E-Beam Lithography

Ivor Brodie and Julius Muray
"The Physics of Micro/Nano-Fabrication"

E-Beam Lithography: Some Pros and Cons

• Spot size <100 Å as compared to photolithography (5000 Å).
• High speed and precision of e-beam deflection and modulation.
• Good control over the energy and dose delivered to resist.

• Either scanning the beam by controlling its deflection from a computer (sequential exposure) or electron imaging through a special mask (parallel exposure).
• Exposure in the spot takes ~10^{-7} s, but there are ~10^{10} spots that are typically required → high speed is important.
• 10^{10} spots requires also a precision of ~1ppm along each of the axis → strict demands on DA converters, max areas of up to 1 mm^2 can be exposed by direct beam deflection.
• Also, a mechanical table is used to move the beam along larger distances.

(Then, alignment is made for each table position, either by checking for registration marks, or use laser interferometers to precisely measure the table movement.)

Types of E-Beam Machines

- Scanning systems
  - Single beam system
    - Vector
    - Raster
  - Multiple beam system
    - Vector
    - Raster

• pattern information in computer's memory
• distortion-, and proximity corrections are needed
• expensive but flexible

- Hybrid systems
  - Shaped beam
  - Character projection

- Parallel exposure systems
  - Photocathode projection
  - e-Image projection
  - Fly's eye lens projection

• pattern information is stored in masks
• high throughput
• less expensive

Two distinct uses of e-beam lithography:

1. direct exposure of resist for device fabrication
2. mask fabrication for subsequent optical lithography

Raster- vs Vector Control

• The raster-scan systems meticulously cover the area of pattern, *switching the e-beam on and off as required* by the patterns shape

• The vector-control systems deflect the beam to follow paths dictated by the pattern. "Go to that address and do exposure there".

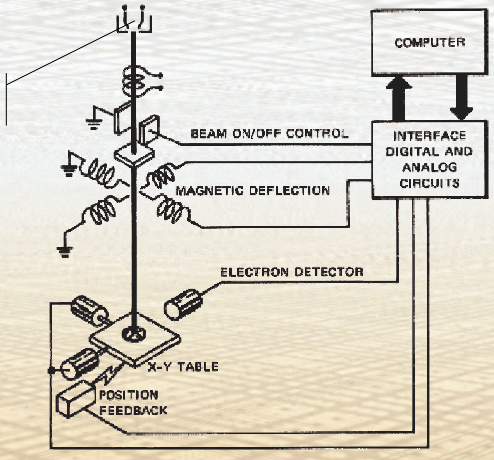
Analogy:

Compare the bitmap- and vector formats for digital-image files (i.e. "*.bmp" vs "*.eps")

Typical Schematics

is similar to electron microscopy

A heated source giving rise to thermionic emission of electrons



Schematic illustration of an electron-beam lithography system.

5

Electron Beam

- In general, our ability to view or fabricate small objects depends on availability of strongly focused particle beams.
- Diffraction limits the spot size. The smaller the wavelength, the smaller the spot.

Particle wavelength (Å) at various energies

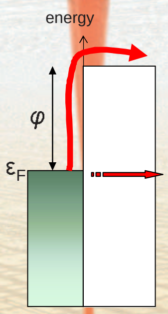
Particle:	Particle energy E_0 (eV)						
	1	10	10^2	10^3	10^4	10^5	10^6
photons	12400	1240	124	12.4	1.24	0.124	0.012
electrons	**12.3**	**3.89**	**1.23**	**0.39**	**0.12**	**0.037**	**8.7e-3**
protons	0.29	0.091	2.9e-2	9.1e-3	2.9e-3	9.1e-4	2.8e-4

$\lambda=1240/E_0$ (photons);
$\lambda=12.3/(E_0+1e\text{-}6E_0^2)^{0.5}$ (electrons);
$\lambda=0.28/E_0^{0.5}$ (protons).

