Fundamentals of Micro and Nanofabrication
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Lecture – 29
Optical lithography basics: resist process – 1

The last lecture discussed pattern transfer and how the intermediate layer is important in indirect pattern transfer. It is important to understand the property of indirect pattern transfer and the intermediate layer quality. In this lecture, we will understand the properties of photoresist and also the dynamics of this photoresist.

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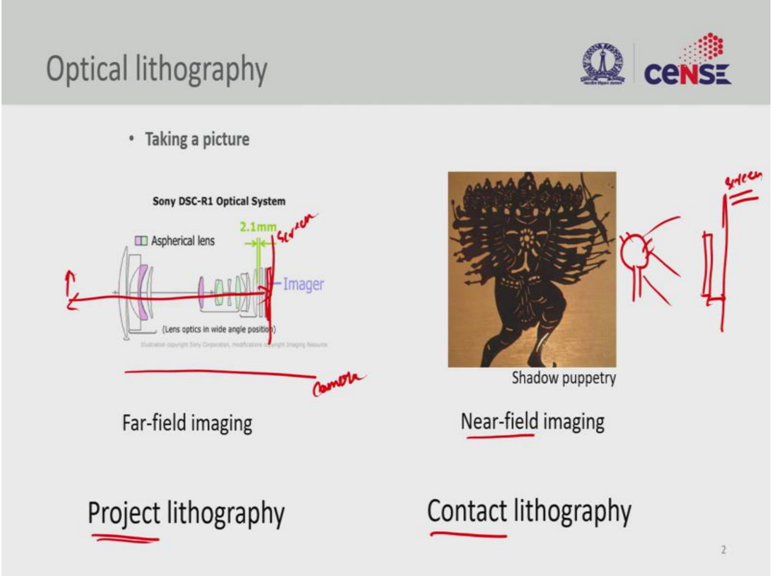

Lithography is all about taking an image; there are two generic ways of doing that. Left image of the above slide shows camera with multiple lens arrangements that allow an object placed in front of it, imaged on CCD, a solid-state device. Here the object is far, so far-field imaging, in other words, called projection lithography. The Shadow puppetry image of the above slide is an example of near-field imaging. Here the screen and the object are close to each other, and while the light source is far away. This technique is called contact lithography.

. So, what is happening on the screen becomes very important.

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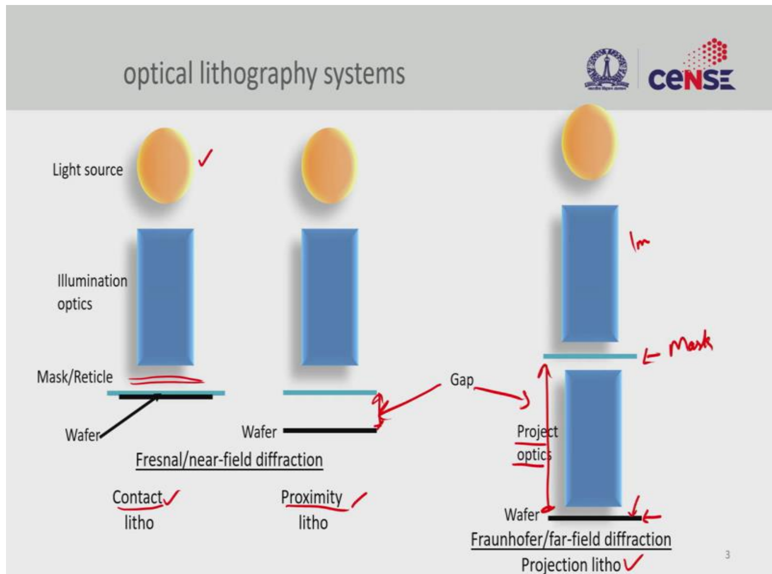

The above slide shows technical details of how optical lithography works. In an optical lithography system, the light source is the first element, and then there is an illuminating optics. Illuminating optics uses multiple lens systems that allow profiling of the optical light source so that uniform light falls onto the mask in contact with the wafer. This is called contact lithography. When a gap separates the wafer and the mask, then it is called proximity printing or proximity lithography. Both contact and proximity lithography are near-field imaging techniques, where fresnel's diffraction comes into the picture.

Next, we have a little more sophisticated technique where the illuminating optics on the top look exactly like the near field imaging, the only difference is that between the mask and the wafer, it has projection optics. Projection optics has dedicated optics that offers Fraunhofer diffraction. Here the gap between the wafer and the mask is large. This technique is called far-field or projection lithography.

In R&D and industry combination of near-field and far-field lithography processes is used. So, this irrespective of whether it is contact or proximity, or projection, what happens on the wafer to form an image becomes essential; we will see that in this lecture.

