Immersion Lithography

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Immersion lithography. Two years ago saying this phrase to a lithographer might have elicited a perplexed look, or possibly the knowing smile one usually reserves for an eccentric uncle. Today it is the great wet hope of the semiconductor industry. The quick escalation of immersion lithography from idea to practice would be an interesting study in human (or possibly mob) psychology, especially since the scientific principles underlying the technology have been know for well over 100 years. In any case, immersion lithography is changing the industry's roadmap and seems destined to extend the life of optical lithography to new, smaller limits. In this column I'll explain why there is so much excitement around a cup of pure water.

The story of immersion lithography begins with Snell's Law. Light traveling through material 1 with refractive index n_1 strikes a surface with angle θ_1 relative to the normal to that surface. The light transmitted into material 2 (with index n_2) will have an angle θ_2 relative to that same normal as given by Snell's law.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

Now picture this simple law applied to a film stack made of up any number of thin parallel layers (Figure 1a). As light travels through each layer Snell's law can be repeatedly applied:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3 = n_4 \sin\theta_4 = ... = n_k \sin\theta_k \tag{2}$$

Thanks to Snell's law, the quantity $n\sin\theta$ is *invariant* as a ray of light travels through this stack of parallel films. Interestingly, the presence or absence of any film in the film stack in no way affects the angle of the light in other films of the stack. If films 2 and 3 were removed from the stack in Figure 1a, for example, the angle of the light in film 4 would be exactly the same.

We find another, related invariant when looking at how an imaging lens works. A well made imaging lens (with low levels of aberrations) will have a *Lagrange invariant* (often just called the optical invariant) that relates the angles entering and exiting the lens to the magnification m of that lens.

$$m = \frac{n_o \sin\theta_o}{n_i \sin\theta_i} \tag{3}$$

where n_o is the refractive index of the media on the object side of the lens, θ_o is the angle of a ray of light entering the lens relative to the optical axis, n_i is the refractive index of the media on the image side of the lens, and θ_i is the angle of a ray of light exiting the lens relative to the optical axis (Figure 1b). Note that, other than a scale factor given by the magnification of the imaging lens and a change in the sign of the angle to account for the focusing property of the lens, the Lagrange invariant makes a lens seem like a thin film obeying Snell's law. (It is often convenient to imagine the imaging lens as 1X, scaling all the object dimensions by the magnification, thus allowing $m = 1$ and making the Lagrange invariant look just like Snell's law).

These two invariants can be combined when thinking about how a photolithographic imaging system works. Light diffracts from the mask (the object of the imaging lens) at a particular angle. This diffracted order propagates through the lens and emerges at an angle given by the Lagrange invariant. This light then propagates through the media between the lens and the wafer and strikes the photoresist. Snell's law dictates the angle of that ray in the resist, or any other layers that might be coated on the wafer. Taking into account the magnification scale factor, the quantity $n\sin\theta$ for a diffracted order is constant from the time it leaves the mask to the time it combines inside the resist with other diffraction orders to form an image of the mask.

So how does this optical invariant affect our understanding of immersion lithography? If we replace the air between the lens and the wafer with water, the optical invariant says that the angles of light inside the resist will be the same, presumably creating the exact same image. Is there then no impact of immersion lithography? There is, from two sources: the maximum possible angle of light that can reach the resist, and the phase of that light.

Consider again the chain of angles through multiple materials as given by equation (2). Trigonometry will never allow the sine of an angle to be greater than one. Thus, the maximum value of the invariant will be limited by the material in the stack with the smallest refractive index. If one of the layers is air (with a refractive index of 1.0), this will become the material with the smallest refractive index and the maximum possible value of the invariant will be 1.0. If we look then at the angles possible inside of the photoresist, the maximum angle possible would be

$$\sin\theta_{\max,resist} = 1/n_{resist} \tag{4}$$

Now suppose that the air is replaced with a fluid of a higher refractive index, but still smaller than the index of the photoresist. In this case, the maximum possible angle of light inside the resist will be greater

$$\sin\theta_{\max,resist} = n_{fluid}/n_{resist} \tag{4}$$

At a wavelength of 193nm, resists have refractive indices of about 1.7 and water has a refractive index of about 1.44. The fluid does not make the angles of light larger, but it *enables* those angles to be larger. If one were to design a lens to emit larger angles, immersion lithography will allow those angles to propagate into the resist. The numerical aperture of the lens (defined as the maximum value of the invariant $n\sin\theta$ that can pass through the lens) can be made to be much larger using immersion lithography, with the resulting improvements in resolution one would expect. Numerical apertures above 1.3 seem probable for future 193nm immersion scanners.

