Field distortion correction, Also provide high accuracy within the field.



Height sensor control maintains constant working distance

E-beam lithography technic basics

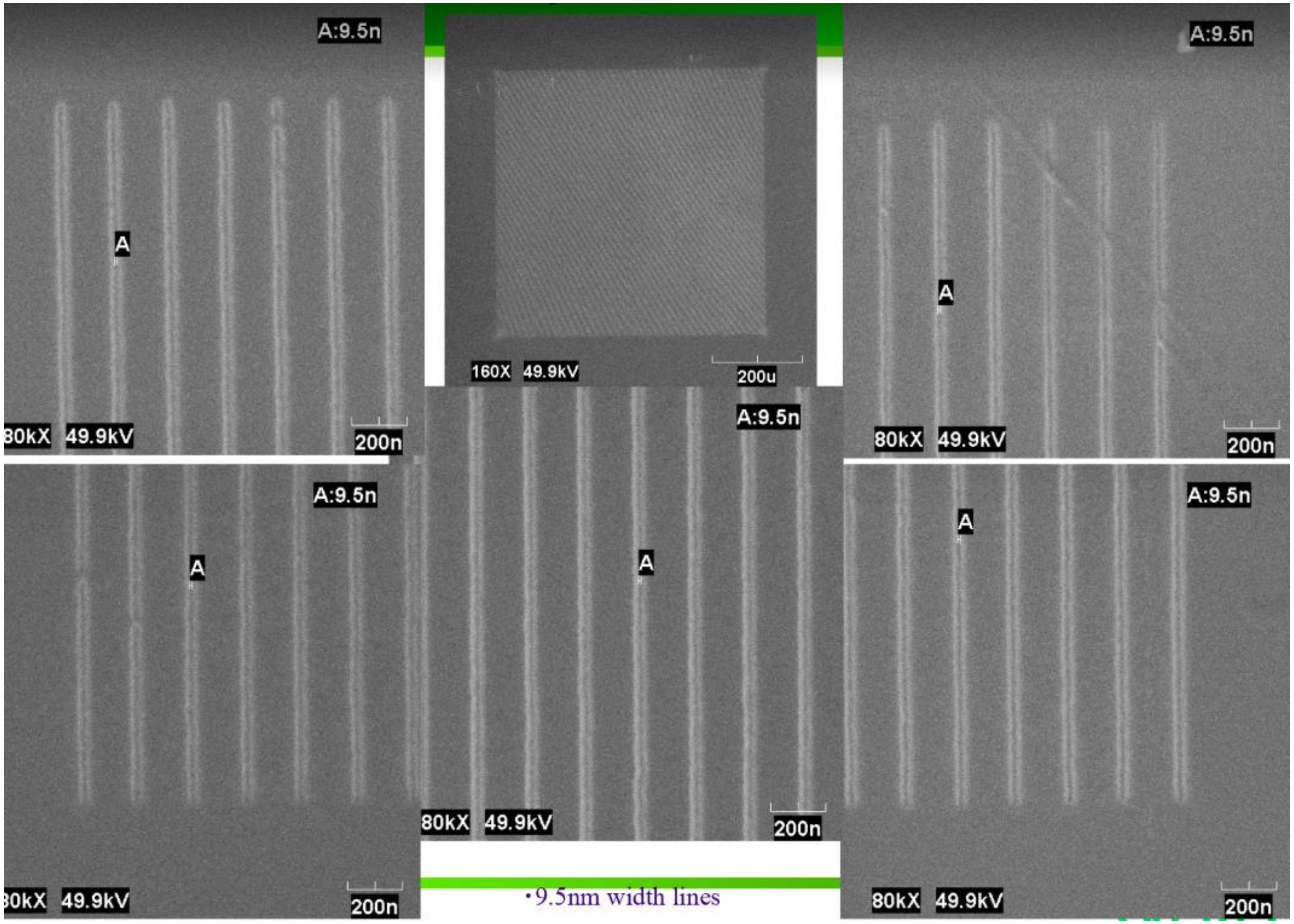
Stigmatism as cause non-uniformity beam size and shape, leading a lack of uniformity in the exposure within the field:

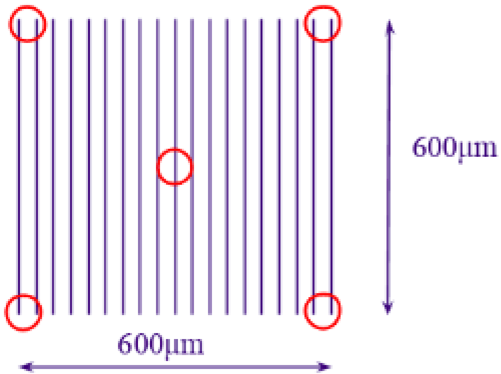


Stigmatism and distortion coming from electron-optical lenses asymmetries, once the correction is taken for a given e-beam current, it is independent of sample, resist…

E-beam lithography technic basics

600 µm field uniformity:

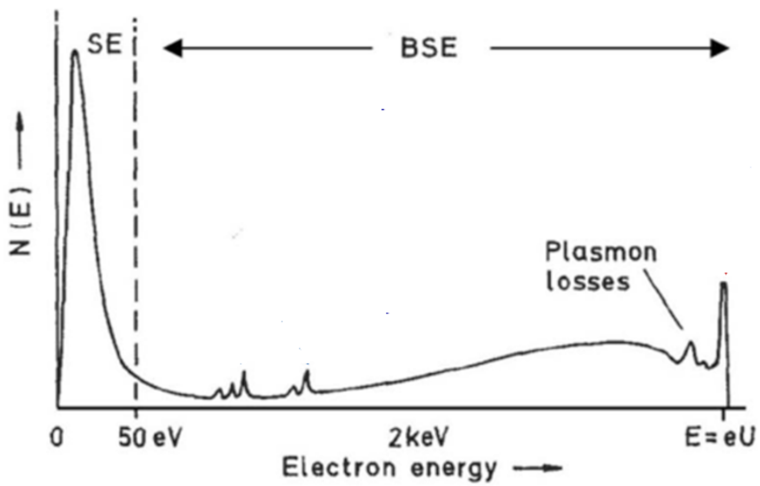


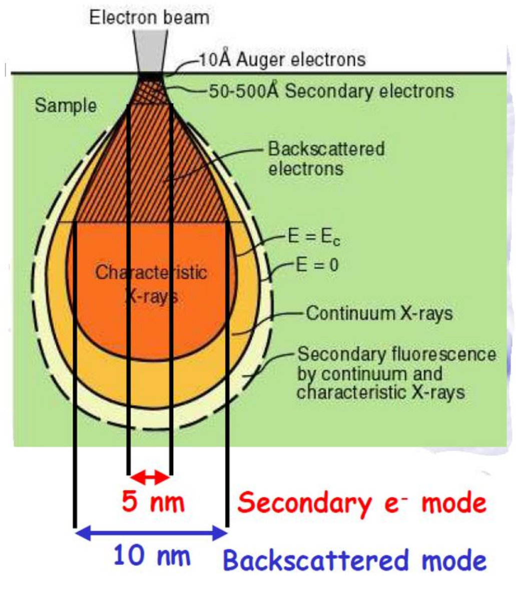


E-beam lithography technic basics

Proximity effect

Interactions of electrons with matter
Energy and spatial distributions.
Several eV needed for resist exposure.

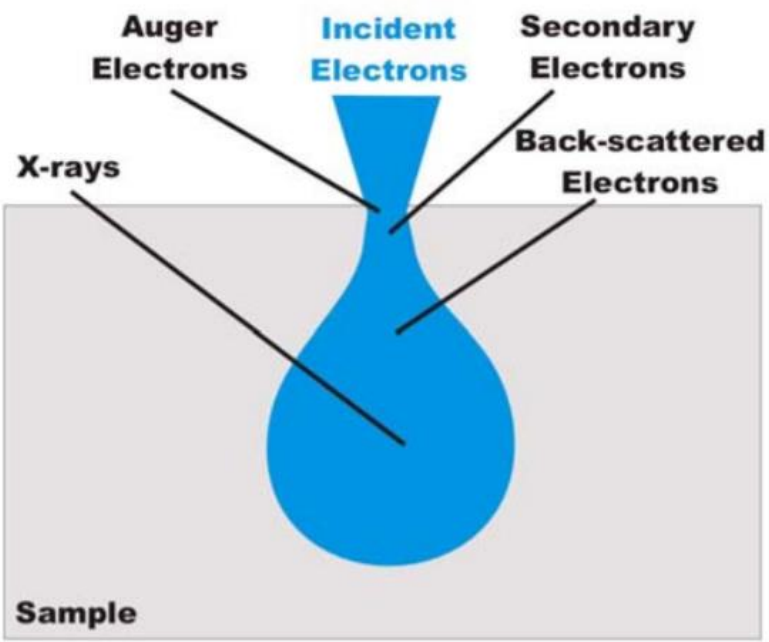




Energy spectrum of signal electrons (Reimer, 1998) consisting of Secondary Electrons (SE), Back-Scattered Electrons (BSE) and Auger Electrons (AE).

E-beam lithography technic basics

Proximity effect

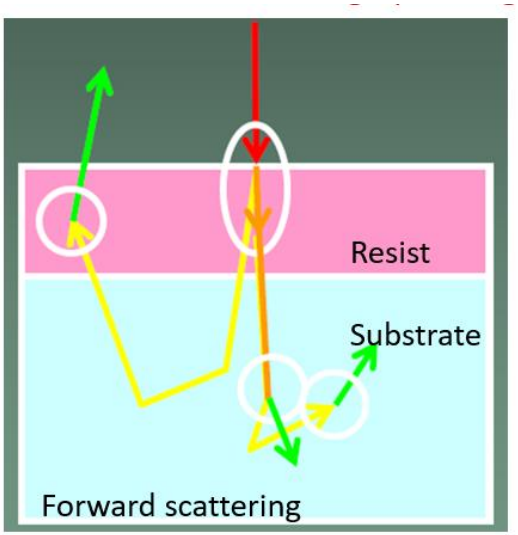


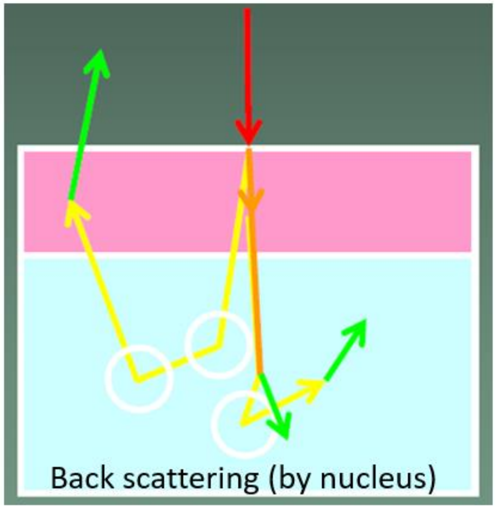
* Secondary electron scatter small angles (inelastic), responsible of resist exposure, e^-- e^- interactions.
* Backscattered electrons scatter big angles (elastic) by nucleus.

