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

## Lecture – 33
## Projection Lithography: Image formation basics

In this session, we are going to look at image formation in a projection lithography system. We will understand how an image of the mask is formed on the wafer in a projection lithography system. Fundamental ideas of optics involved and their concepts will be explained in this chapter.

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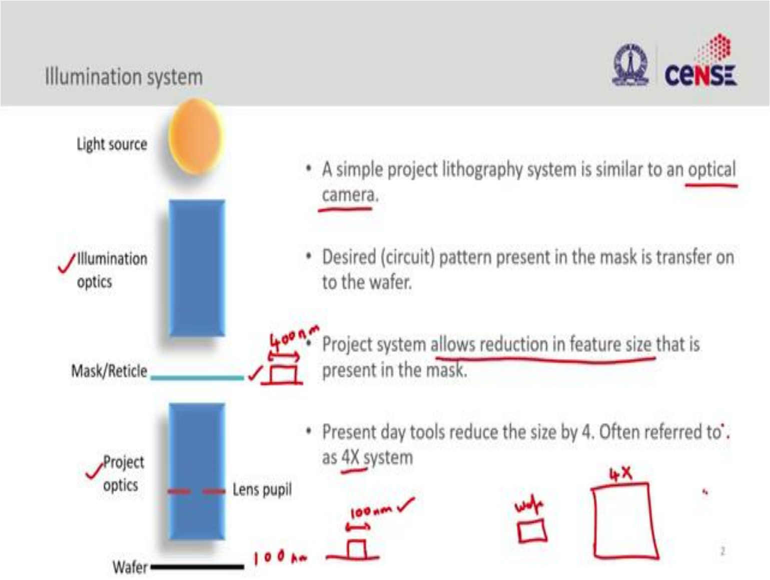

Illumination system

- A simple project lithography system is similar to an optical camera.
- Desired (circuit) pattern present in the mask is transfer on to the wafer.
- Project system allows reduction in feature size that is present in the mask.
- Present day tools reduce the size by 4. Often referred to as 4X system

The projection system is similar to an optical camera. It consists of illuminating optics and projection optics; all the patterns that we want to print on the wafer are captured in the mask. Unlike contact litho and proximity litho, the projection system allows a reduction in feature size between mask and wafer.

Typically the reduction factor could be 4X or 5X. For example, if the required line width on the wafer is 100 nm, at the mask level in contact lithography, it should be 100 nm because it is one to one, but in this case of the projection litho at the mask level, it can have 400 nm. There are many advantages of the reduction; one primary advantage is the mask technology, where getting 100 nm would be technology-intensive, but getting 400 nm may not be. Hence, we can make larger features and then reduce their size.

This shrinking applies to the die size on the wafer as well. On the mask level, the die size will be 4X; all the circuits are going to look larger at the mask level, but when they are projected onto the wafer, they are reduced. This is one of the main advantages of using a projection system.

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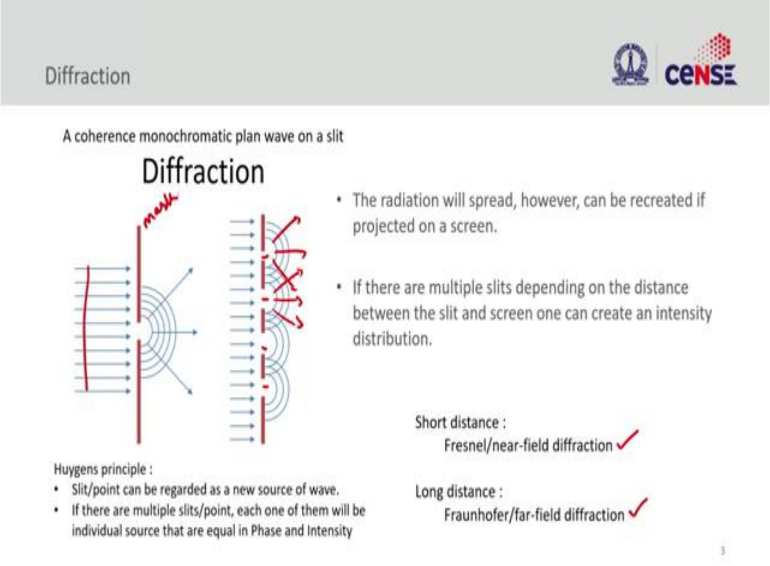

Diffraction

A coherence monochromatic plan wave on a slit

Diffraction

- The radiation will spread, however, can be recreated if projected on a screen.
- If there are multiple slits depending on the distance between the slit and screen one can create an intensity distribution.

Short distance :
Fresnel/near-field diffraction ✓

Long distance :
Fraunhofer/far-field diffraction ✓

Huygens principle :
- Slit/point can be regarded as a new source of wave.
- If there are multiple slits/point, each one of them will be individual source that are equal in Phase and Intensity

Before understanding the imaging, we should understand how the light propagates beyond the mask. To understand the basics, we will consider a plane wave falling on a mask. A mask has a little opening that creates the spherical wavefront and will spread because of diffraction. This is similar to single slit diffraction.

