Fundamentals of Micro and Nanofabrication
Prof. Shankar Kumar Selvaraja
Centre for Nano Science and Engineering
Indian Institute of Science, Bengaluru

Lecture – 36
Optical Lithography: Mask Technology

So far, we have looked at the imaging process, the resist process, and different image formation techniques. In this lecture on optical lithography, we are going to look at Mask Technology. Mask is repeatedly used in optical lithography, and we need to understand what kind of technology is used to make the mask and the specifications of the mask layers.

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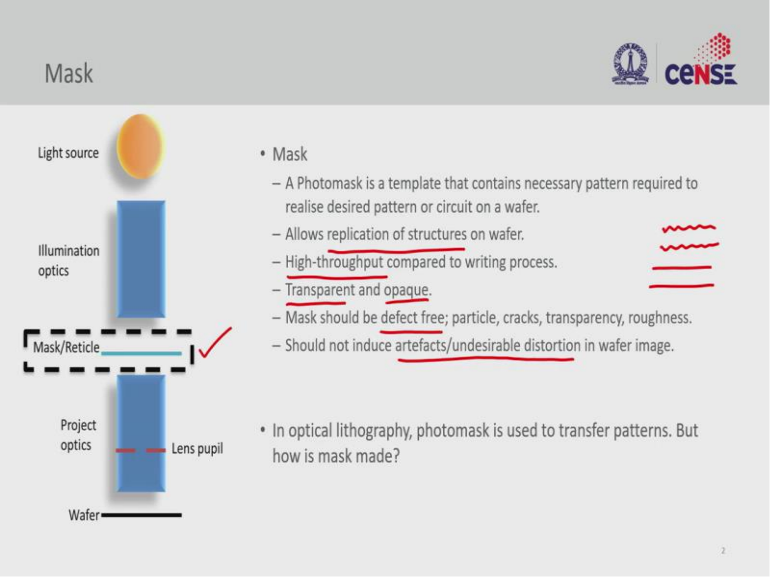

Mask

- Mask
  - A Photomask is a template that contains necessary pattern required to realise desired pattern or circuit on a wafer.
  - Allows replication of structures on wafer.
  - High-throughput compared to writing process.
  - Transparent and opaque.
  - Mask should be defect free; particle, cracks, transparency, roughness.
  - Should not induce artefacts/undesirable distortion in wafer image.
- In optical lithography, photomask is used to transfer patterns. But how is mask made?

In the projection lithography system, the mask is the primary element with all the circuit or desired patterns that we would like to project onto the wafer. Mask is a template; we can generate patterns on the wafer n number of times without causing any damage to the mask in projection lithography. But in the case of contact lithography, the mask comes in contact with the wafer.

- Irrespective of projection lithography or contact lithography, the mask is templates with the desired circuit patterns.
- It is used to realize the structure of the wafer.

- Mask has high throughput than writing.

- Mask has two regions, a transparent region, and opaque regions, to define the structure.

- The mask should be defect-free. Defects in the mask will create undesirable structures on the wafer. The defect could be either particles or cracks or some transparent region instead of opaque. The roughness of the mask is also considered a defect; this roughness will be transported onto the wafer during exposure.

- Mask should not transfer artifact or undesirable distortion to the wafer. There are multiple artifacts like undesirable structures or underdeveloped structures, or no precise edges defined. These will create undesirable distortion on the image.

In optical lithography, if a photomask is used to transfer the pattern, then it is important to understand the development of masks and their properties.