Properties of Electrons, their Interactions with Matter and Applications in Electron Microscopy
Frank Krumeich Laboratory of Inorganic Chemistry, ETH Zurich, HCI-H111, CH-8093 Zurich

Proximity effect

Forward and back scattering:

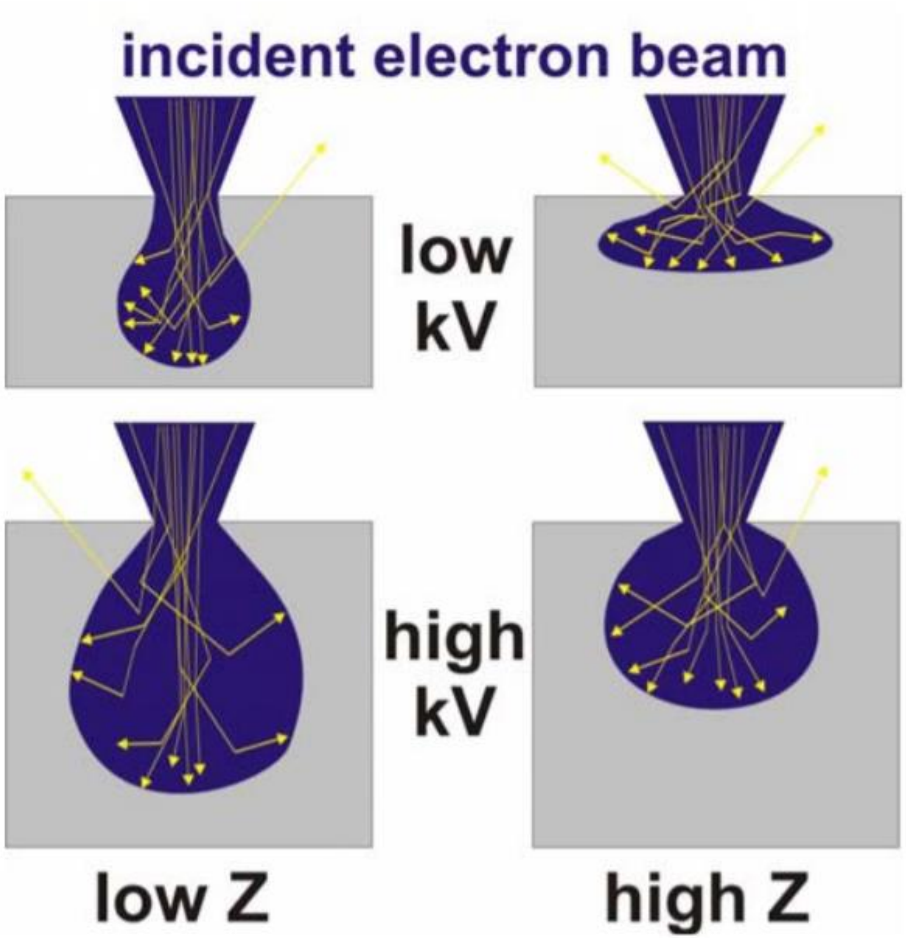




Forward scattering is responsible of resist exposure and broadening theoretical line width. Back scattering is responsible of proximity effect, when electrons arise again into the resist and cause subsequent inelastic exposure far from incident beam.

E-beam lithography technic basics

Proximity effect



Interaction volumes of the incident electron beam (blue) in compact samples (grey) depending on electron energy and atomic number Z. The trajectories of some electrons are marked by yellow lines.

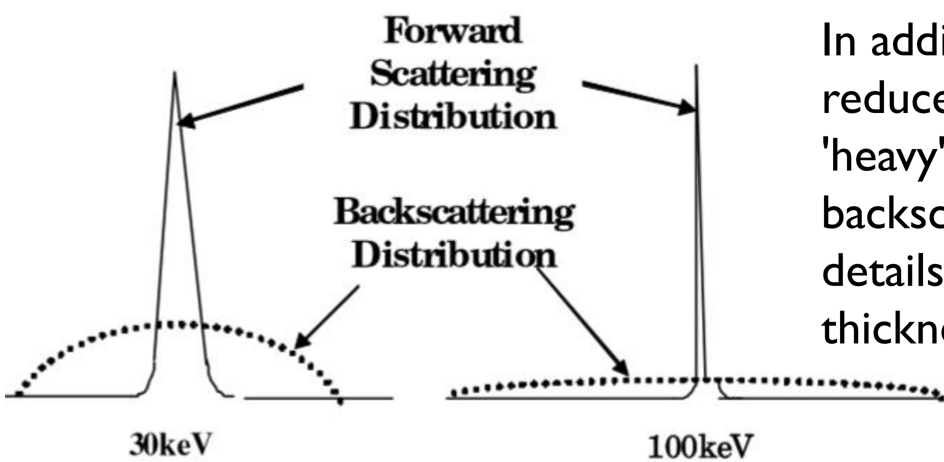
Scattering probability varies as square of atomic number Z, and inversely as the incident kinetic energy.

High-energy Electron Beam Lithography for Nanoscale Fabrication
Cen Shawn Wu1, Yoshiyuki Makiuchi2 and ChiiDong Chen3 1Department of physics, National Changhua University of Education.

Proximity effect

Practical conclusions I:

As the beam energy increases, the forward scattering is reduced and the back scattering area gets deeper and wider, leading a smaller PE and a lower resist sensitivity.



In addition, substrates made of light nuclei will reduce backscattering. On substrates with 'heavy' films, such as gold coatings, electron backscattering increases significantly, but the details also depend on the substrate's thickness.

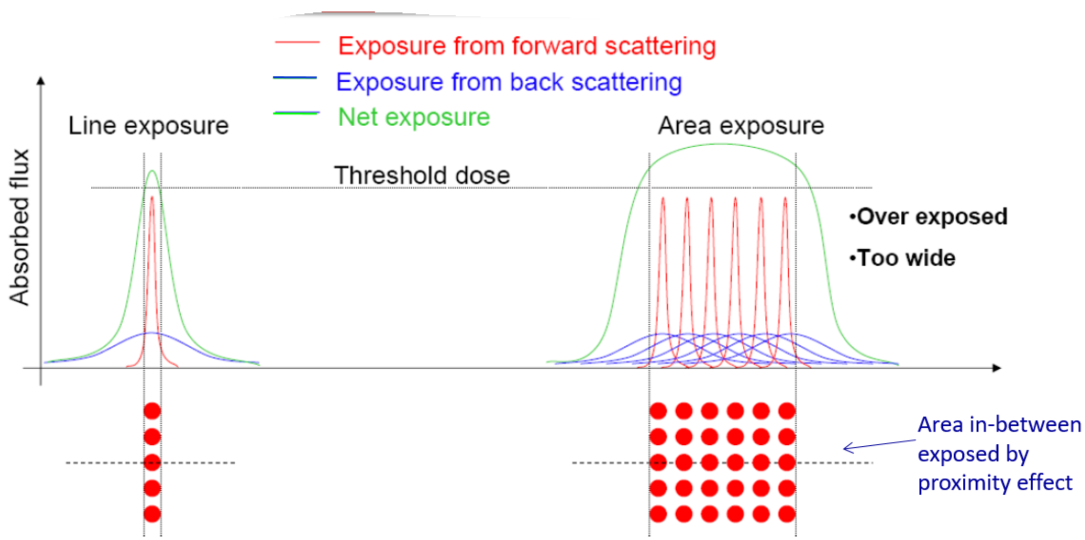
- At very low energies(2 kV):resist sensitivity is higher, so faster writing, for optical mask fabrication with low resolution due to aberrations.

High-energy Electron Beam Lithography for Nanoscale Fabrication
Cen Shawn Wu1, Yoshiyuki Makiuchi2 and ChiiDong Chen3 1Department of physics, National Changhua University of Education.

Proximity effect

Practical conclusions II:

- Proximity effect is negligible for isolated/sparse fine features.
- It is good for *area* exposure (e.g. a big square >>1μm), since pixel can be much larger than beam spot size (right figure). E.g., beam step size (pixel) of 50nm is usually enough to give uniform areal exposure, even with a beam spot size of only 5nm.
- Proximity effect is worst for dense and fine patterns, such as grating with sub-50nm pitch and for high size accuracy.



