Fundamentals of Micro and Nanofabrication
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Lecture – 35
Optical lithography: Surface Reflection

In past lectures, we discussed image formation on a wafer due to interference of different diffraction orders. This lecture will discuss Surface Reflection occurring at the interface between the resist and the substrate and the interface between resist and air. We will also discuss how to avoid undesirable image formation due to these reflections.

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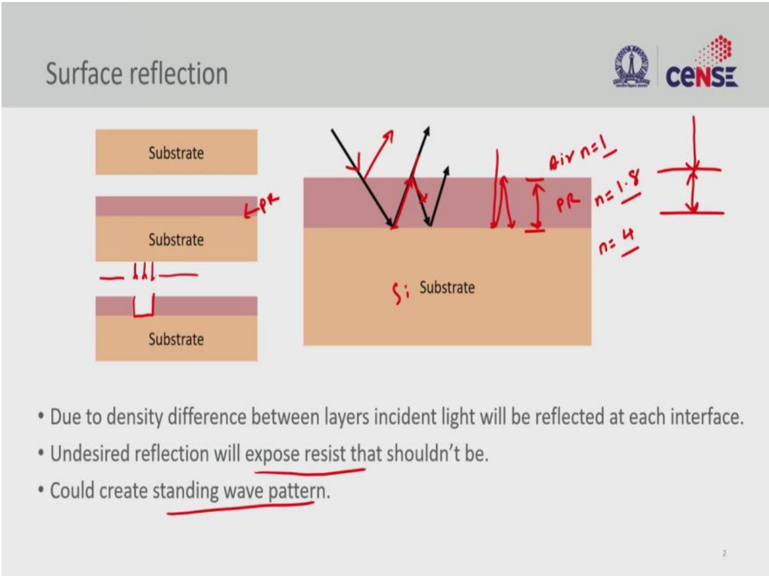

The above image shows substrate and coated with photoresists. When we illuminate the resist with light using a mask, a trench is formed on the exposed region if the resist is positive. The process can be contact or proximity, or projection lithography.

A substrate coated with a resist system has two interfaces. One between air and resist, other between resist and substrate. When illuminated with light to expose the resist, there will be reflection and refraction at these interfaces due to refractive index change. For example, resist of refractive index 1.8 coated on a substrate of refractive index 4, with air surrounding it (refractive index 1).

Few rays will be reflected at the top air and resist interface, and few will refract into the resist. These refracted rays in the resist will be incident on the resist and substrate interface. Again at the resist and substrate, there will be refraction and reflection. The reflected beam will fall on the resist air interface, few will refract, and few reflect back to resist, which continues—this exaggerated image of the ray model show all the possible reflection paths. For a normal incidence, rays bounce back and forth in the resist.

Ideally, we need a single beam exposing the photoresist giving desired patterns, but beams bounce back and forth, creates standing waves because of cavity-like structure formation on resist, which will result in undesirable exposure.

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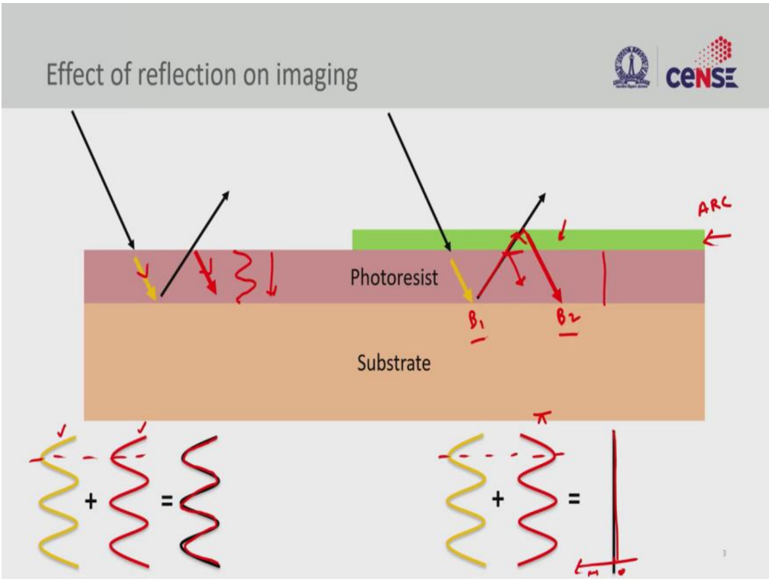

In the above slide, the left-hand side image shows a photoresist-coated substrate. In this case, the refracted beam at the air–resist interface (shown as yellow ray) and reflected beam from the resist-air interface (red ray in the image) has no phase difference; hence they interfere constructively to form standing waves. These standing waves create undesirable intensity variation along with the thickness of resist instead of the required uniform intensity.