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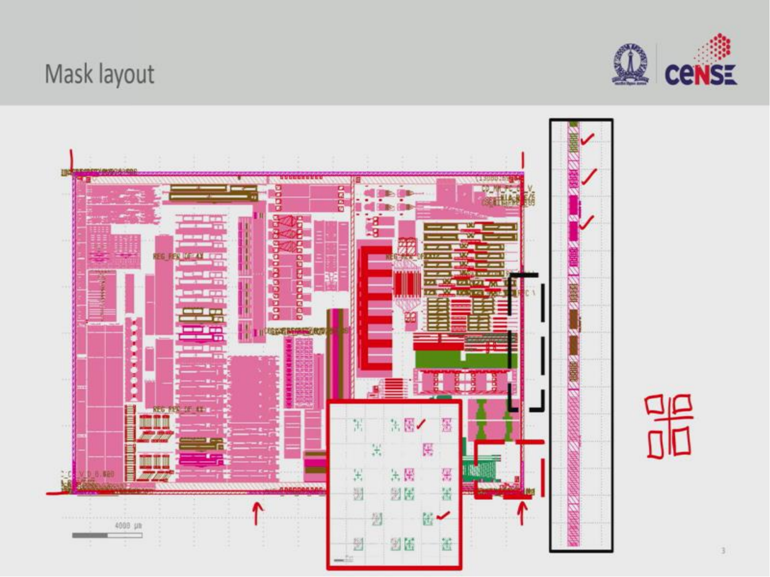

The above slide shows a design file or GDS file of the circuits with different colors showing different layers in lithography. The circuit designer will come up with these circuits, which will be transferred onto the wafer. To align the two different layers, it needs alignment structures in the mask, crosses, and boxes, as shown in the zoomed-in image above.

The edges of the mask show some line space features called metrology structure or scribe lines. We cannot measure every circuit in a circuit design, so by measuring the structures in these scribe lines at the edges, dimensions are confirmed. Since we are illuminating the whole mask with the same amount of energy, the scribe line structure and the center of the mask are expected to yield the same dimension as in the design.

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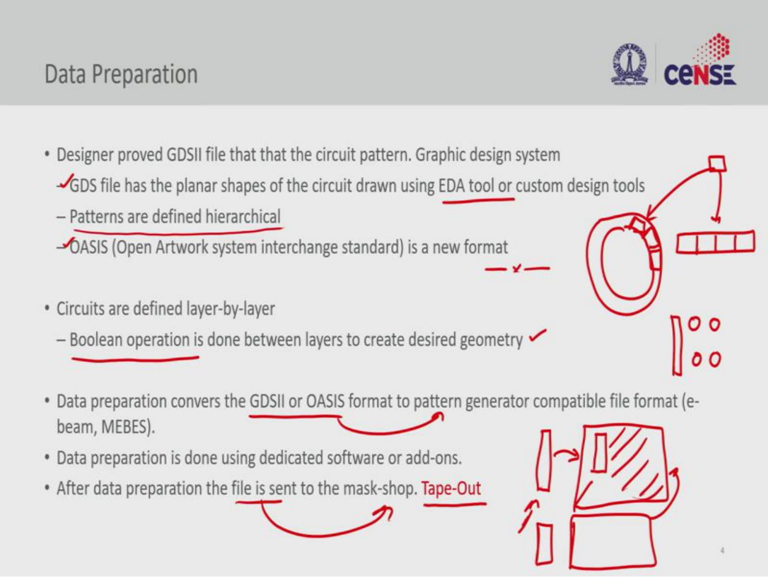

Data Preparation

- Designer proved GDSII file that that the circuit pattern. Graphic design system
  - GDS file has the planar shapes of the circuit drawn using EDA tool or custom design tools
  - Patterns are defined hierarchical
  - OASIS (Open Artwork system interchange standard) is a new format
- Circuits are defined layer-by-layer
  - Boolean operation is done between layers to create desired geometry
- Data preparation convers the GDSII or OASIS format to pattern generator compatible file format (e-beam, MEBES).
- Data preparation is done using dedicated software or add-ons.
- After data preparation the file is sent to the mask-shop. Tape-Out

The process of making the mask:

The designer comes up with the circuit pattern using EDA tools or custom design tools right. These patterns are defined as a hierarchical structure- simple square shape structures are arranged to draw circular or rectangular patterns. This is used to reduce the overhead on the design, and it depends on the design strategies. After designing, the output will be in GDSII (global design system) or OASIS (open artwork system interchange standard) format. The design file shows the two-dimensional structure. These structures are defined layer by layer, so before translating the design onto the wafer, some Boolean operations are done to create desired structures. The designers provide the GDS to the mask preparation team, and they do Boolean to get desired structure.