Proximity effect

PE Correction

1. By software

Double Gaussian model. Simulation and correction

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

α: range of forward scattering (in μm)
β: range of backscattering (in μm)
η: ratio of backscattering to forward scattering

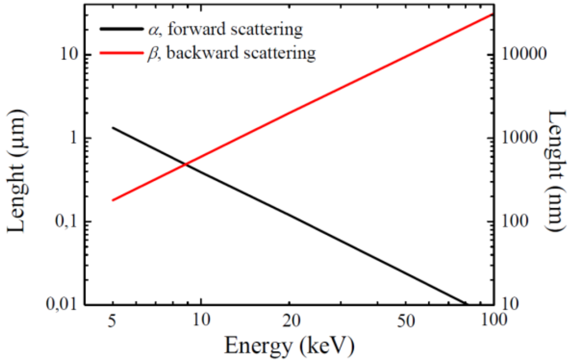


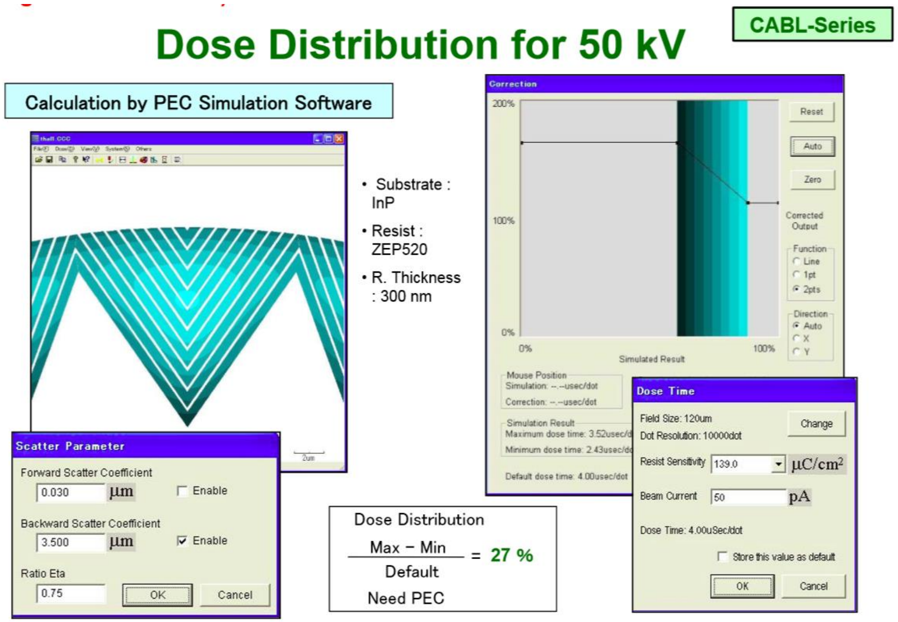
Table-3.12. Double Gaussian fitting parameters at different conditions

energy / keV	substrate	resist thickness/μm	α /μm	β/μm	η
25	silicon	0.2	0.019,7	2.295,4	0.479,7
50	silicon	0.5	0.016,5	6.689,1	0.314,6
50	silicon	0.5	0.025	5.896,2	0.194,1
50	GaAs	0.5	0.025	3.55	0.674

E-beam lithography technic basics

Proximity effect

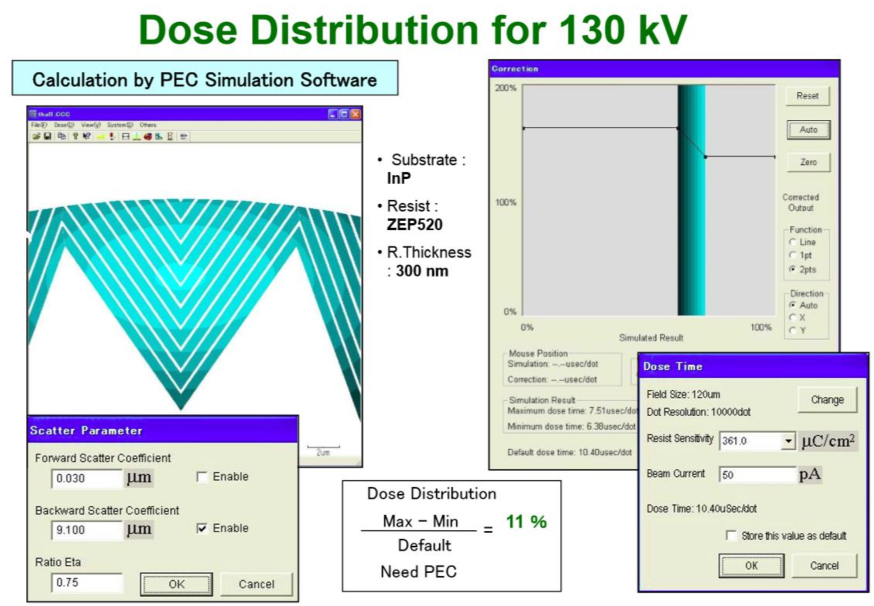
Simulation of dose distribution for 50 kV and 135 kV



Resist Thickness	Forward Scattering (α)	Backward Scattering (β)	Ration (η)
300nm	Around 0.3um	Around 4.5um	1.1
100nm	Around 0.2um	Around 3.5um	0.9

Experimental values of α, β, η from our tests.

Values above were got by our own experiments under the conditions as bellow.
HV : 30KV
Substrate: Si
Resist : ZEP520



E-beam lithography technic basics

Proximity effect

Correction Rules

Original patterns are broken into a lots of **Line** patterns with **Layer** number.
Layer means the group which has the same dose timer.
Number of Layers is equal to the **Quantization Level.**
Each Layer is created base on the **Overlapped Layer Method** which means exposure should be undertaken by Layer on Layer as bellow.

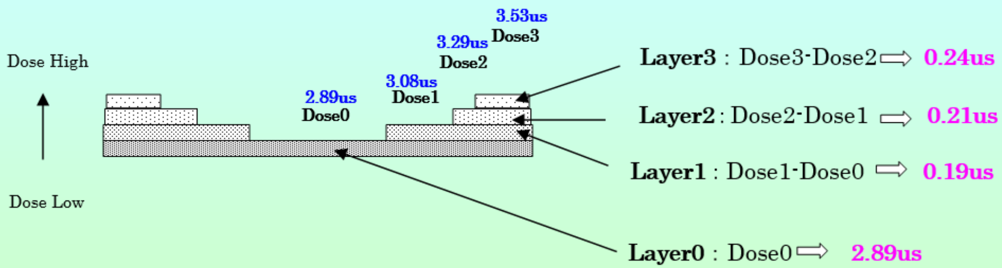
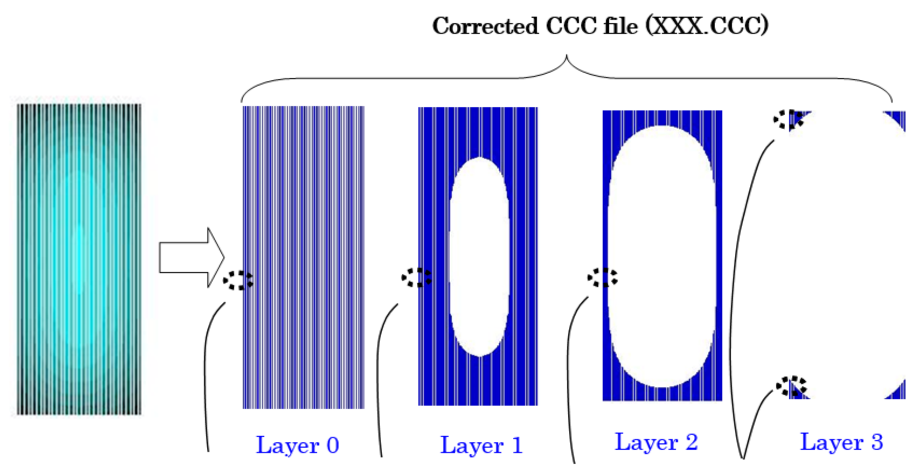


Fig.3 **Overlapped Layer Method**

Therefore the dose timer of No.N Layer is the difference between N and N-1.

CRESTEC approach for dose correction



E-beam lithography technic basics

Proximity effect

PE Correction

2. Resizing patterns

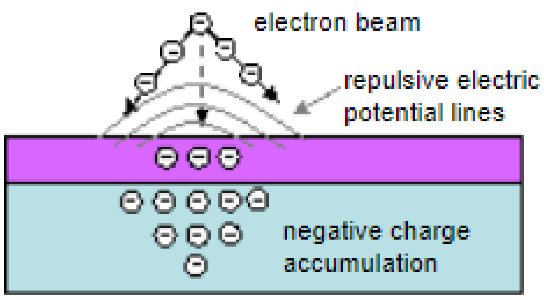
Nominal feature

Widening due to PEC

Resizing for get nominal Feature or single line with dose variation

E-beam lithography technic basics

Charging effects. Insulating substrate produce charge-induce error in position and shape (distortion).
Avoidance: conductive polymer (or metal) on top of the resist and use low e-beam currents(50- 100 pA)



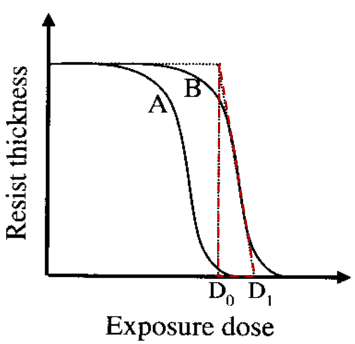
Item	ESPACER 300™
pH	**Weak acid**
Guarantee Shelf Life	**3 months at 5±3 degC**
Impurities	**< 50ppb**
Sheet Resistance	**$1 \times 10^3 \sim 5 \times 10^7$ ohm/sq**

Parameters to be chosen

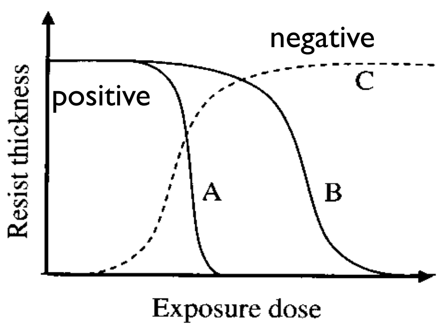
- Presentation.
- E-beam lithography system basics.
- E-beam lithography technic basics.
- Parameters to be chosen.
- Application examples
- New developments in e-beam lithography

Parameters to be chosen

Parameter	Affects to
Exposure energy	Resolution, sensitivity, PE.
Beam size (beam current)	Resolution, throughput
Exposure dose	Pattern quality
Pattern density	PE
Resist material	Sensitivity, resolution, contrast, pattern transfer.
Resist thickness, resist multi stack	Sensitivity, resolution, pattern transfer
Developer temperature	Sensitivity, resolution, exposure window
Field size	Resolution, accuracy: Stig&Distortion and overlay
Field resolution	Resolution



(a)



(b)

