Fundamentals of Micro and Nanofabrication
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Lecture – 31
Optical Lithography: Contact and Proximity printing

In the last lecture, we saw in detail the resist processing and the applications of resist. This lecture will look at the imaging technique to transfer the image onto the photoresist, in particular contact and proximity printing.

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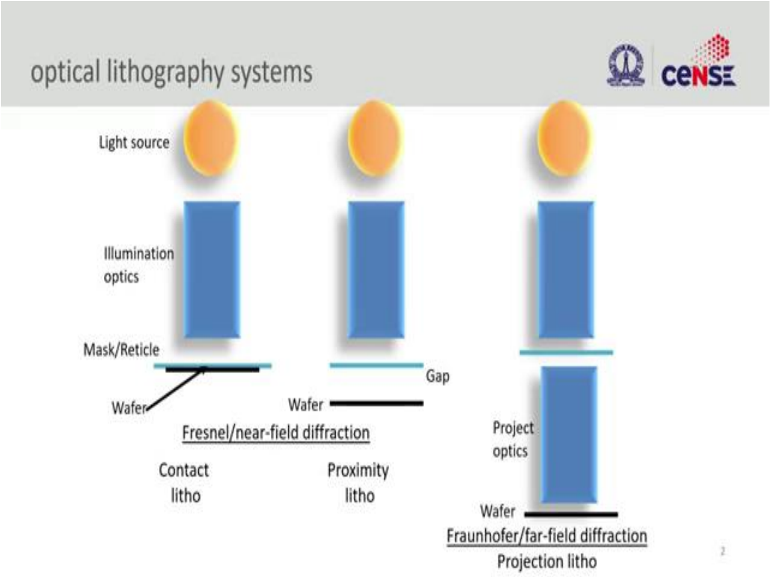

optical lithography systems

There are three types of optical lithography system contact litho, proximity litho, and projection lithography. Contact and proximity lithography are near-field lithography techniques. Both have similar source and illumination optics used to profile the beam and fall uniformly on the mask. Underneath the mask, the wafer is placed directly, unlike projection lithography, which requires additional optics. Contact and proximity method is also called shadow imaging as the wafer directly captures the shadow of the mask, containing required designs.

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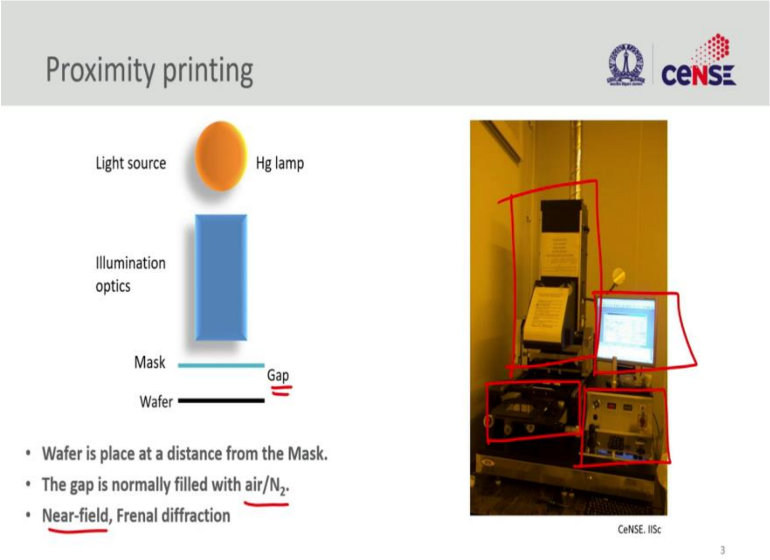
Proximity printing

- Wafer is place at a distance from the Mask.
- The gap is normally filled with air/N_2.
- Near-field, Frenal diffraction

CeNSE, IISc

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The image on the above slide shows a simple proximity printing setup at Nano Science Department in IISC. It consists of a long tower with the optics, a wafer and mask stage underneath the tower, a controller, and a monitor to see all the process parameters. The light source and the illuminating optics are located in the tower. The proximity printing has a non-zero gap between the wafer and the mask. The gap is filled with either air or an inert gas like nitrogen. This is to keep away any contamination outside this gap. Thus, proximity printing captures the near-field image.