For instance, if we have a line in the design, which is opaque for exposure light, we need that line to be transparent. So a large path is defined around the opaque line, and Boolean operation AND is used between the large patch and line to get desired transparent line.

After Boolean operations, the mask preparation team converts the design format into a different pattern generator or the file format required to write the mask. Then the file is sent to the mask shop, which makes the mask; this stage is called tape-out.

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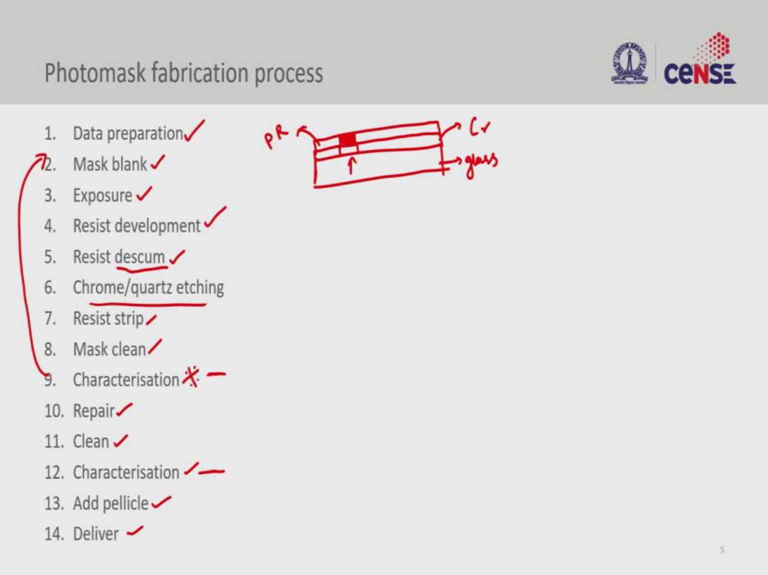

Photomask fabrication process

1. Data preparation ✓
2. Mask blank ✓
3. Exposure ✓
4. Resist development ✓
5. Resist descum ✓
6. Chrome/quartz etching
7. Resist strip ✓
8. Mask clean ✓
9. Characterisation
10. Repair ✓
11. Clean ✓
12. Characterisation ✓
13. Add pellicle ✓
14. Deliver ✓

There are various fabrication steps involved in mask preparation. Process involved are

1. Data preparation: Tape out phase provides the design in the desired format.
2. Blank mask: To make transparent and opaque regions in a mask, an opaque chromium layer on a glass substrate is used as a blanket layer.
3. Exposure: Similar to lithography, the mask layer will have a photo definable resist, a photoresist and which is exposed to define the patterns.
4. Resist development: To develop the patterns on photoresist coated mask
5. Resist descum: To clear out the resist sitting at the bottom due to underdevelopment in few regions.
6. Chrome etching: The patterns are generated by etching the chromes and defining transparent regions with glass underneath.
7. Resist strip: After chrome etch, the resist is removed.

8. Mask cleaning

9. Characterization: Measuring all the critical dimensions obtained to check if it meets the required specification.

10. Repair: If the mask fails to produce a critical dimension as specified, the defects are repaired without redoing all the steps it is required.

11. Cleaning mask

12. Characterize: To make sure the repair has worked or not.

13. Add pellicle: Pellicle is a protection layer

14. Deliver the mask.

In cases repair does not work or even in the first characterization step mask was found completely out of specification, then all the processes are done, starting with a blank mask. Suppose the specifications show a critical dimension variation within less than 1 percentage or critical dimension very close to the resolution limit of the mask process. In that case, the mask will be very expensive. That expense comes from the repetition of the process to get the required critical dimension or specification.

