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)

- 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

- 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
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

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


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**Tennant’s Law**

- For direct-write technologies, we observe empirically that: 
  \[ A_t \sim R^5 \]
  
  \[ A_t = \text{Areal Throughput (nm}^2/\text{s}) \]
  
  \[ R = \text{Resolution (nm)} \]

- 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

**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

**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