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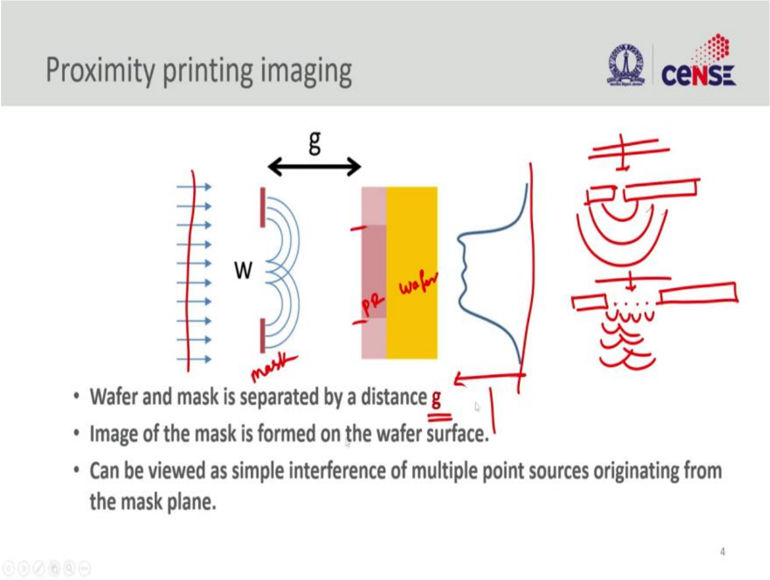
Proximity printing imaging

- Wafer and mask is separated by a distance g
- Image of the mask is formed on the wafer surface.
- Can be viewed as simple interference of multiple point sources originating from the mask plane.

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The zoomed-in view of the mask and photoresist-coated wafer is shown in the above slide. The light from the illuminating system falls uniformly on the mask. Mask will have multiple transparent regions or gaps, if the gap is small, it will act as a single source, and a circular wavefront emerges from that. If the gap is large, there will be n number of points and each will act as an individual source; these will propagate through the gap between mask and wafer and interfere and expose the photoresist on the wafer. Upon illumination, this photoresist will chemically change and become soluble or insoluble based on the resist tone. Hence the design of the mask will be transferred onto the photoresist.

The optical intensity profile that is falling onto this photoresist is shown on the left-hand side of the above slide.

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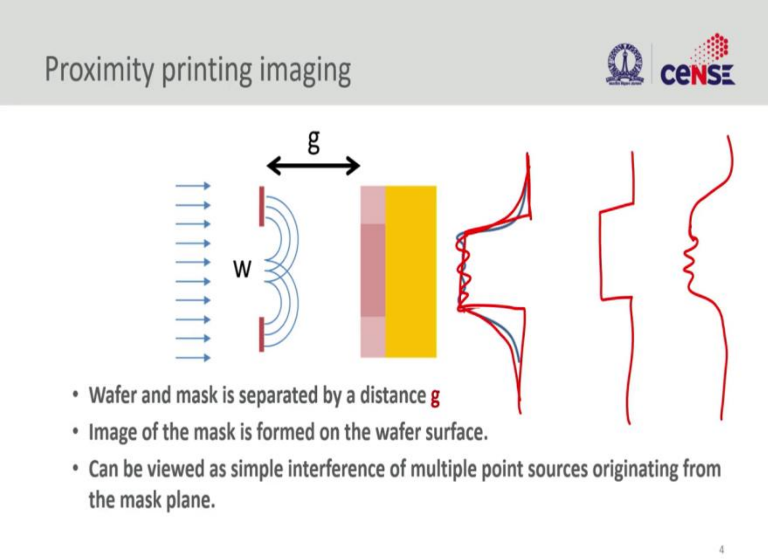

Proximity printing imaging

- Wafer and mask is separated by a distance **g**
- Image of the mask is formed on the wafer surface.
- Can be viewed as simple interference of multiple point sources originating from the mask plane.