Table-3.8. Conventional e-beam resists and properties

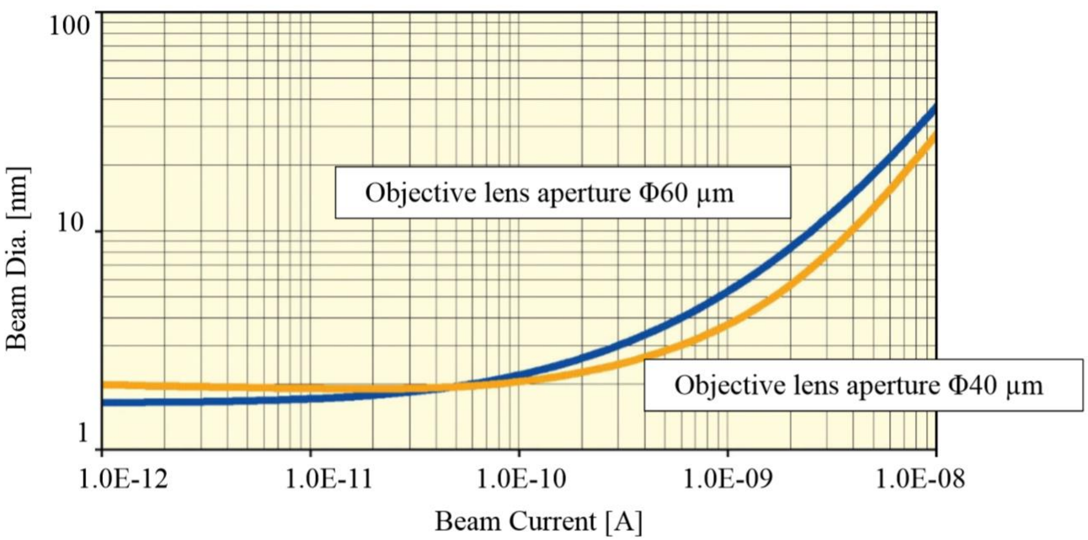
	resist tone	resolution / nm	sensitivity*	developer
PMMA	+	10	100	MIBK:IPA
ZEP-520	+	10	30	xylene : p-dioxane
ma-N 2400	–	80	60	MIF726
EBR-9	+	200	10	MIBK:IPA
PBS	+	250	1	MIAK: 2-pentanone 3:1
COP	–	1,000	0.3	MEK : ethanol 7:3

* sensitivity measured at 20 keV beam energy, unit: $\mu C/cm^2$.

Contrast definition $\gamma \equiv \frac{1}{\log_{10}(D_1 / D_0)}$

Parameters to be chosen

Beam current vs. beam diameter

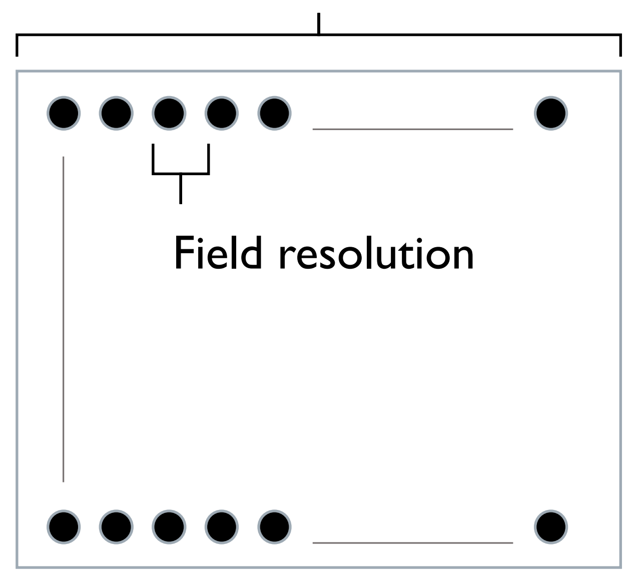


$$t = \frac{S \cdot x^2}{I_B}$$

S	Sensitivity, (Area dose) [µAs/cm^2]
x	Step size [µm]
I_B	Beam current [pA]

Dose time calculation

Field size



Field size and field resolution

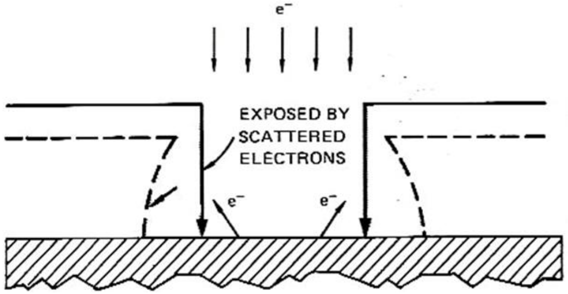
Application examples

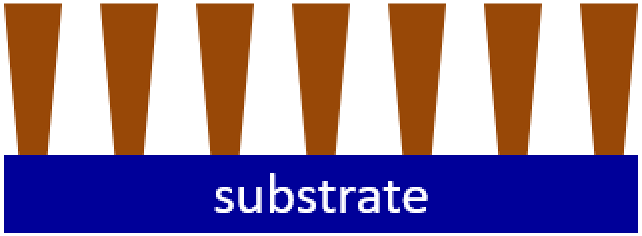
- Presentation.
- E-beam lithography system basics.
- E-beam lithography technic basics.
- Parameters to be chosen.
- Application examples
- New developments in e-beam lithography

Application examples1

Dry etch using a ICP. Very high aspect ratio and dense structures as resonator for bio-optical applications:

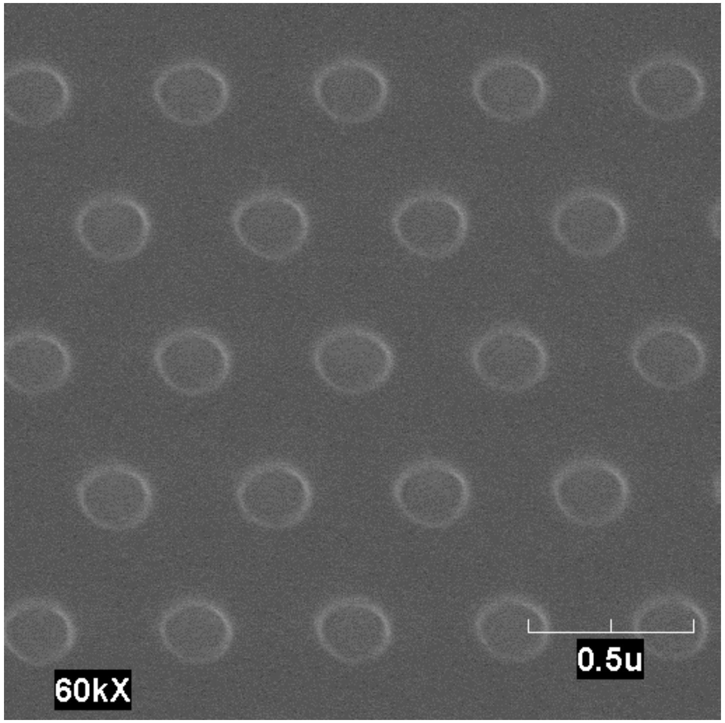
Beam current: 2 nA
Single shot exposure, 500 nm pitch, 175 nm diameter
Dose: 140 us
600 um field and 60.000 dots. Only using 300 um inner field
Resist: PMMA. 3000 rpm, 10min@160ºc
Developer: AR-600-55, 3 min sonication
170 nm Nickel metallization and lift-off
ICP etch: low density plasma: RF: 75 W, HDP: 0W, 20sccm CHF3, 4sccm O2
Time: 50 min, rate: 40 nm/min (total etch: 2 um)



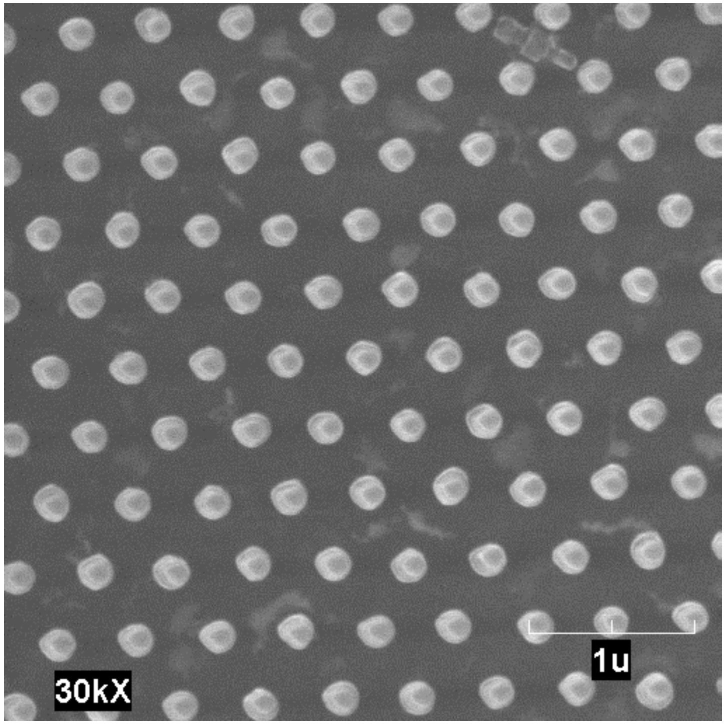


Profile of Pmma resist helps to get a good lift-off

Application examples I

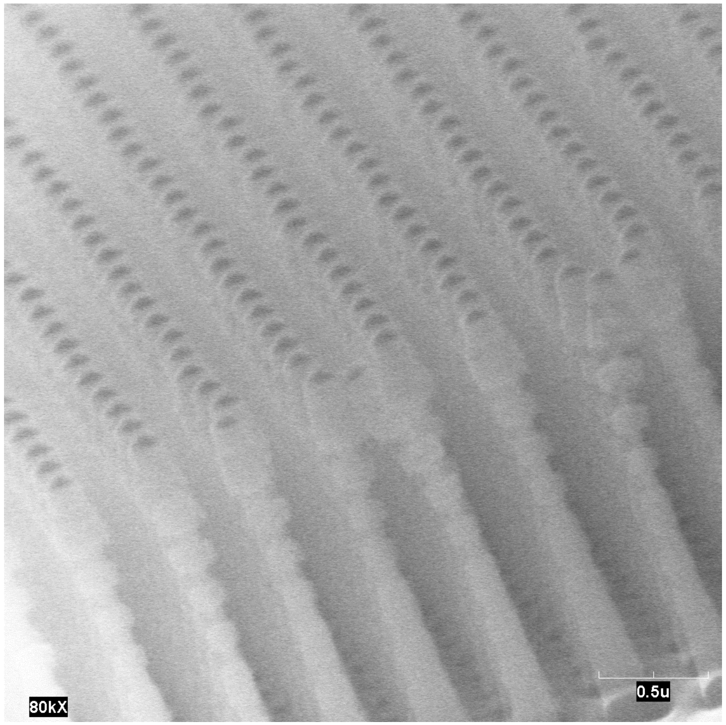


Resist after exposure and development.
Pitch 500 nm.
175 nm diameter.

