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

Bonus Lecture 2: Introduction to Mask Making, Part 2

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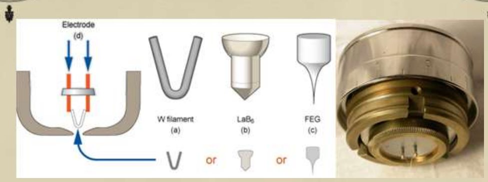
E-Beam Mask Writing

- 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

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)

Electron Gun (Source)

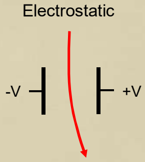


http://www.ammrf.org.au/myscope/sem/practice/principles/gun.php

- Thermionic emitters
  – Electrons “boiled” off the surface by giving them thermal energy to overcome the barrier (work function)
  – Tungsten in low vacuum, LaB_6 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

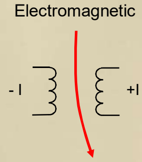
E-Beam Deflection and Focus

Electrostatic



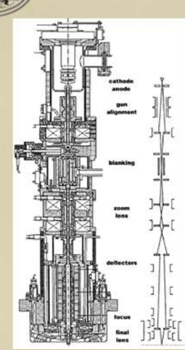
$$F = q(\vec{E} + \vec{v} \times \vec{B})$$

Electromagnetic

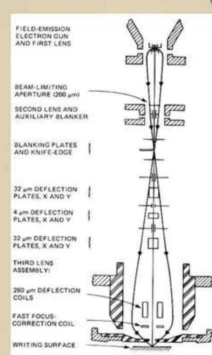


- By varying the electric or magnetic field as a function of radial position, a lens can be made
- Correcting aberrations in the lens is very difficult (spherical and chromatic), so NA is low

E-Beam System



Leica Lithography Systems Ltd



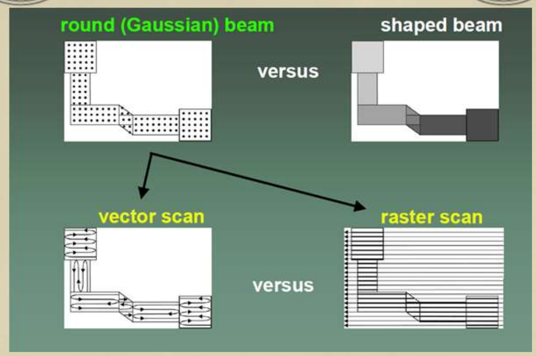
The optical components of the EBES-4 column.

J. Vac. Sci. Technol. B **5**, 53 (1987)

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

Writing Strategies

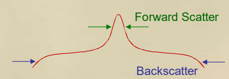


From: *Marco Salerno*, http://www.lira.dist.unige.it/

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)

Electron Energy

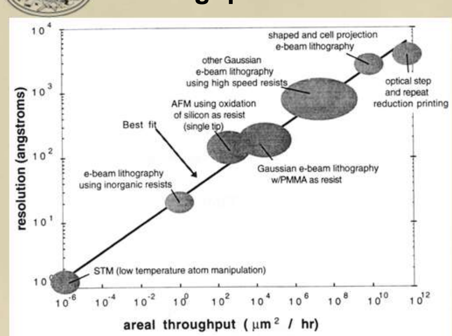


- Electron energy affects both resolution and throughput
- Higher beam energy has
  - Less forward scattering (better resolution, better CD control, can be used with thicker resists)
  - More backscattering (larger proximity effects)
  - Lower resist sensitivity (more electrons pass through the resist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

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

Tennant's Law: Throughput vs. Resolution



Cornell NanoScale Science and Technology Facility (CNF)

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

Tennant's Law

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

$$A_t \sim R^5$$

A_t = Areal Throughput (nm^2/s)
R = Resolution (nm)

Circa 1995:
$A_t = 4.3R^5$

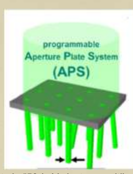
- Where does the power of 5 come from?
  - Pixel size = R^2
  - Shot noise requires a minimum number of electrons per pixel, so this adds another R^2 for constant current density

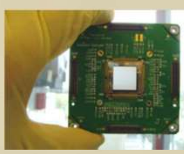
Mask Writing Times

- 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

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).

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