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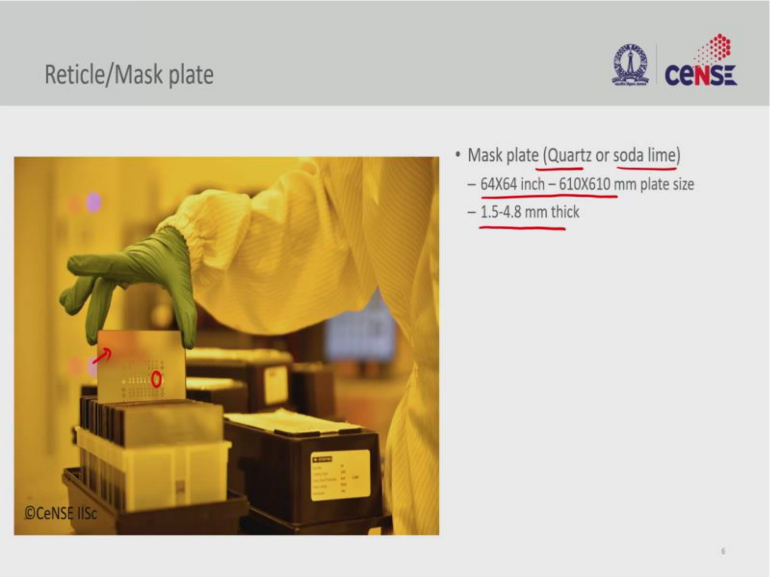
Reticle/Mask plate

- Mask plate (Quartz or soda lime)
  - 64X64 inch – 610X610 mm plate size
  - 1.5-4.8 mm thick

The image shows a mask plate from Nano-Science Department at IISC. The mask plate shown has chrome as opaque regions and openings that are transparent for the light to go through. The mask plate can be either quartz or soda-lime; both are transparent in the region of interest. And the mask plate size can vary based on the tools and the circuit to define. The thickness of the substrate also can vary; e.g., a larger mask uses thicker plates for mechanical strength.

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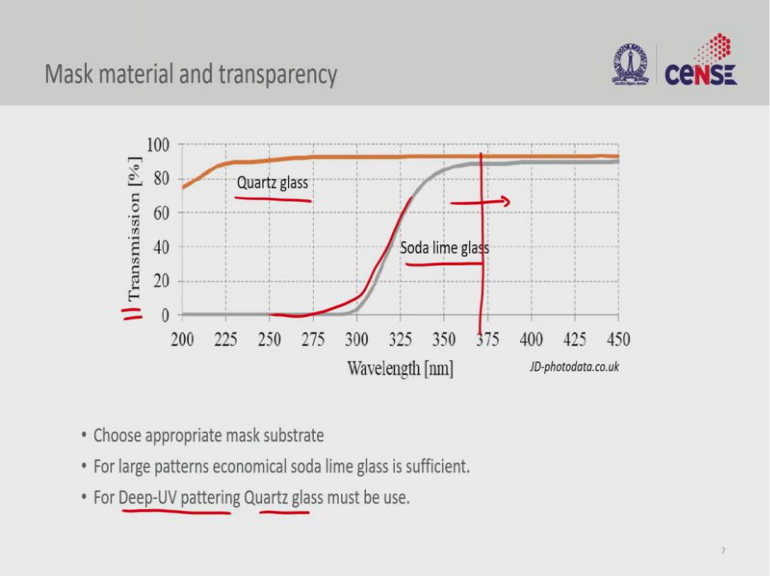

Mask material and transparency

- Choose appropriate mask substrate
- For large patterns economical soda lime glass is sufficient.
- For Deep-UV pattering Quartz glass must be use.