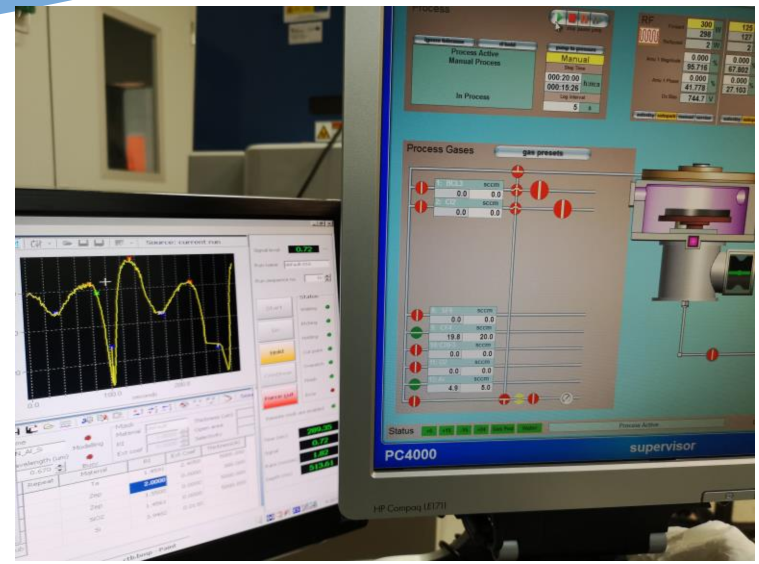


170 nm Nickel disc after lift-off.

Application examples I



2 micron deep high aspect ratio nanostructures.



ICP system with end point detection

Application example 2

Two layer approach for thick metallization:

First resist layer: LOR, 7B Microchem

Diluted 2:1 in Cyclopentanone 250 nm or 650 nm no diluted

Coating speed: 3000 rpm, 5 min@200°c

Second resist: PMMA 950 K 2:1 in Chlorobenzene

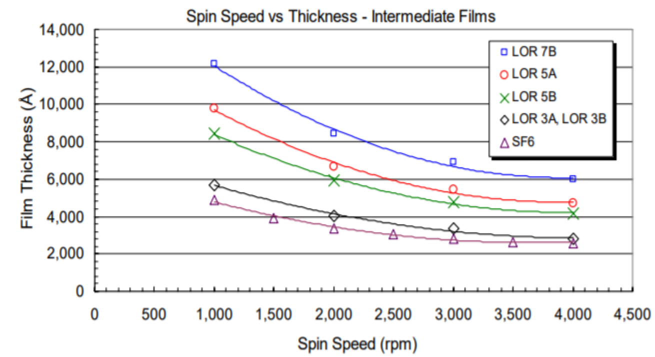
Diluted 2:1 in Chlorobenzene 260 nm thick

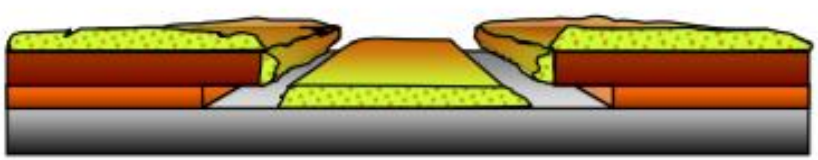
Coating speed: 3000 rpm, 10 min@160°c

Step 1: e-beam exposure

Step 2: PMMA development, AR-600-55, 3 min

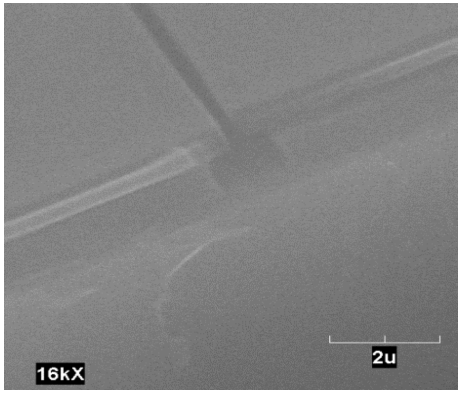
Step 3: LOR development, MF319, 30 s. Depend on undercut desired



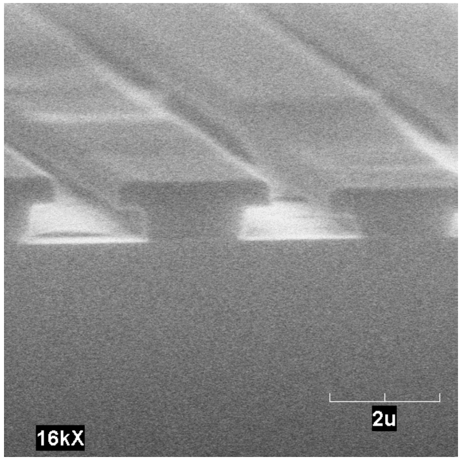


Two resist stack plus metal deposition

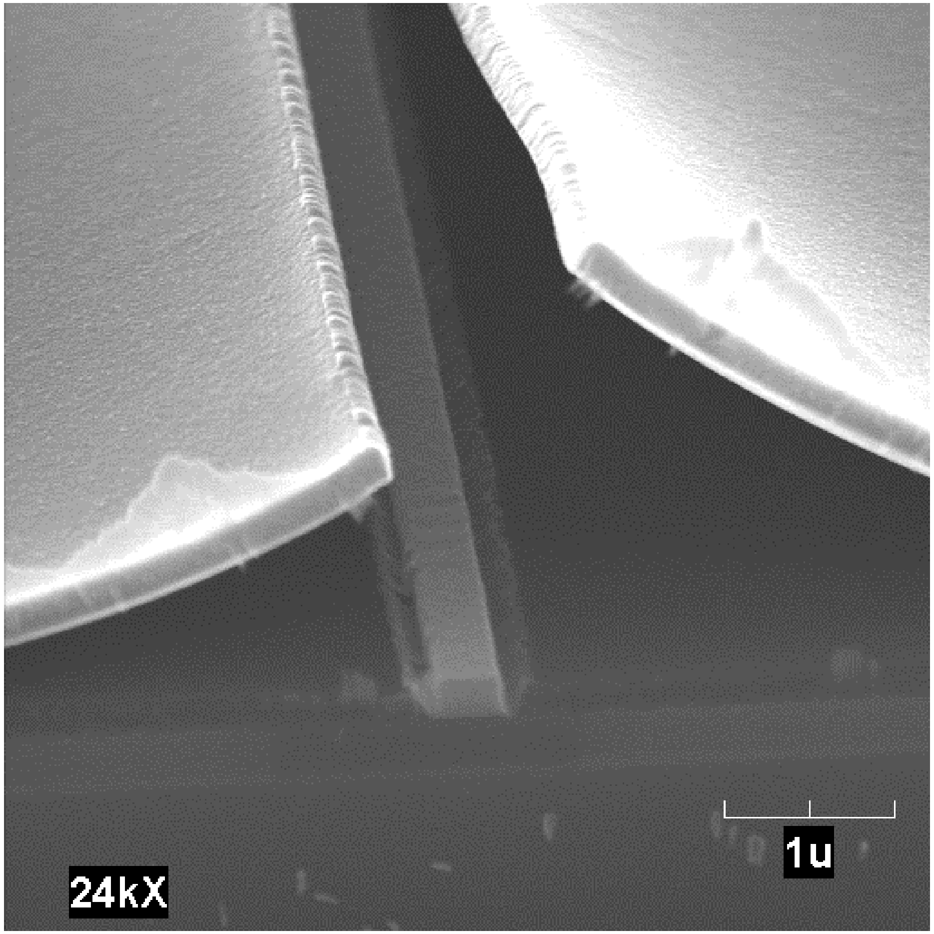
Application examples 2



No diluted LOR



2:1 diluted LOR



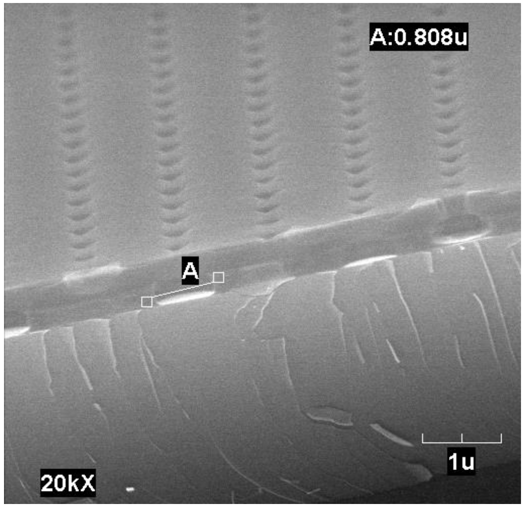
250 nm of Nickel before lift-off

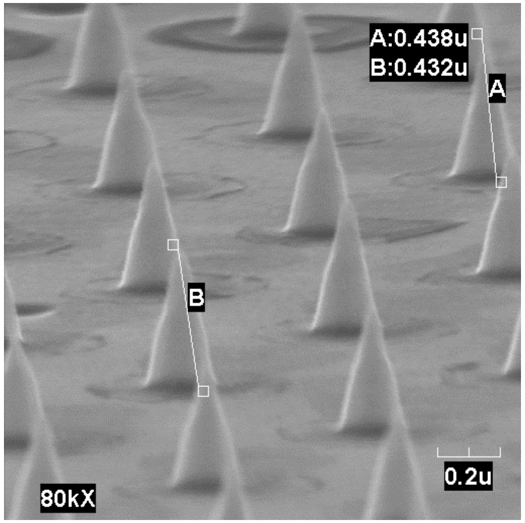
Application examples 3

Dry etch using a ICP. Very high aspect ratio and very deep etched structures of GaN for material X-ray analysis:

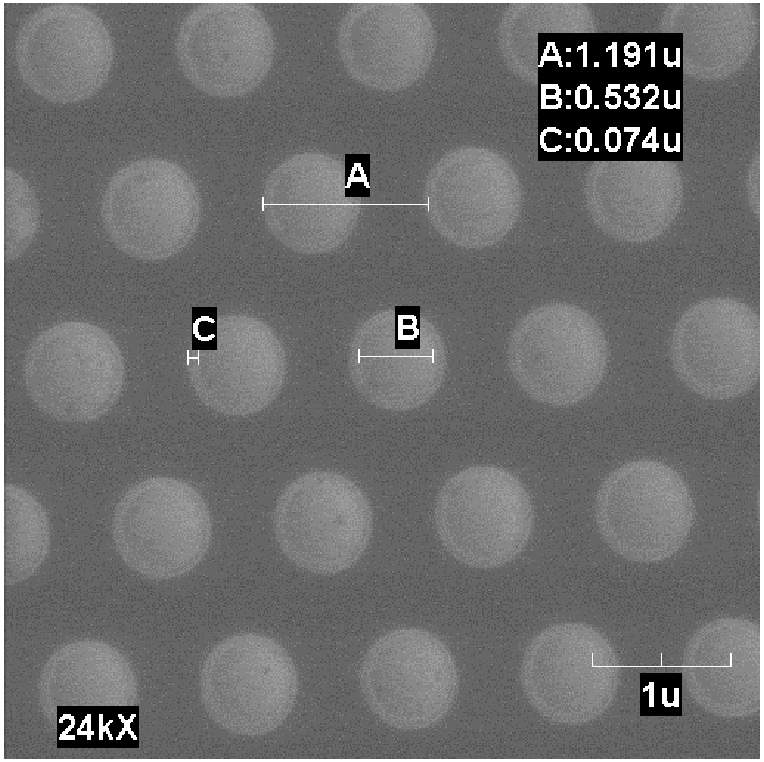
Beam current: 2 nA and 5 nA
Single shot exposure, 1.2 um pitch, 530 nm diameter
Dose: 300 us for 2nA and 47 um defocused. 140 us for 2 nA
500 um field and 60.000 dots. Only using 300 um inner field
Resist: LOR/PMMA , 260/ 260 nm thick.
Developer: AR-600-55, 3 min for PMMA and MF319, 30 s for LOR
500 nm Nickel metallization and lift-off
ICP etch: high density plasma: RF: 250 W, HDP: 250W, 20sccm BcL3, 4sccm Cl2
Time: 12 min, rate: 0.3 um/m.

Application examples 3



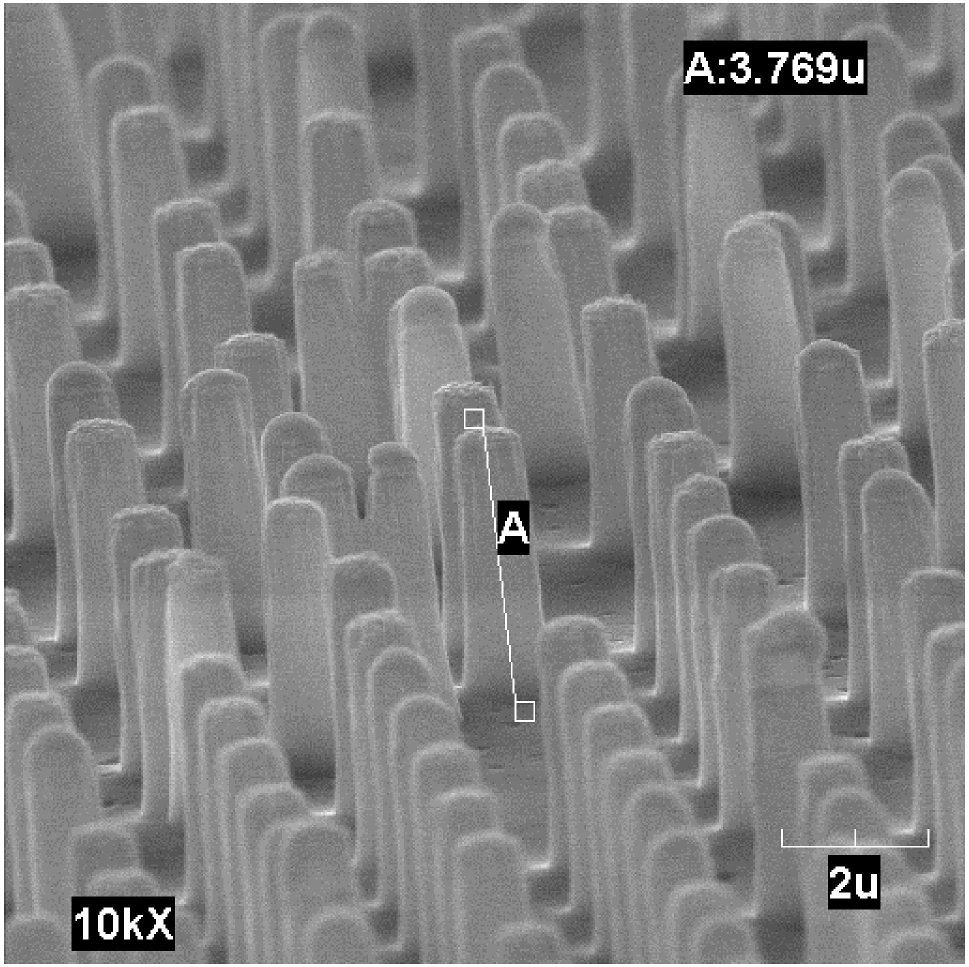


2 nA, 300 us, 47 um defocused.



5 nA, 140 us, resist profile and 500 nm Ni.

Application examples 3



ICP etch: high density plasma: RF: 250 W, HDP: 250W, 20sccm BcL3, 4sccm Cl2

Application examples 4

HSQ for waveguide applications

Beam current: 5 nA
Area dose: 1000 uc/cm2
300 um field and 60.000 dots.
Resist: xr-1541 (6%) Dow Corning
Thickness: 120 nm, 3000 rpm, 2min@90°c
Developer: MF319 @ 50°c, 70s

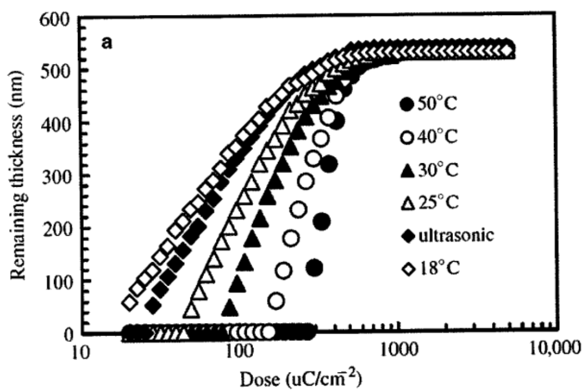
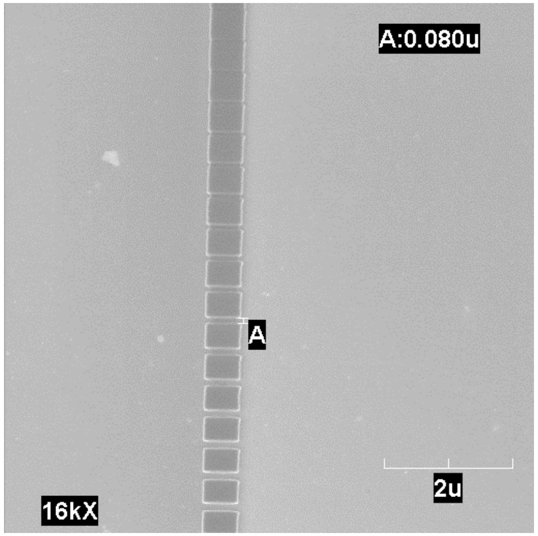
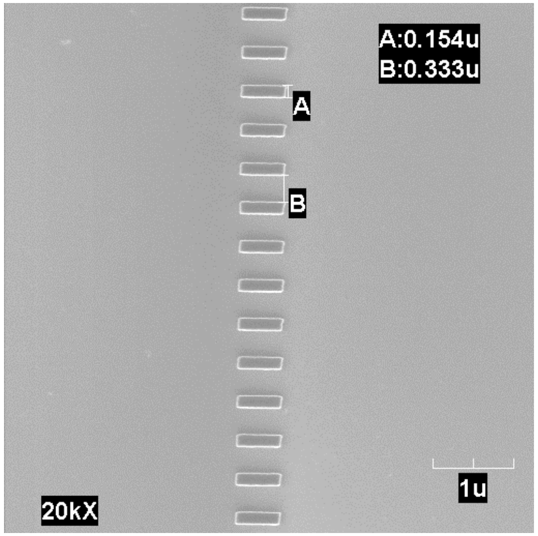
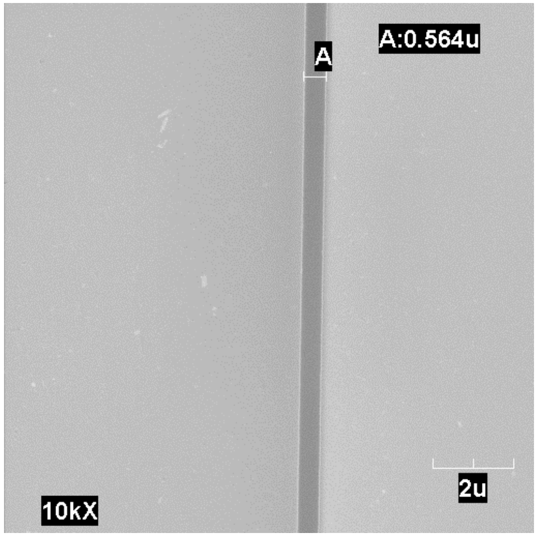
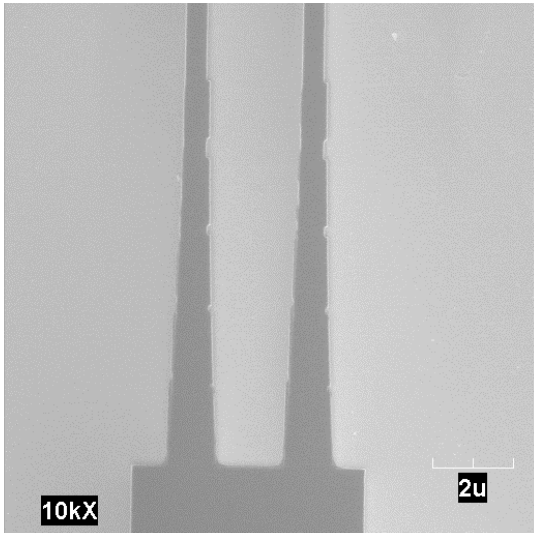


Fig. 3.32 Contrast curves of HSQ resist at different development temperatures









Application examples 4

Resist: xr-1541 (6%) Dow Corning for high contrast

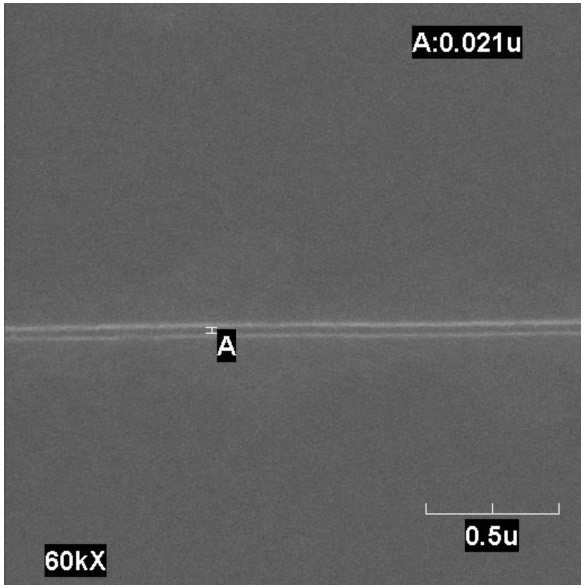
Field Size/resolution: 60/60000.