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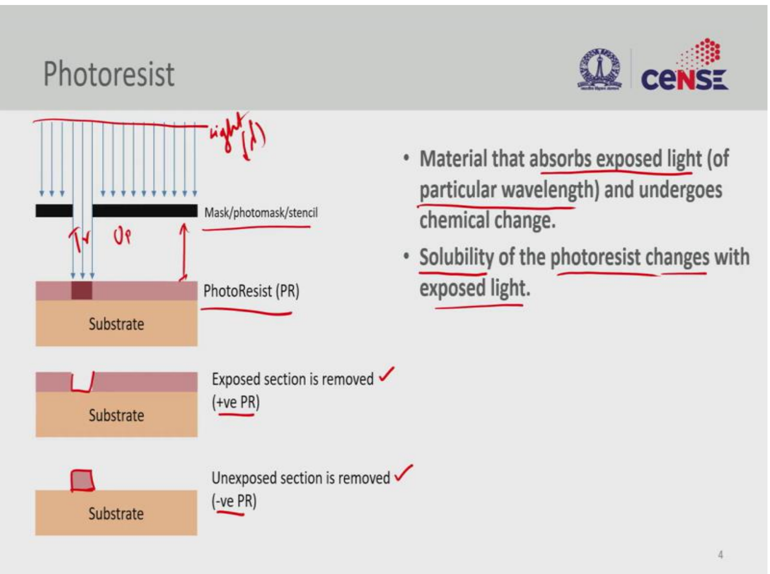

A uniform light is illuminated on top of mask, which is kept in contact or with a gap on top of a photoreisit coated wafer. Mask has transparent and opaque regions; opaque region does not allow the light to pass through while the transparent region will. When light through transparent region of the mask falls on the photoresist, depending on if the photoresist is positive or negative, part of the resist will be removed. In the case of positive resist, the exposed part is removed, and in negative resist, the unexposed part is removed. In both cases, when the photoresist is exposed to light, the solubility of the photoresist will change, which is why this photoresist material should be photosensitive. It should not be photosensitive to all the light or all the wavelengths; it should be specific to a certain wavelength and absorb only that particular wavelength.

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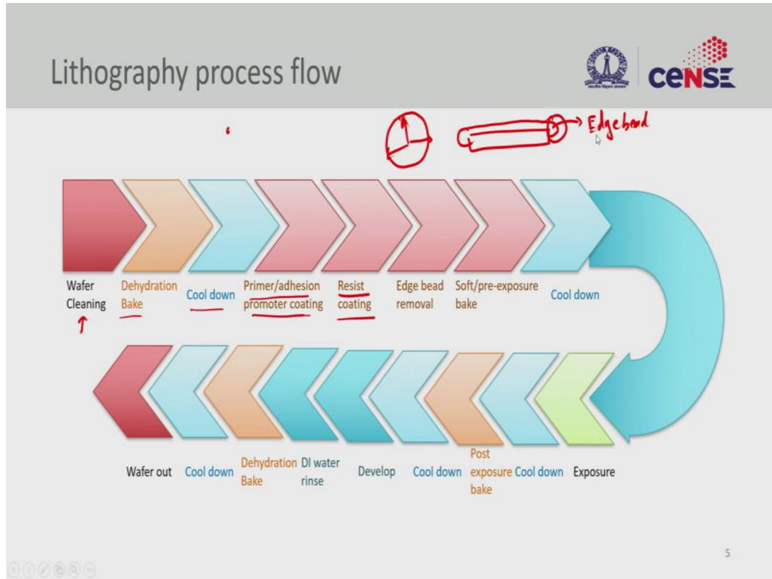

Lithography is not a single-step process; it involves multiple steps. It starts with wafer cleaning, which we saw earlier lecture; this cleaned wafer is baked to remove water or moisture present on the wafer; this step is called dehydration bake. After baking, the wafer is allowed to cool, and then it is coated with an adhesion promoter. The adhesion promoter is used to increase the adhesion between the photoresist and substrate, followed by photoresist coating.

A circular wafer on resist spin coating shows resist curled at the edge of the wafer when viewed in cross-sectional view; this is called edge bead. This is removed during edge bead removal step. Then the substrate is baked to remove the solvent present in the resist, called soft bake or pre-exposure bake; the sample is then cooled before the next step. Once the wafer reaches room temperature, it is exposed to light and cooled again to release the heat absorbed during the illumination step. Again the sample is baked, called post-exposure bake, and cooled down; then we develop the sample. The exposed region is dissolved during development (in case of positive resist) and then rinsed with deionized water to remove the excess developer. The wafer is again baked (hard bake), cooled, and the wafer is taken out.

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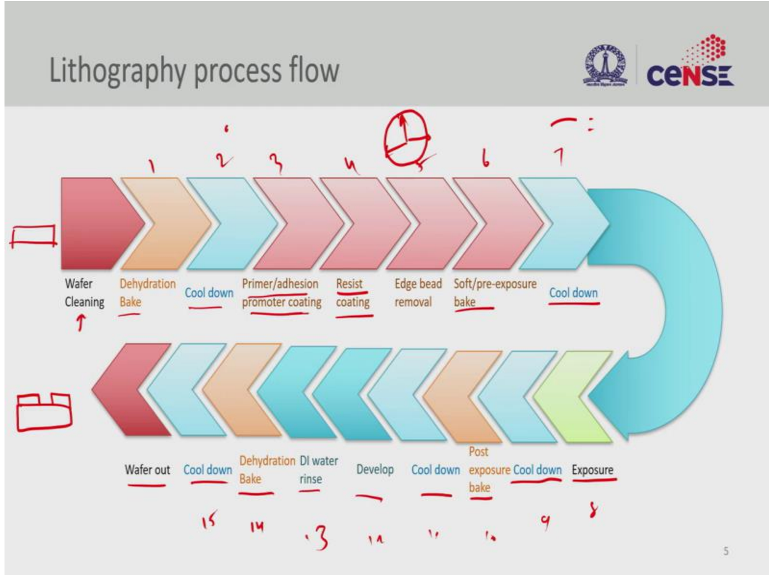

There are 15 steps involved, from wafer cleaning to wafer out to get a clean wafer with patterns. We must follow all these steps carefully so that we get the desired result.