The transparent part of the mask acts as an opening through which light passes, and the opaque region blocks the light. We expect a step function kind of profile, but we observe ripples on the optical intensity profile because of interference and the gradual decay in optical intensity.

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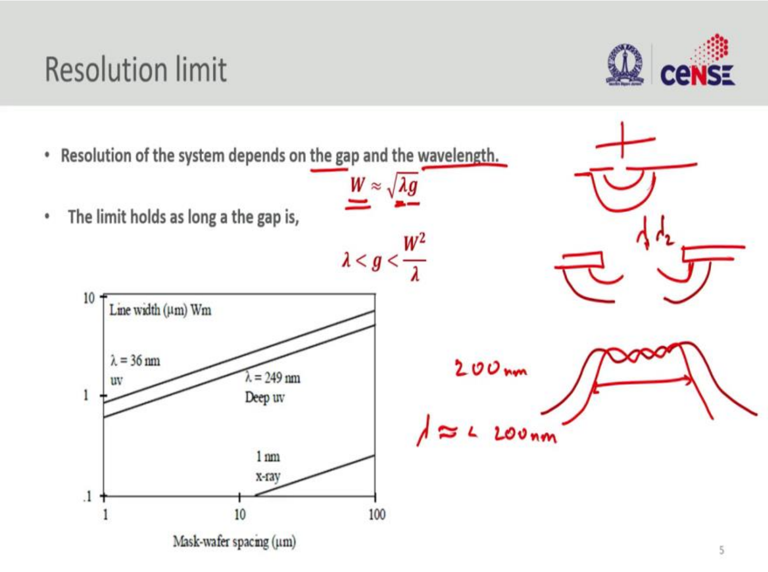

Resolution limit

- Resolution of the system depends on the gap and the wavelength.

$W \approx \sqrt{\lambda g}$

- The limit holds as long a the gap is,

$\lambda < g < \frac{W^2}{\lambda}$

The resolution of the proximity printing depends on the gap and wavelength. The resolution,

$$W \sim \sqrt{\lambda g}$$

Here λ is the wavelength, and g is the gap between the wafer and mask.

Wavelength dictates the scattering. For a given opening, a higher wavelength will have larger diffraction and larger width of the intensity profile compared to the lower wavelength. Hence lower wavelength yields a highly refined image and smaller dimension than an illumination with a larger wavelength. So, it is important to choose the right wavelength for the right structure. For instance, if the feature size is 200 nm, then the choice of wavelength should be equal to or less than 200 nm, which is important to avoid the diffraction effects.

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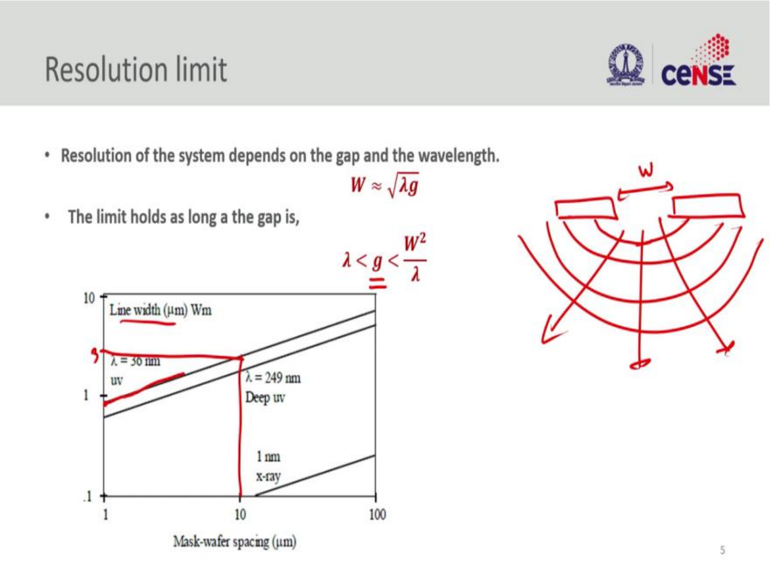

Resolution limit

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$\lambda < \underline{\underline{g}} < \frac{W^2}{\lambda}$

The plot in the above slide shows the effect of mask wafer spacing, g on the line width of the patterns. Suppose we increase the spacing g, the diffraction increases. The diffracting beam will always diverge, which will increase the dimension of the structure that we get on the wafer. So, it is important to choose the right gap as well.

