FIB Lithography and FIB Implantation

Scope

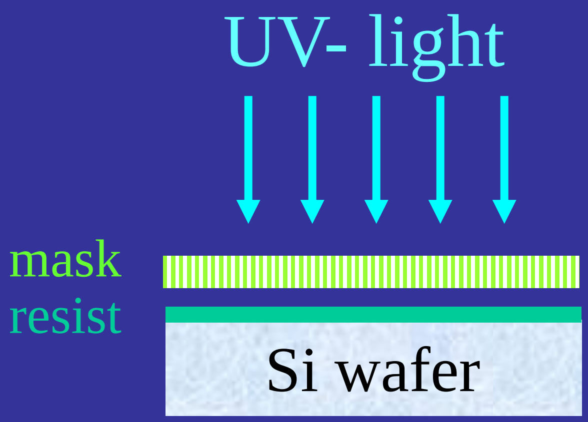
- Focused ion beam lithography (FIBL)
  - Resist sensitivity
  - Proximity effect
- Focused ion beam implantation (FIBI)
  - Implanted profiles
  - Lateral spread
- Application of FIBL and FIBI

We are here

FIB Application II

—— Principle of FIB lithography

lithography
- Optical lithography(OL)
- e-beam lithography(EBL)
- FIB lithography(FIBL)



optical lithography —— main technique

Advantage:

mask ⟶ large area (high throughput)

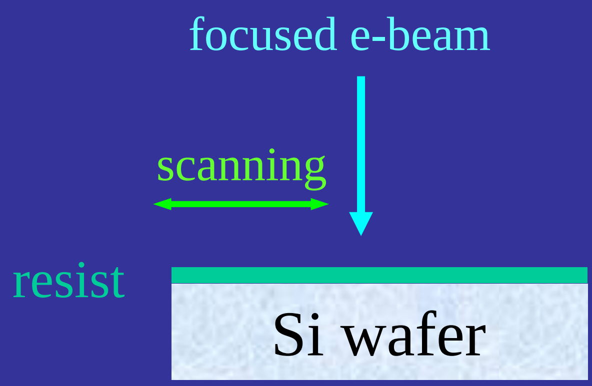
Drawback:

long wavelength ⟶ low resolution

e-beam lithography (EBL) —— **e-beam scanning and no mask need**

Advantage:

Short wavelength → high resolution



Drawback:

scanning → low throughput

Strong proximity effect

for e-beam , the proximity effect is due to backscattered electrons

EBL *usually be used to fabricate high resolution mask*

FIB lithography (FIBL)
—— FIB scanning and no mask need

Advantage (compare to e-beam)

high resist sensitivity

Many resist are found to be more sensitive to ions than electrons

short exposure time

high throughput

no proximity effect

higher resolution

Drawback issue: ion implantation caused index change of substrate material

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    We are here

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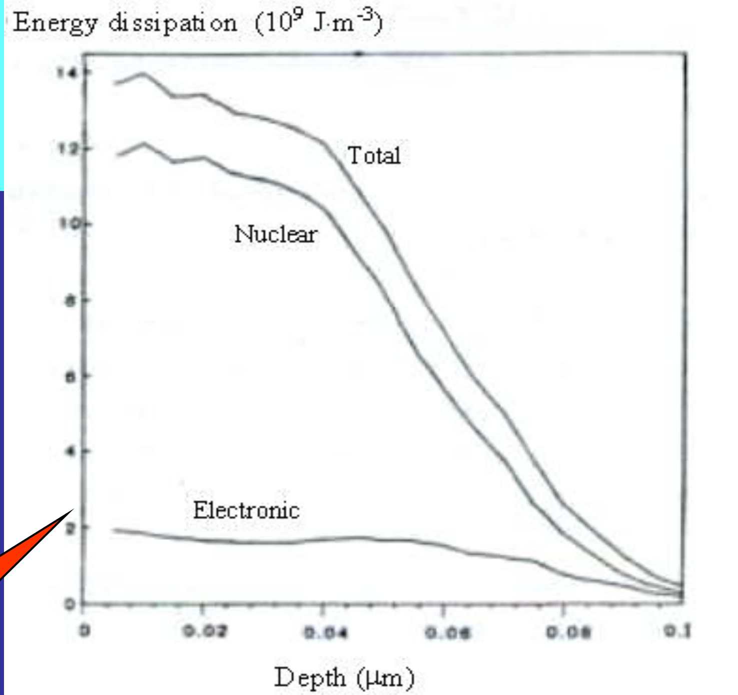
Resist Sensitivity

Energy dissipation of energetic ions in matter consist of two parts, *i.e.*, electronic stopping and nuclear stopping

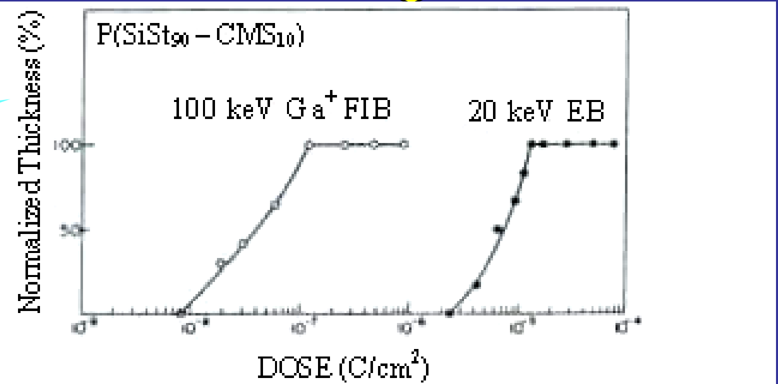
Nuclear stopping is much higher than electronic stopping



Energy transfer from gallium ions to PMMA (positive) resist by electronic and nuclear stopping (70keV Ga^+)

Sensitivity of FIB is ~100 times greater than EB

Example



Exposure sensitivities for heavy ion and electrons under typical FIBL and EBL conditions

Resist sensitivity comparison of several lithography

Lithography	N_m	S	D (cm^{-2})	R (Hz)
Optical projection	1300	0.33 mJ/cm^2	-	1.2×10^{14}-1.2×10^{17}
X ray(conventional)	24	23 mJ/cm^2	-	9.9×10^{8}
X ray (plasma)	24	15 mJ/cm^2	-	1.3×10^{9}-1.1×10^{12}
X ray (synchrotron)	24	15 mJ/cm^2	-	2.6×10^{12}
Scanning e-beam	**900**	**4 C/cm^2**	**2.5×10^{13}**	**2.0×10^{7}**
Scanning ion beam	**29**	**0.18 C/cm^2**	**1.1×10^{12}**	**2.3×10^{7}**
Masked ion beam	29	0.18 C/cm^2	1.1×10^{12}	2.1×10^{11}

Minimum number of particles per pixel N_m, minimum dose (S,D) and corresponding pixel transfer rate for different lithography techniques

R is pixel transfer rate corresponding to the throughput

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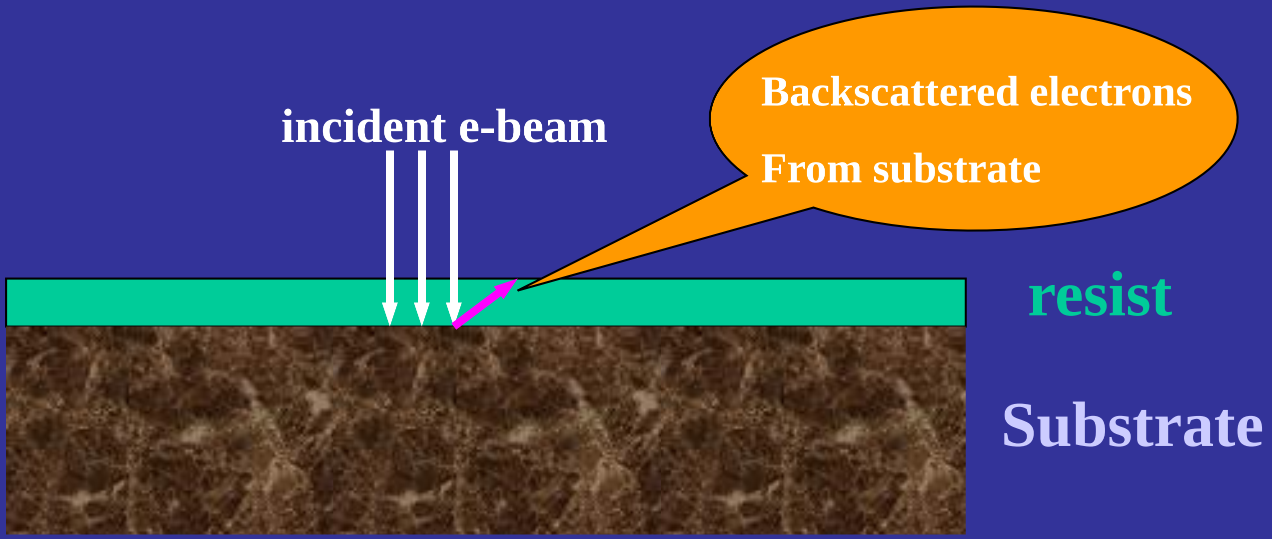
Proximity Effect