On the other side, if the mask has periodic openings, according to Huygen’s principle, each opening will act as an independent source and produce spherical wavefronts. And, these spherical wavefronts also spread in a different direction. As they propagate, they interfere with each other. This is the basic principle of diffraction from a single slit and multi-slit.

If the slits and screens are close to each other, then the diffraction is a Fresnel; if they are apart, it is called Fraunhofer diffraction limit. If we look at the image at a longer distance, we see an interference pattern. These interference patterns will have variations in intensity, indicating the type of slit opening at the mask level.

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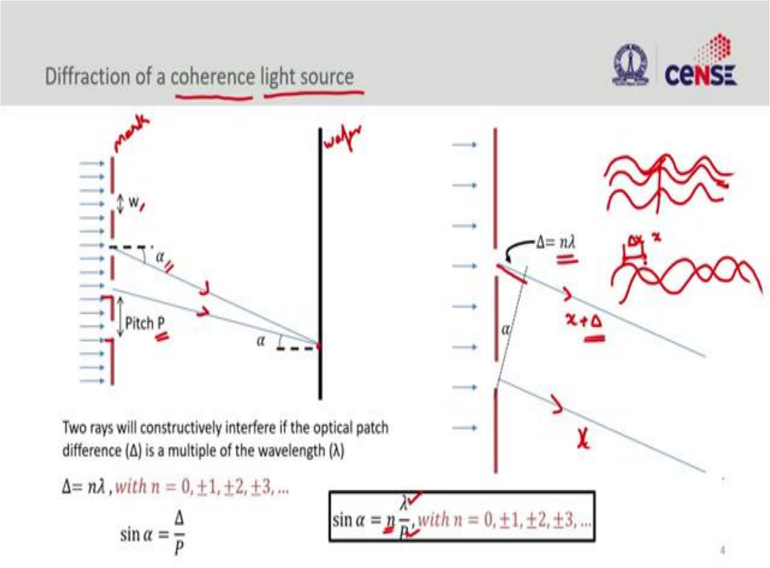

Diffraction of a coherence light source

Two rays will constructively interfere if the optical patch difference (Δ) is a multiple of the wavelength (λ)

$\Delta = n\lambda$, with $n = 0, \pm1, \pm2, \pm3, \ldots$

$\sin\alpha = \frac{\Delta}{P}$

$\boxed{\sin\alpha = n\frac{\lambda}{P}, \text{with } n = 0, \pm1, \pm2, \pm3, \ldots}$

Let us look at the diffraction due to a coherent light source. Light source is said to be coherent if all the waves from the sources have uni-phase or the phase difference between them is 0.

On the other hand, if two waves are traversing with a non-zero phase difference, then the waves are said to be incoherent. For example, a laser light source is a coherent light source, while an incandescent light is an incoherent light source, which you cannot focus. We can focus or propagate a laser without any divergence because the phase difference is 0. The phase difference leads to divergence.

Let us look at how you know diffraction happens in a coherent light source using the ray theory approach.

We will consider a mask with multiple openings, and this opening is characterized by pitch or duty cycle. The opening width is w, as shown in the above slide. The light falling onto the mask will diffract at a certain angle α, and this diffracted light from different slits will meet each other at a certain point and at a certain angle called diffracted angle on the wafer.

The two isolated beams though coming from the same source, act as an individual light source. When these beams interfere, the zoom-in image above shows that a beam from one slit will cover an additional path length compared to the other. This additional path length dictates the phase difference because of the light. If x is the distance travelled by one beam and x+Δx by the other beam, then Δx = nλ is a path difference that dictates the phase difference.

According to the interference principle, the phase difference is very important to create either constructive or destructive interference, and it depends on the order of diffraction (n), the wavelength(λ), and the pitch(P). The interference condition is given by,

$\sin\alpha = n\frac{\lambda}{P}$, n= 0, ±1, ±2, ±3

The angle α between 2 beams(shown in the slide).

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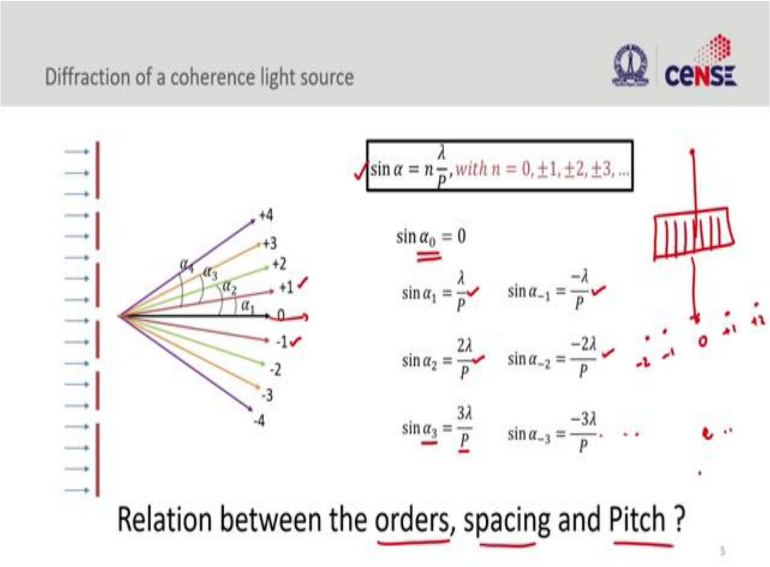