To avoid this standing wave, the right-hand side of the above image shows a thin coating on top of the photoresist called anti-reflective coating. This anti-reflective coating is a polymer material that also reflects. Now along with the refracted beam from the air–resist interface (shown as yellow ray) and reflected beam from the resist top (red ray in the image), there is one more reflected beam from the anti-reflective coating and air interface(also a red ray). The reflection from the photoresist and coating interface is reduced by controlling the refractive index contrast between the anti-reflective coating and the photoresist. Now the two primary beams, yellow and red (reflected from the coating), are out of phase (π phase difference). These two beams will interfere destructively to arrest the effect of reflection, and so, the exposure is only due to the incident light. Hence we get uniform exposure with an anti-reflection coating.

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The above slide shows the result of with and without anti-reflective coating. The right image of the photoresist without anti-reflection coating shows wavy sidewalls formed due to the standing waves on both edges. These are undesirable, as roughness on the photoresist will be transferred to the underlying material. The left image shows a smooth photoresist sidewall resulted due to the presence of anti-reflection coating—the anti-reflective coating arrests the reflection, and the photoresist is exposed with uniform intensity.

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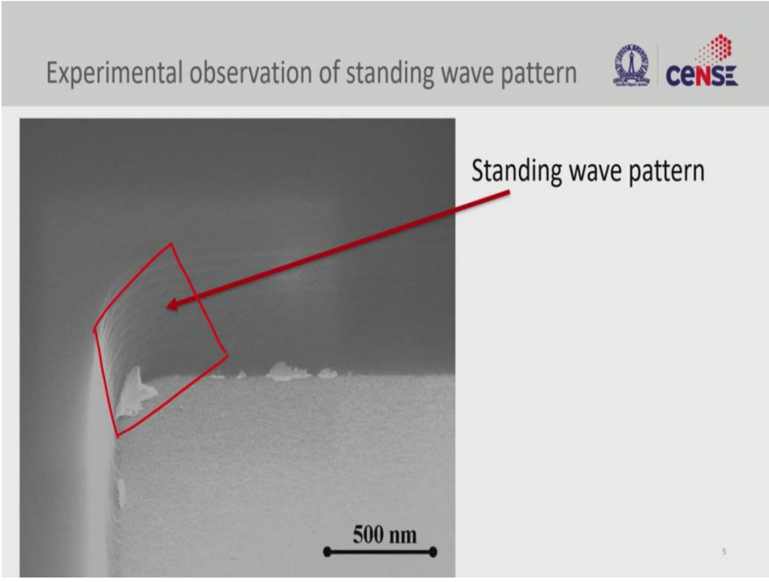

The scanning electron microscope image shows the wavy pattern on the sidewall of the photoresist after development because of the absence of an anti-reflective coating. This non-uniformity on the photoresist will be transferred to the underlying silicon during dry etching.

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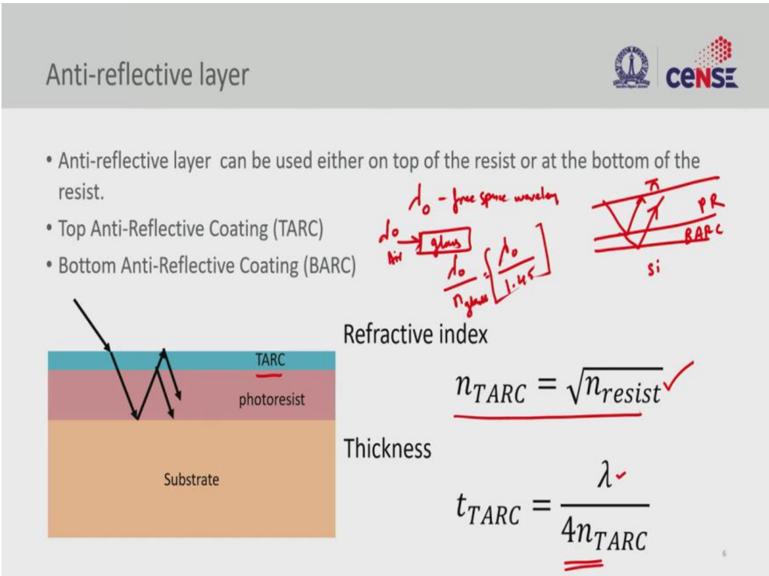

The anti-reflective layer should be a polymer, and we should be able to coat this layer using a spin coater. This anti-reflective layer can either be on top or at the bottom of the photoresist. If it is on top of photoresist, it is called Top Anti-Reflective Coating or

TARC, and If it is at the bottom of photoresist, it is called Bottom Anti-Reflective Coating or BARC. Similar to top reflective coating, BARC arrests the reflections by creating a pi phase difference between the reflected beam of the photoresist and the reflected beam from BARC. The phase shift attained depends on the refractive index and the thickness of BARC or TARC.