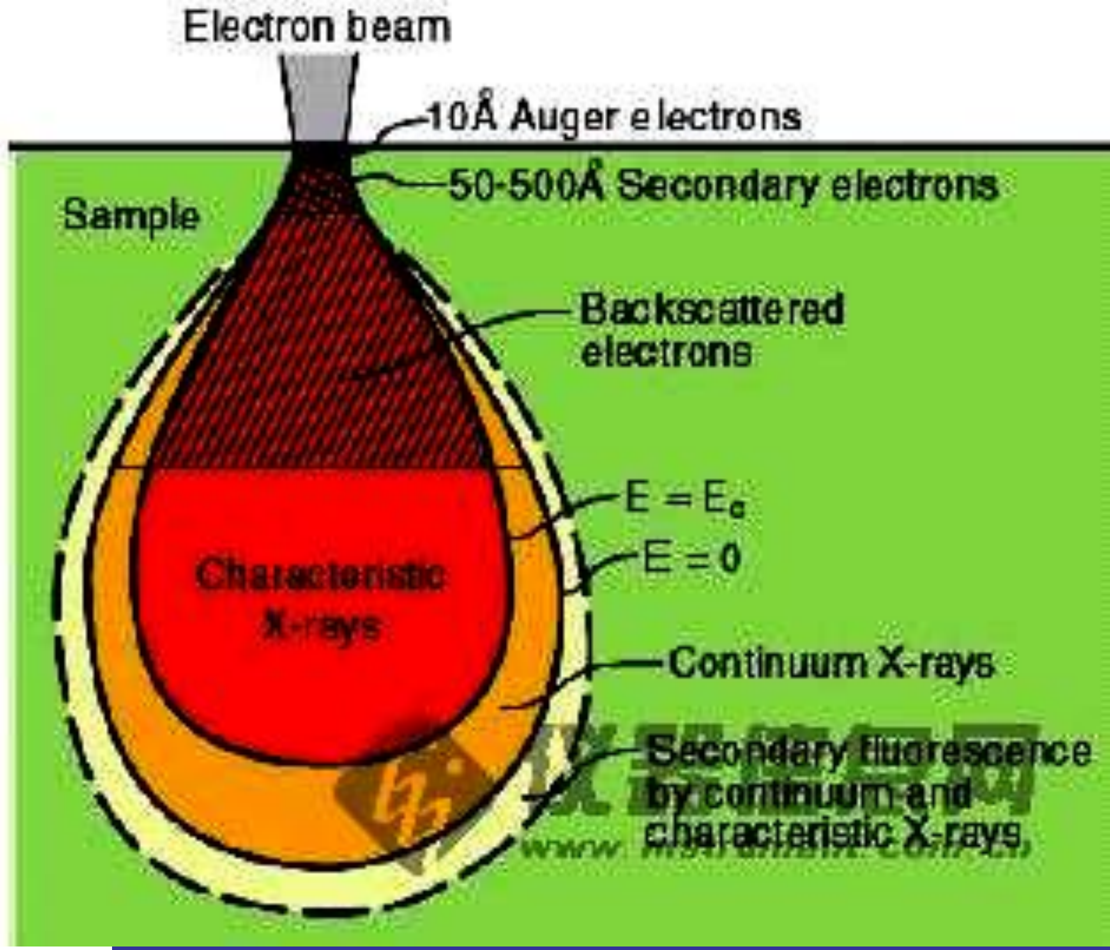
Proximity effect of EBL

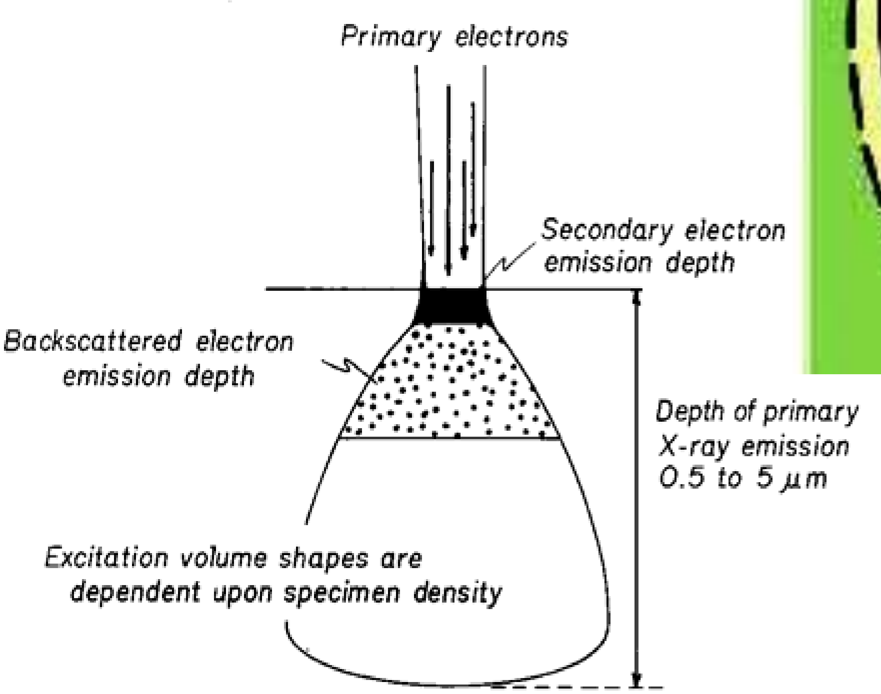
The proximity effect is a major barrier to further progress in reduction sizes in VLSI microcircuits patterned by EBL.

The proximity effect in EBL is *caused by backscattered electrons* from the substrate, which give rise to a resist exposure profile wider at the substrate/resist interface that at the surface of the resist layer

