ECE 541/ME 541
Microelectronic Fabrication Techniques

MW 4:00-5:15 pm

Mask Design

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Masks

- Cr on soda lime glass (most common)
- Cr on fused silica
- Cr on quartz glass (transparent to deep UV, expensive)
- Photographic emulsion on soda lime glass (less expensive)
- Fe$_2$O$_3$ on soda lime glass (semi-transparent to visible light)
- High resolution laser printing on transparency
  • Dimensions: 4” x 4” for 3 inch wafers, 5” x 5” for 4 inch wafers, …
  • Polarity:
    – “light-field” = mostly clear, drawn feature = opaque
    – “dark-field” = mostly opaque, drawn feature = clear
Masks

• If you need one, buy it!
  • There are many companies that exclusively make masks
  • There are also many companies that make masks according to your design

• If you need to do it on your own:
  • E-beam writer
  • Same as lithography…
**Mask Costs**

- Lithography accounts for about 1/3 of total IC fabrication cost
- Technology performance is often set by lithographic control
- From 15-25 different masks in a typical process (up to 30)!
- Mask making has become a costly, materials intensive, time consuming process (predicted cost of a mask set for 65nm node is $3M)
- Any defect in the mask propagates through all wafers - Cleaning, pellicles, FIB, and laser mask repair
**Pellicle on a Reticle**

- Pellicle film
- Chrome pattern
- Frame
- Reticle

The particle on the pellicle surface is outside of optical focal range.

- Antireflective coatings
- Depth of focus
- Pellicle film
- Chrome pattern
- Mask material
Reticle (mask) Enhancement Technology (RET)

Optical Proximity Correction (OPC)
Add shapes to design data (GDS II)
Corrects for litho optics & process

Rule based OPC - one mode fits all

Model-based OPC - customized to shape neighborhood

Phase-Shift
“Strong” PSM - Phase mask + binary (“cut”) mask
Used for gate printing CD, sheet rho, control

“Weak” PSM - Via clear areas include attenuator

Tiling
Rule based tiling - Doesn’t guarantee global planarity
Model-based tiling - POR for future reticles
**Diffraction**

Long and narrow aperture

Rectangular aperture
Fresnel diffraction

Separation Depends on Type of System

Incident Plane Wave

Mask Aperture

Resist

Wafer

Light Intensity at Resist Surface

Proximity

Projection

Contact
OPTICAL PROXIMITY CORRECTION IMPROVES PRINTING
(ADDS SHAPES TO MASK)

Photo downloaded from MicroUnity
(now ASML MaskTools) web site
Mask engineering: Optical proximity correction (OPC)
Rule-Based OPC

Model-Based OPC

Fig. 1A

Fig. 1B
Phase-Shifting

- Uses phase-modulation at the mask level to further the resolution capabilities of optical lithography

**Benefits:**
- Smaller feature sizes
- Improved yield (process latitude)
- Dramatically extended useful life of current equipment
- Performance Boost
- Chip Area/Cost Advantage for Embedded Systems

Printed using a ~0.18 μm nominal process
Phase-Shifting Mask

a) BIM

![BIM Diagram]

Electric field on mask

Electric field on wafer

Intensity on wafer

b) APSM

![APSM Diagram]

Absortive phase shifters

Rim phase shifters

Blockers

c) Rim PSM

![Rim PSM Diagram]
Rule-Based Tiling

- Done with Boolean operations
- Only density of the template is variable
- Not adequate for arbitrary design
Model-Based Tiling - Large Manuafacturability Enhancement

Untitled reticle (768A) (unmanufacturable)

Conventional Rule-Based Tiling (702A)

193 nm ASML Stepper N.A. = 0.85!!!

Model-Based Tiling (152A) (80% uniformity improvement)
Alignment and Exposure

Modern memory chip production processes have some 25 lithographic steps.

In all steps the masks have to align, otherwise no proper connections are made.

The total misalignment budget is about 1/3 of the feature size, i.e. 40 nm for the 130 nm node.
Grid of Exposure Fields on Wafer
Step-and-Repeat Alignment System
Alignment Marks

RA, Reticle alignment marks, L/R
GA, Wafer global alignment marks, L/R
FA, Wafer fine alignment marks, L/R

RAL
RAR

+ GA

+ FAL

FAL/R
FAL/R +
+ From 1st mask

FAL/R +
+ From 2nd mask

+ GAL

1st mask layer

GAR

Notch, coarse alignment

2nd mask layer

For 2nd mask
+  
+  
+  
+  

On-Axis Versus Off-Axis Alignment System

On-Axis Alignment System

- Microscope objectives for video camera
- Reticle
- Alignment BLC fiducial
- Projection optics
- Wafer stage

Off-Axis Alignment System

- Alignment laser (633 nm)
- Off-axis alignment unit
- Video
- Optical fiber
- Alignment laser (633 nm)
Effects of Defects

Positive resist more desirable!
Mask Error

![Graph showing the relationship between Chip edge (mm) and Chip size (mm²) for different yield percentages and defect densities. The graph includes lines for 0.025, 0.1, 0.25, and 1.0 defect/cm². Each line corresponds to a different yield percentage at the top edge of the chip.]
Mask Repair

• Usually protected by Pellicles
• Focused Ion Beam (FIB)
• Laser Ablation
Photomask and Reticle for Microlithography

1:1 Mask  
4:1 Reticle
Clear Field and Dark Field Masks

Clear Field Mask

Simulation of metal interconnect lines (positive resist lithography)

Dark Field Mask

Simulation of contact holes (positive resist lithography)
Example 3: IBM-DuPont-Altis Supply Chain
The masking layers determine the accuracy by which subsequent processes can be performed.

The photoresist mask pattern prepares individual layers for proper placement, orientation, and size of structures to be etched or implanted.

Small sizes and low tolerances do not provide much room for error.
Masks

- Transparent substrate coated with patterned, UV-opaque material
  - Hard
  - Flexible
  - Reflective
Mask Material

- Substrate: Flat, Stable, Transparent
- Soda-lime, Borosilicate, Quartz, Mylar

![Spectral Transmittance Curve (2.3mm Thick Substrate)](image)

- Absorber: Patternable, UV-opaque, Cleanable, Damage Resistant, Defect-Free
- Chrome, Iron Oxide, Ink

Substrate info from nanofilm, www.nanofilm.com
Mask Design Flow
Device Concept
Fabrication Process Flow
ID Photolithographic Steps
Determine Resist Type(s)
Determine Alignment Needs
Make CAD
Send CAD to Mask Foundry
Basics of Mask Design

- Smaller Features -> Higher Cost
- Complex Features -> Higher Cost
- Larger Area -> Higher Cost

Feature Size ↔ Resolution
Alignment Accuracy

- Mark Resolution
- Stage Resolution ✗
- Microscope Resolution ✗
- Operator Patience ✗
- Design to Relax Alignment
Alignment Mark Design

- Lock and Key
- Vernier Scale
- Mark “Material”
  - Etched
  - Deposited
- Tool Requirements
  - For MJB4, 3.5cm separation; MA6, 5cm