In the above plot for a given wavelength, say 365 nm, as we increase the gap between the mask and the wafer, the line width increases. For instance, if the spacing is 1 µm, the line width will be approximately 900 nm. On increasing the spacing to 10 µm, the structure width will increase to 3 µm. There is a limit to the spacing. The spacing should be greater than the wavelength and less than the mask width. Given as,

$$\lambda < g < \frac{W^2}{\lambda}$$

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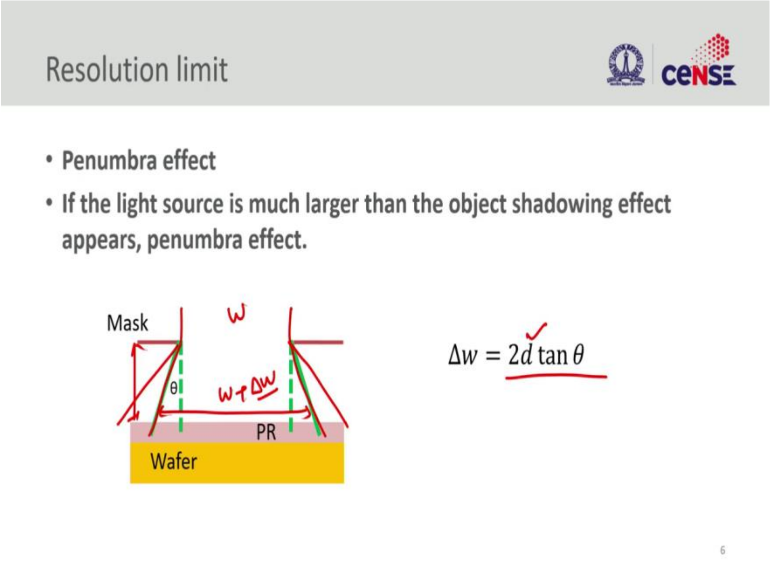

Resolution limit

- Penumbra effect
- If the light source is much larger than the object shadowing effect appears, penumbra effect.

$$\Delta w = 2d \tan\theta$$

The line width of the pattern obtained on the wafer will be larger than that we have on the mask. If w is the width on the mask, the obtained patterns width will be w+Δw. This is due to the gap between the mask and the wafer. ΔW, the increase in dimension is due to the penumbra effect. The increase in the width is given as,

$\Delta w = 2d\tan\theta$, d is the gap between mask and wafer

If we increase the gap, the penumbra effect will also increase. So, it is important to choose the right gap to get the required critical dimension.

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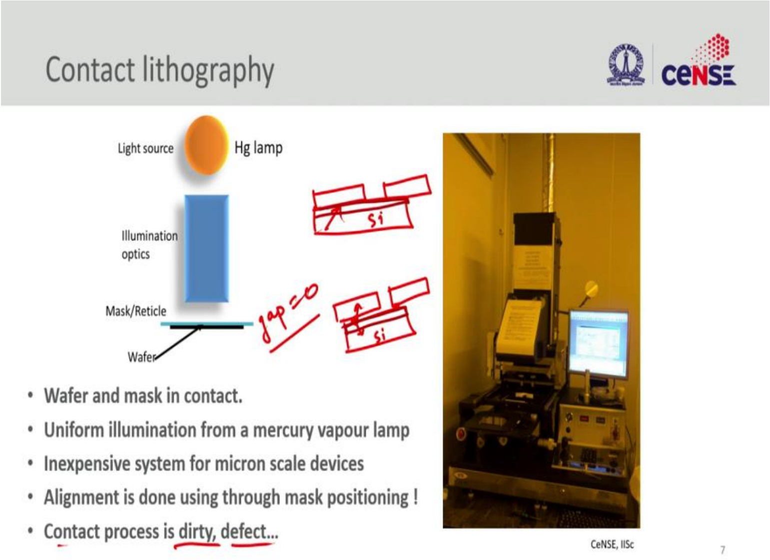

Contact lithography

- Wafer and mask in contact.
- Uniform illumination from a mercury vapour lamp
- Inexpensive system for micron scale devices
- Alignment is done using through mask positioning !
- Contact process is dirty, defect...