6

Electron Emission

- Fermi-Dirac energy distribution of conduction electrons in metals.
- The energy required to remove an electron from metal into free space is called the *work function*, φ (1.5−6 eV).
- The electric field E and temperature T can lower φ.



$$\varphi = \varphi_0 - \alpha T - \sqrt{\frac{eE}{4\pi\varepsilon_0}}$$

$$\Delta\varphi_{[\mathrm{eV}]} \sim 3.8\times10^{-5}\sqrt{E_{[\mathrm{V/m}]}}$$

$$j = e\int_{-\infty}^{\infty} N(T,\varepsilon)D(E,\varepsilon,\varphi)d\varepsilon$$

$$N(T,\varepsilon) = \frac{4\pi m k_B T}{h^3}\ln\left[1+\exp\left(-\frac{\varepsilon}{k_B T}\right)\right]$$

Supply function N: $N(\varepsilon)d\varepsilon$ is the No. of e incident upon the surface per unit area per second with velocity component ⊥ to the surface in the energy range from ε to $\varepsilon+d\varepsilon$

$$D = \begin{cases} 0, & \text{for } \varepsilon \le \varphi - \sqrt{\dfrac{eE}{4\pi\varepsilon_0}} \\ 1-r(\varepsilon), & \text{for } \varepsilon > \varphi - \sqrt{\dfrac{eE}{4\pi\varepsilon_0}} \end{cases}$$

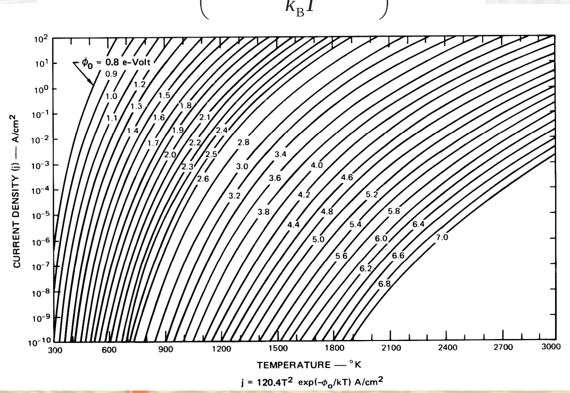
D is the probability of an electron with energy to penetrate the barrier when an electric field E is applied

- φ can be substantially modified by foreign atoms adsorbed at the metal surface (electropositive Ba & Th decrease-, while electronegative O or F increase φ).

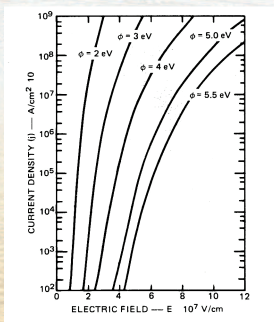
7

Thermionic and Field Emission

$$j = 120.4\cdot T^2\cdot\exp\left(-\frac{\varphi_0 - 3.8\cdot10^{-5}\sqrt{E}}{k_B T}\right)\quad [\mathrm{A/cm^2}]$$



$$j = 1.5\cdot10^{-6}\frac{E^2}{\varphi}\exp\left(\frac{10.4}{\sqrt{\varphi}} - \frac{6.44\cdot10^7}{E}\varphi^{3/2}\right)$$



8

Cathodes

Cathode Requirements

- The uniformity of emission over the cathode surface
- The current density required from the cathode
- The energy distribution of the emitted electrons
- The current fluctuations as a function of time
- The evaporation of material from the cathode surface
- The ability of the cathode to operate in a given environment
- The lifetime of the cathode under given operating conditions

9

Practical Cathodes

- Thermionic cathodes:

thoriated tungsten (1700°C & 3 A/cm^2); $WC + ThO_2 \rightarrow W + Th + CO_2$ (→bad vacuum)
lanthanum hexaborid;
oxide coated (750 C & 0.5 A/cm^2); Ni coated by Sr-O, Ba-O, Ca-O; can be poisoned
tungsten sponge filled with Ba/Ca aluminate (1100 C & 5 A/cm^2)

- Field-Emission cathodes (best but most expensive):

- emission occurs in ”lobes” because of crystal facets present at the surface
- emission can be unstable.