Diffraction of a coherence light source

$\sin\alpha = n\frac{\lambda}{P}, with\ n = 0, \pm1, \pm2, \pm3, \ldots$

$\sin\alpha_0 = 0$

$\sin\alpha_1 = \frac{\lambda}{P}$ $\sin\alpha_{-1} = \frac{-\lambda}{P}$

$\sin\alpha_2 = \frac{2\lambda}{P}$ $\sin\alpha_{-2} = \frac{-2\lambda}{P}$

$\sin\alpha_3 = \frac{3\lambda}{P}$ $\sin\alpha_{-3} = \frac{-3\lambda}{P}$

Relation between the orders, spacing and Pitch ?

Now we will look at how this angle evolves with change in n.

In the equation,

$\sin\alpha = n\frac{\lambda}{P}$, n= 0, ±1, ±2, ±3 is the order of diffraction

For, n=0, $\sin\alpha_0 = 0$, no diffraction, the beam passes straight.

+ n represents the diffraction orders falling above n=0 on the screen and – n falls below the n=0.

n=1 $\sin\alpha_1 = \frac{\lambda}{P}$, n= -1, $\sin\alpha_{-1} = -\frac{\lambda}{P}$

n=2 $\sin\alpha_{-2} = \frac{2\lambda}{P}$, n= -2 $\sin\alpha_{-2} = -\frac{2\lambda}{P}$

n=3 $\sin\alpha_{-3} = \frac{3\lambda}{P}$, n= -3 $\sin\alpha_{-3} = -\frac{3\lambda}{P}$

We can see how diffraction, order spacing, and pitch are all related. Any periodic structure eliminated with a coherent light source will create these diffraction orders. The angle changes as we increase the orders, and it is related to pitch as well. When we change the pitch, the angle will change for a given lambda.

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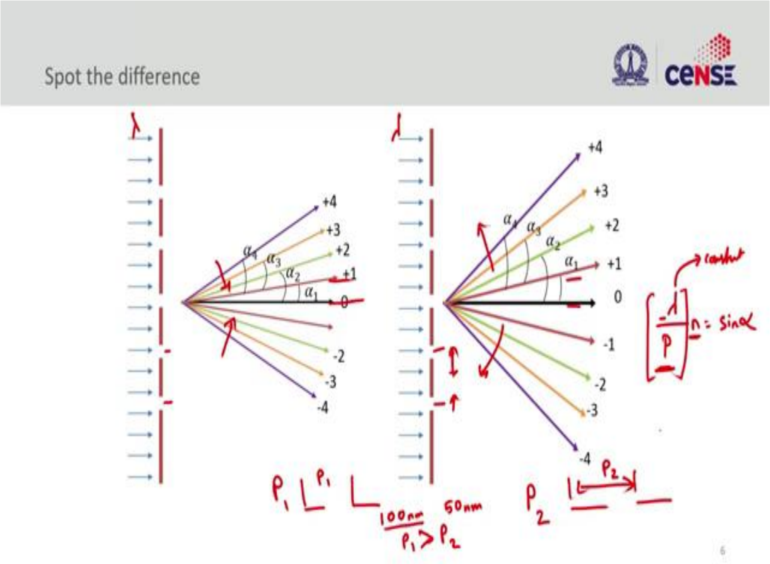
Spot the difference

The above shows two diffraction order images; the left side shows the distance between 0th order and the 1st order or $\alpha_1$ is smaller than the right side's $\alpha_2$. Here we assume that both patterns are illuminated with the same wavelength.

Equation, $\sin\alpha = n\frac{\lambda}{P}$, shows that angle α depends on n, λ, and P. In the above case, the only change is the pitch. These two diffraction orders come from two different pitches.

The above equation shows that the larger the pitch P, α will be smaller. Pitch being the distance between the slits, the left pitch is P1, and the right one is P2, then P1> P2. For example, if P1 is 100 nm and P2 could be 50 nm.

If the pitch is larger, then the diffraction orders will be densely spaced, and if the spacing is narrower, then the diffraction orders will move away or spread widely. Here the angle between the diffraction orders is between the 0th order and the other orders, and the angle is evolving.

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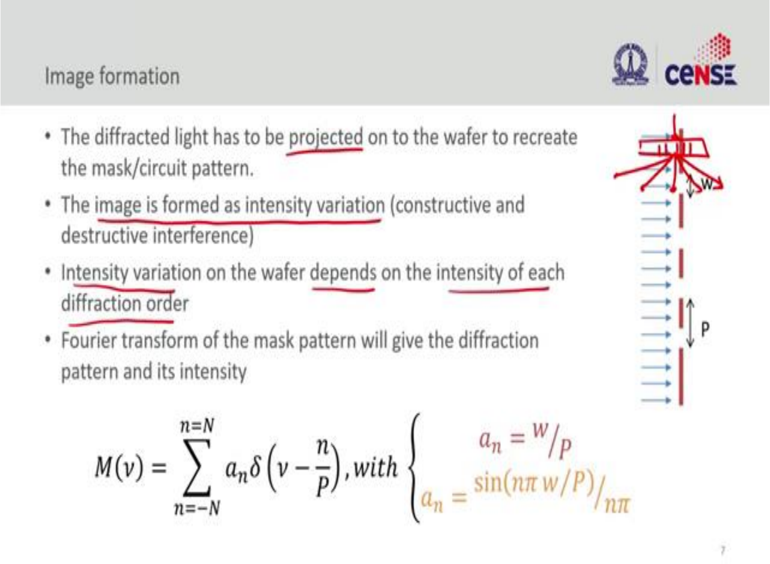