The next type of illuminating mechanism is contact lithography. As the name suggests, it is a contact mode; the gap between mask and wafer is zero. Sometimes, it is also called a hard contact technique. The mask and the wafer are in complete contact, which helps in a uniform illumination.

This system, similar to others, is an inexpensive way to fabricate any microscale device. The alignment is done through the mask for multiple layers. In two layers lithography process, say the first layer has some device. In the second layer, we have electrodes for electrical contacts that require alignment, and that alignment is done through the mask positioning.

The only problem in this contact process is that it will make the mask dirty or pass on the dirt in the mask onto the wafer. This will eventually result in a defect in the devices that we are fabricating. Hence the mask and photoresist coated wafer should be kept clean. So, whenever we use contact lithography, we should wash the mask to remove the contaminants or particles sticking to it. If the resist coated wafer or the mask has some particle, the particle will damage the mask or get into the photoresist when they come in contact with each other.

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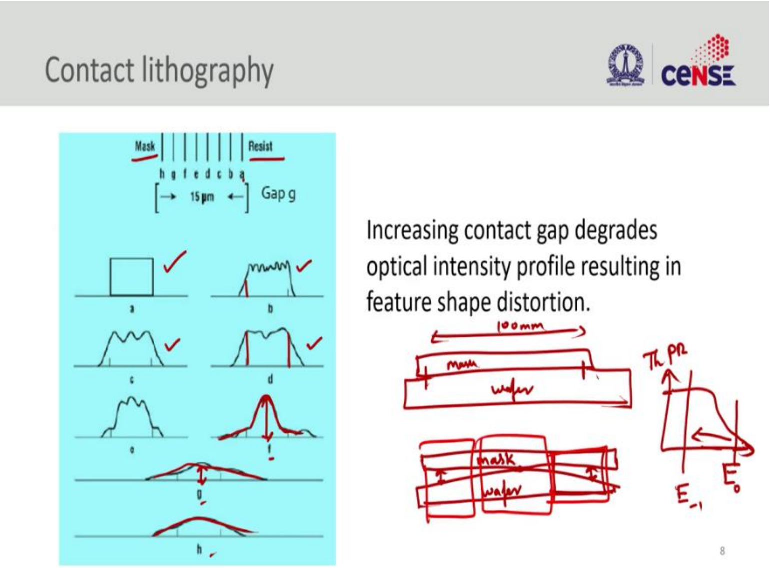

Contact lithography

Increasing contact gap degrades optical intensity profile resulting in feature shape distortion.

In hard contact, the gap between the mask and the wafer should be 0, but in practice there will always be some non-uniformity while fabricating on a large wafer. For example, consider a 100 mm wafer; the mask and the wafer should contact the wafer's length and breadth without any gap. This is hard to achieve. The reason for this is wafer bowing, non-uniformity in the thickness. When this wafer brought in contact with mask, there will be a contact at the centre and some gap at the edges. In the same way, if there is a non-ideal flatness in the mask, the contact will not be uniform throughout the wafer. This would create some unintentional gaps.

The above slide shows the effect of the gap on the optical intensity. If the distance between the resist and the mask is zero, the mask position is at *a*, no gap, then you get step like response, which is ideal. If we slowly increase the gap, non-ideal characteristics, small diffraction start showing similar to the projection proximity printing. On increasing the gap more, this effect worsens, and the critical dimension increases because of the penumbra effect. And intensity, too, goes down.

At point *f*, further away from your resist, we can still see some reasonable intensity, but then it dies down quickly. At positions, g and h intensity profile dies down. In the resist contrast graph, the energy vs. thickness of the photoresist shows that if the energy is too low, it cannot expose the photoresist. The energy should be large enough to clear all the photoresists. But, because of the proximity, the gap is increasing. Hence the intensity is reducing. So, the gap affects the critical dimension and results in unexposed part or underexposure beyond a certain gap.