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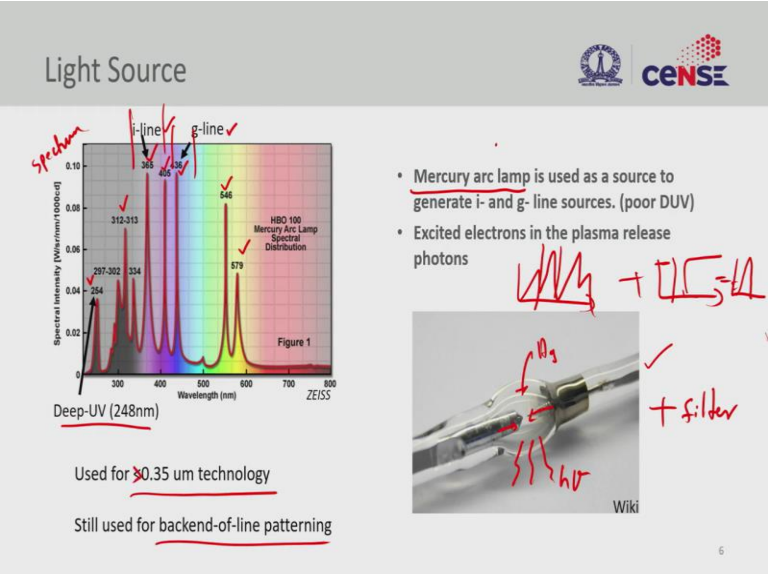

Now let us look at the light source used for illumination. When we take a photosensitive material and illuminate it with a light source, we should be clear with what kind of light source to use. The photoresist material should be sensitive to only a particular wavelength. Because when we work in the presence of white light, it has all the wavelengths, and if the resist is absorbing to any wavelength, it will bring in the

chemical change on exposure to the atmosphere. This is similar to the photo films used in the olden days, where we had camera reals coated with a photosensitive material and developed in the darkroom. When the film is exposed to light, the photochemical reaction will occur, and the image will not be formed. To avoid this, photoresists should be responsive to a particular wavelength. Then we can restrict your environment so that the material is unexposed when you are taking it out.

So, if there is a selective wavelength, we also want a source from a selective material. Consider a light source, particularly a mercury vapor lamp. The above slide shows the spectrum of a mercury vapor lamp. In a very simple mercury vapor lamp, the tube is filled with mercury gas and has an electrode inside it. When a voltage is applied, an arc is created, and photons are emitted. These photons are generated due to the transition between different energy levels of mercury. These correspond to peaks as shown in the spectrum in the above slide. The intensity of peaks is not the same, few are strong, and few are weak. The peaks corresponding to 365 nm, 405 nm, and 436 nm are distinctive. The 436 nm peak is called g-line, 365 nm is called i-line, and 254 nm is called deep-UV. Deep-UV also includes 248 nm, which is used. If you use a mercury vapor lamp, you will get this whole spectrum from deep-UV to visible wavelength. that is why a mercury vapor lamp looks like a broadband white light source.

As mentioned earlier, we do not want all these emissions; we want to restrict ourselves to a particular region. Suppose we filter i-line; it is called i-line source. Light source lamp source cannot be used standalone; the filter is used along with the source to select a particular region of the spectrum.

If we have multiple peaks, then the filter used will be a band stop filter, allowing only a particular region to pass through. So, all the other wavelength regions of the light sources will be killed.

Mercury vapor lamp is used in CMOS technology for dimensions greater than 350 nm. In the back-end compatible process, metal lines or features with large critical dimensions (CDs) can be fabricated using this technology.

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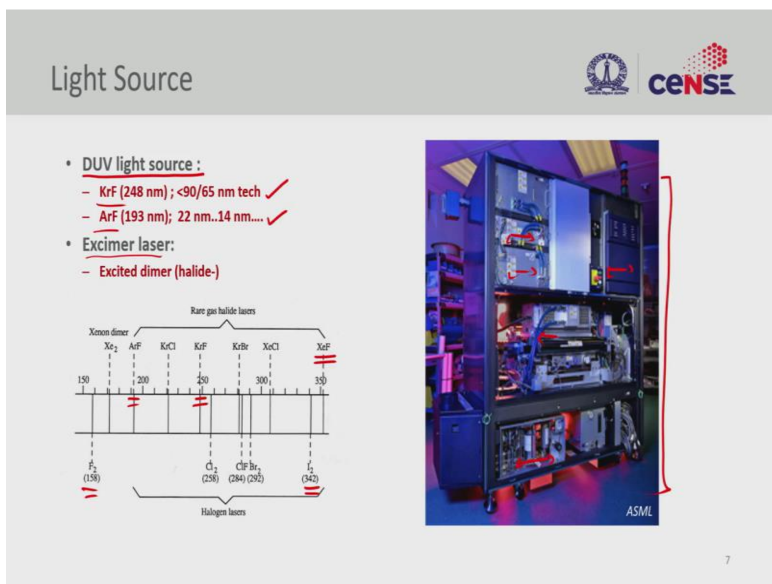

The wavelength has a direct implication on the feature size, so next, we will see how to reduce the wavelength to use deep-UV wavelength. The intensity of deep-UV in mercury vapor lamps is very small, so we go for halide based excimer laser source.