The choice of different substrate materials depends on their transparency. Soda-lime is a very commonly used substrate material in academia and industries for illumination wavelength of 375 (i-line) or the longer wavelength, as they are transparent for those wavelengths.

But, if the exposure light is deep UV, quartz is used because of the absorption of soda-lime gas at the deep UV region. Quartz glass is expensive compared to soda lime, but they are transparent to deep UV.

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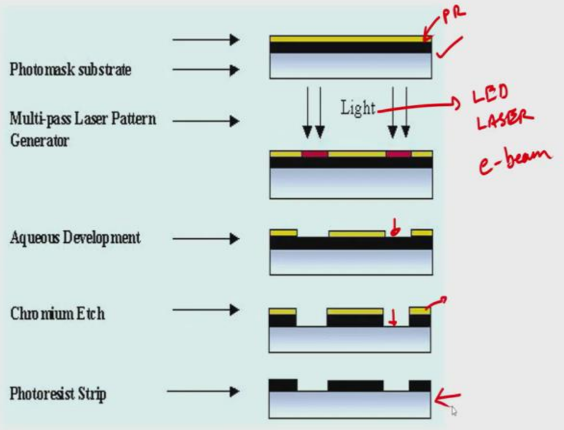
Photomask: Fabrication Process



Photomask substrate

Multi-pass Laser Pattern Generator

Aqueous Development

Chromium Etch

Photoresist Strip

The above slide shows the fabrication steps involved in preparing a mask. Photoresist coated photomask is taken, and then it is illuminated. The illumination could be either LED, laser, or electron beam. In mask fabrication, the writing process is used. After writing sample is developed to remove the photoresist in the exposure region (in case of positive resist). After development, the chromium layer will be exposed; this exposed chromium layer is removed using chromium etchant. In the end, resist is removed to get the final mask.

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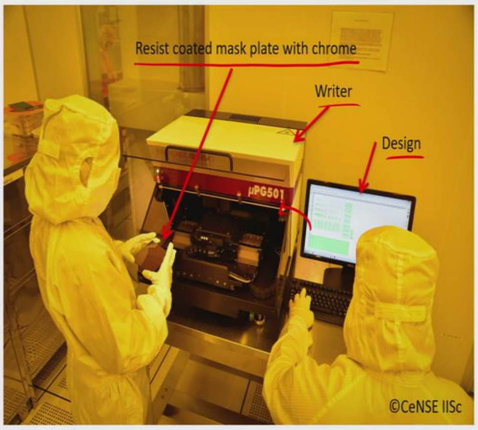
Mask writing



- Mask less lithography-direct writer
- LED or LASER → 0.8 µm
- Advanced CMOS mask uses electron-beam lithography

The above picture shows an engineer holding a resist coated mask with chrome and the monitor with design, which is fed to the writing machine. When the mask is loaded into the tool, it will start writing the layer onto the photoresist. For the mask, the writing process is used, and the tool is shown in the above slide.

The writing process is called maskless lithography; it can be used to directly define patterns on a substrate with photoresist. This litho process can use LED or laser, or for advanced CMOS masks, electron beam lithography is used. Because LED and laser will not give the required dimensions less than 0.8 micrometer, electron beam lithography is used for sub-micron or sub-nanometer scale.

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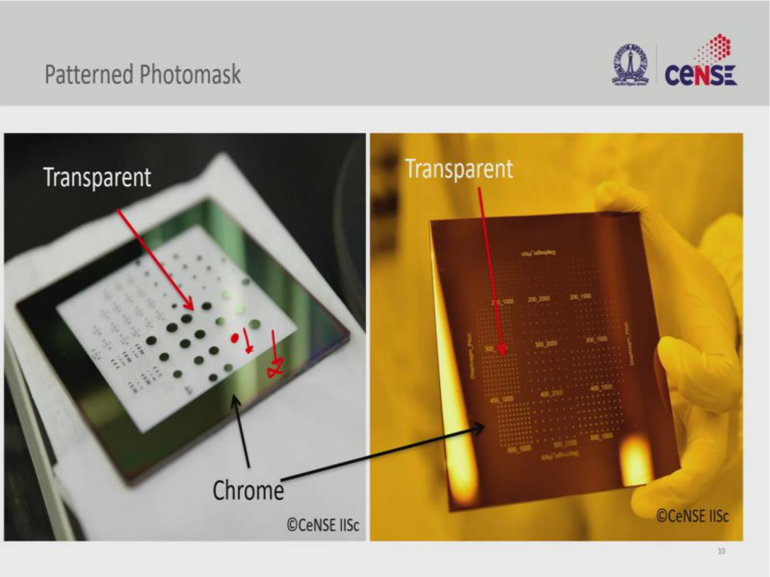