Type of emission	Type of cathode	Emission (A/cm^2)	Operating temperature (T_c) (K)	Upper pressure limit (Torr)	Brightness (β) ($A/cm^2 \cdot sr$ at 20 kV)
Thermionic	Tungsten	0.6	2470	10^{-4}	1.8×10^4
		7.3	2700		1.9×10^5
Thermionic	Tantalum	0.5	2300	10^{-5}	1.6×10^4
Thermionic	Thoriated tungsten	1–3	2000	5×10^{-6}	$3.75 \times 10^4 \rightarrow 1.1 \times 10^5$
Thermionic	Oxide coated	0.5	1050	10^{-6}	3.4×10^4
Thermionic	Barium dispenser	0.5–6	1150–1400	5×10^{-6}	$3.3 \times 10^4 \rightarrow 3.2 \times 10^5$
Thermionic	Lanthanum hexaboride	20.4	2100	10^{-6}	9.5×10^5
Field	Single-crystal tungsten	Up to 10^6	Room	10^{-10}	10^8
Temperature field	Zirconated tungsten		1400–1800 (1.5 eV)	10^{-9}	10^{10}
Photo	Pd	2×10^{-5}	Room (2 eV)	10^{-7}	2×10^{-1}
Photo	CsI	5×10^{-6}	Room (0.5 eV)	10^{-4}	2×10^{-1}

e-Beam Characteristics

Assumptions:
- e-beams are circular;
- emitted *e* have Maxwell velocity distribution, both axially and radially;
- object and image are related by the Helmholtz-Lagrange relation;
- space-charge forces are neglected.

The brightness is the *e*-current per unit solid angle

$$\beta_{max} = \frac{jeV}{\pi kT}$$

j is the current density at the cathode;
V is the acceleration energy;
T is the cathode temperature.

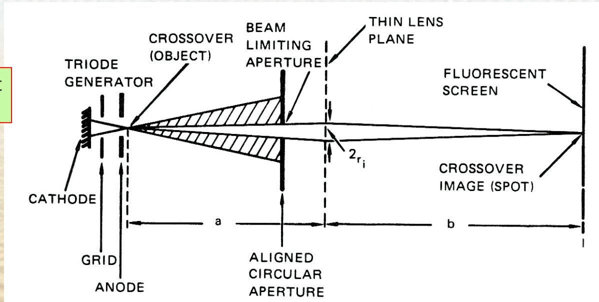
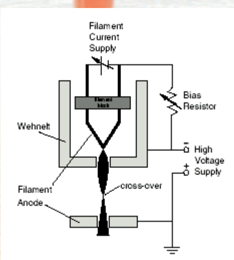
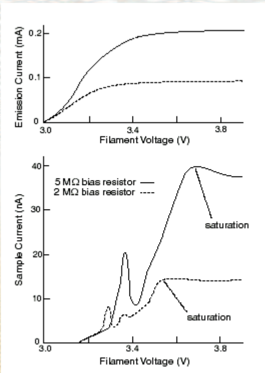
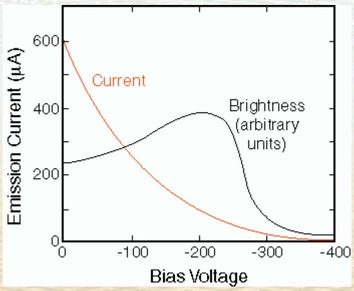


FIGURE 2.24. Gun configuration for beam fabrication.

E-Guns: Self-bias







A bias resistor allows the gun to be self-regulating. Any increase of the emission current causes a larger voltage drop across the bias resistor and a larger negative voltage is applied to the Wehnelt, reducing the current. As the emission increases, so does the voltage difference between Wehnelt and filament, causing the emission to saturate. Proper bias voltage also optimizes the electron beam brightness.

http://jan.ucc.nau.edu/~wittke/Microprobe/Column-ElectronGun.html

Crossover Spot Size Limits the Resolution

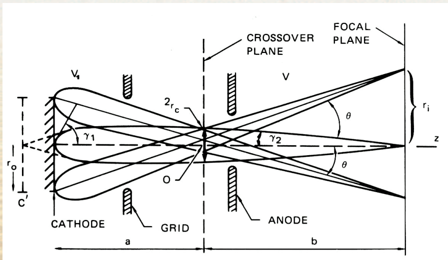
$$r_c^{max} = a\sqrt{\frac{V_0}{V}}$$

To a first approximation, the crossover radius does not depend on the area of the emissive surface and is only determined by the initial energy of the electrons relative to their energy in the crossover region.

The current density at the crossover center:

$$j_0 = j\left(\frac{eV}{kT}\right)\sin^2(\theta)$$

j is the cathode emission current



Electron trajectories in the near-cathode region.