The refractive index can be chosen to a large extent with the following relation,

$$n_{TARC} = \sqrt{n_{resist}}$$

The thickness of the anti-reflection coating is given as,

$$t_{TARC} = \frac{\lambda}{4n_{TARC}}$$

The wavelength of light inside the anti-reflective coating is the ratio of free space wavelength to the refractive index of the anti-reflective coating. Hence we have a refractive term in the above thickness equation. For instance, if λ_o is the free space wavelength of light through a medium, say glass, then the wavelength inside the glasses will be $\lambda_o/n_{glass.}$ Similarly, here, λ is the free space wavelength, and λ/n_{TARC} is the wavelength of light inside TARC. n_{TARC} is the refractive index of TARC.

Hence the reflection can be arrested with the right choice of refractive index and thickness of the anti-reflection coating.

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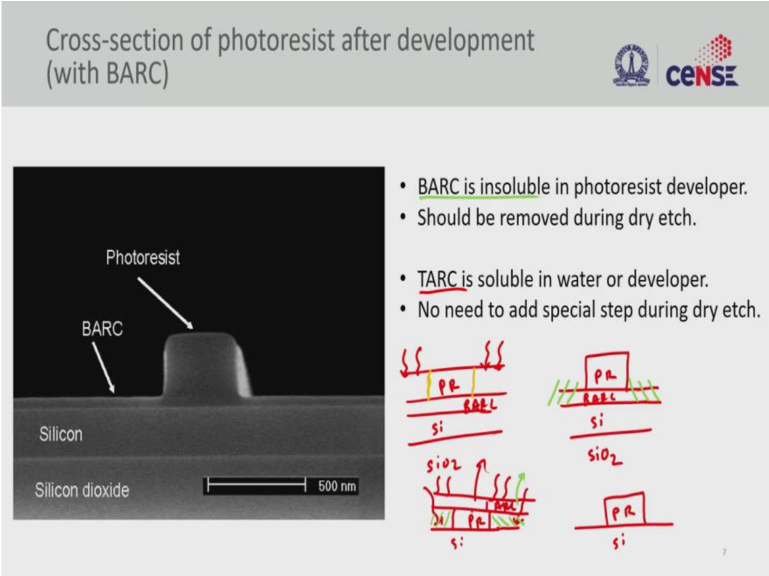

The above image shows the BARC coated resist on silicon on insulator (silicon on silicon dioxide) substrate. The pattern is formed after illumination and development; if the resist is positive, then the illumination region of resist is removed during development, and only the pillar remains, as shown in the above SEM image. During development, BARC is not removed as it is insoluble in the resist. Hence, if the subsequent process is dry etch process to etch silicon, BARC is removed using dry etch before accessing silicon for etching.

In the case of TARC, some are soluble in water, and some are soluble in the developer. Since the TARC will be on top of the resist, it should be transparent to the exposure wavelength; otherwise, the resist will not get sufficient energy for exposure as the TARC will be absorbing it. And also, TARC should be soluble either in water or developer. If the TARC is insoluble, the developer won't have access to the exposed resist to develop the patterns. Only after the top TARC is removed, the developer will have access to develop the resist.

The choice of using anti-reflective coating depends on the subsequent process. For example, if dry etching is the subsequent process, both TARC and BARC can be used; just in BARC, extra etching steps to remove the bottom anti-reflective coating is required before the silicon etch. But then, if the subsequent process is lift-off, for metal deposition and so on, BARC layer, we need a separate removal step to get access to silicon and then material deposition. Similarly, in the case of ion implantation, the BARC layer should be removed to expose silicon; otherwise, the BARC layer will reduce the energy of the implant ions. These are all the various considerations while using the bottom anti-reflective coating.

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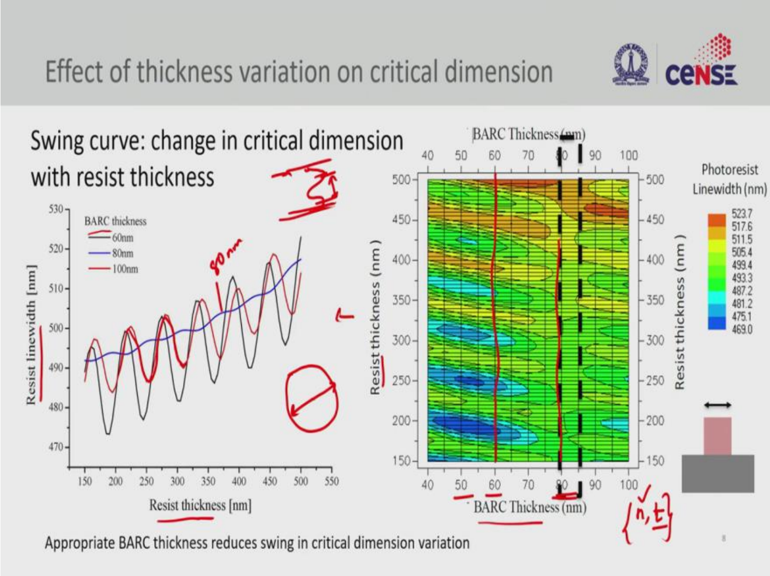