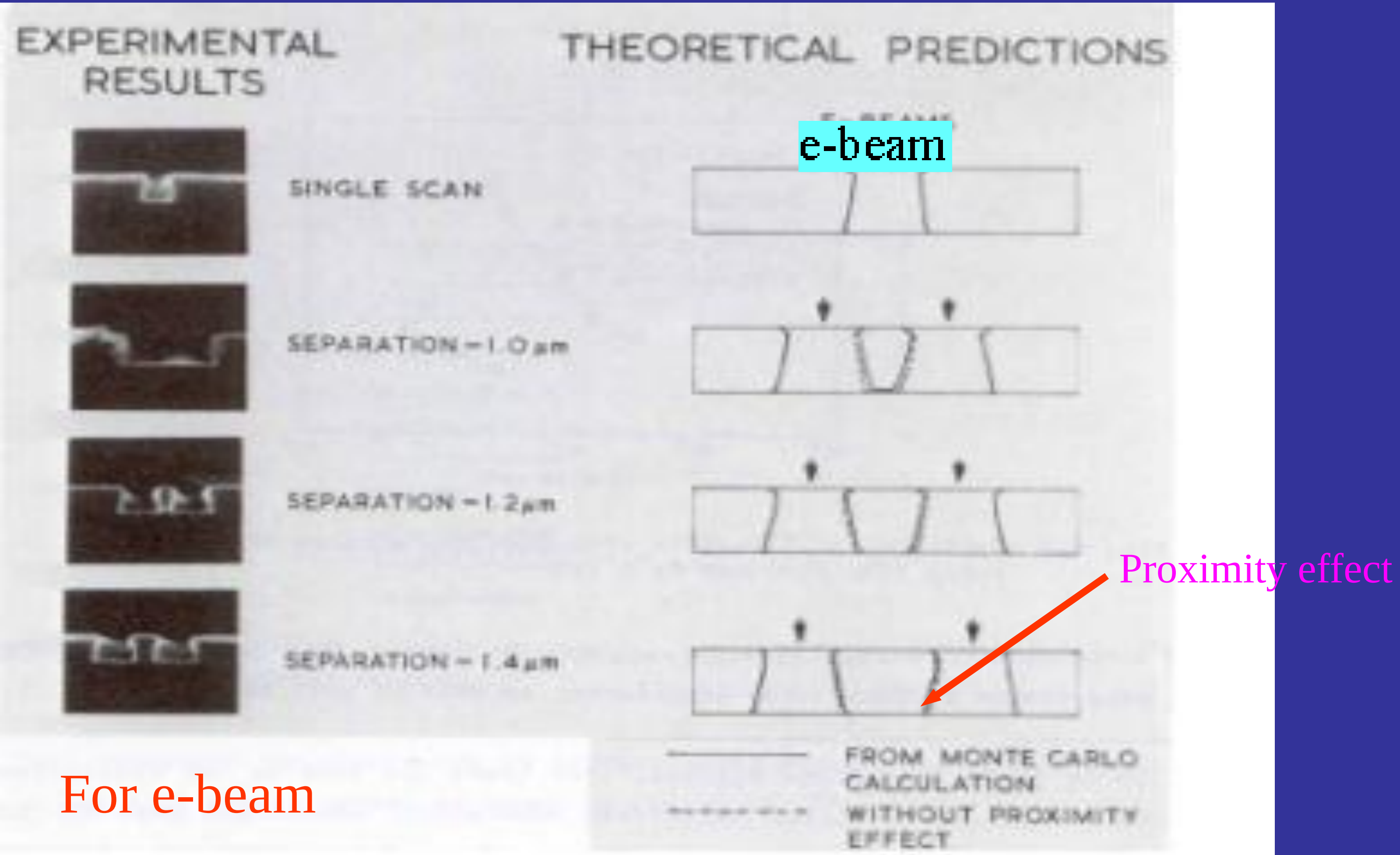


Backscattered electrons





Example of EBL proximity effect

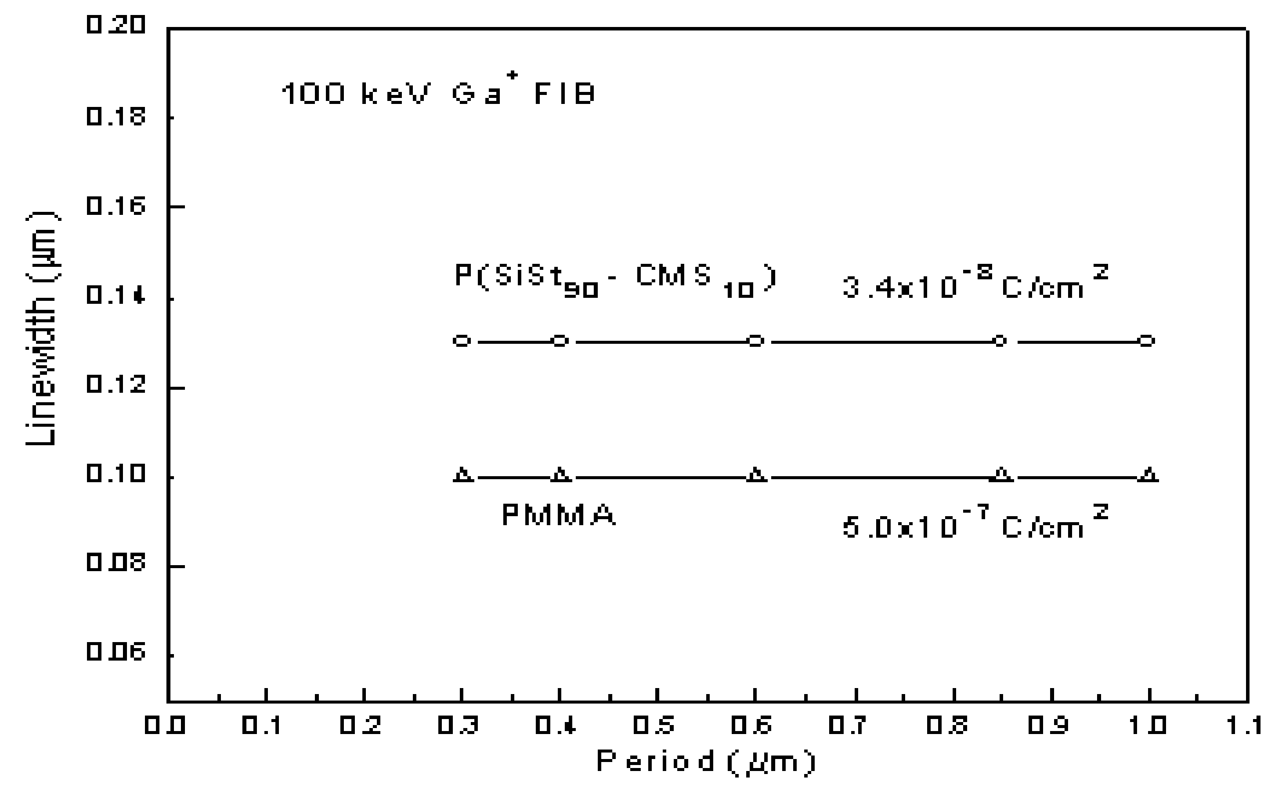


Theoretical predictions and experimental results showing proximity effects in PMMA for 1 µm lithography (20 keV, 0.5 µm electron beam ; 0.7µ PMMA on Si; D=2×10^{11}/cm^2)

Proximity effect of FIBL

Monte Carlo Simulation → 100keV Ga^+ to Si backscattering yield <1/3000

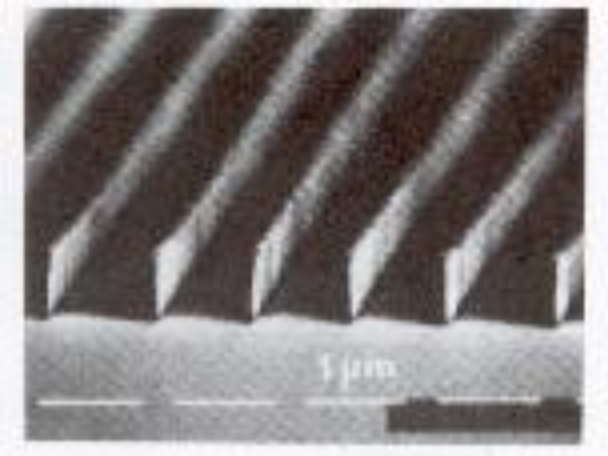
100keV p to Si backscattering yield <1/2300



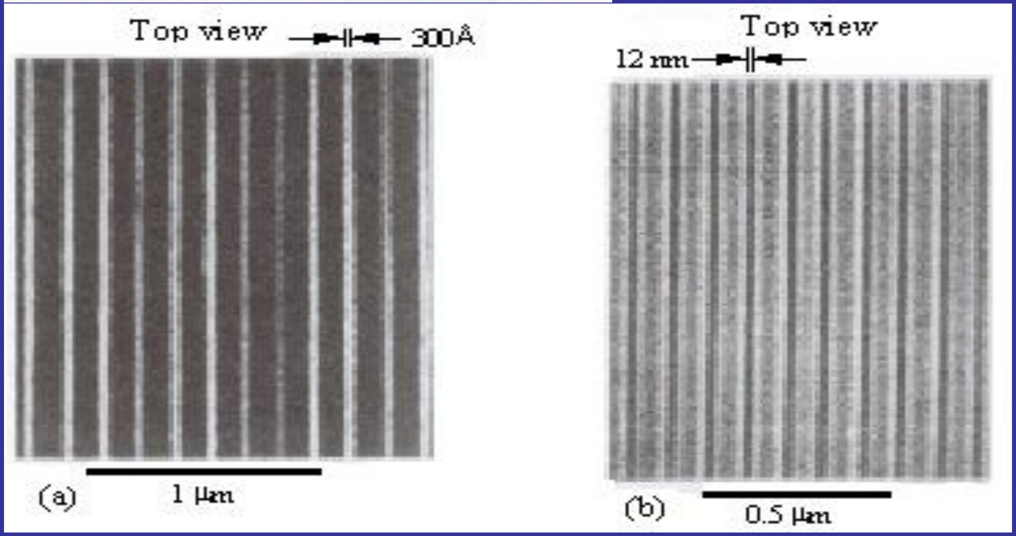
Variation of line width with separation, demonstrating absence of proximity effect using FIBL

Proximity effect can be ignored in FIBL.