Non-Idealities

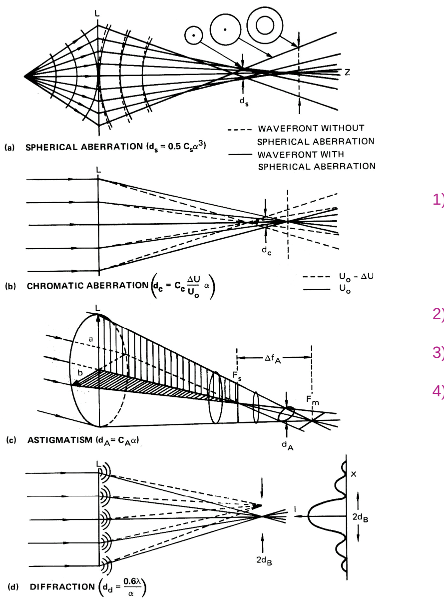
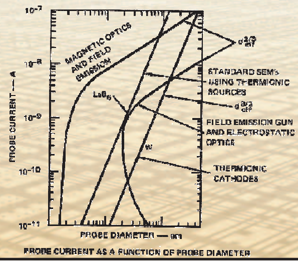


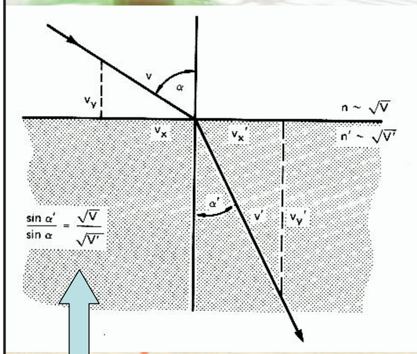
FIGURE 2.28. Aberrations and diffraction. (a) Spherical aberration ($d_s = 0.5\, C_s\alpha^3$) (– – –, wavefront without spherical aberration; ——, wavefront with spherical aberration); (b) chromatic aberration [$d_c = C_c(\Delta U/U_0)\alpha$] (– – –, $U_0 - \Delta U$; ——, U_0); (c) astigmatism ($d_A = C_A\alpha$); (d) diffraction ($d_d = 0.6\lambda/\alpha$).

- Space –charge effects are not very important in microlithography but can be essential in higher-current applications, like ion-implantation. (number of crossing paths Should be minimized)
- Aberrations and diffraction

1) Spherical aberration: the minimum diameter resulting from crossing of trajectories that do not come to a focus at the same axial position. It is impossible to compensate for this aberration later on using any subsequent electron optics. Trade-offs for thermionic sources.
2) Chromatic aberration, i.e. sensitivity of focus to the energy of the electrons (slow e is easier to focus)
3) Astigmatism or asymmetric focal spot (non-circular apertures, misalignment relative to the optical axis).
4) Diffraction



Electrostatic Optics



(geometrical optics)

Fermat's law :

$$\delta \int_A^B \frac{ds}{v} = \delta \int_A^B \frac{n}{c} ds = 0$$

A light ray will take that path that has the shortest transit time.

Corresponding principle governs the motion of particles in the conservative force fields (the principle of least action):

$$\delta \int_A^B mv\, ds = 0$$

$$\frac{mv^2}{2} = eV \quad \Rightarrow n = \sqrt{V}$$

Magnetic optics:

$$\mathbf{F}_m = \frac{e}{c}[\mathbf{v} \times \mathbf{B}]$$

Refraction index : $n_m = \frac{e}{m}(\mathbf{A} \cdot \mathbf{s})$

Unlike electrostatic case, the magnetic focusing depends on e/m ration of a particle; A: the vector potential, s trajectory

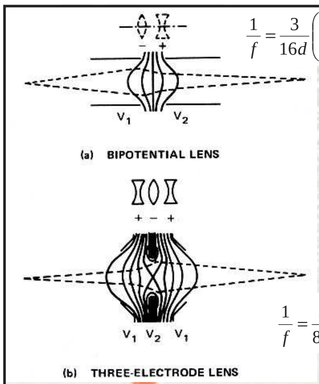
15

Light- vs. Electron Optics

- Unlike photons, the energy of electron may change
- In the electron optics, the refraction index changes continously
- The electron interact with each other
- Electron lenses are always converging
- Magnetic lenses twist the beam
- Electrostatic optics has larger aberrations than magnetic