Argon fluoride and krypton fluoride gases are used to generate 193 nm and 248 nm deep UV light, respectively. Source wavelength 193 nm is used for 90 nm, and 248 nm is used for 650 nm technology. Currently, we are using 193 nm for advanced CMOS technology. All these sources are halide-based excimer lasers. Based on halides, we can get the right wavelengths depending on the energy levels; if we increase the energy level, the laser wavelength decreases. The wavelength of xenon fluoride lamp is at around 351 nm; krypton fluoride is at 248 nm, argon fluoride is 193 nm; with just fluoride (F_2) alone, the wavelength is reduced to 158 nm; hence the choice of halide dictates the wavelength of the laser.

Unlike a simple light source, these excimer lasers are exotic. Because it uses halides and gases, the light source is not a simple tube, as we can see in the above slide; it has a water cooling system, multiple cavities, cooled, active electronics, and gas with pressure control chambers. Hence becomes a complex system for one to use; the reason for that is the transition itself is important to control.

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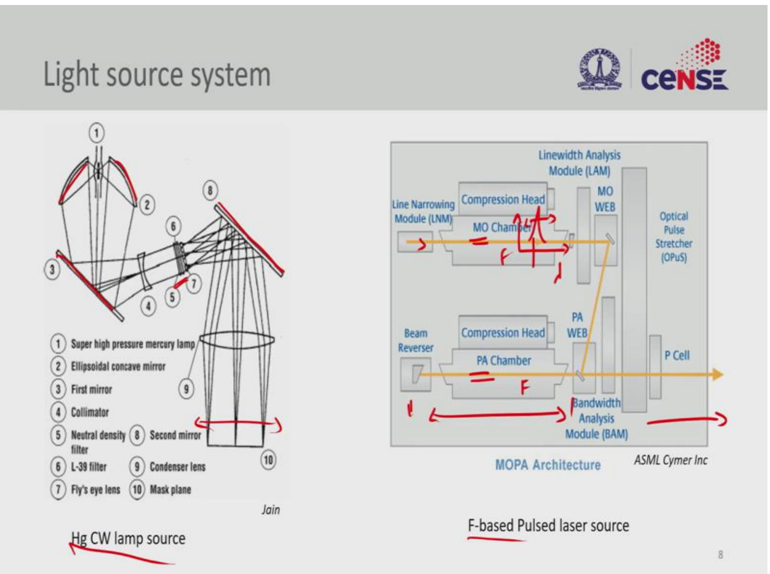

Now we will see the light source system level to appreciate why halide-based device systems are interesting in terms of system engineering. In the case of mercury source, we have a lamp with mirrors acting as an illuminating system, and then we have a mirror that reflects the illuminating light and projects it to a filter. The filter chooses a particular wavelength that we are interested in and then uses illuminating optics to make a uniform distribution of light. The system uses two mirrors to get a uniform illumination onto the mask plate. This system uses simple optics, shown in the left image of the above slide.

A halide-based or fluorine-based system has a master oscillator chamber and a power amplifier chamber filled with halide or fluoride-based gas. An external pump signal goes through the master oscillator and creates a pulse of a particular wavelength, and then it is fed into the power amplifier. Low energy photon generated in the master oscillator and is amplified in the power amplifier chamber. Power amplifier consists of a cavity, where the light will be bouncing back and forth, and once it achieves the energy, the light comes out.

The master oscillator always operates at low power so that it can have wavelength stability. Wavelength stability is very important because the resist will respond only to a particular wavelength. So, if we increase the temperature of the master oscillator, it will cause oscillations in the wavelength. To avoid that master oscillator is operated at low power, while the power amplifier is operated at high energies to use it for illumination.

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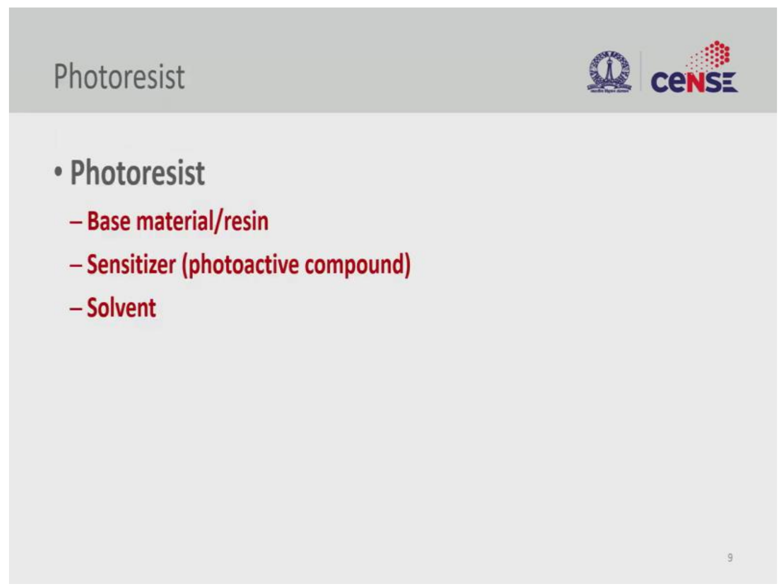

Next is the photoresist. Photoresist consists of three essential elements; a polymer resin material called base material, a photosensitive substance called sensitizer, and a solvent to form photoresist a liquid to be spin-coated.