The above slide shows the swing curve is nothing but variation in critical dimension with respect to resist thickness. If there is a thickness variation, resist line width will change. The reason for this is twofold; one, the amount of energy used for exposure, and the other is the reflection. The reflections create the standing wave pattern; the pitch of these patterns formed on the sidewall depends on the thickness of the photoresist. This change in the standing wave pattern will result in varying resist line width or varying critical dimensions with respect to thickness.

The swing curve shows, with the thickness increase, there is no monotonic increase in resist line width for various BARC thicknesses. At an optimal thickness, in this case, 80 nm of BARC shows the swing is almost null right very minimal, i.e., the resist thickness variation has a very small change in the critical dimension. The reduced swing is desirable; there will always be some resist thickness variation from center to the edge right. This thickness variation should not affect the line width across the wafer. So, resist thickness variation with minimal effect on critical dimension variation can be obtained using a bottom anti-reflective coating of optimum thickness, which arrests the standing wave completely.

The righ-hand side map with BARC thickness in the x-axis and the resist thickness variation in the y-axis, the color shows an increase in the line width from blue to red.

For optimal BARC thickness, we need the right refractive index and the right thickness. Assume we took the right refractive index but not the correct thickness; this will lead to reflection captured in this map. If we consider a 50 nm thick layer of BARC or 60 nm along the length, parallel to the y-axis, the swing is observed, the CD is varying with respect to resist thickness. But, if the BARC thickness is 80 nm, we see no change over a large range of photoresist thicknesses. This is the BARC thickness to have optimal CD uniformity for resist thickness variation. So, we choose a particular thickness of BARC for the particular thickness of resist, so that the CD variation is minimal.

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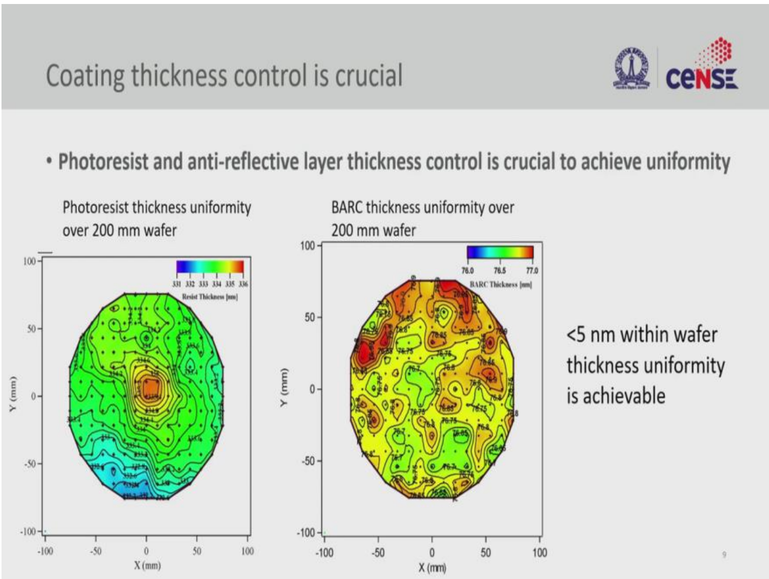

The above slide shows thickness variation of photoresist over 200mm wafer on the left and thickness variation of BARC over 200 mm wafer on the right. The range of thickness variation of photoresist is about 5 nm, while for BARC, it is about 1 nm. This is achievable with the current technology.

While designing a process, we should make sure that the anti-reflective coating thickness matches the photoresist thickness variation. A uniform critical dimension can be obtained by achieving the maximum uniformity for photoresist and choosing the optimal anti-reflective coating thickness.

To summarize, we have discussed the reflection from different interfaces of the photoresist-coated substrate and how the reflection is affecting the critical dimension. The effect of thickness variation on reflection, which can be mitigated using an anti-reflective coating layer. By using the right kind and the right thickness of the anti-reflective coating, uniformity in the critical dimension over the wafer can be achieved, even with a slight variation in photoresist thickness. With an additional step of anti-reflection coating, better yield and the uniformity of CD are achieved, leading to a better process in lithography.