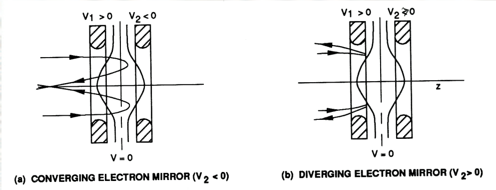
16

Electron Optics



$$\frac{1}{f} = \frac{3}{16d}\left(\frac{V_2 - V_1}{V_1}\right)^2$$

$$\frac{1}{f} = \frac{3}{8d}\left(\frac{V_2 - V_1}{V_1}\right)^2$$



1) Axially symmetric lenses where trajectories are || to field
Longitudinal systems : focusing by small perp. Component
2) Transverse systems (field perp. to the beam) more effective

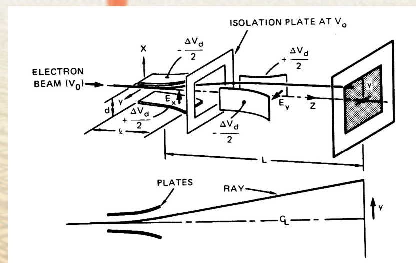
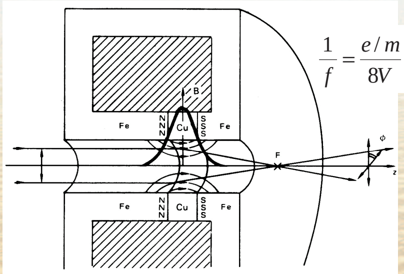


FIGURE 2.51. x, −y electrostatic deflection system. From Ref. 69.



$$\frac{1}{f} = \frac{e/m}{8V}\int_1^2 B_0^2 dz$$

FIGURE 2.41. Magnetic lens configuration.

17

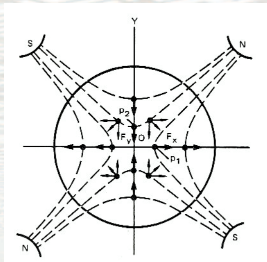
Quadrupole lenses

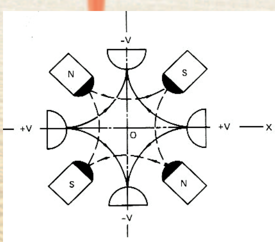
The quadrupole lens (stigmator) is used to compensate for astigmatism. Focuses in one direction and de-focuses in the perpendicular one.

Doublet – two quadrupole lenses: point image of a point object

Pros:
- Compensation for the spherical aberrations can be made;
- Achromatic combination of electrostatic and magnetic quadrupoles can be built.

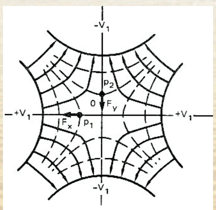
Magnetic quadrupole





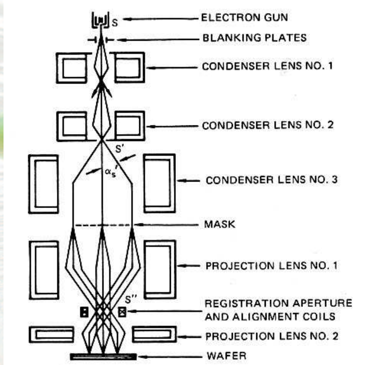
Combined electric and magnetic lens

Electrostatic quadrupole



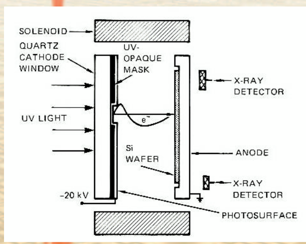
18

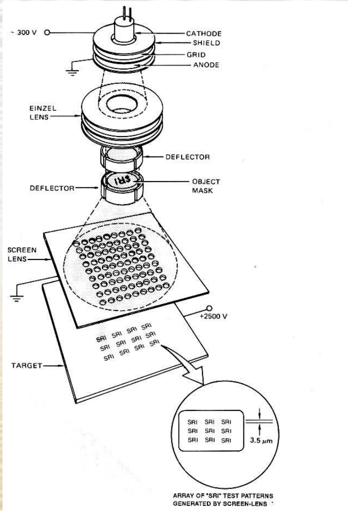
e-Beam Systems



Reduction-type electron-beam projection system developed at IBM.