Applications of FIBL



SEM photographs of high aspect ration 0.1 μm features in AZ1450J resist, produced using bilevel resist strategy with O_2 plasma pattern transfer. Feature height 0.75 μm. (100KeV Ga^+).

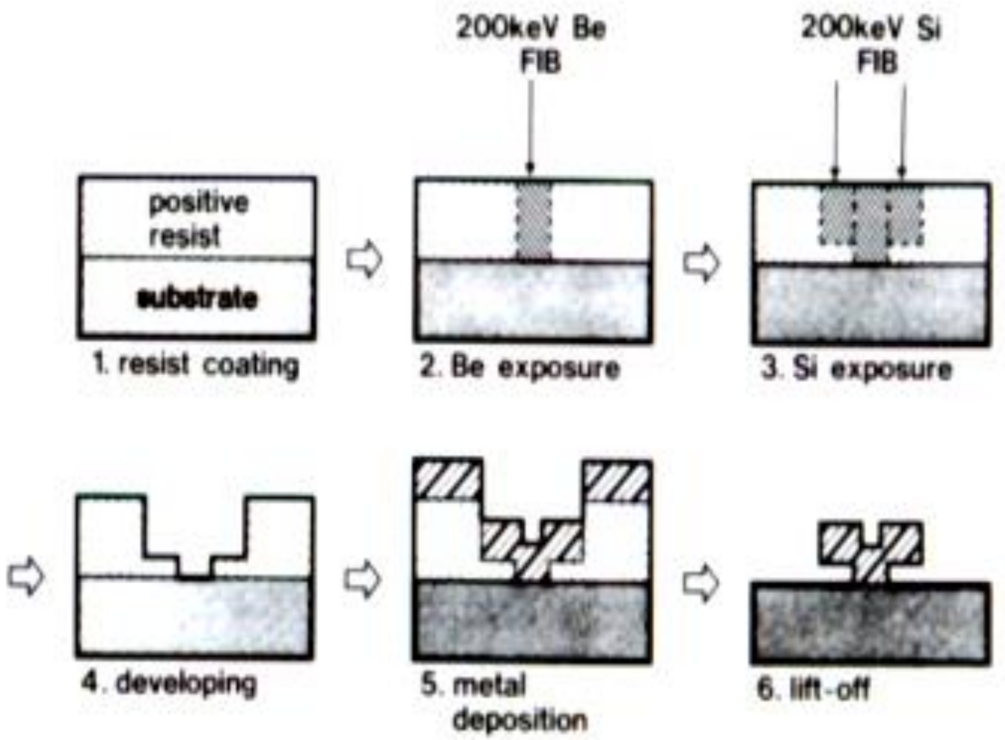


SEM photographs of ultra fine lines in resist, produced by FIBL (50KeV Ga^+)

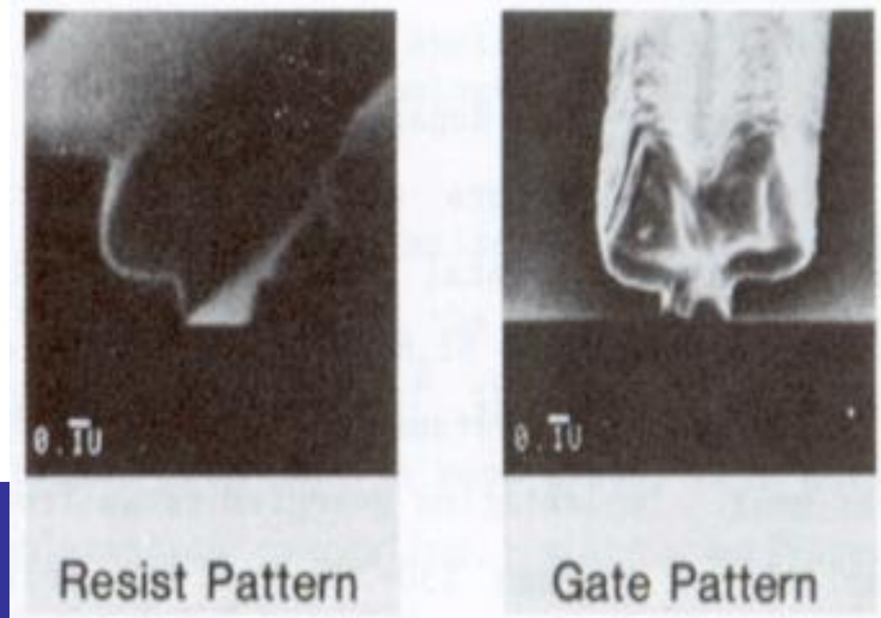
(a) 30 nm lines, negative acting bilevel resist

(b) 12 nm exposed spaces in PMMA positive resist

Applications of FIBL



Process steps for mushroom gate fabrication by FIBL



Resist and metallized gate profiles for mushroom gate short channel FET in GaAs

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Ion Beam implantation

Semiconductor Doping —— three methods

Thermal diffusion

Ion exchange

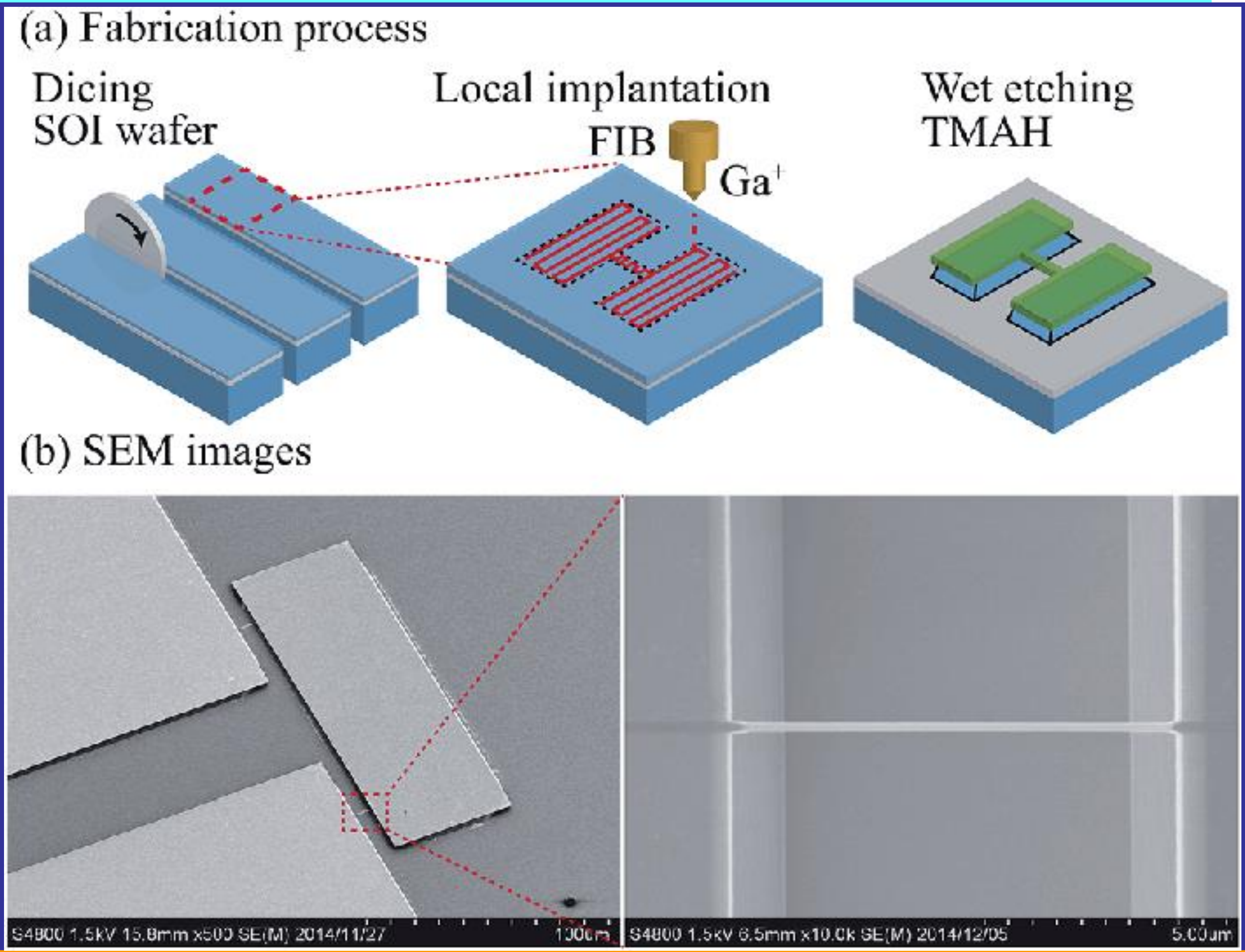
Ion implantation
- **Precise dose control**
- **high purity of dopant (mass filter)**
- **uniform**
- **abrupt profile**