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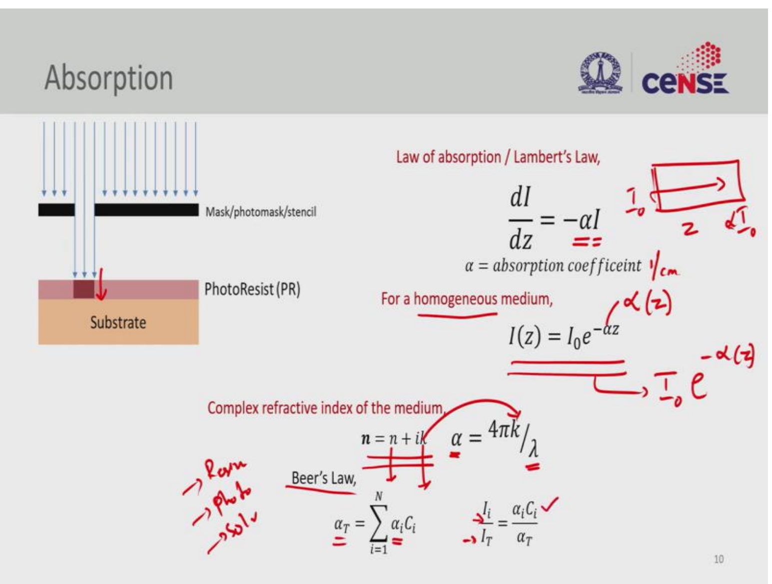

Now we see how the light gets absorbed into the system. Lambert's law is used to understand the absorption in photoresist along the length, and it is given by,

$$\frac{dI}{dz} = -\alpha I$$

Here, α is the absorption coefficient which is per unit length, and I is the intensity of the light. If a bulk material is illuminated with light of intensity I_o after a distance z output power is a result of absorption,α after passing it.

The intensity profile of light traveling in a homogeneous medium as a function of length is given by,

$$I(z) = I_0 \ e^{-\alpha z}$$

If the medium is non-homogeneous, then the absorption coefficient, α becomes a function of length, i.e., α(z). In a homogenous medium, α is a constant. This way, light is getting absorbed as it progressed through the resist from top-down.

The light absorption property is decided by the material's complex refractive index, which is **n**= n+ik, n is the real part of the refractive index, and k is the imaginary part. The imaginary part contributes to the absorption; this absorption is a wavelength (λ) dependent factor, given as,

$$\alpha = \frac{4\pi k}{\lambda}$$

The complex refractive index is important to understand the extent of absorption at a particular wavelength. This is explained by Beer's law ,

$$\alpha_T = \sum_{i=1}^{N} \alpha_i C_i$$

where the total absorption, α_T in the medium depends on the absorption of the individual constituents; resin, photosensitive material, and solvent, light is absorbed by all these three. The total absorption is a combination of all these individual absorptions.

The ratio of individual absorption to the total absorption,

$$\frac{I_i}{I_T} = \frac{\alpha_i C_i}{\alpha_T}$$

This gives the individual contribution to the total absorption.

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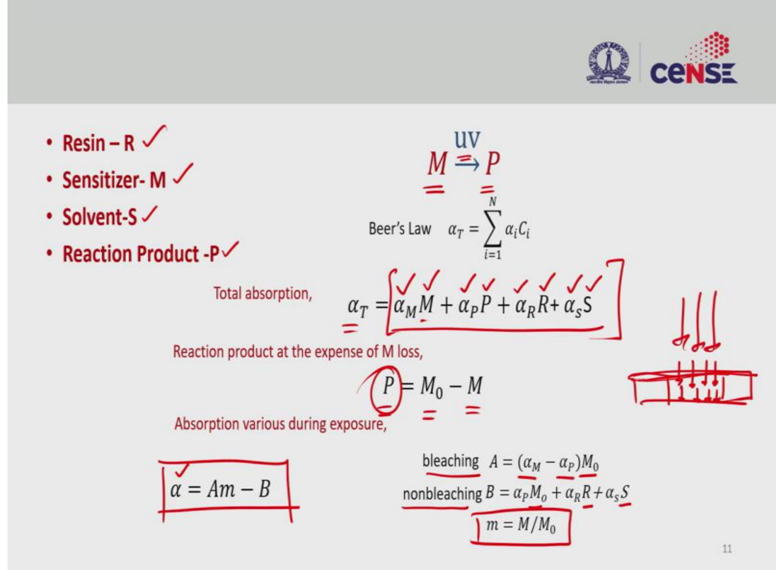

In resist, we have resin, sensitizer, solvent; along with that, there will be reaction products (P). This is formed by the illumination of sensitizing it M, in this case, using a UV source.

$$M \overset{UV}{\rightarrow} P$$

This product too absorbs some light. So, the total absorption is given by,

$$\alpha_T = \alpha_M M + \alpha_P P + \alpha_R R + \alpha_S S$$

Here,

α_S is solvent absorption coefficient and S is the amount of solvent present

α_P is product absorption coefficient and P is the amount of product.