Projection systems

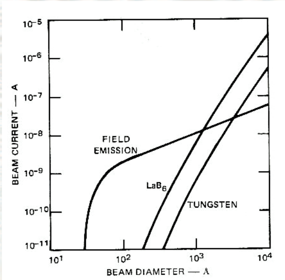


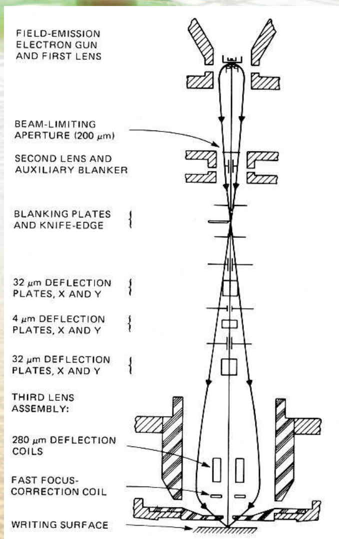


Screen lens parallel-image electron-beam projection system developed at SRI

Parallel-image projection system 19

Optical Components





The optical components of the EBES-4 column.

Apertures: the beam limiting apertures;
Spray aperture stops any stray electrons
Blanking aperture for deflecting the beam out of the aperture hole;

Deflectors:
Magnetic ones have lower abberations but the electrostatic ones are much faster (important for writing 10^{10} points)

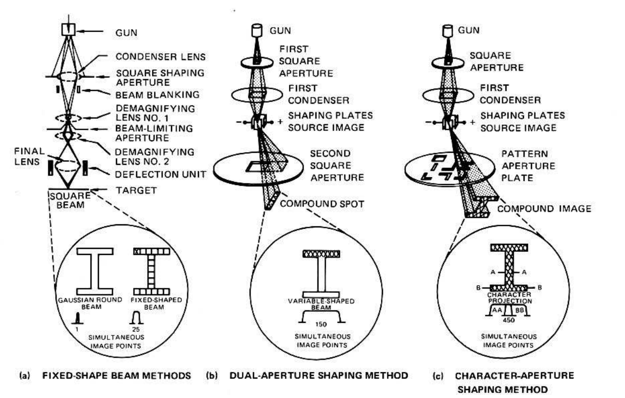
Beam blanking: high-speed electrostatic deflectors.

Stigmator: compensate for astigmatism 0→O

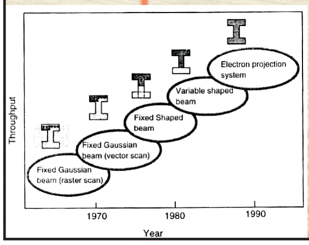
Faraday cage measures current below the final aperture

Electron detection (for focusing, deflection calibration, alignment). 20

Beam-shaping



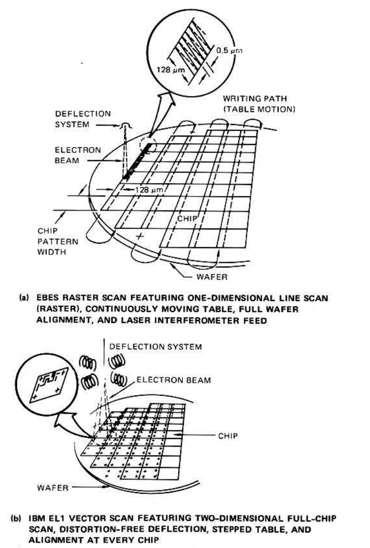
Beam-shaping techniques



Increasing throughput by beam shaping:

21

Raster vs. Vector Scan



Raster scan. A scanning technique where the beam scans line by line a section of the surface. The beam is turned on or off depending on whether the current pixel is to be exposed or not.