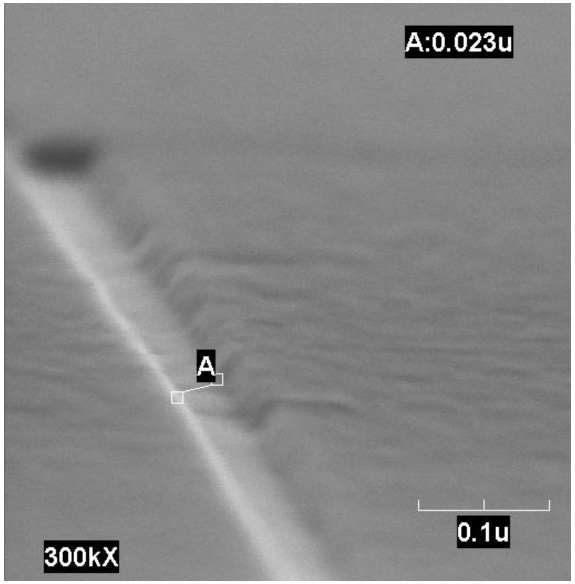
Resist thickness: 40 nm

Beam current: 50 pA.

Developer: NaOH (1%)/NaCl(4%) in DI water during 4 minutes.

Dose: 750 uC/cm2

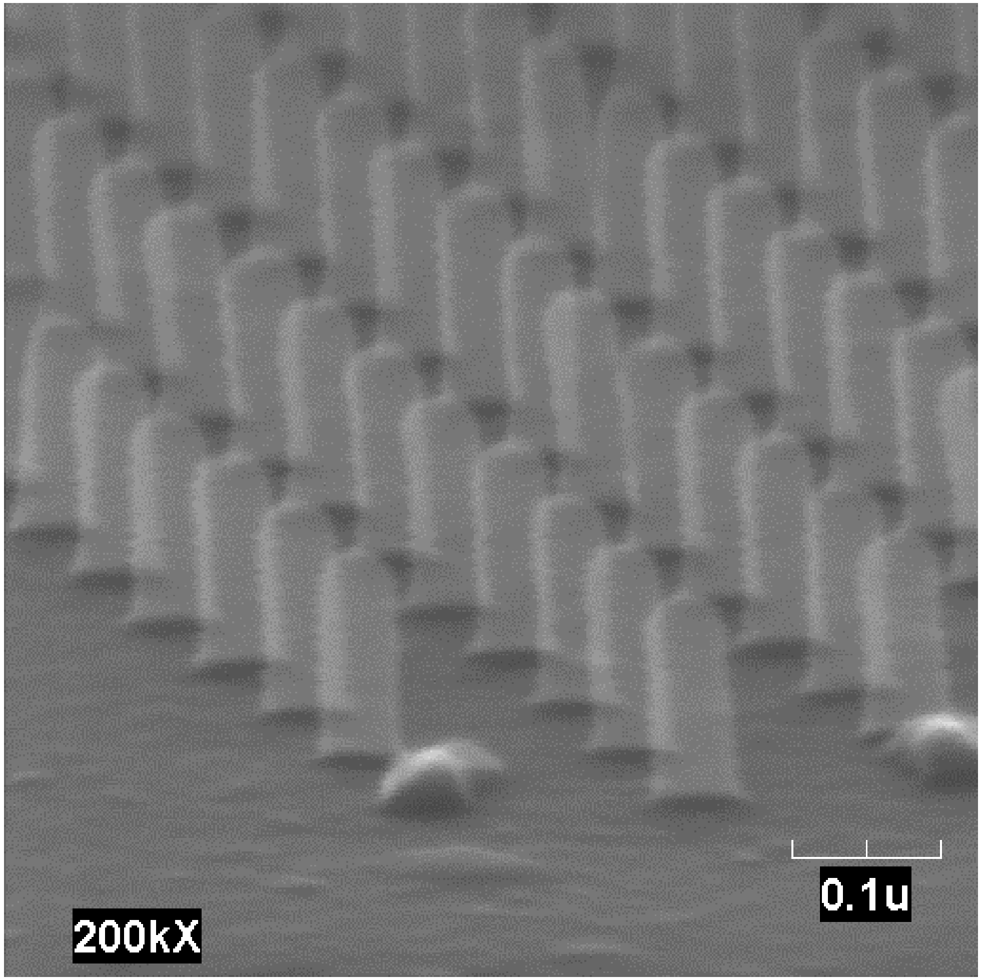




Application examples 5

Negative tone resists: Ma-N direct writing for interferometric applications

Beam current: 100 pA
Dose time single shot: 21 us
60 um field and 60.000 dots.
Resist: Ma-N 4203 MicroChem
Thickness: 200 nm. 5000 rpm.
2min@90°c
Developer: MF319 , 70s
Pitch:200 nm/Diameter: 50 nm
Area dose: 230 uC/cm2

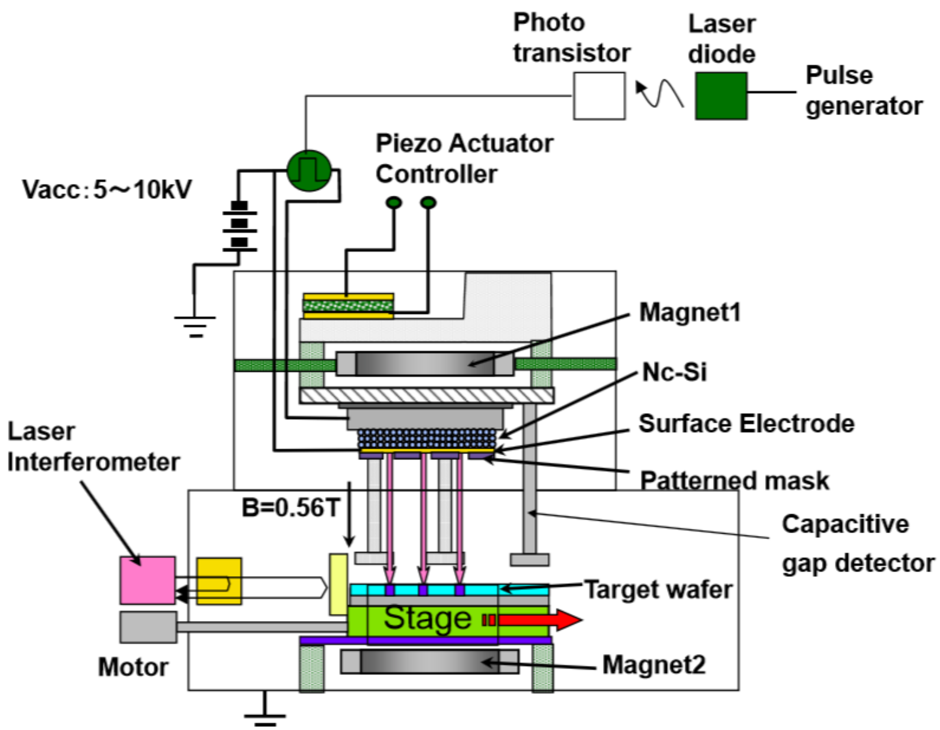


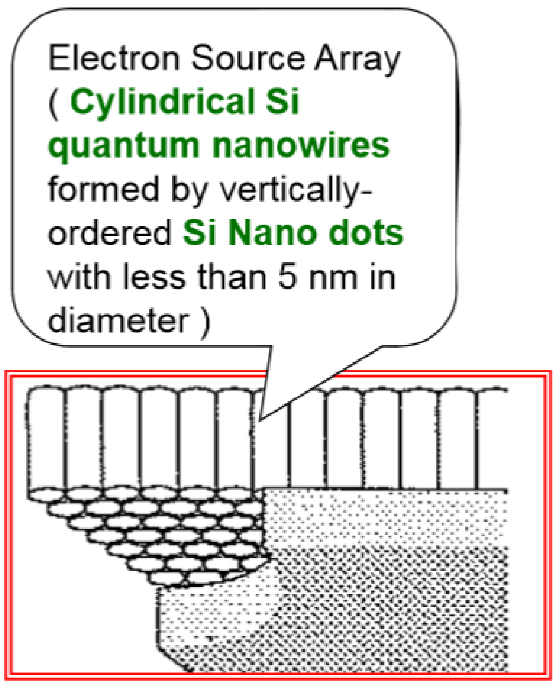
New developments

- Presentation.
- E-beam lithography system basics.
- E-beam lithography technic basics.
- Parameters to be chosen.
- Application examples
- New developments in e-beam lithography

New developments I

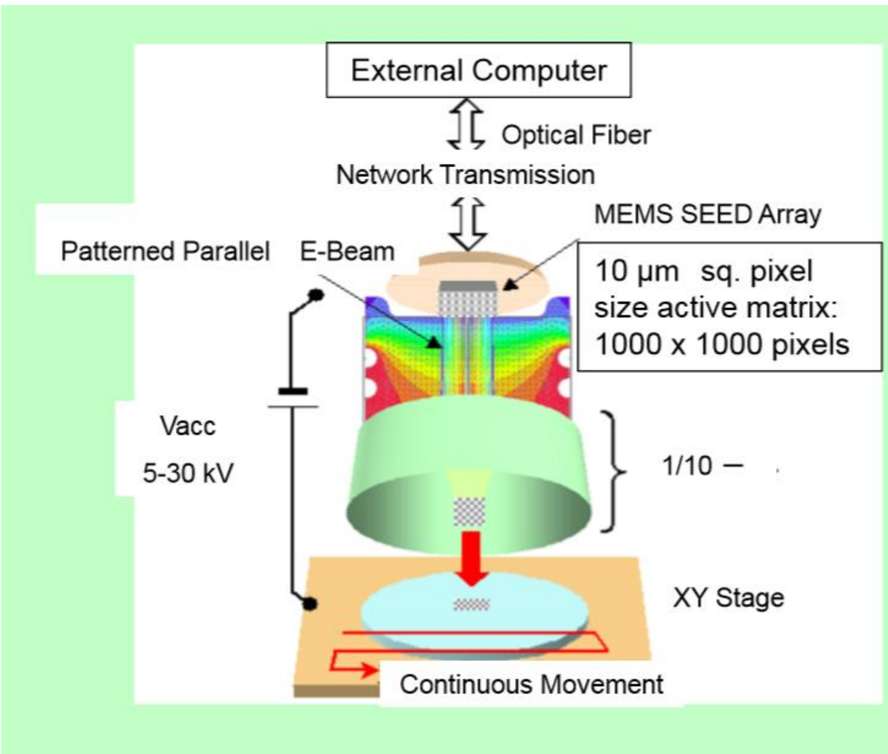
Prototype: Surface Emission EB Lithography System.
Pursuing throughput.