The second way in which the use of an immersion fluid changes the results of imaging is the way in which the fluid affects the phase of the light as it reaches the wafer. Light, being a wave, undergoes a phase change as it travels. If light of wavelength λ travels some distance Δz through some material of refractive index n, it will undergo a phase change $\Delta\phi$ given by

$$\Delta\varphi = 2\pi n\Delta z / \lambda \tag{4}$$

A phase change of 360º will result whenever the optical path length (the refractive index times the distance traveled) reaches one wavelength. This is important in imaging when light from many different angles combine to form one image. All of these rays of light will be in phase only at one point – the plane of best focus. When out of focus, rays traveling at larger angles will undergo a larger phase change than rays traveling at smaller angles. As a result, the phase difference between these rays will result in a blurred image.

How does immersion lithography affect this picture? For a given diffraction order (and thus a given angle of the light inside the resist), the angle of the light inside an immersion fluid will be less than if air were used. These smaller angles will result in smaller optical path differences between the various diffracted orders when out of focus, and thus a smaller degradation of the image for a given amount of defocus. In other words, as discussed in the last edition of this column, for a given feature being printed and a given numerical aperture, immersion lithography will provide a greater depth of focus.

In summary, immersion lithography provides two major benefits. First, higher numerical apertures can be built than would be possible when using lenses in air, resulting in improved resolution. These lenses may be enormously complex, but they are possible. Second, while smaller features always have less depth of focus, immersion allows a slower loss of DOF as we progress toward printing ever smaller features. And since these benefits come without a change in exposure wavelength, existing materials and methodologies can be extended further. In the end, immersion will be successful, or not, depending on how economically it delivers on its promise of improved resolution and better depth of focus.

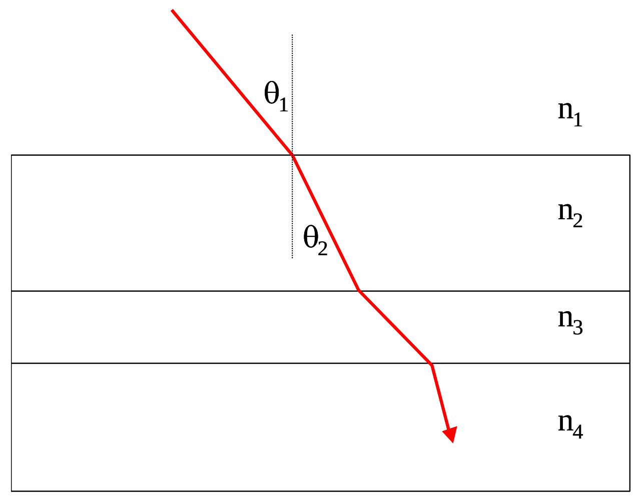

Figure 1a

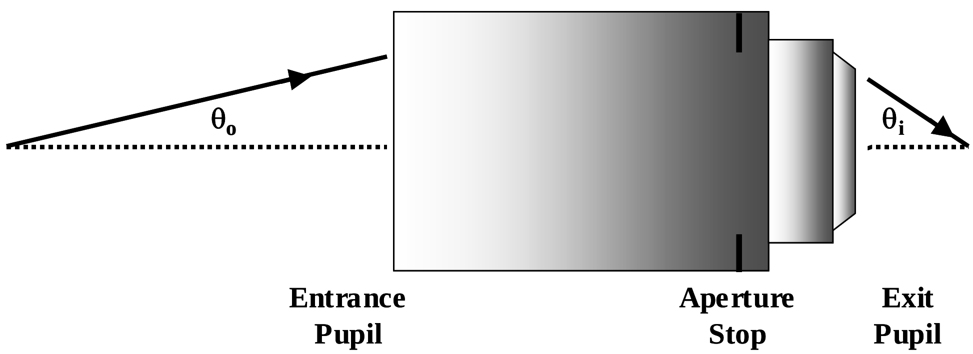

Figure 1b

Figure 1. Two examples of an “optical invariant”, a) Snell’s law of refraction through a film stack, and b) the Lagrange invariant of angles propagating through an imaging lens.