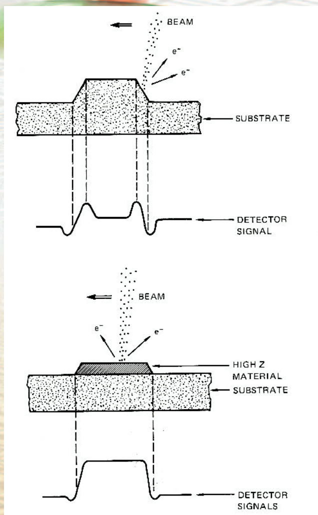
- The chip is divided into stripes of ~2^8 pixels
- The selected strip is written onto the substrate
- The beam scans over the substrate line by line
- If the current pixel is to be exposed, the beam is on
- If the current pixel is not to be exposed, the beam is off
- The substrate is moved perpendicular to the scan lines by a laser-controlled table

Vector scan. A scanning technique where the beam is positioned over an area of the substrate, and the features in that area (according to the pattern data) are drawn out using lines. The beam remains on at all times.

- An area of an individual die is aligned under the electron beam
- The beam is deflected so as to draw out the features in that area of the chip
- The chip is completed either by a step-and-repeat method, or by continually moving the substrate
- The alignment of features in adjacent scanning area is important. A measure of misalignment is the butting error, i.e. a measure of the misalignment between adjacent scan areas

22

Registration Marks



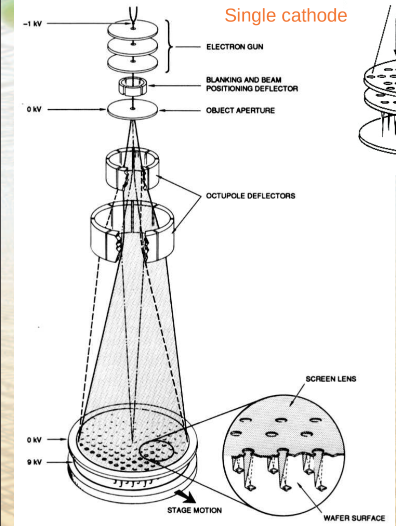
- Signals:
  Backscattered electrons
  Secondary electrons
  Luminiscent radiation
- Detectors:
  Scintillation detector
  Solid-state detector
  Photomultiplier

Backscattered electrons are better for the mark detection because of the resist that can absorb the secondary electrons.

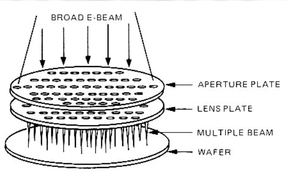
23

Multiple e-Beam Exposure

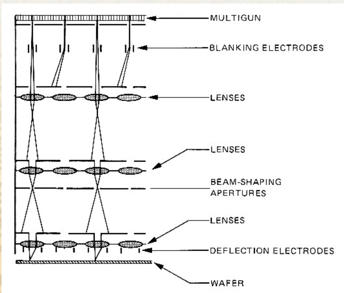
Single cathode



Multiple-electron-beam exposure system—principles of operation.

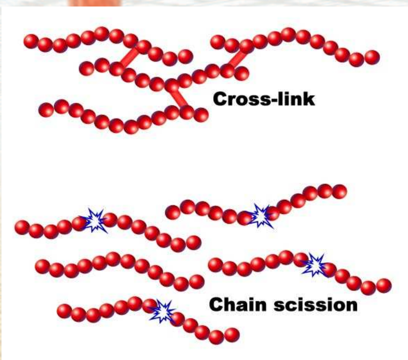


Multiple cathodes



24

Effects in the Resist



Negative resist (SAL601-SR7)

6-8 µC/cm^2 @ 50kV (medium resolution, high sensitivity)

Positive resist (e.g. PMMA, ZEP7000)

Also thermal effects: 30 kV × 10 nA / 100 nm^2 = 300 MW/cm^2 !!

Development:

For a given polymer, organic solvents dissolve polymer chains of molecular weight below some critical value M_{fc}

25

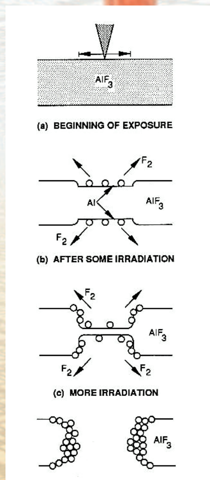
Organic E-Beam Resists

Polymer[a]	Tone	Sensitivity (C/cm^2)	Resolution (μm)
PMMA	Positive	4×10^{-5}–8×10^{-5}	0.1
P(GMA-co-EA)	Negative	3×10^{-7} (10 keV)	1.0
PBS	Positive	8×10^{-7} (10 keV)	0.5
COP	Negative	4×10^{-7}	1.0
P(GMA-co-EA)	Negative	3×10^{-7} (10 keV)	1.0
PGMA	Negative	5×10^{-7} (20 keV)	1.0
PCA	Positive	5×10^{-7} (20 keV)	0.5