Ion implantation

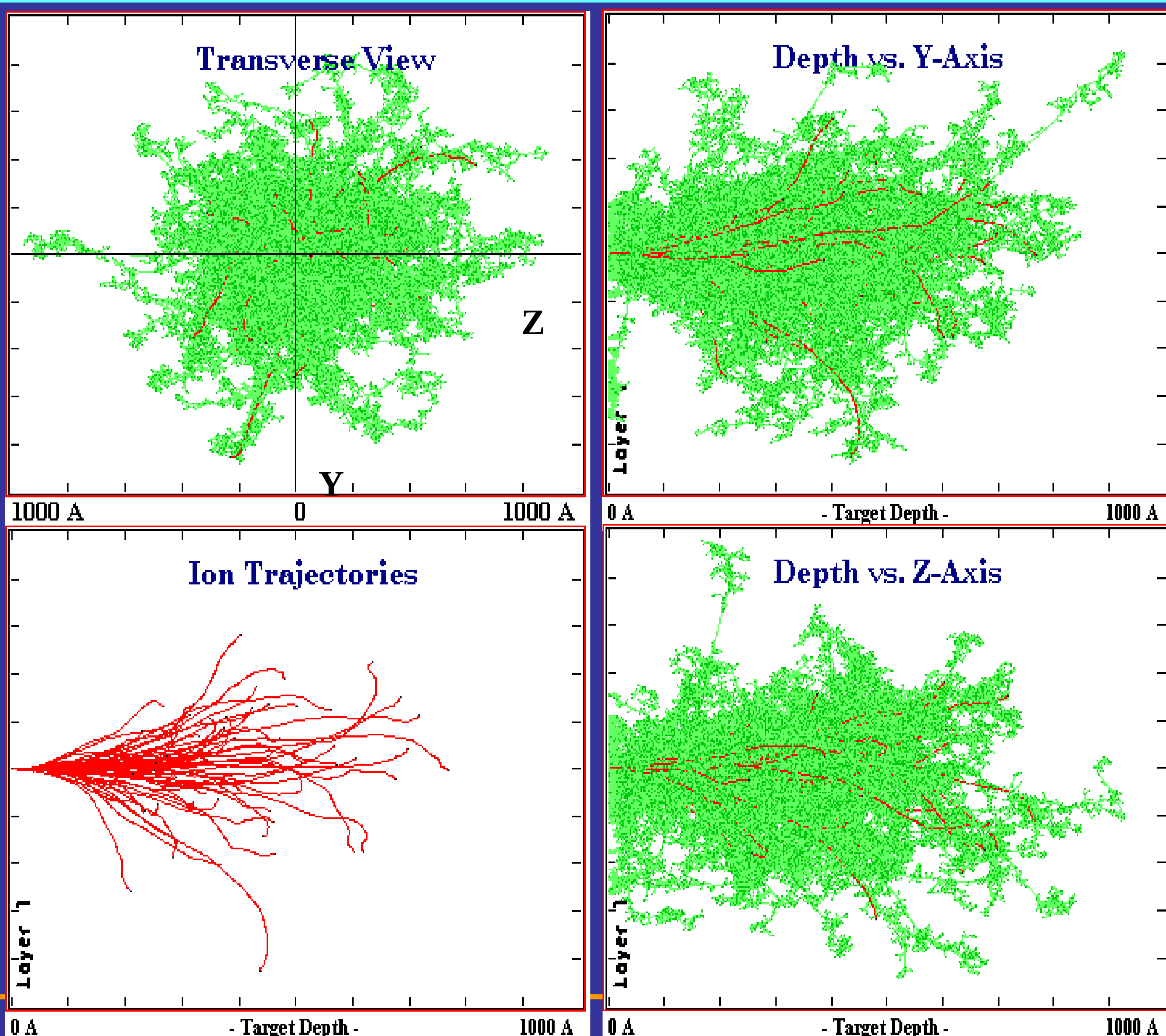
- **Broad area implantation (flood ion)**
- **FIB implantation (maskless)**

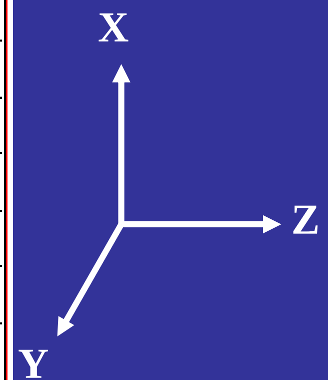
- ***Flood implantation is main technique for wafer production***
- ***FIB implantation is a complementary technique in VLSI***

FIB implantation (FIBI)



Ga^+ diffusion in Si in lateral and vertical directions under energy of 50 keV, incident angle of 0° .





SRIM

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Implanted profile

$$n(x) = n_0 \exp\{\frac{-(x-R_P)^2}{2\Delta R_P^2}\}$$

Broad area flood
Ion implantation

damage

Thermal Annealing

Dopant diffusion

$$\Delta R_P \cong \frac{2R_P}{3}\frac{\sqrt{M_1 M_2}}{M_1+M_2}$$

n(x) is density
R_P is average project range
ΔR_p is standard deviation
***M_1* is FIB ion mass**
***M_2* is substrate atom mass**

damage restore

Shorten annealing time

Rapid Annealing
to reduce diffusion

$$n(x,r,t) = R_0' \exp\{-(x-R_p)^2/(2DR_p'^2)\cdot \exp\{-r^2/(2\Delta R_t'^2)\}$$

$$\Delta R_P = (\Delta R_P^2 + 2Dt)^{\frac{1}{2}}$$

D is diffusion coefficient, and ***t*** the annealing time

FIB implantation difference

for FIBI I ~ A/cm^2, 10^6 times of flood implantation

negative effects

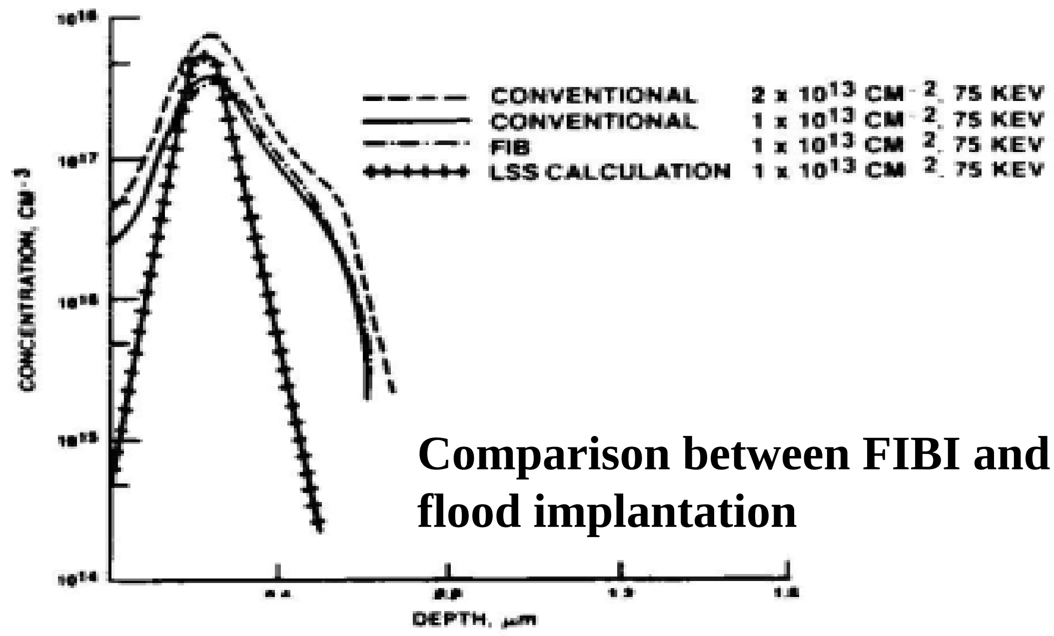
Related effects:

(a) enhanced damage

(b) greater radiation enhanced diffusion

(c) self annealing (positive effect)

It has been demonstrated that FIBI can be used to replace conventional implantation and has identical electrical characteristics for some ions implantation.



Comparison between FIBI and flood implantation

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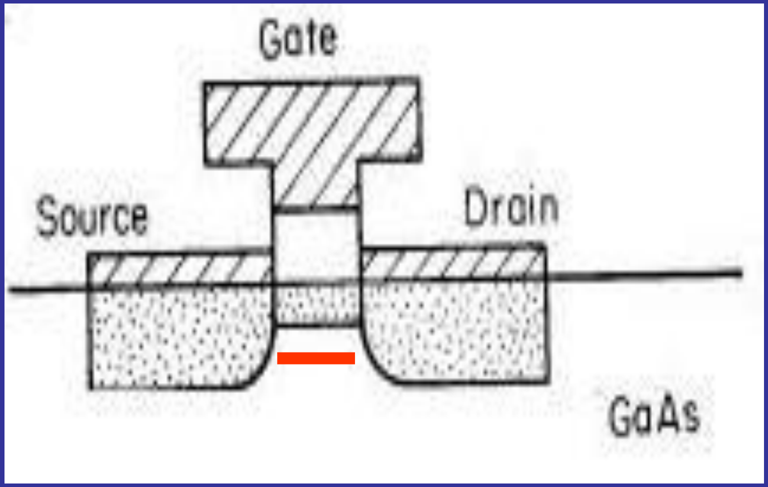
Applications of FIBI

♥ **Application in Microelectronics**

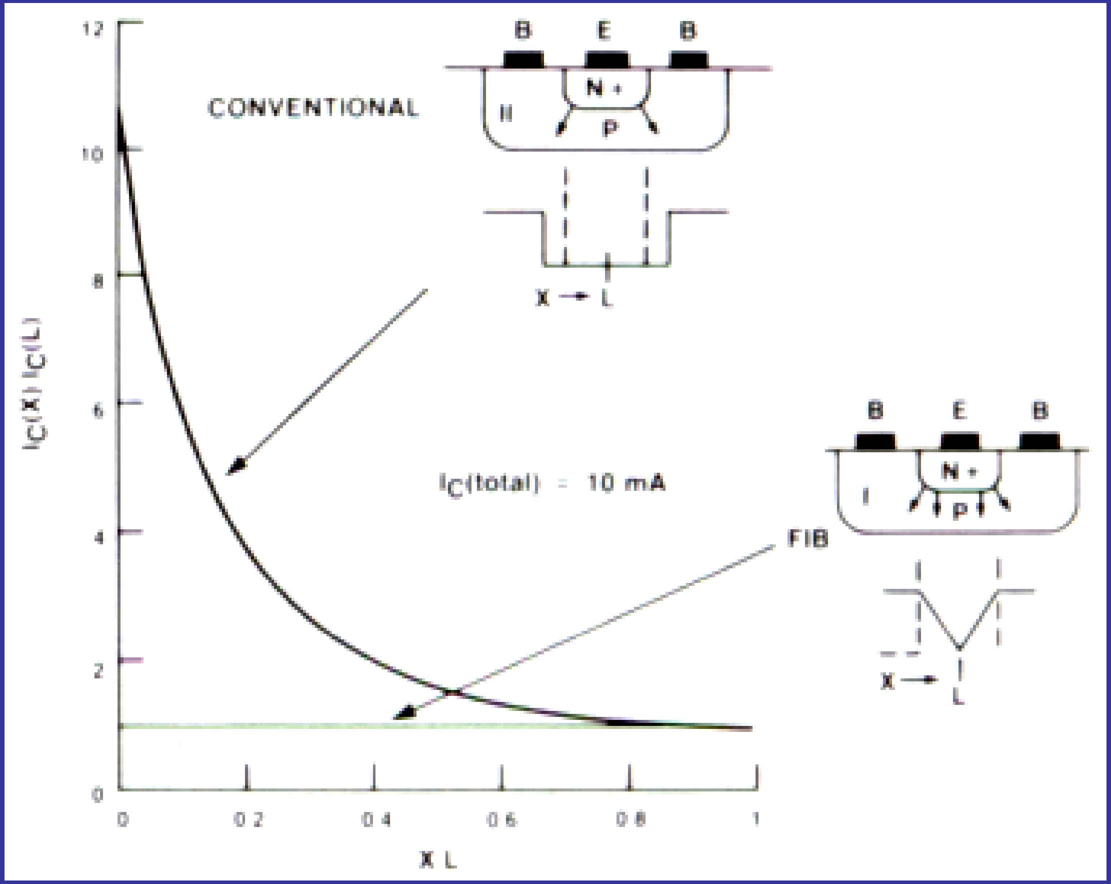
♦ **Novel structure fabrication —— mushroom gate fast FET**



Schematic showing **short channel** FET with mushroom gate for low resistance

♦ FIBI lateral grading doping

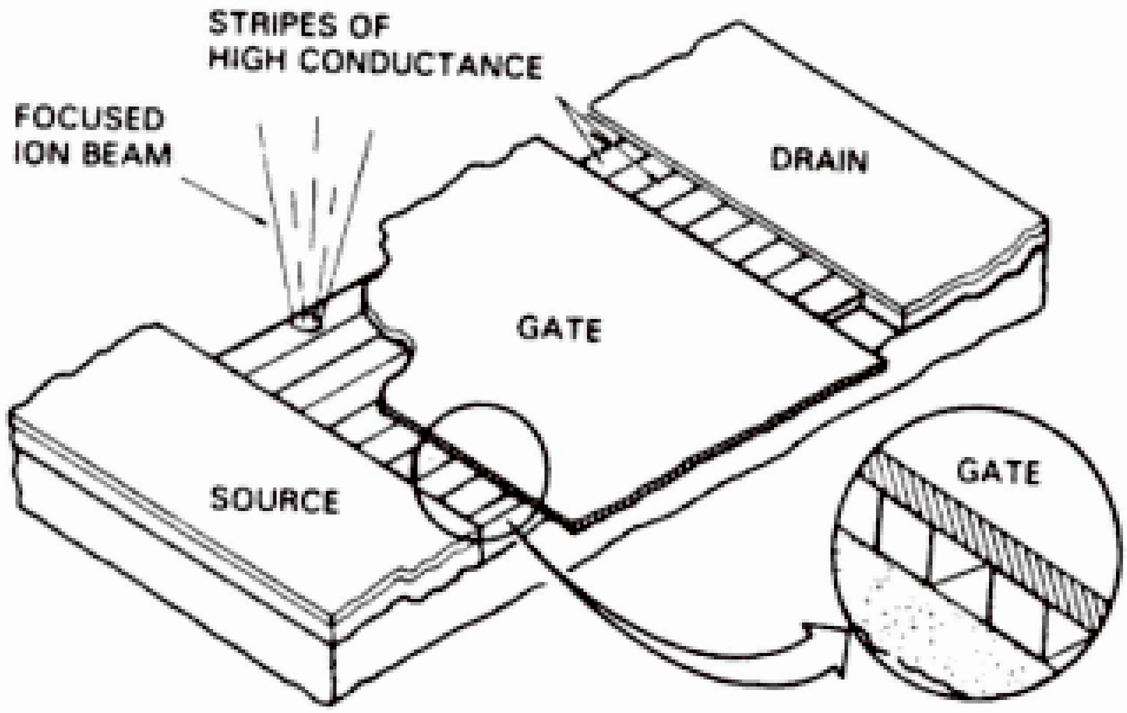
♣ Vertical npn structure fabrication



Schematic of vertical npn transistor with calculated distributions of injected current for conventional uniform and laterally graded FIB base implants.

♣ Lateral graded MESFETs (metal-semicon. FET)

♣ Focused Ion Striped Transistor (FIST)



Schematic of the FIST structure

the source to drain channel takes the form of a series of high conductance stripes instead of a uniformly implanted region

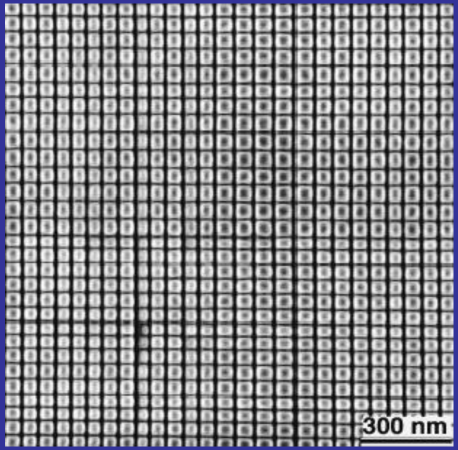
♦ **Device tailoring and prototyping**

FIBL Applications

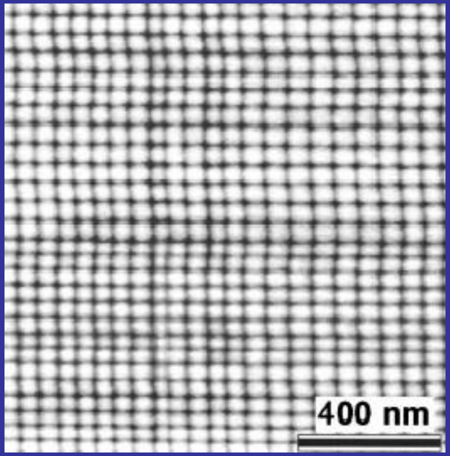
♥ prototyping of device

♣ High density magnetic storage prototyping by FIB

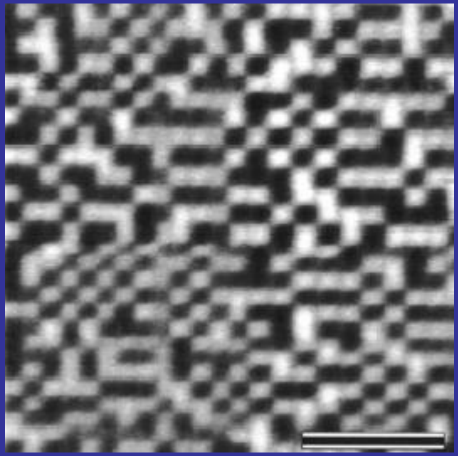
Density $\approx$ 150 $\mathrm{Gbit/in^2} \approx 23\mathrm{Gbit/cm^2} \approx 3\mathrm{Gbyte/cm^2}$



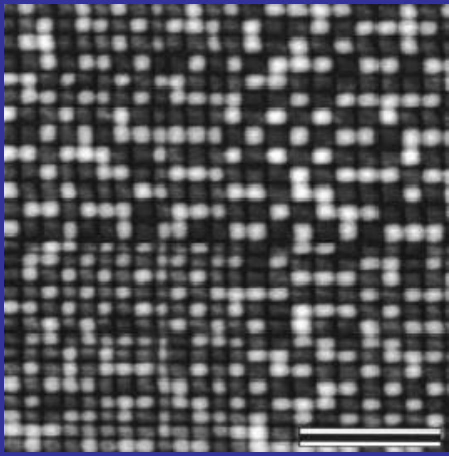
(a)



(b)



(c)



(d)

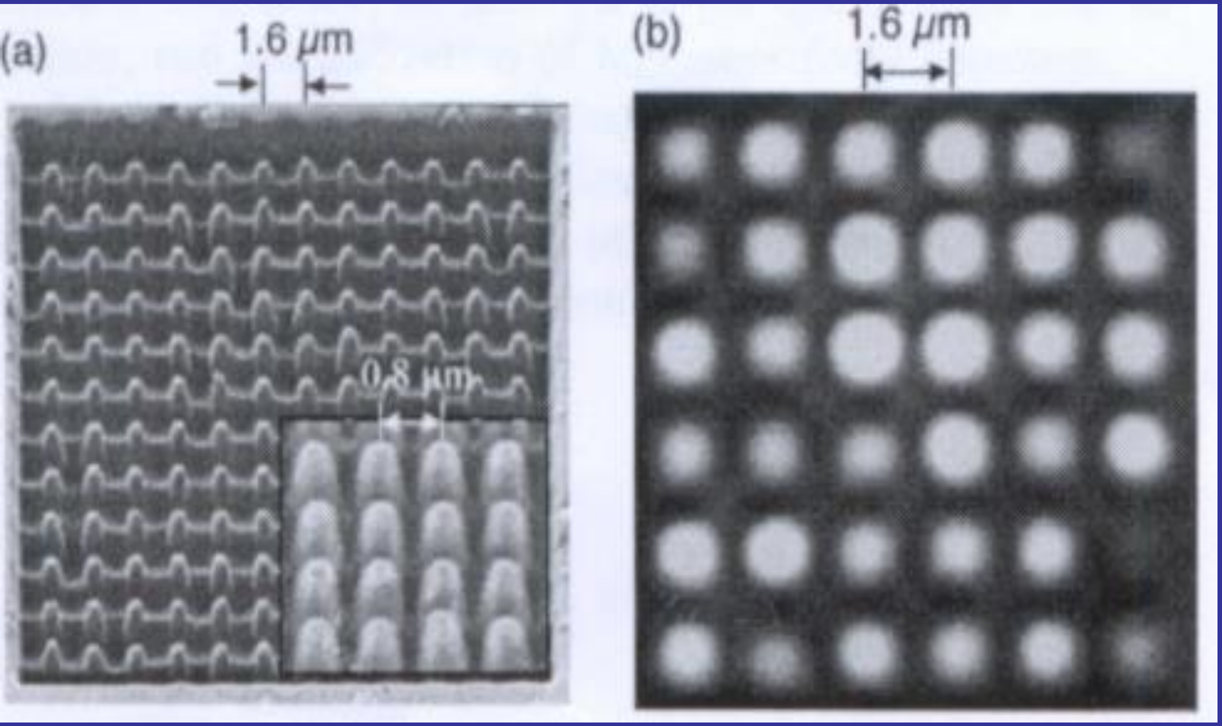
(a) SEM image of a magnetic block array

(b) AFM image of the array in Fig.(a)

(c) MFM image of the area in Fig.(b)

(d) superposition of the grooves seen in (b) and (c)