Patterned Photomask

The above slide show two masks, in one, there are chrome patterns with the transparent region surrounding it, so that light will pass through the transparent region, and then the light will be arrested in the chrome region. And, another mask is covered predominantly by chrome and then small openings.

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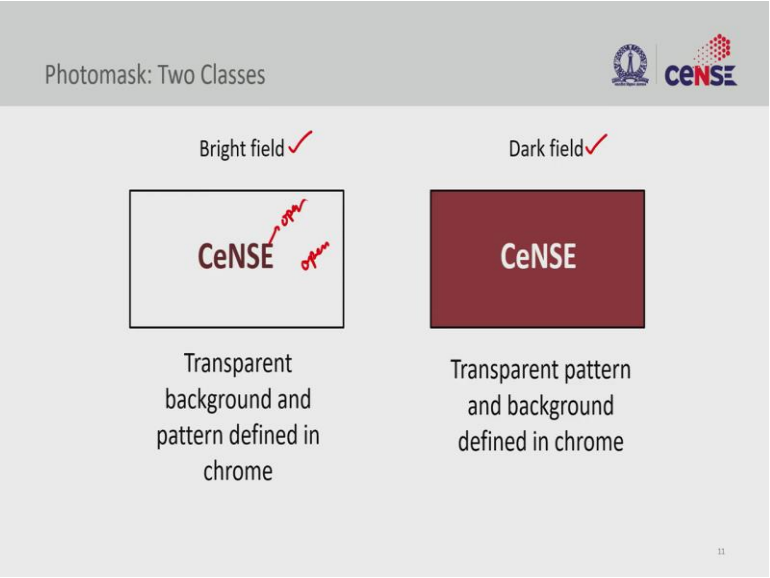

Photomask: Two Classes

Bright field✓

Dark field✓

Transparent background and pattern defined in chrome

Transparent pattern and background defined in chrome

Masks are classified into two groups –bright field and dark field. If the opaque region is much less than the open region, we call it a bright field. In the dark field, a small amount of area is transparent while the maximum part is opaque.

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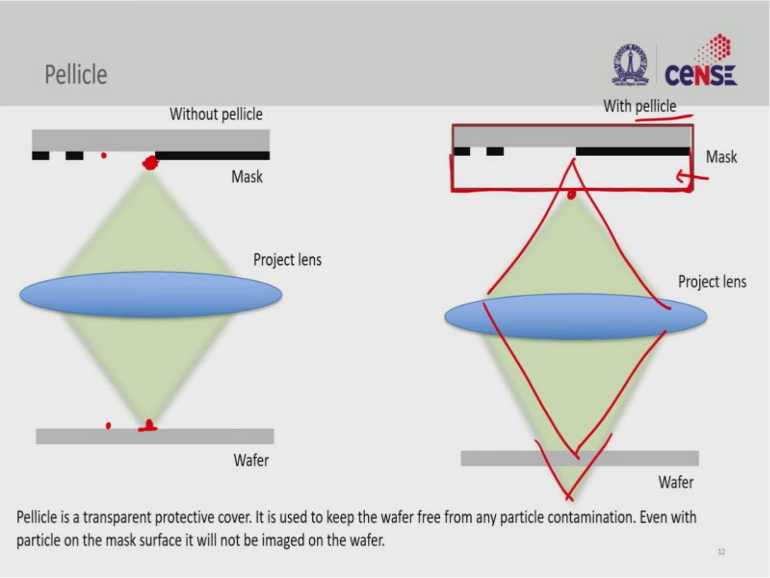

Pellicle

Pellicle is a transparent protective cover. It is used to keep the wafer free from any particle contamination. Even with particle on the mask surface it will not be imaged on the wafer.