PMMA: polymethyl methacrylate;
P(GMA-co-EA): poly(glycidyl methacrylate-co-ethyl acrylate;
PBS: poly(butene-1-sulfone);
COP: copolymer methyl methacrylate;
PGMA: poly(glycidyl methacrylate;
PCA: copolymer of α-cyano ethyl acrylate and α-amine ethyl acrylate

26

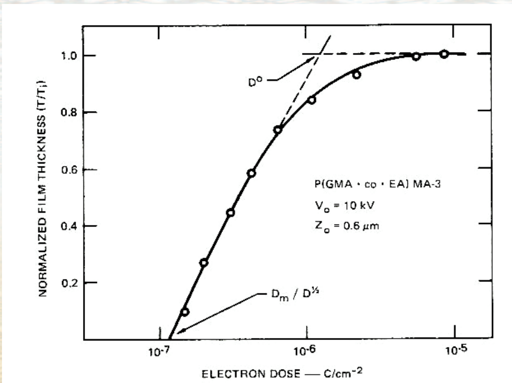
High-Res. Positive Inorganic Resists



Resist	Minimum linewidth	Typical aspect ratio	Deposition	Dose at 100 keV to expose 500-nm-thick layer (C/cm^2)	Mechanism of exposure
PMMA	8–10 nm	45	Spinning	5×10^{-4}	Bond breaking
NaCl	1.5 nm	>40	Sublimation 40-Å grain	10^{2}–10^{3}	Dissociation of Cl_2 Diffusion of Na
LiF	1.5 nm	>40	Sublimation 50-Å grain	10^{-1}–10^{-2}	Dissociation of F_2 Diffusion of Li
MgF_2	1.5 nm	>40	Sublimation 50-Å grain	1–10^{-1}	Dissociation of F_2
AlF_2	1.5 nm	>40	Amorphous	1–10	Dissociation of F_2 Diffusion of Al
KCl	1.5 nm	>40	Deposition 50-Å grain	1–10	Dissociation of Cl_2 Diffusion of K
Metal–alumina	1.5 nm	>40	Cut thin-film slabs	1×10^{7} (2000 Å thick)	

Self-development of metal halides by e-beam

Sensitivity

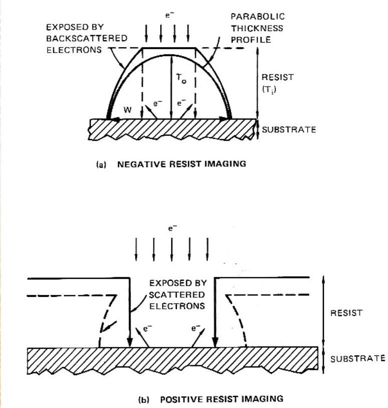


Contrast $\gamma = |\log(D^0/D_m|^{-1}$ (negative resists)

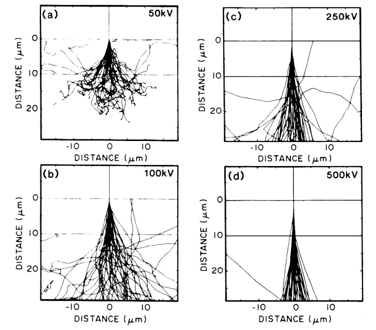
D^0 is the dose required to polymerize 100% of thickness;
D_m is the minimum dose required for any detectable polymerized layer to form

Scattering Effects

Proximity corrections are required



High-Energy e-Beam Lithography



Less prone to proximity effects

Specifications for E-Beam Exposure System

τ – the pixel exposure time (s);
D – the dose for large areas (C/cm^2);
fD – the dose for one pixel;
l^2p – the pixel area;
l^2p/τ – the area exposed per second;
j – the current density in the spot (A/cm^2)

• The bandwidth of the deflection and focusing systems as well as resist sensitivity limit the speed of pattern writing: