Fundamentals of Micro and Nanofabrication
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Lecture – 34
Projection Lithography: Image formation in photoresist

In the last lecture, we saw how the intensity patterns are created on the wafer. In continuation, in this lecture, we will see image formation by variation in intensity, particularly how the image is formed on the resist.

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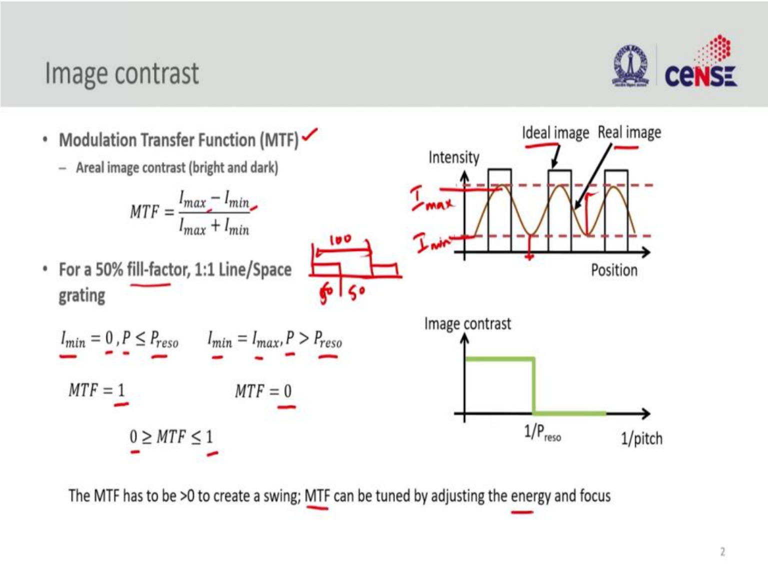

The image contrast on the photoresist is what brings out the solubility change in the photoresist. So an ideal grating image should have a step-like function, with high-intensity I_{max} and low intensity, I_{min} on the wafer. But in a real image, we will have an oscillating or a cosine type image, as we see in the above slide.

The metric that we use to quantify whether this image contrast that we have is sufficient to create the modulation that we are looking for on the wafer or on the photoresist is called the modulation transfer function.

Modulation transfer function,

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

The larger the ratio, the image can be transferred reliably.

For a 50-50 fill-factor (duty cycle). For example, if the pitch is 100 nm, for the 50 % fill factor, the line width is 50 nm and space is 50 nm.

If Imin =0, then the pitch is below the limit right of the system right, i.e., P≤ Pres so that we can reproduce the image. Here MTF=1, perfect reproduction of the image.

If $I_{min} = I_{max}$, then there is no contrast in the system. That means the pitch used is greater than what the system can. It is beyond the resolution. In this case MTF=0

0< MTF ≤ 1, MTF anywhere between 1 and 0 there will be partial reproduction, which is reasonably good for a lot of applications.

For a step-like function image contrast, 1 will create the image and 0 will not. So, we have to make sure that we create this contrast by tuning and adjusting the energy and the focus. We will see that in the next slide why we do not need MTF=1 in order to reproduce the image.

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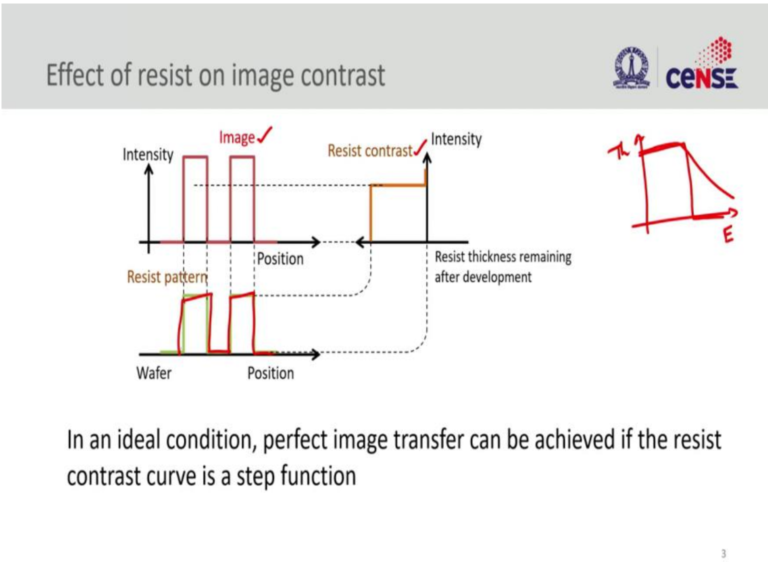

In an ideal situation, if image contrast is a perfect square-like pattern and the resists contrast (energy versus thick remaining thickness) is also a perfect step-like function, then the image that we get on the wafer is also a reproduction of that intensity that we had in the image contrast. So, in an ideal condition, perfect imaging is possible when we have a high contrast image and high contrast photoresist.

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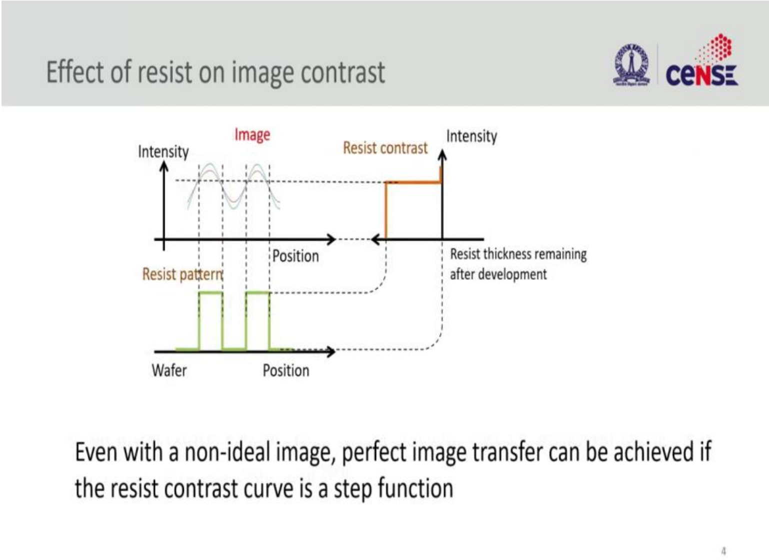

In practice, the image is not a perfect square. The image contrast is not 1 anymore; it is less than 1 but more than 0. In the above slide, we can see that the image contrast is not a perfect step-like response, but the resists contrast is a step-like function. Still, a perfectly square pattern on the wafer is reproduced. The reason for this is the resists contrast actually takes care of the variation because there is only one threshold optical intensity point, above which it will not dissolves the photoresist, and below that, it will dissolve (in case of negative resist). So, this is an example of using a high contrast or perfect resist with a non-ideal image. This is again not practical because it is impossible to get a step like resist contrast; we will always have some slope.

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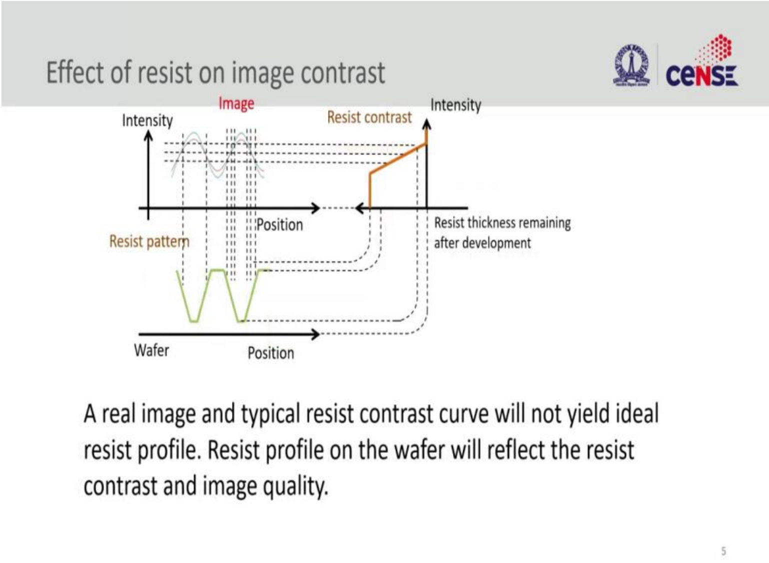

This is the practical real image case. The image has a modulation transfer function, MTF less than 1. And the resist contrast has a slope; this is a more practical approach. When on the projection of these different intensities, will develop the resist following the same profile. The resist pattern profile on the wafer is a combination of the resist slope and the image intensity slope.

In the above slide, we can see in the resist image that the resist is not completely removed; if we increase the dose, the remaining photoresist can be removed and try to reduce the slope to some extent. But the bottom line is that we will have a sidewall that is a reproduction of photoresist contrast in a real image. But then again, we can solve this problem by using a proper development process and baking process. Hence, the resist process technology will be useful in addressing the slope issue and make it reasonably vertical.

So, this is how we transfer the pattern from the image contrast or intensity pattern onto the photoresist pattern. So, we have understood how the change in the intensity profile is converted to the three-dimensional pattern on the photoresist.

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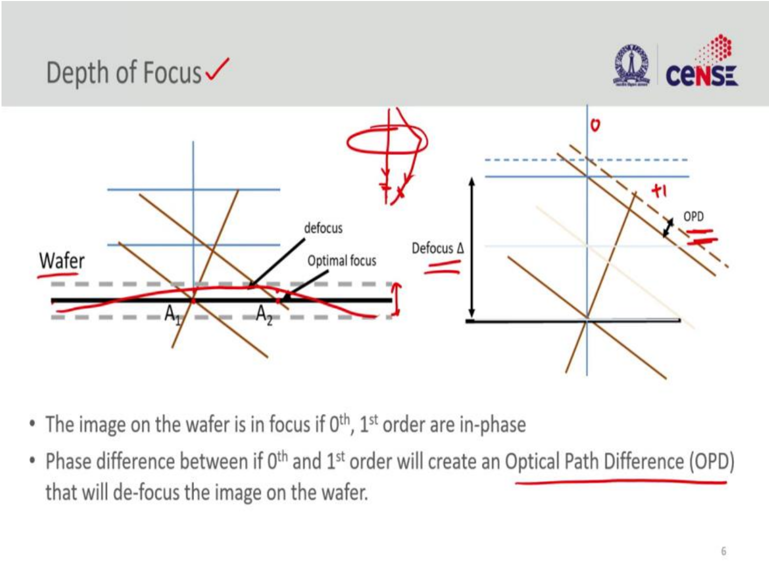

Now let us look at some important practical scenarios.

The interference is the main process that we need in order to create an image. But then, so far, we did not discuss anything about the wafer flatness, we assumed that the wafer is flat, but in practice, there can be non-uniformity in the wafer thickness. In the case of non-uniformity in the wafer thickness, to reproduce the same image, we have to understand the depth of focus concept.

In a practical scenario, to focus on an image using an optical camera, we will change the lens position. If we go beyond an optimal focus, the image will get blurred, and also under focus will make the image blurred. If the image plane is not flat, few parts of the image will go into the defocus regime and will not reproduce the required image quality. But when we are in optimal focus, if we change the focus very slightly, we will not see any change in the quality of the image, both plus or minus. This small change in focus is the tolerance of the focal plane within which the image quality is maintained; only beyond this, the image quality will degrade—this called depth of focus.

The same concept is applied here on the wafer. In this case, the depth of focus depends on the interference. If the wafer is not flat because of wafer bending or the placement of the wafer, then there is a change in the focal plane. Hence we need some defocusing depth within which we have perfect imaging, which is called a defocus width.

The defocusing width is a result of the non-flatness of the wafer and the diffracted image orders. When a 0th order and 1st order fall on the wafer, 1st order would have traveled an extra path than the 0th order, as it travels straight. This optical path difference will lead to the phase difference, which will lead to defocusing. Hence, even if we have a flat wafer, there can still be some path difference, creating defocus of the image on the wafer.

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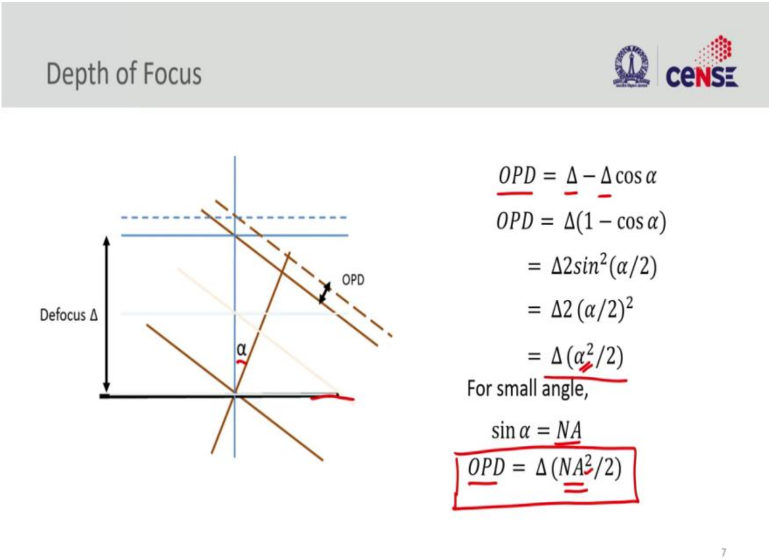