α_R is resin absorption coefficient and R is the amount of resin.

α_M is sensitizer absorption coefficient and M is the amount of sensitizer present

Product of absorption coefficient and amount of component present gives the absorption of individual component

Since the sensitizer forms the product, the amount of product is the difference in the amount of sensitizer present initially and finally.

$$P=M_o-M$$

M_o is the initial amount of sensitizer, and M is the final.

The absorption variation during exposure be given by

$\alpha = Am - B$

Absorption is the difference between the bleaching parameter and the non-bleaching one.

Sensitizer in photoresist will become transparent on exposure of light. So, the illumination of light on a photoresist top layer absorbs energy. It will become transparent so that light can penetrate through this material and reach the bottom of this material. This is called bleaching.

Bleaching parameter, $A= (\alpha_M - \alpha_P)\, M_o$

When the sensitizer is completely exposed, then we say the material is completely bleached.

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Solvent, resin, and the product generated do not change their absorption coefficient. Hence the absorption due to these is called the non-bleaching part. This is given by,

$B= \alpha_P Mo + \alpha_R R + \alpha_S S$

The bleaching and non-bleaching part together gives the total absorption change.

$m= {}^{M}/_{M_O}$ is a differential, the change in the concentration of the sensitizer. Ideally, we want all the sensitizers present in bulk to absorb light and converted into a product.

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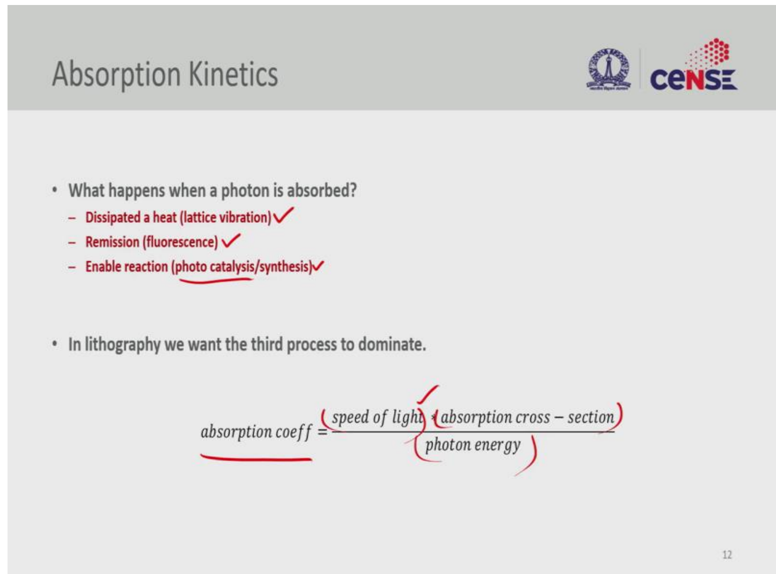

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When the photoresist absorbs a photon, it can dissipate heat due to lattice vibration, re-emit the absorbed light (fluorescence), and a photon-assisted reaction or photo-catalytic process. The photon is used to change the solubility and is also used for other processes mentioned above. Co-efficient

So, theabsorption coefficient that happens is dominated by various fractions,

$$absorption\ co-efficient = \frac{(speed\ of\ light) * (absorption\ cross-section)}{photon\ energy}$$

If we have a low-energy photon, absorption will be high because the penetration depth will be low. So, a lot of photons can be absorbed in bulk. One needs to think about what kind of energy can be used and how the absorption cross-section affects your lithography process.

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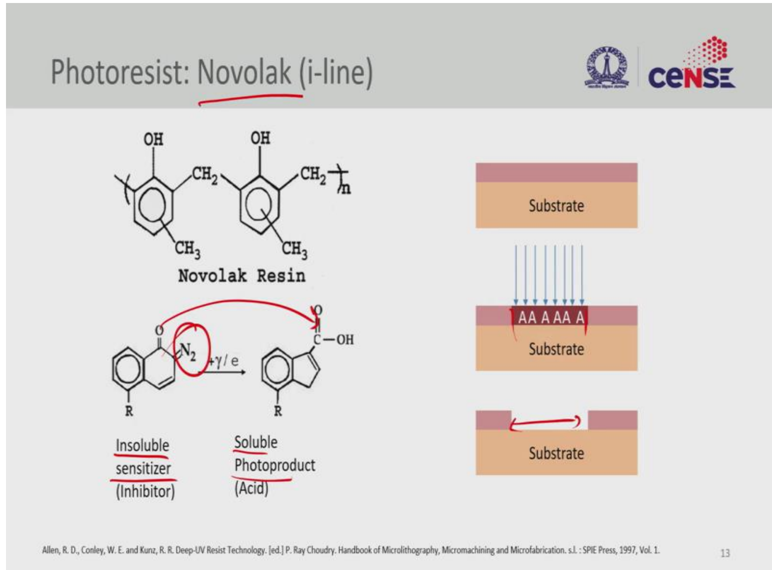

The above slide shows an example of a resist process. Novolak resists is a phenol formaldehyde-based resin. This resist on illuminating with the light source; photo active components are generated, making the exposed region dissolve. Here we are trying to convert insoluble sensitizer to soluble resin. The molecular formula in the above slide shows the removal of nitrogen group and exchange of oxygen; how to achieve this exchange process is what we are interested in.

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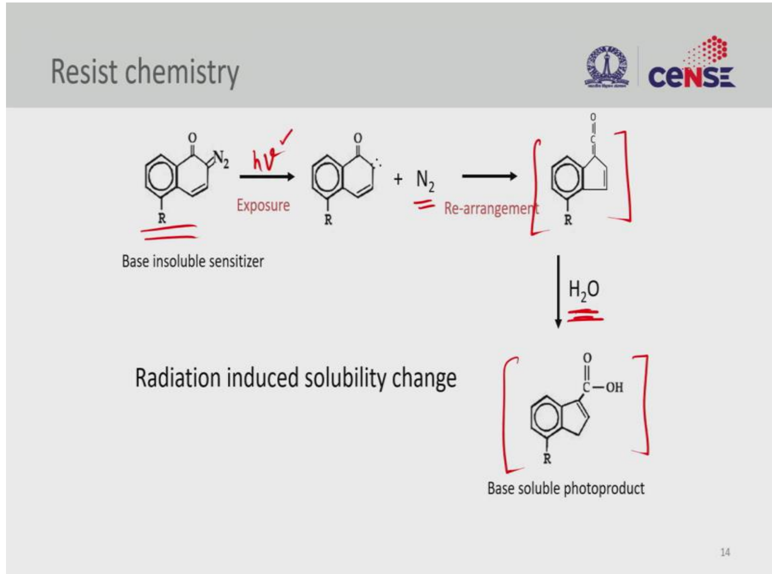

In the presence of exposure light, a photon takes out the nitrogen, leaving a dangling bond. The dangling bond compound will rearrange in the presence of oxygen and carbon in bulk, which is still insoluble. In the presence of humidity or water molecule, it will turn the compound into a soluble form. Here in the above example, the COH group is soluble in the base. The insoluble sensitizer is converted to a soluble product. Just exposure will not help to arrive at soluble product; it needs humidity, an important parameter to control. So, in any lithography process, we need a light source and controlled humidity.

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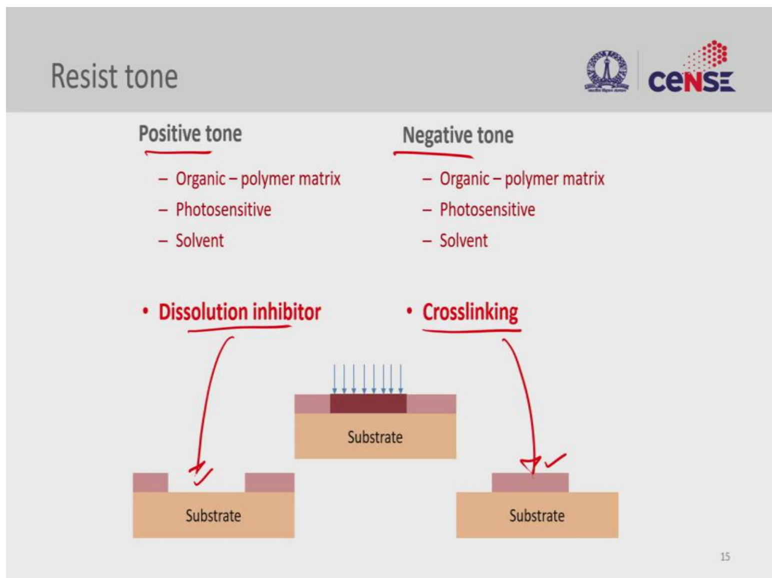

Based on the solubility factor, resist can be classified into two; positive and negative. If an exposed part is removed during development, it is called positive resist, and if an unexposed part is removed, then it is called negative resist.

In the case of negative resist cross-linking happens, the backbone chain is strengthened so that they are not soluble. While in the case of positive resist, dissolution inhibitor is created so solubility increases, so the material is removed.