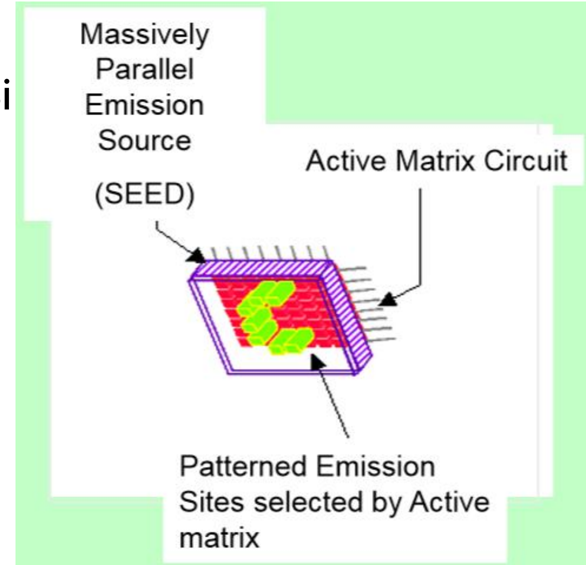


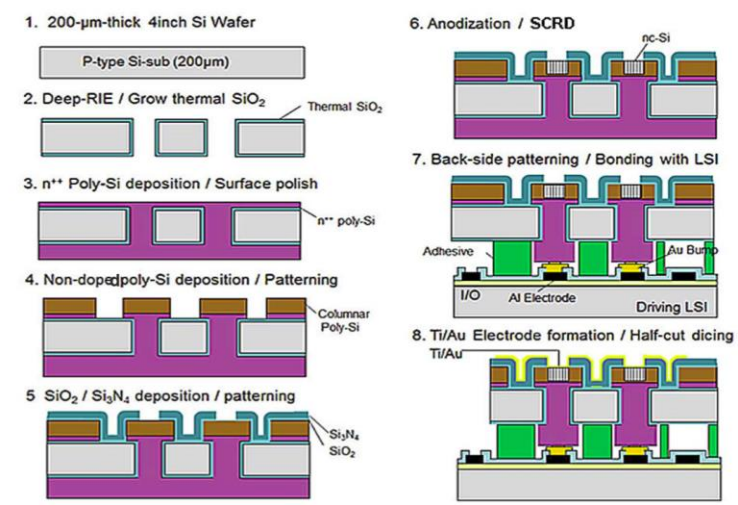


New developments 2

New concept: Massively Parallel EBL System based on nc-Si emitter array







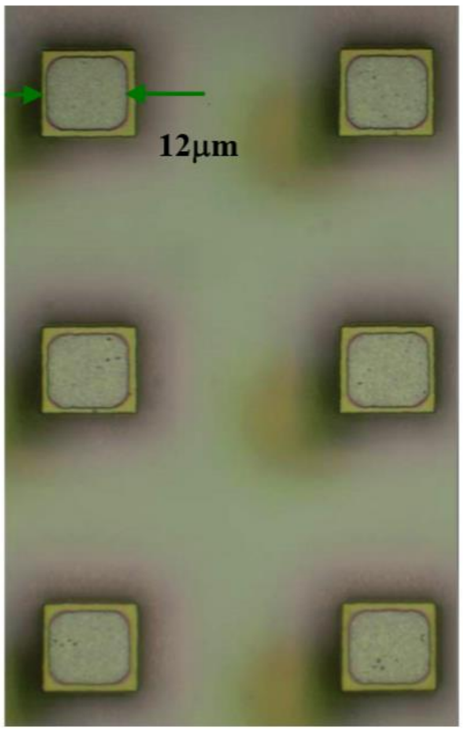
Massively parallel emitter

Crestec, Tohoku Univ. and TUAT are jointly developing supported by the Cabinet Office in Japan

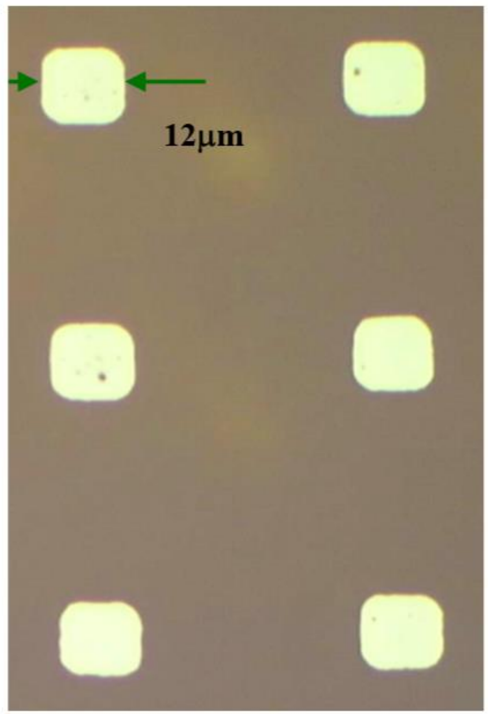
New developments 2

Exposure Test of nc-Si Emitter Array integrated with Active Matrix LSI

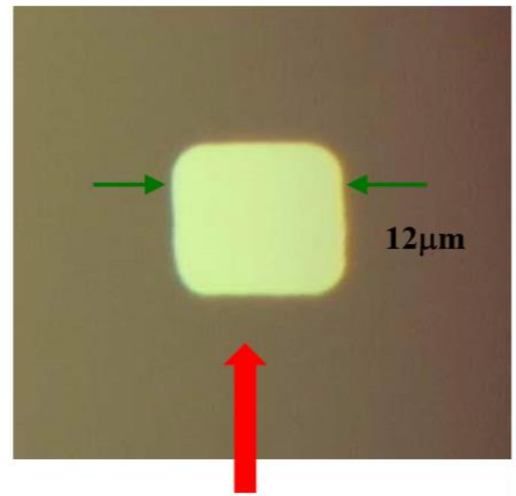
CMPL-6000



Nc-Si Emitter Array



Exposed Image on Target



No fluctuations at pattern edge due to small energy dispersion of emitted electrons

< Exposure condition >

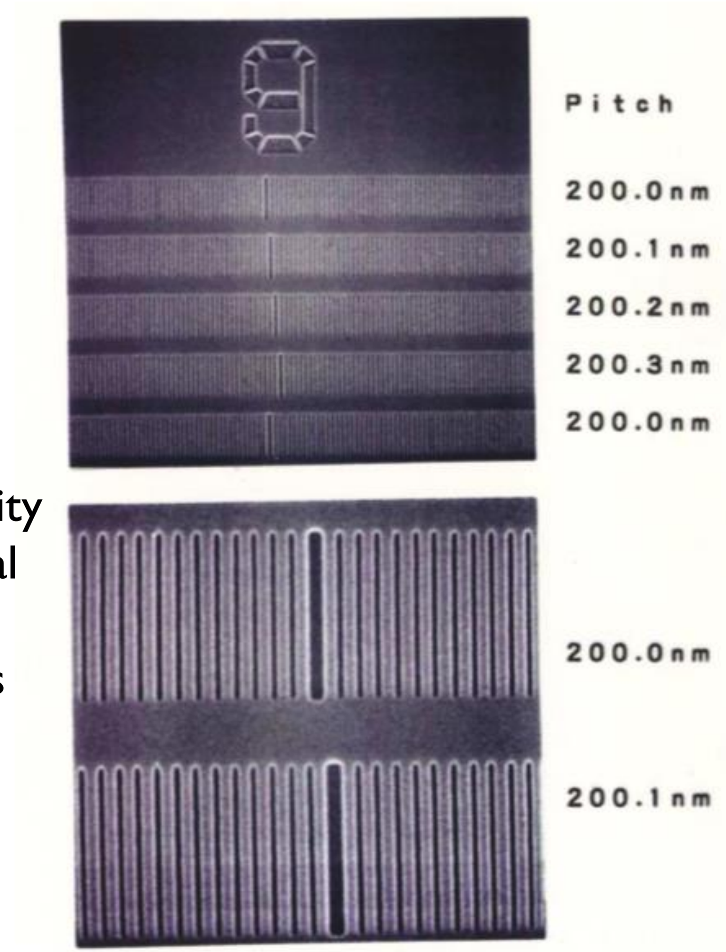
Acceleration Voltage:5.7 kV, Magnetic Field:0.56 T, Resist: ZEP520 (t 60 nm), Dose:30.0 uC/cm^2

New developments 3

In optical devices such as DFB laser, pitch grating uniformity and pitch control along the device are critical for optical output and single frequency operation.

Pitch control is controlled since several years using the field size modulation (FSM) function

The grating pitch can be controlled by changing the deflection amplifier gain through the 2nd DA converter. Positioning accuracy is 0.01 nm.



Nowadays, the challenging reside in grating uniformity in 1.2 mm cavity lenght DFB lasers, to ensure optical output and single frequency operation, no stitching errors are needed, so the use of 1.2 mm field size is compulsory. Stig&distortion and focus should be corrected.

High resolution an accuracy writing for field size wider than 1 mm is been developed for general purpose fabrication

Thank you for your attention¡¡¡