♣ High density optical storage prototyping by FIB



Density > 20 Mbyte/cm^2

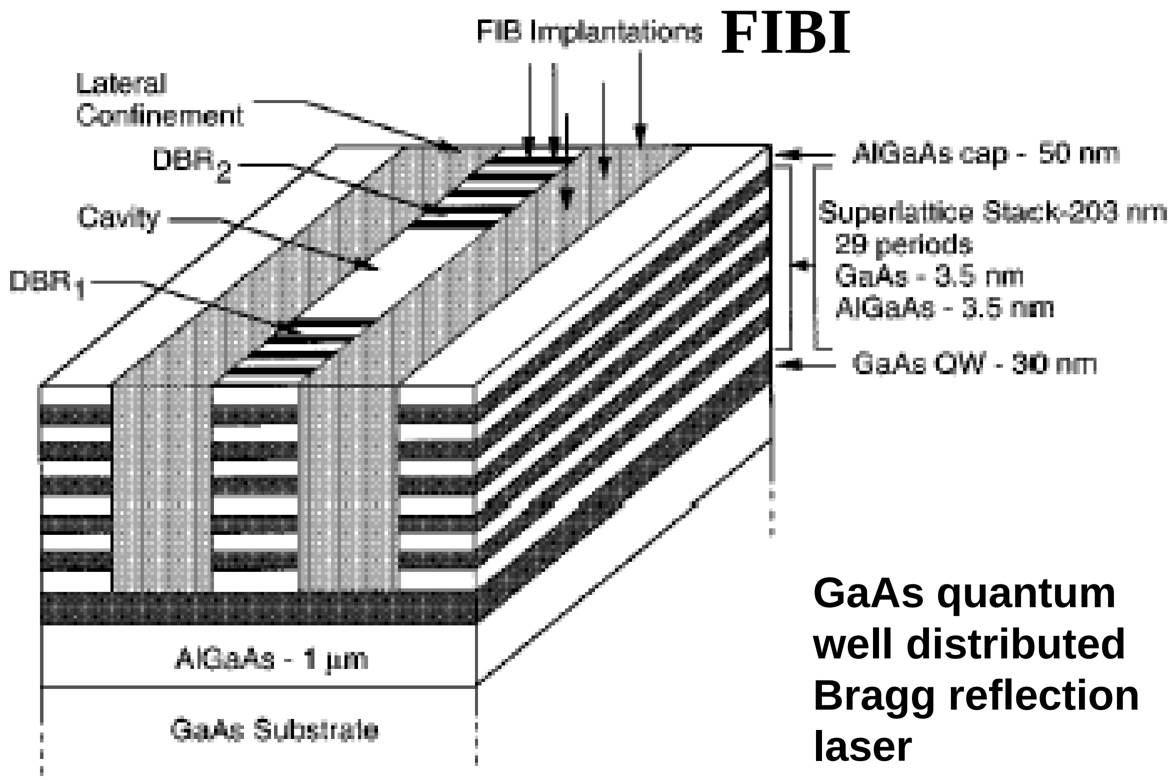
Current CDROM density < 15 Mbyte/cm^2

Data written by FIB has a theoretical storage capacity approaching

1000 Mbyte/cm^2

(a) Microphotographs of 1.6-μm-pitch and 0.8-μm-pitch bit patterns
(b) CCD optical image of upconversion emission from 1.6-μm-pitch bit pattern.

♥ application in opto-electronics

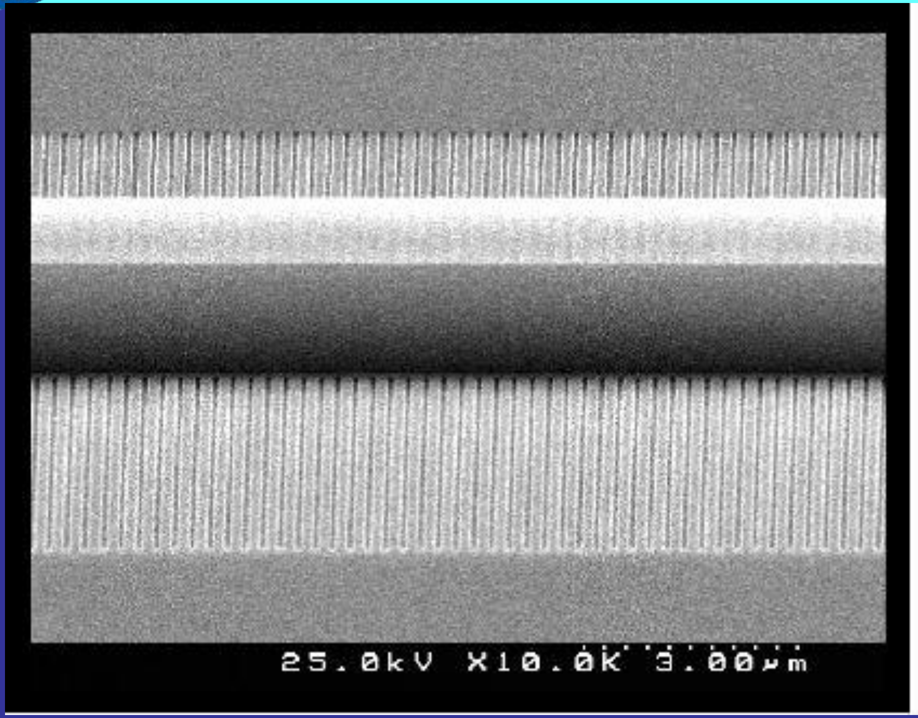


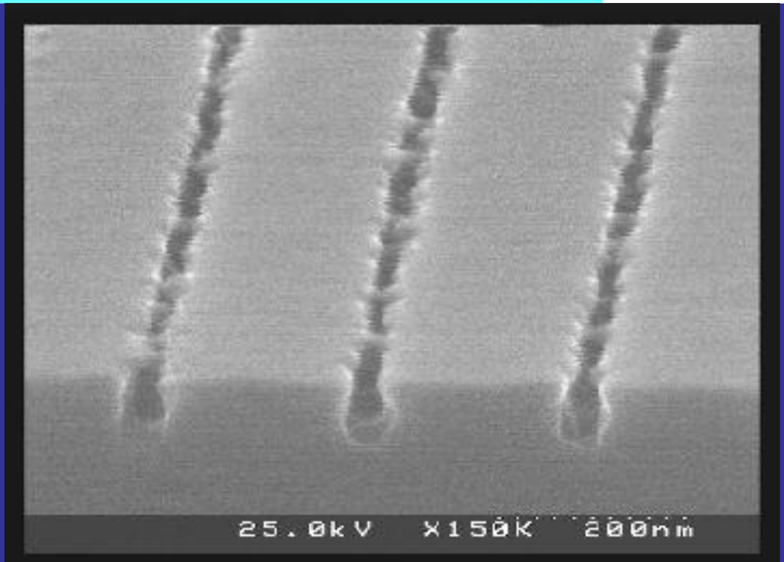
GaAs quantum well distributed Bragg reflection laser

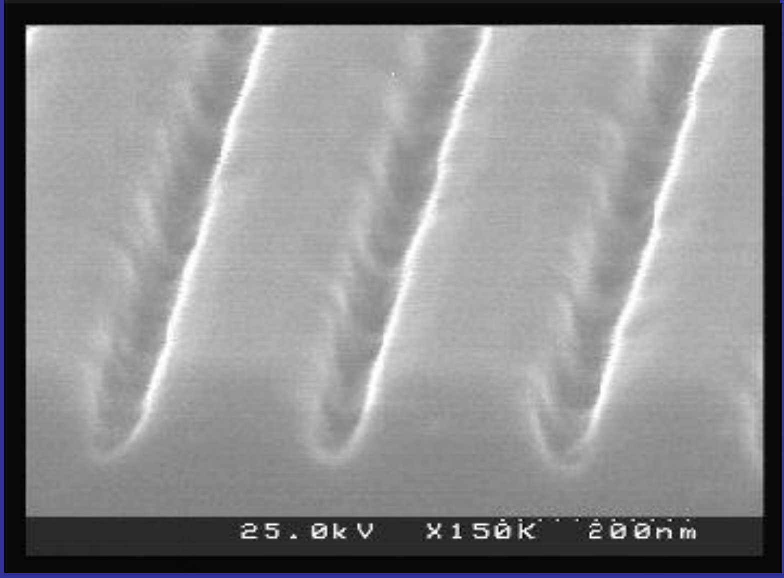
Distributed Bragg reflection (DBR) lasers are attractive candidates for light sources in *monolithic photonic* and *optoelectronic integrated circuits* (PICs and OEICs).

DBR laser structure cross section, indicating the FIB implanted region which provides both the gratings and the waveguide.

♥ application in opto-electronics







✓FIB defined DFB grating etched by HF lateral to a ridge waveguide after implantation into the InP cladding layer of laser.

✓Well defined etch depths due to high sensitivity contrast between quaternary etch stop layers and InP.

THE END