The left side image shows a mask without a pellicle or protection right. If a defect or some dust particle is accumulated on the mask, then the dust particle will be imaged on the wafer. Open masks tend to collect dust over time, and it is very hard to remove if it is stuck onto the mask. So, that is the reason the industrial process uses pellicle.

A pellicle is a transparent protective layer covering a mask. If a dust particle sits on the pellicle, the image will be focused out of the wafer, as shown in the right image, so that all the defects getting imaged onto the wafer are avoided.

Pellicle adds additional complexity as it should be tightly sealed to avoid any particles entering inside.

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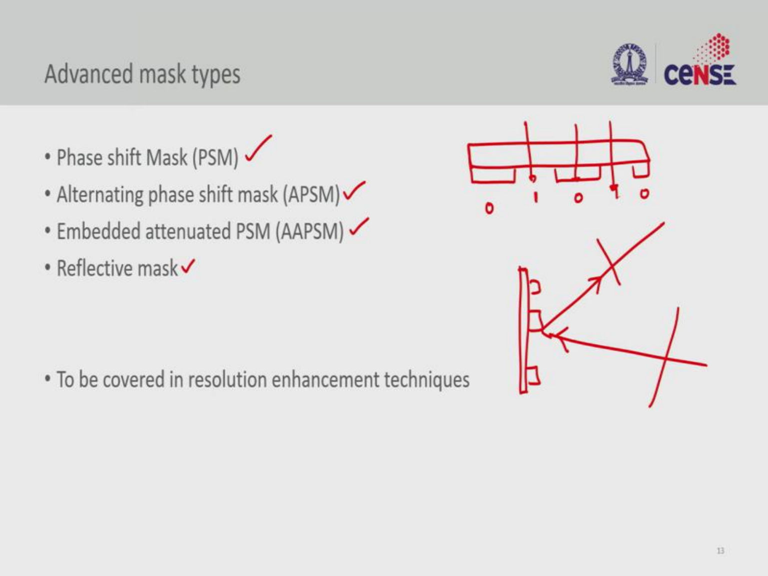

Advanced mask types

- Phase shift Mask (PSM) ✓
- Alternating phase shift mask (APSM) ✓
- Embedded attenuated PSM (AAPSM) ✓
- Reflective mask ✓

- To be covered in resolution enhancement techniques

So far, we discussed a simple mask right with binary features; transparent and opaque.

Some advanced mask technologies are

- Phase shift mask: In a simple mask, chrome is not used to arrest the light propagation, but the phase is used.
- Alternating phase shift mask
- Embedded attenuated phase shift mask
- Reflective mask: In extreme UV, sub ten-nanometer technology a mask reflects the incident beam, and the reflected optical beam contains the mask details.

To summarize, we discussed different types of masks and working principles in the resolution enhancement technique—process flow for mask fabrication and important features of the mask similar to imaging on a wafer. The only difference is we do not use printing which requires a template; instead, a focused LED or a focused laser is used to write patterns on a resist coated mask, and in advanced lithography mask where the structures are very small, electron beam lithography is used.

To get a100-nanometer pattern or even smaller features using laser, technology similar to projection lithography is used. Also, for a smaller dimension, electron beam lithography is used, as electrons have a smaller wavelength, which can define finer features.

We also discussed how defects would affect the mask and use pellicle to avoid that. In the following classes, we discuss different types of optical litho processes and enhance the resolution.