Image formation

- The diffracted light has to be projected on to the wafer to recreate the mask/circuit pattern.
- The image is formed as intensity variation (constructive and destructive interference)
- Intensity variation on the wafer depends on the intensity of each diffraction order
- Fourier transform of the mask pattern will give the diffraction pattern and its intensity

$$M(\nu) = \sum_{n=-N}^{n=N} a_n \delta\left(\nu - \frac{n}{P}\right), with \begin{cases} a_n = {}^{W}/_{P} \\ a_n = {}^{\sin(n\pi w/P)}/_{n\pi} \end{cases}$$

In the image formation, to capture the image or circuit present on the mask, we have to project the diffraction orders onto the wafer. The image formation is nothing but an intensity variation on the wafer, and this intensity variation will change the solubility of the photoresist.

The intensity variation depends on the intensity of each diffraction order and the number of orders captured. When we illuminate the mask with a light source, it creates the diffraction orders, which is a Fourier transformation of the patterns of the mask. These different diffraction orders depend on the pitch, and then we expand it as the Fourier series. The above slide shows the Fourier series expansion of the structure given on the right-hand side of the slide.

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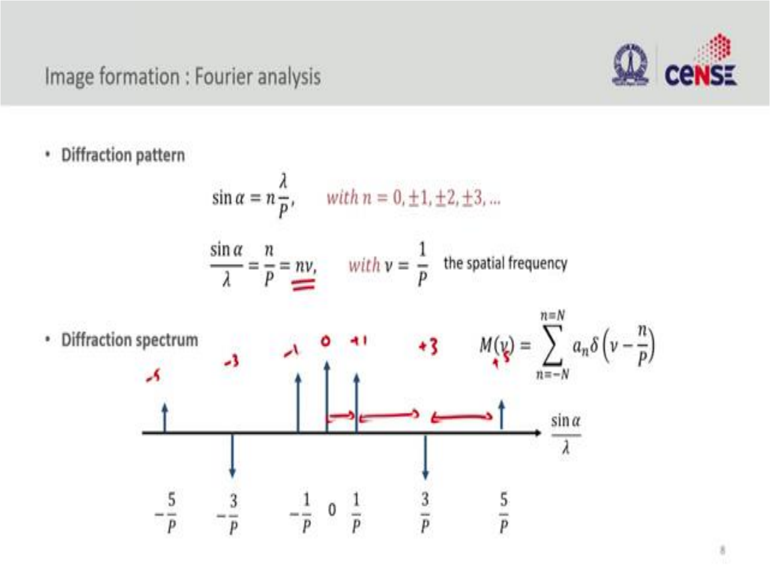

Image formation : Fourier analysis

- **Diffraction pattern**

$$\sin\alpha = n\frac{\lambda}{P}, \quad with\, n = 0, \pm1, \pm2, \pm3, \ldots$$

$$\frac{\sin\alpha}{\lambda} = \frac{n}{P} = \underline{\underline{n\nu}}, \quad with\, \nu = \frac{1}{P} \text{ the spatial frequency}$$

- **Diffraction spectrum**

$$M(\nu) = \sum_{n=-N}^{n=N} a_n \delta\left(\nu - \frac{n}{P}\right)$$

We know, $\sin\alpha = n\frac{\lambda}{P}$, n= 0, ±1, ±2, ±3

On rearranging, we get $\frac{\sin\alpha}{\lambda} = \frac{n}{P} = n\nu \quad with\, \nu = \frac{1}{P}$ is the spatial frequency.

The diffraction pattern appears as a spectrum of diffraction orders. These different diffraction orders have some spatial frequency, i.e., they are located at some frequencies from the $0^{th}$ order, as shown in the slide above. As we move outside from the $0^{th}$ order, we see the distance between the orders change; this we know from Fourier analysis. This property also dictates the resolution.

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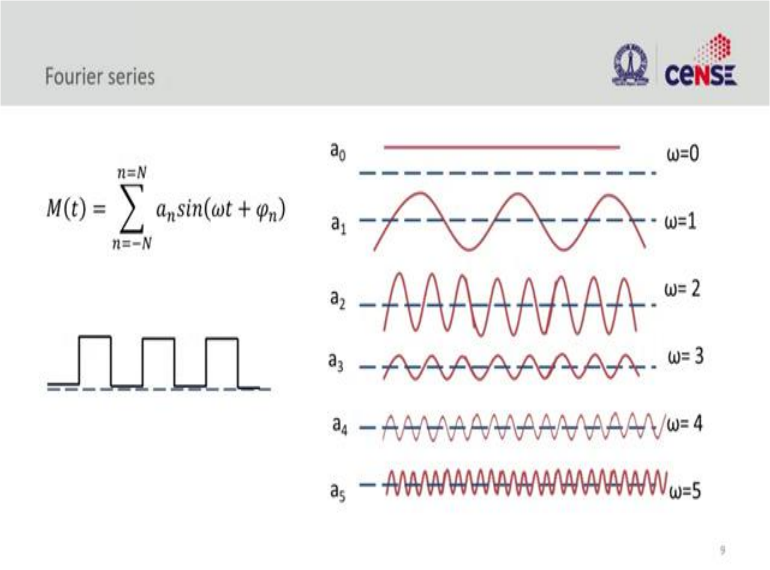

Fourier series

$$M(t) = \sum_{n=-N}^{n=N} a_n sin(\omega t + \varphi_n)$$

The sinusoidal decomposition of a square pulse is shown in the above slide. It is the series expansion that gives series of different coefficients with various frequencies. Each corresponds to different diffraction orders

If we want to reconstruct the square wave, we have to capture these orders and then add them, which is nothing but interference. To accurately reproduce the image, here the square pulse, we need as many coefficients as possible. If the series is infinite, then the perfect reconstruction could be done by all the possible coefficients. But in practice, it is impossible to do it, which is why we use the series to restrict our data set. So, for instance, we can reasonably well reproduce the square pulse by using ω=0, 1, 2, and 3.

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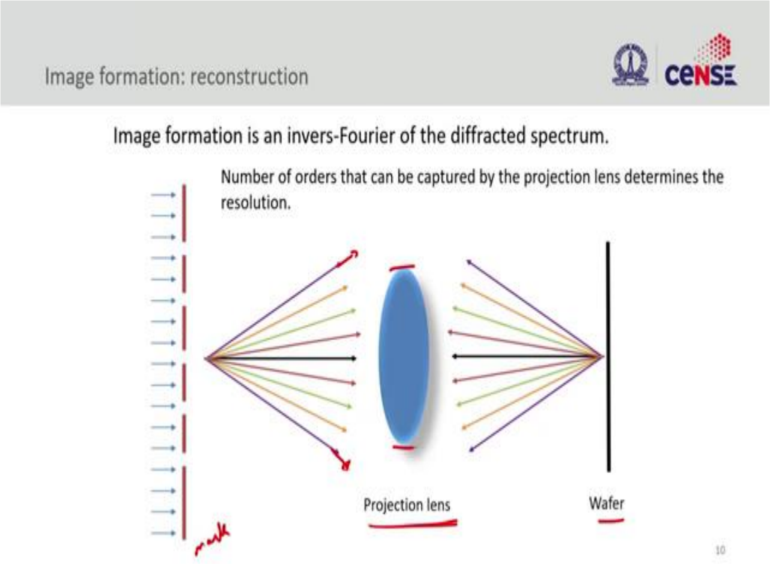

### Image formation: reconstruction

Image formation is an invers-Fourier of the diffracted spectrum.

Number of orders that can be captured by the projection lens determines the resolution.

The projection lens captures the diffraction orders, nothing but the Fourier terms. The image from the mask in projection litho is imaged onto the wafer using the lens system. As mentioned, we need to capture as many coefficients as possible. But there is a physical limitation of the lens; we cannot have a large lens.

The resolution depends on the projection lens system.

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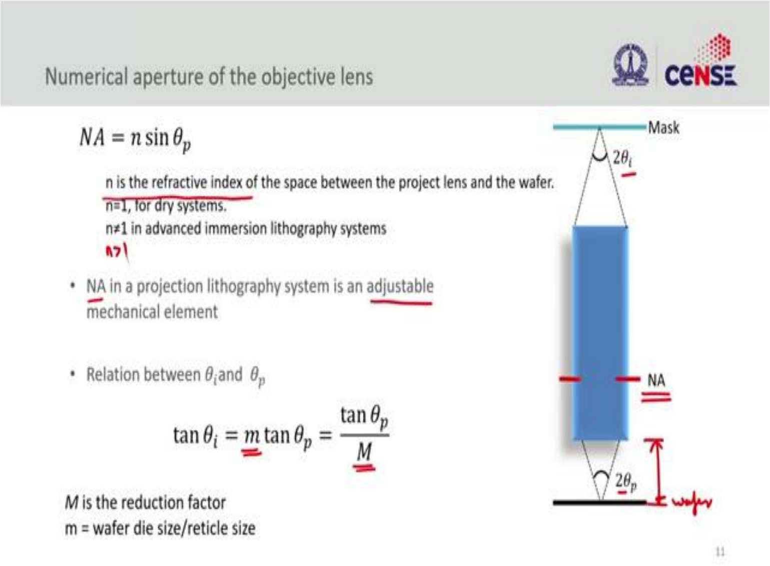

### Numerical aperture of the objective lens

$NA = n \sin\theta_p$

n is the refractive index of the space between the project lens and the wafer.
n=1, for dry systems.
$n \neq 1$ in advanced immersion lithography systems
$n > 1$

- NA in a projection lithography system is an adjustable mechanical element
- Relation between $\theta_i$ and $\theta_p$

$$\tan\theta_i = \underline{m}\tan\theta_p = \frac{\tan\theta_p}{\underline{M}}$$

M is the reduction factor
m = wafer die size/reticle size

In the projection lens has a characteristic numerical aperture.

$NA = n \sin\theta_p$

Where n is the refractive index of the space between the projection lens and the wafer. Similar to microscopy, space can be filled with air, n= 1 or some liquid (water or oil) with n>1. It is called immersion lithography used for advanced litho patterning

Here the NA is tunable. In most of the system, this is a mechanical blanker and which blanks the beam. The relation between the incident angle coming from the mask after diffraction and the projection angle is given by

$$\tan\theta_i = m \tan\theta_p = \frac{\tan\theta_p}{M}$$

Here m is the ratio of the size of the die on wafer to that on the mask ( reticle size). It is nothing but the size deviation, and M is the reduction factor.

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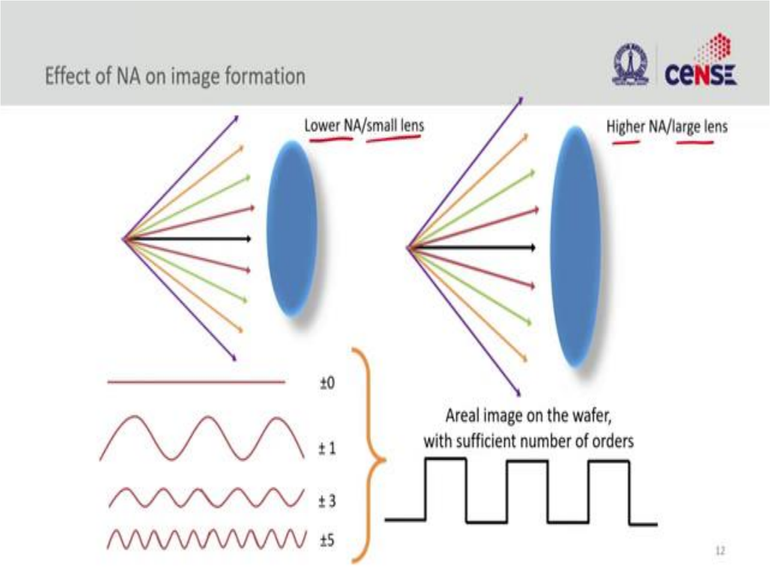

Effect of NA on image formation

Lower NA/small lens

Higher NA/large lens

Areal image on the wafer, with sufficient number of orders

If NA is low or the lens is small, then the lens will be unable to capture all the diffraction orders; capture only a few orders will be captured. If we have a larger NA or larger lens, it will capture the majority of diffraction orders that we would want. So, this is adding more number of higher-order Fourier terms.

When we increase the number of terms, then the areal image will be much better. The areal image is nothing but the reconstructed image on the wafer or the intensity variation.

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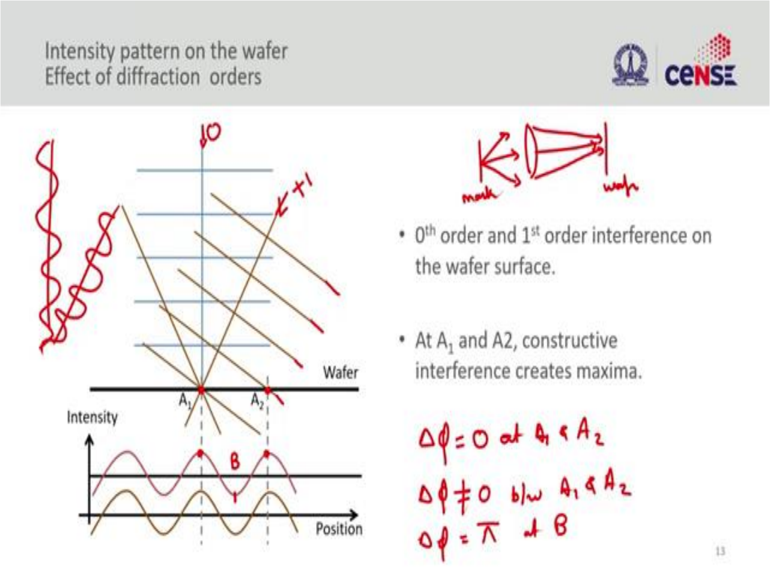

Intensity pattern on the wafer
Effect of diffraction orders

- $0^{th}$ order and $1^{st}$ order interference on the wafer surface.
- At $A_1$ and A2, constructive interference creates maxima.

$\Delta\phi = 0$ at $A_1$ & $A_2$

$\Delta\phi \neq 0$ b/w $A_1$ & $A_2$

$\Delta\phi = \pi$ at B

Initially, we saw the diffraction effect on a mask, and then we saw what is going to happen in the projection optics, and now we are on the surface of the wafer.

In the above slide, we see 0th order, without any angle, and then 1st order (n=1). The angle is changed because the diffracted beam is focused using the lens. The figure shows ray path of 2 waves, $0^{th}$ order $1^{st}$ order, and below it is the instance where both the wave are in phase.

In order to create constructive interference, the phase difference between the two beams should be 0. In the above figure, at A1 and A2 phase difference between 2 rays is zero, hence the high intensity. And if the phase difference is $\pi$, then they destructively interfere.

This is how interference happens on the wafer and creates this intensity profile, and it is the primary requirement for removing the resist.

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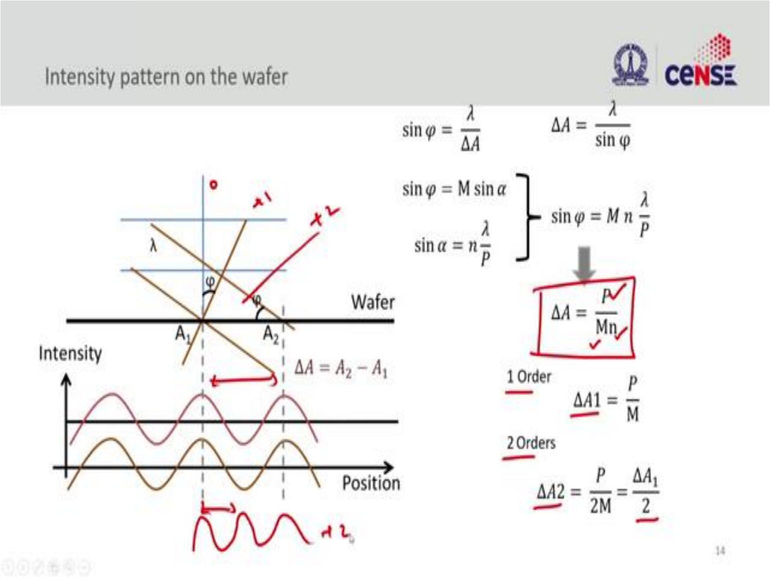

Intensity pattern on the wafer

$$\sin\varphi = \frac{\lambda}{\Delta A} \qquad \Delta A = \frac{\lambda}{\sin\varphi}$$

$$\left.\begin{aligned}\sin\varphi &= M\sin\alpha\\ \sin\alpha &= n\frac{\lambda}{P}\end{aligned}\right\} \sin\varphi = M\,n\,\frac{\lambda}{P}$$

$$\boxed{\Delta A = \frac{P}{Mn}}$$

1 Order

$$\Delta A1 = \frac{P}{M}$$

2 Orders

$$\Delta A2 = \frac{P}{2M} = \frac{\Delta A_1}{2}$$

Now we will see what happens if we add more orders. Given as,

$$sin\phi = \frac{\lambda}{\Delta A} \text{ ……….1}$$

Where ΔA is the distance between the two constructive interference patterns. ϕ is the projection angle, which is the angle between the 1st order and 0th order ray falling on the wafer.

For small angles, sinϕ = M sinα…….2

and α is the incident angle coming from the mask after diffraction.

$$\sin\alpha = n\,\frac{\lambda}{P}\text{……….3}$$

Substituting eqn 3 in eqn1Gives,

$$\sin\phi = Mn\,\frac{\lambda}{P}\text{………4}$$

On substituting eqn4 in eqn1 gives,

$$\Delta A = \frac{P}{Mn}$$

ΔA depends on the pitch, P and the magnification,M that you have and also order.

$$\text{For, n=1,}\ \Delta A1 = \frac{P}{M}$$

$$\text{n=2,}\ \Delta A2 = \frac{P}{2M}$$

when order is 2 distance between A1 and A2, i.e., ΔA2 is less compared to ΔA1

Hence with the higher number of orders, we can realize small dimensions; one can increase the resolution by adding or capturing more orders.

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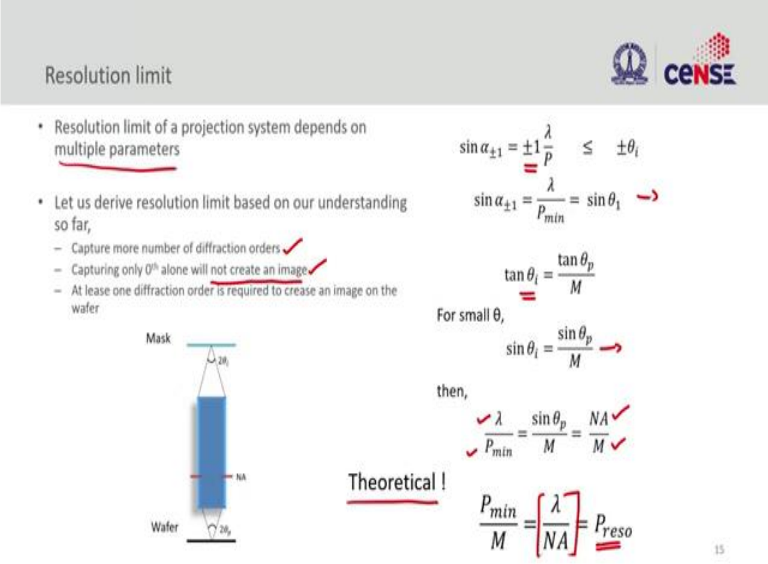