So, it is important to understand the level beyond which there will not be any illumination. According to the gap, the dose or the intensity of light used for exposure is calibrated in proximity printing. But in hard contact, we always presume there is good contact and that contact dictates the dose. The structures present in the unintended gap will get low or no exposure. If we take the wafer, circuits at the center of the wafer will have desirable dimensions, while the dimensions of the structure at the edges of the wafer will be out of spec.

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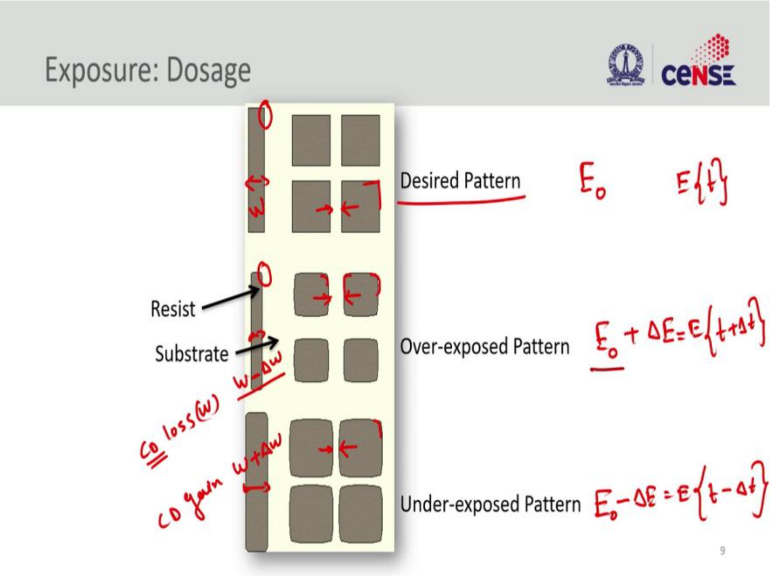

Exposure: Dosage

The exposure dose is the integration of the intensity over time. So, over time, we integrate how much light is passing through the desired pattern called dose. The desired pattern will have sharp corners and well-defined features; we obtain this on ideal exposure E_o.

Overexposure: When we supply more energy compared to the ideal requirement, it will result in corner rounding.

Overexposure, $E_o + \Delta E$.

There are different ways to calculate overdose; for instance, if we keep energy but increase the time, it will give an additional dose.

$E_o+\Delta E = E (t+ \Delta t)$, So, this is called overexposure.

Underexpose: $E_o-\Delta E = E (t - \Delta t)$ we again see corner rounding; this is a resolution limiter.

The important difference between the over and underexposure is the line width of the features. Ideal width is w, overexposure gives w-Δw and underexposure gives w- Δw. (In the above slide we consider the resist is positive and bright regions are exposed region)

When we underexpose, the structure becomes bigger; we are not exposing all the resist that we should have. This argument will completely flip for negative resist. So, one should be you know aware of CD loss or CD gain. CD is the critical dimension, i.e., the width in this case.

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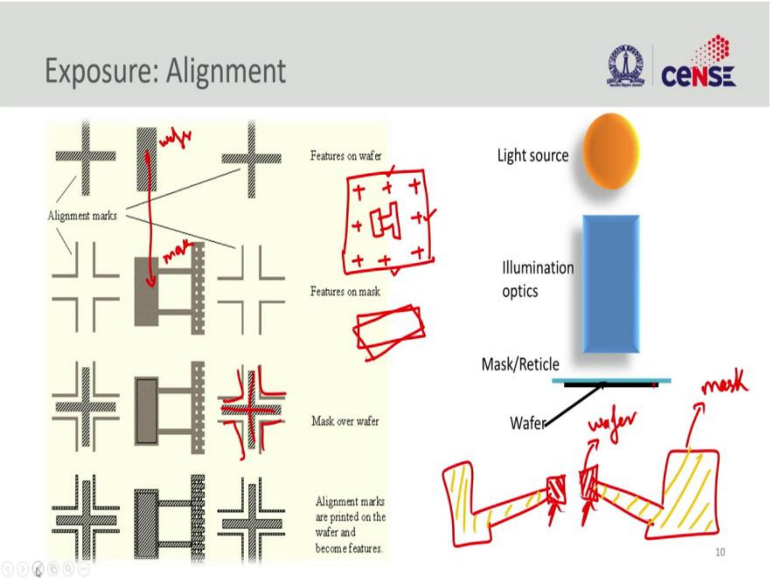