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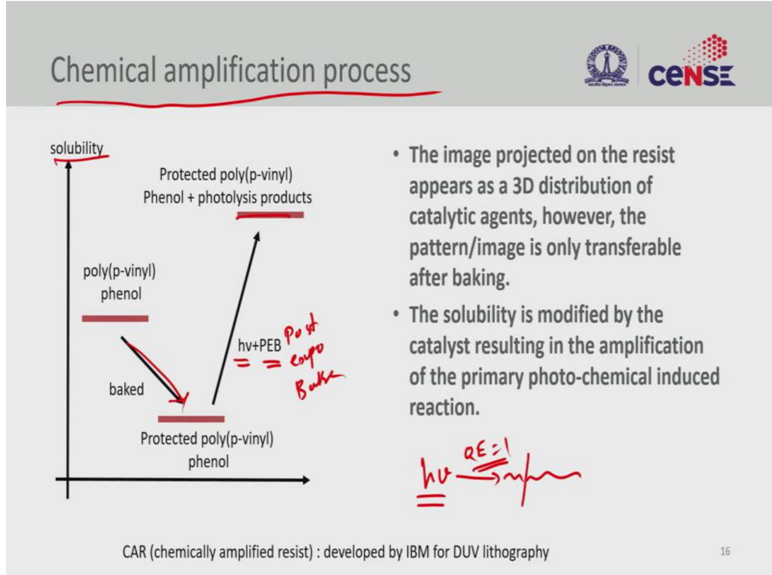

Next is the amplification process. When one photon is used to de-link or break one polymer chain, then the reaction has a quantum efficiency of 1. this is high ask for any chemical process. To have this process simplified, chemical amplification is used. When we have a low number of photons, we use a chemical amplification process to achieve enough chain breakage. Chemical amplification is nothing, but one photon will generate a multiple de-linking.

In the solubility graph shown in the slide, a simple resin on baking, solubility goes down because we are removing the solvent during the process. The baked resist on exposure with photon and post-exposure bake; energy is added to the system hence the solubility increases; this is called chemical amplification process.

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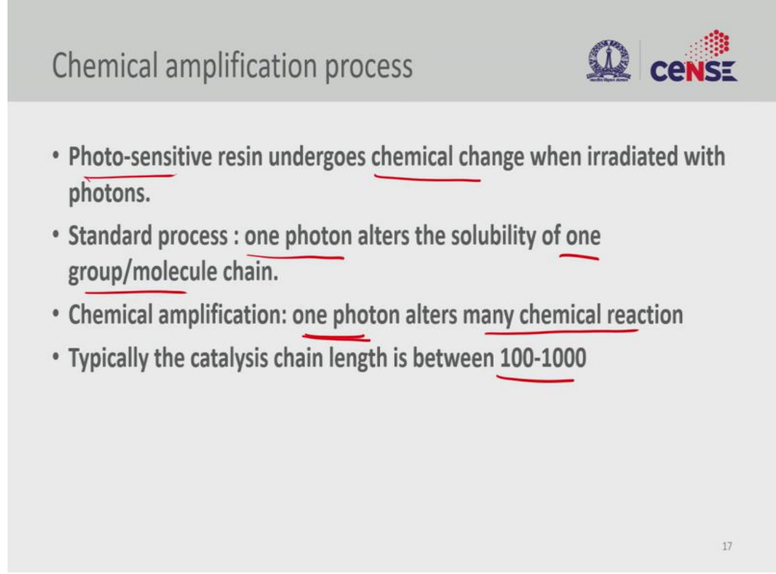

One photon de-links one chain in the standard process, but the photosensitive material undergoes a chemical change in chemical amplification. One photon alters many chemical reactions; this makes the process more efficient. Typically during chemical amplification, it can de-linked about 100 to 1000 chains; it does not need a lot of photons. This process using less illumination energy it can de-link a lot of chains.

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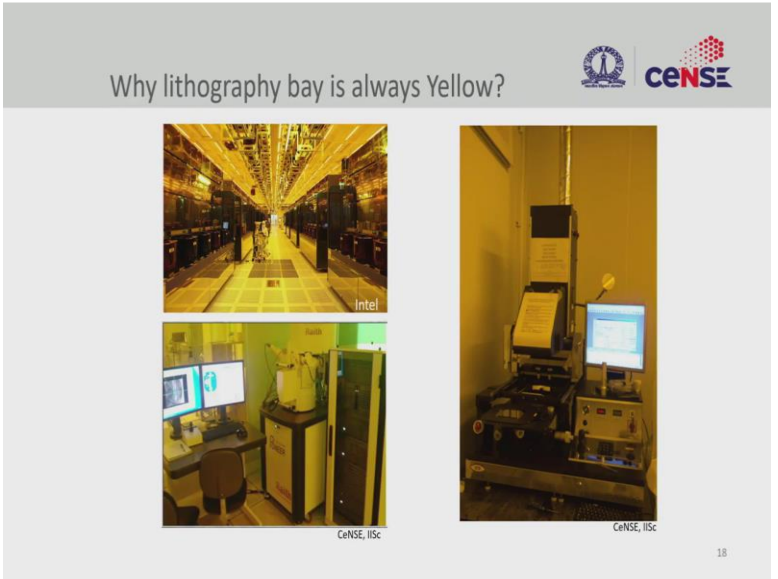

The slide shows the intel manufacturing unit and the nano science fab at IISC. We can see two lithography tools; one is electron beam lithography, and the other one is optical

lithography. In both fab labs, the room has a yellow light. So, why should it be yellow light? This we will discuss in detail in the next lecture.

In this lecture, we tried to understand how the resist process works, the property of resist, and how illumination helps change the solubility, which is an important factor; it can be positive or negative resist. We also saw how the amplification adds additional dimension in handling the solubility and the power that we need to increase the solubility.

In the next lecture, we will understand more about the kinetics involved in this photoresist.