## Resolution limit

- Resolution limit of a projection system depends on multiple parameters
- Let us derive resolution limit based on our understanding so far,
  - Capture more number of diffraction orders ✓
  - Capturing only 0th alone will not create an image ✓
  - At lease one diffraction order is required to crease an image on the wafer

$$\sin\alpha_{\pm 1} = \pm 1\frac{\lambda}{P} \quad \leq \quad \pm\theta_i$$

$$\sin\alpha_{\pm 1} = \frac{\lambda}{P_{min}} = \sin\theta_1$$

$$\tan\theta_i = \frac{\tan\theta_p}{M}$$

For small θ,

$$\sin\theta_i = \frac{\sin\theta_p}{M}$$

then,

$$\checkmark\frac{\lambda}{P_{min}} = \frac{\sin\theta_p}{M} = \frac{NA}{M}\checkmark$$

Theoretical !

$$\frac{P_{min}}{M} = \left[\frac{\lambda}{NA}\right] = P_{reso}$$

The resolution of the projection system does not just depend on the wavelength,  there are multiple factors associated with it. Let us arrive at this resolution limit.

$$\text{For n= ±1,}\ \sin\alpha_{\pm 1} = \pm 1\frac{\lambda}{P} \leq \theta_i$$

$$\sin\alpha_{\pm 1} = \frac{\lambda}{P_{min}} = sin\theta_i\ldots\ldots 1$$

$$\tan\theta_i = \frac{tan\theta_p}{M}$$

For small θ,

$$\sin\theta_i = \frac{\sin\theta_p}{M}\text{.............}2$$

$$NA = \sin\theta_p \text{ , for } n=1\text{..........}3$$

From equation 1 , 2 and 3

$$\frac{\lambda}{P_{min}} = \frac{\sin\theta_i}{M} = \frac{NA}{M}$$

$$\frac{P_{min}}{M} = \frac{\lambda}{NA} = P_{res}$$

$\frac{\lambda}{NA}$ is the diffraction limit.

We have arrived at this relation completely different way compared to traditional optics. The resolution depends on the number of captured orders.

We should also know that only one order will not create any image. If we just use 0th order or only 1st order, that will not create an image. Image creation is always based on interference. So, interference requires at least two orders.

The resolution limit derived is just a theoretical limit because we focused only on the optics, the magnification factor, NA, and diffraction at the mask.

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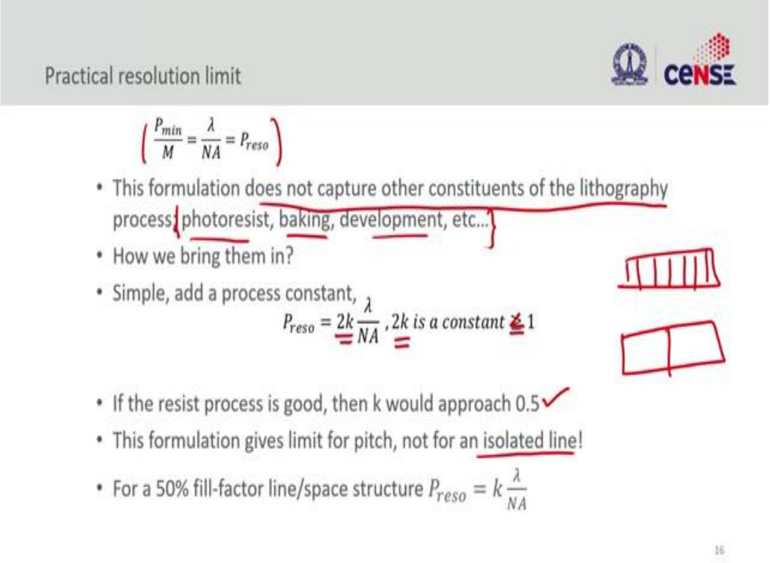

Practical resolution limit

$$\left(\frac{P_{min}}{M} = \frac{\lambda}{NA} = P_{reso}\right)$$

- This formulation does not capture other constituents of the lithography process{photoresist, baking, development, etc...}
- How we bring them in?
- Simple, add a process constant,

$$P_{reso} = 2k\frac{\lambda}{NA}\text{, }2k \text{ is a constant} \leq 1$$

- If the resist process is good, then k would approach 0.5✓
- This formulation gives limit for pitch, not for an isolated line!
- For a 50% fill-factor line/space structure $P_{reso} = k\frac{\lambda}{NA}$

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$$\frac{P_{min}}{M} = \frac{\lambda}{NA} = P_{res}$$

The theoretical limit is derived considering only the optics. It does not capture other constituents in lithography, process parameter like photoresists, baking, the development. So, we cannot rely on the above equation as the limit.

$P_{res} = 2k\frac{\lambda}{NA}$, $2k \leq 1$

Here k is some constant; it dictates how good the process could be. By controlling the photoresist process like baking and development, we will get features that are lower than the diffraction limit dictated by optics, k will approach 0.5. It means that we can reduce dimension and have better resolution.

What happens in an isolated line? What is the resolution limit for such an isolated line? It is left to think of as an exercise.

We focused on the dense line-space pattern because most of the fabrication, like memory or microprocessor-based devices, require many lines as gates and very closely spaced metal lines.

In this lecture, we saw how to create patterns, the areal image or intensity pattern on the wafer; this image or intensity pattern should be translated into the photoresist. In the next lecture, we will see how one can transfer the pattern that we have on the mask onto the resist.