Exposure: Alignment

More often, device fabrication involves multiple layers; a single layer process is hardly used. So, it is important to understand how to align layer 1 with layer 2. For instance, we have a capacitive structure in layer one and electrodes with contact pads in layer 2. So, both device and electric pads should sit on top of each other.

First, we pattern the structures in layer 1 and bring the wafer to the lithography station for the second layer. Now the layer 1 is in the wafer, and the second layer is the mask. It is impossible to align structure by structure, as a mask can have hundreds of devices. Hence to align the two layers together, we use alignment markers. For example, if we have a cross in the first layer, the second layer should have a cross covering that of the first layer. Then we align the cross of layer 1 in the wafer and cross of layer 2 in the mask. This will take care of device alignment as all structures are positioned relatively. Then we do the contact and start illuminating.

In a circuit design, devices will always present at the center and alignment markers at all corners. The alignment markers align the two structures on top of each other and help to avoid rotational misalignment. To take care of rotational misalignment, alignment markers at four corners may not be sufficient; additional markers are desirable too. So, there are many alignment strategies, but these are few simple alignment strategies used in fabrication.

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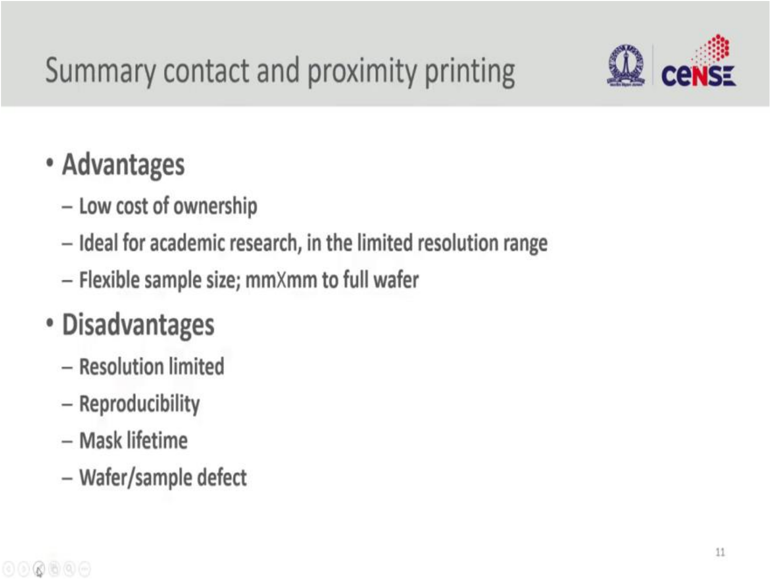

Summary contact and proximity printing

- Advantages
  - Low cost of ownership
  - Ideal for academic research, in the limited resolution range
  - Flexible sample size; mmXmm to full wafer
- Disadvantages
  - Resolution limited
  - Reproducibility
  - Mask lifetime
  - Wafer/sample defect

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To summarize the contact lithography and proximity printing, the major advantage of the system is that these systems are very simple to use, and the cost of ownership or the amount of money spent in maintaining this system is low. Hence it is used a lot in R&D and research world. The limitation of this system is the critical dimension or the resolution that can be achieved. Using a mercury vapor lamp, the minimum wavelength is deep UV.

The other problem associated with this system is damage like scratches or defects due to hard contact. That is the reason we tend to go for the small gap between the mask and the wafer.

Though it is limiting for many high-resolution applications, it is a workhorse for many MEMS technology and devices and circuits that require larger features. Very simple to use, straightforward, no complex optics, easy to maintain the tool, and so on. So, a lot of the R&D establishments use these systems. And another thing is the lifetime of the mask, in both system, there will be some contact that will damage the mask and reduces the mask life time.

In the next lecture, we will see how projection lithography works.