

Chemical Processes for Micro- and Nanofabrication
www.lithoguru.com/scientist/CHE323

**Bonus Lecture 2:
Introduction to Mask
Making, Part 2**

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E-Beam Mask Writing

- High-end masks use electron-beam writers of various properties
 - Number of beams
 - Electron energy
 - Beam shape
 - Writing strategy
- Performance metrics
 - Throughput
 - Resolution, pattern fidelity
 - Critical dimension and registration/overlay control

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Electron-Beam Tools

- Electron gun (source) supplies the electrons
- Electron column shapes and focuses the electron beam, including beam blanker
- Mechanical stage positions the mask under the electron beam
- Substrate handling system
- Computer system that controls the equipment and provides the data to be written (data path)

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Electron Gun (Source)

<http://www.amnrf.org.au/myscope/sem/practice/principles/gun.php>

- Thermionic emitters
 - Electrons "boiled" off the surface by giving them thermal energy to overcome the barrier (work function)
 - Tungsten in low vacuum, LaB₆ in high vacuum
- Field Emitter Gun (FEG)
 - Apply a large electric field to a solid (e.g., Tungsten, carbon nanotubes)
 - Electrons tunnel out when the surface barrier becomes very narrow

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E-Beam Deflection and Focus

Electrostatic

Electromagnetic

$$F = q(\vec{E} + \vec{v} \times \vec{B})$$

- By varying the electric or magnetic field as a function of radial position, a lens can be made
- Correcting aberrations in the lens is very difficult (spherical and chromatic), so NA is low

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E-Beam System

Leica Lithography Systems Ltd

The optical components of the EBES-4 column.
J. Vac. Sci. Technol. B 5, 53 (1987)

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Writing Strategies

- Raster Scan: scan back and forth, blank beam where you don't want to write
 - Easy, slow, spot size can be adjusted
 - Spot size gives direct trade-off between resolution and throughput
- Vector Scan: move the beam to only those areas that are to be exposed
 - Can be much faster, especially for sparse patterns
- Variable-Shaped Beam
 - A rectangle or triangle is projected at one time

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Writing Strategies

The diagram illustrates four writing strategies in a 2x2 grid. The top-left quadrant shows a 'round (Gaussian) beam' with a circular spot size. The top-right quadrant shows a 'shaped beam' with a rectangular spot size. The bottom-left quadrant shows a 'vector scan' with a sparse pattern of dots. The bottom-right quadrant shows a 'raster scan' with a dense grid of dots. Arrows indicate comparisons: 'round (Gaussian) beam' versus 'shaped beam', and 'vector scan' versus 'raster scan'.

From: Marco Salerno, <http://www.lira.dist.unige.it/>

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Commercial Systems

- MEBES from ETEC/AMAT was the dominant choice down to 130-nm node
 - 10 keV, raster scan (now discontinued)
- Since 130-nm node, high-end masks have been made with 50 keV variable shaped beam tools
 - JEOL JBX-3050MV, JBX-9000
 - Vistec (Leica) SB-250 through SB-3050
 - NuFlare EBM:4000 through EBM:9500
- Below 10-nm node, a new approach may be needed (multibeam)

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Electron Energy

The graph shows two curves: a green curve for 'Forward Scatter' and a blue curve for 'Backscatter'. The Forward Scatter curve is higher and narrower, while the Backscatter curve is lower and broader.

- Electron energy affects both resolution and throughput
- Higher beam energy has
 - Less forward scattering (better resolution, better CD control, can be used with thicker resists)
 - More backscattering (larger proximity effects)
 - Lower resist sensitivity (more electrons pass through the resist without interacting)
 - Greater substrate heating and damage
- Most mask writers use 10keV – 100keV

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Throughput vs. Resolution

- Three possible limits to resolution
 - Spot size due to electron wavelength and lens NA, aberrations
 - Electron-electron repulsion if current is too high
 - Electron scattering in the resist/substrate
- To get higher throughput:
 - Larger spot size (Gaussian systems)
 - Larger address grid (shaped beam systems)
 - Higher current (can result in electron-electron repulsion)
 - Faster stage (harder to control)
- Higher throughput results in lower resolution
 - Higher resolution results in lower throughput

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Tennant's Law: Throughput vs. Resolution

The plot shows resolution in angstroms on the y-axis (log scale from 10 to 10^4) and areal throughput in $\mu\text{m}^2 / \text{hr}$ on the x-axis (log scale from 10^-6 to 10^2). A diagonal line represents the 'Best fit' for conventional lithography. Various techniques are plotted as points: STM (low temperature atom manipulation), e-beam lithography using inorganic resists, AFM using oxidation of silicon as resist (single tip), Gaussian e-beam lithography w/PMMA as resist, other Gaussian e-beam lithography using high speed resists, shaped and cell projection e-beam lithography, and optical step and repeat reduction printing. A portrait of a man is shown in the bottom right corner.

Limits of Conventional Lithography, Chapter 4, *Nanotechnology*, G. Timp, ed., AIP Press (1999)

Cornell NanoScale Science and Technology Facility (CNF)

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Tennant's Law

- For direct-write technologies, we observe empirically that:

$$A_t \sim R^5$$

Circa 1995:
 $A_t = 4.3R^5$

A_t = Areal Throughput (nm²/s)
 R = Resolution (nm)
- Where does the power of 5 come from?
 - Pixel size = R^2
 - Shot noise requires a minimum number of electrons per pixel, so this adds another R^2 for constant current density

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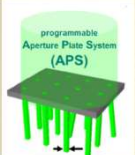
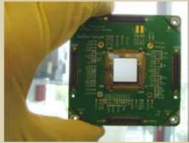
Mask Writing Times

- Up till about 2010, most high-end masks could be written in about 6 hours
 - Increases in number of pixels or shots was accompanied by increases in writer pixel throughput
- Lately, mask writers have not been keeping up
 - OPC complexity increases the number of shots faster than the number of resolution pixels
 - Since 2011, write times have increased by 25% a year
 - Masks today typically take 15 – 20 hours to write (and up to 50 hours), a problem for cost & write tool stability

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Multibeam Tools

- One solution to the problem of slow *serial* writing is to write multiple features in *parallel*
 - Use multiple miniature e-beam columns
 - Use one column with multiple pixels

Christof Klein, et al., "50-keV electron multibeam mask writer for the 11-nm HP node: first results of the proof-of-concept electron multibeam mask exposure tool", *J. Micro/Nanolith. MEMS MOEMS*, 11(3), 031402 (2012).

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Maskwriting – the Big Ideas

- All high-end masks today are written with 50 keV variable-shape writers
 - Laser writers can be used for lower-resolution applications
- Mask writing speed goes down as the resolution of the writer goes up (Tennant's Law)
 - Today, high end masks take too long to write
- In the near future, multiple-beam e-beam writers may be used for mask making

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