If Δ is the defocus, and α is the angle between the first order and the 0th order, then the optical path length difference between the first order and the 0th order is given as

$OPD = \Delta - \Delta \cos\alpha$

$OPD = \Delta (1 - \cos\alpha)$

$= 2\Delta \sin^2(\alpha/2)$

$= \Delta (\alpha^2/2)$

For small angle, $\sin\alpha = NA$

Then , $OPD == \Delta (NA^2/2)$

Earlier, we saw that a larger lens would allow us to collect more diffraction orders, and more orders we collect, the better the image.

But in the above equation for optical path difference, NA is in the numerator. So, if we increase NA, the optical path difference will increase. Consequently, you will have to defocus effects, and the image won't form perfectly on the image plane as a consequence of the optical path lens difference. Hence NA shouldn't be large.

We have to restrict to optimum NA; it should not be large. If NA is large, it captures more light, reducing focus depth; focus depth becomes very thin. Hence NA is a deciding factor.

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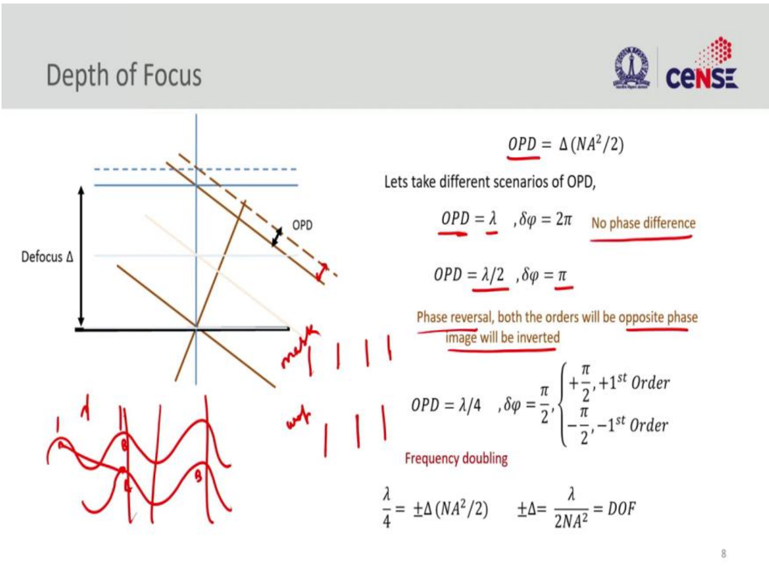

We will see how a change in OPD affects the imaging. We know that

$$OPD = \Delta\,(NA^2/2)$$

If OPD = λ , then phase difference $\delta\phi = 2\pi$

Similar to interference discussion, the wave will be shifted by one λ in comparison to the other, so the phase difference is zero. Hence the two waves will interfere constructively.

.If OPD = $\lambda/2$, then phase difference $\delta\phi = \pi$

This phase reversal between these two orders will create an opposite phase image. So there will be an inverted image. When we illuminate this light on the mask, the wafer will have complete image reversal. If we have lines in the mask, it will form a trench in the wafer, and it will form a line wherever there is a trench. So, there is a total image reversal, which is undesirable.

If OPD = $\lambda/4$, then phase difference $\delta\phi = \pi/2 \begin{cases} +\frac{\pi}{2}, +1\ order \\ -\frac{\pi}{2}, -1\ order \end{cases}$

This is called frequency doubling.

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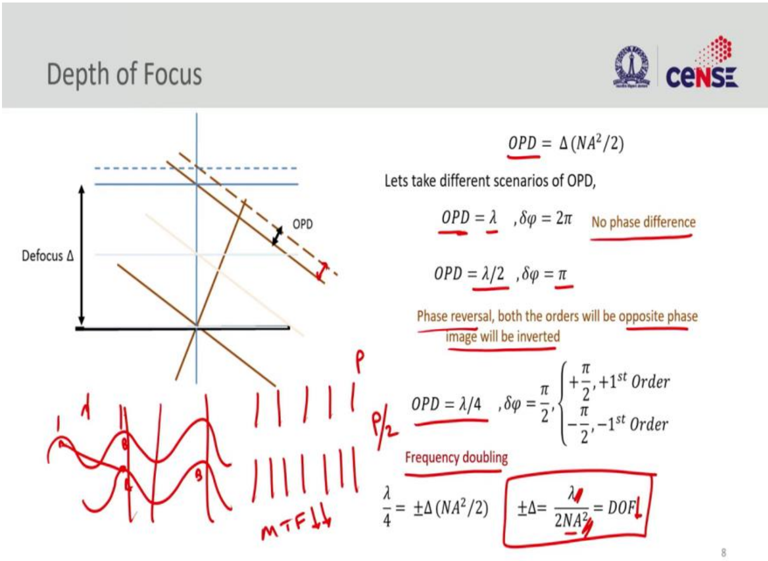

In frequency doubling, if the mask has a pitch of P, then the image on the wafer will have pitch P/2 because of frequency doubling. This is not desirable because the pitch is smaller than expected. The next layer is not prepared to accept these variations because whatever we have on the mask is what we want on the wafer.

This reduction in pitch seems interesting, we will be tempted to use that, but the problem in frequency doubling is that the image contrast, MTF, will go down. In the areal image, we will see the double pitch, but then the MTF will be very poor. So, we would not be able to reproduce, as the exposed light won't be able to remove all the resist and create the image reliably; so, it is not advisable to tune to these phase differences.

To conclude, depth of focus is a factor of NA and wavelength. So, if we increase NA, the depth of focus will reduce and also the image quality.

So far, we have discussed the depth of focus in a practical scenario. But we have considered the light source to be coherent, where all the photons coming out are in phase, and a single laser will be a very narrow line. But lasers do have a line width. Instead, it will be few tens of picometers or hundreds of picometers depending on the laser's quality. And these line width means the photons are not in phase. So, the light is partially coherent; that is the practical scenario. Let us see how the imaging will be affected if this partially coherent light source is used.

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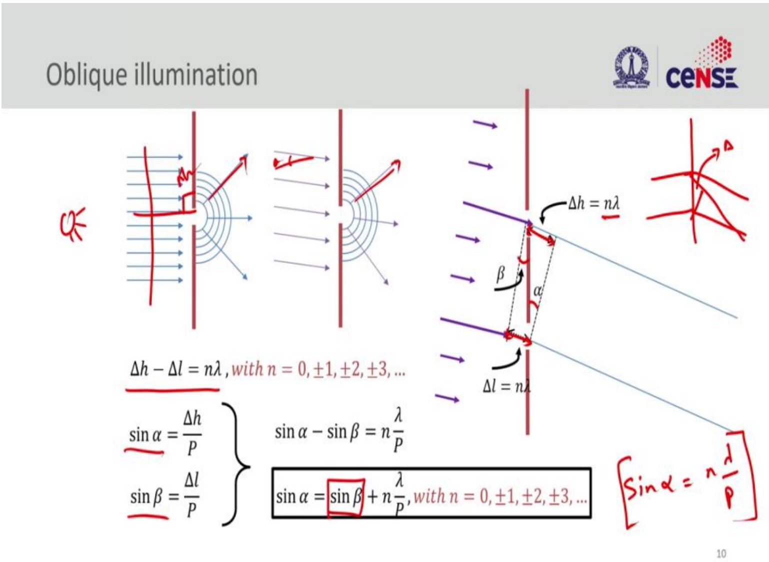

Let us look at the incident first. In previous discussions, we considered perpendicular incidence, but in reality, the light source will have some angle. So, there will be some variation in the angle at which the photons are coming, which will directly influence the diffraction orders.

In the normal incidence, we have one additional distance the wave should travel before interfering, one path difference. But in the oblique incidence case, we have two path length differences because both are at a slightly different angle. So, there is an incident angle, and there is an exit angle, shown in the figure.

So, there are two angles, and two different optical. The condition for a constructive interference now is

$$\Delta h - \Delta l = n\lambda$$

Δh and Δl are the extra path length on the incident side and exit (refer to the above image).

If n=0, ±1, ±2, ±3, then the phase is preserved.

$$sin\alpha = \frac{\Delta h}{P} \text{ for exit angle.}$$

$$sin\beta = \frac{\Delta l}{P} \text{ for incident angle.}$$

$$sin\alpha - sin\beta = \frac{\Delta h - \Delta l}{P} = \frac{n\lambda}{P}$$

$$sin\alpha = sin\beta + \frac{n\lambda}{P}$$

On comparing with normal incidence conditions,

$$sin\alpha = \frac{n\lambda}{P}$$

Oblique incidence has an additional term $sin\beta$.

Now we will see how this additional term will change the diffraction order pattern.

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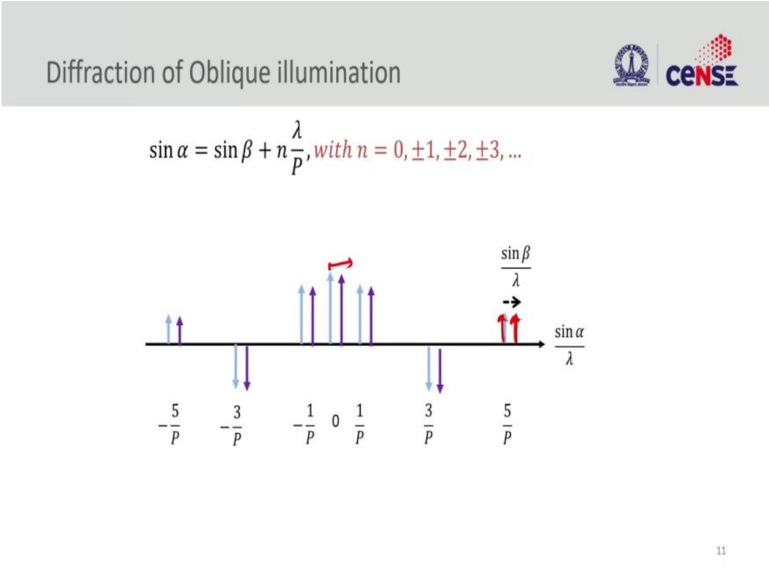

The above image shows the order is not 0 anymore; it is crowded around 0. There are 2 order patterns. And the distance between them is sinβ /λ while the axis is sinα /λ, other things are constant. Here we are looking at the extent of splitting of these different orders because of the oblique incidents.

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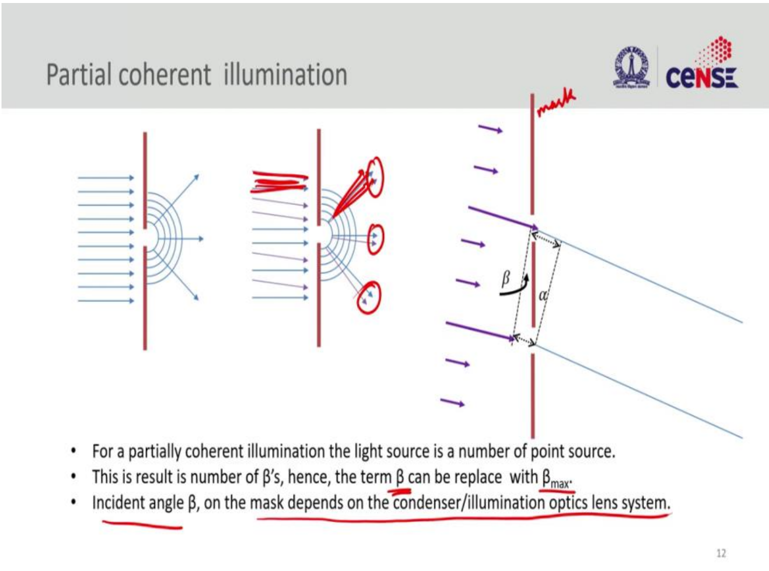

Now we will consider both normal and oblique rays incident on the mask, the diffraction order formed from the normal incidence will have a slightly different angle than from the oblique incidence. Here we considered only two distinct cases, but in reality, there will be a continuous variation between the two diffraction orders because of multiple incident rays. If that is the case, instead of taking just an individual β we take β_{max}, the incident angle term. This incident angle on the mask depends on the optics. To reduce the β, we use a condenser or illumination optics, which is used to control the angle of incidence of this incident light onto the mask.

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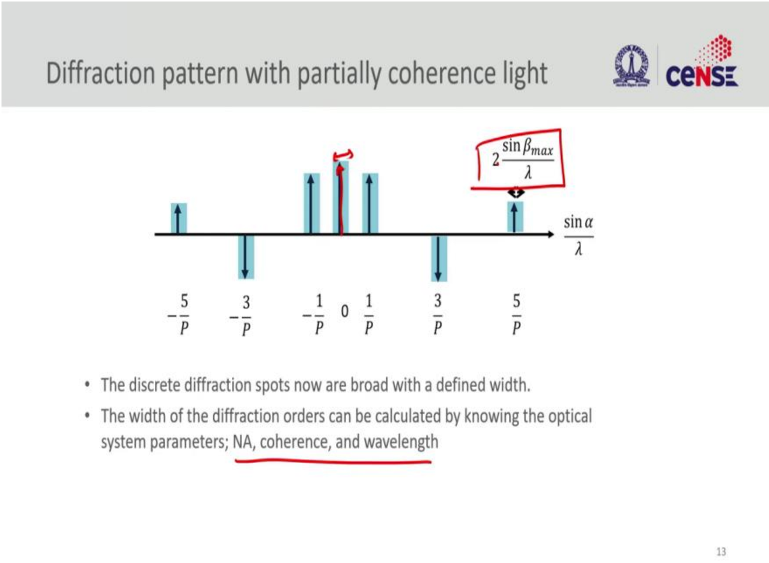

The above slide shows a single diffraction order form a band for a partially coherence light. Unlike normal incidence, it does not have a single order, instead, it has a bunch of orders crowded around it. The width of the band is given by $2\frac{\sin\beta_{max}}{\lambda}$, and it can be calculated by understanding NA, coherence, and wavelength. These bands are symmetric around 0th order, between plus and minus orders.

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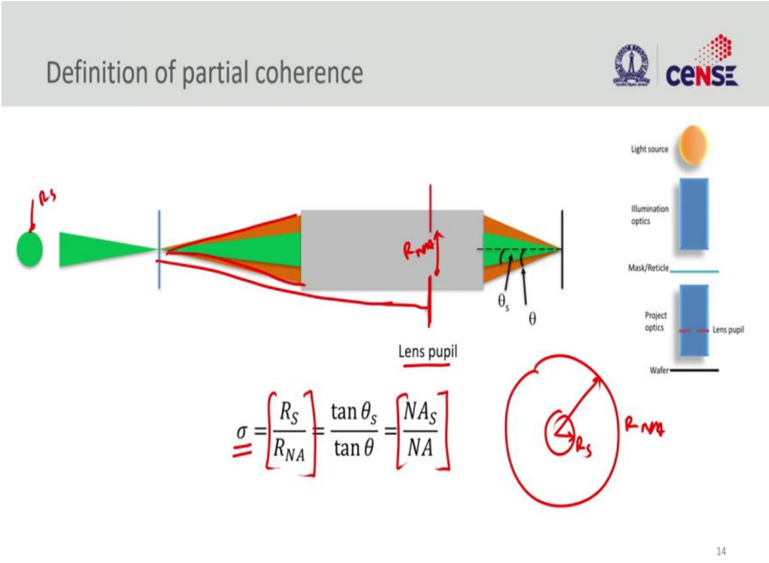

Partial coherence is nothing but a ratio of the radius of the source, R_S to the radius of the lens(NA), R_{NA} .

Coherence, $\sigma = \frac{R_S}{R_{NA}} = \frac{tan\theta_S}{tan\theta} = \frac{NA_S}{NA}$

The numerical aperture radius is larger than that of the source. The diffraction light can go beyond the projection lens, but the NA will restrict those diffracted orders to not propagate beyond the lens plane.

The partial coherence is also given in terms of the numerical aperture, as seen in the above equation, where NA_S is the numerical aperture of the source and NA is the numerical aperture of the projection lens.

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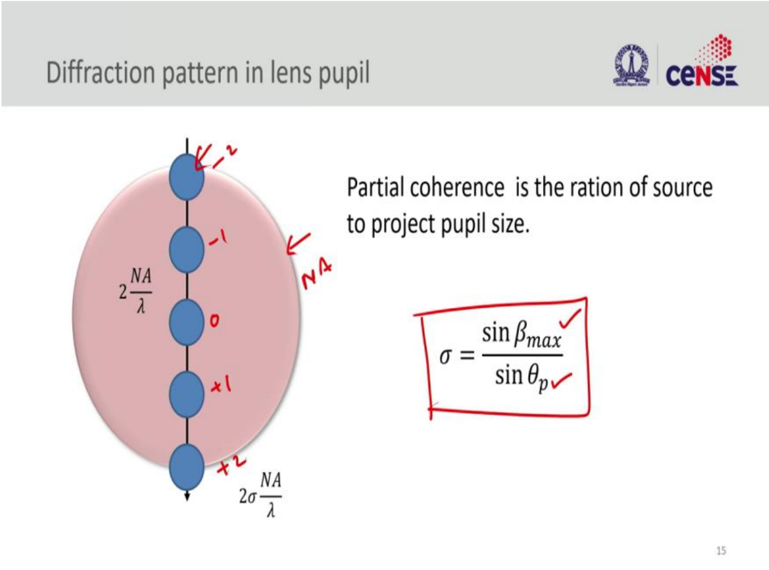

Partial coherence is given below in terms of incident and projection angle.

$$\sigma = \frac{sin\beta_{max}}{sin\theta_p}$$

In the above image, the pink region represents the NA plane of the pupil lens, and the small blue ones are the diffraction orders from the mask showing 0th order, first order (+1, and - 1), and second-order (+2 and -2).

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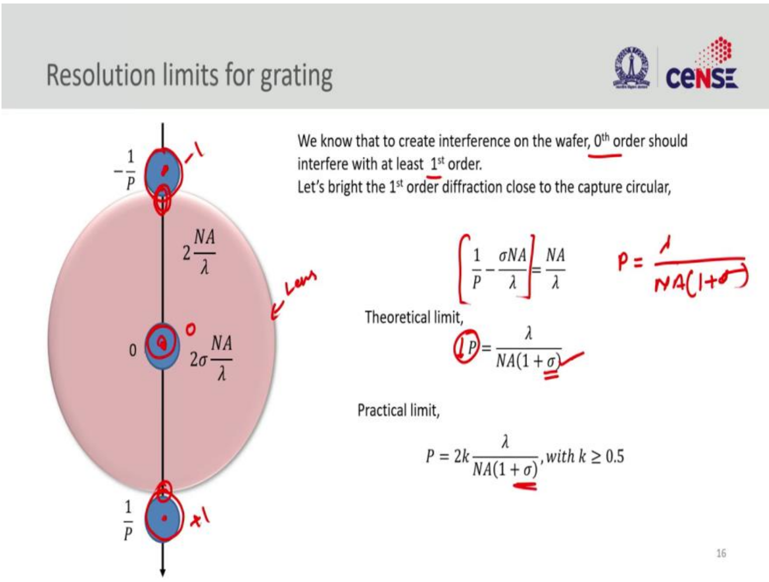

Now we will see the resolution limit of a grating formed using partially coherent light. We know that at least two orders are required to form an image. And the resolution is dictated by λ/NA, which is a theoretical limit when we have a coherence source. For a non-coherence source, the theoretical limit is changed to

$$P = \frac{\lambda}{NA(1+\sigma)}$$

In this case, we have an additional factor σ, and it is in the denominator. When the partial coherence, σ, increases, the pitch will reduce. If σ= 0, then we get theoretical limit for coherent source. But if the presence of non-coherence source σ is nonzero, it will increase the denominator in the above equation. Hence we can have finer features and can increase the resolution.

To understand this visually, in the above slide pink region represents the NA plane of the pupil lens, and the small blue ones are the diffraction orders from the mask (0^{th} and 1^{st} order) due to a partially coherent source. For both coherent case and partially coherent case pitch is the same. Then the center point of the blue circle is the diffraction order due to coherent source; in this case, the 1^{st} orders are formed outside the pupil lens plane. In the case of partially coherent light, there is a band of diffraction orders; hence part of these diffracted orders will fall on the lens plane. The small overlap will get + 1 and - 1 into the system, and it is good enough to image the feature. But using coherent light, it is impossible to image 1^{st} orders. Hence we achieve higher resolution by using a partially coherent light in the place of a coherent system.

To summarize, the practical case of partially coherent light improves the resolution instead of an ideal coherent light source.

In this lecture, we saw the depth of focus and its importance—the effect of the number of orders on the depth of focus and the imaging quality.