Rayleigh Criterion: The Paradigm of Photolithography Equipment

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Abstract: Photolithography equipment used in the manufacture of semiconductors has been predicted to hit a technological limit based on the Rayleigh criterion in terms of resolution. In actuality, however, the predicted limits of resolution are exceeded and increased microfabrication of photolithography equipment is achieved because of a change in the architecture from {mirror system, equal magnification, batch exposure} to {lens system, reduction, divided exposure}. Instead of using the Rayleigh criterion to make such predictions, experts use it to repeatedly generate “a set of recurrent and quasi-standard illustrations” as methods to improve resolution. The Rayleigh criterion itself is a typical example of what Kuhn (1962) termed a “community paradigm,” by which improvements to resolution were achieved by (a) increasing numerical aperture, (b) shortening wavelength, and (c) reducing the k_1 factor.

Keywords: photolithography equipment, paradigm, Rayleigh criterion, technological limit

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Introduction

Although photolithography equipment for semiconductors first appeared in the form of Kulicke and Soffa's 686 model in 1966 (Henderson, 1995), physical technological limitations had already been reported. Initial photolithography equipment used a contact exposure method. In this method, a detailed electronic circuit is formed by creating a mask whose size is the same as that of silicon wafer, affixing the mask to the wafer, and exposing it to light. Around this time, priority was given to alignment more than resolution, and these devices were called "aligners" (Okazaki, Suzuki, & Ueno, 2003, p. 25). Resolutions in this contact exposure method were 10–5 μm , and 1 KB, 4 KB, and 16 KB DRAM chips were manufactured using this method (Okazaki et al., 2003, pp. 17–18).

The mask, or photomask, is a plate of transparent glass or quartz; this plate is covered with a shading film, which has a detailed circuit pattern etched on it. Masks in this early period were manufactured using a step-and-repeat method, in which you draw a pattern that is 10 times the size of one integrated circuit pattern on a reticle and project a shrunk image of the reticle on the plate through the lens. The mask manufacture technology was the foundation for subsequent steppers, at which time the original mask used in wafer exposure came to be called a reticle.

The contact exposure method has a weakness: yield goes down as masks become damaged due to contact with the wafer at each exposure, and positions misalignments also occur at contact. Because of this, the proximity exposure method was developed whereby a proximity gap of 10–30 μm was kept without allowing the mask and wafer to come into contact. However, the practical resolution limit was about 4 μm .

The equal-sized mirror projection exposure method, which combines convex and concave mirrors, was invented around

1970. However, the optimal position for imaging performance was limited; thus, the mask and wafer were moved synchronously (This method creates prototypes of what later became scanners), batch scanning and exposing the wafer. This photolithography equipment was mainstream around 1980, and 64–256 KB DRAM was made using this method. Resolution at the time was 3–2 μm (Okazaki et al., 2003, p. 18).

Rayleigh Criterion

However, around the mid-1980s, it was believed that the theoretical limit of high-numerical aperture of photolithography equipment was 0.167. This theoretical limit of 0.167 was theoretically derived using the Rayleigh criterion, which calculates the resolution of photolithography equipment, and the formula for obtaining the depth of focus, which shows the limits of the wafer surface roughness required for proper imaging on the silicon wafer (Henderson, 1995). The formulas are as described below.

$$\text{Resolution} = k_1 \times \text{wavelength}/\text{NA} \quad (1)$$

$$\text{DOF} = k_2 \times \text{wavelength}/\text{NA}^2 \quad (2)$$

At the time, k_1 was thought to be a constant value almost equal to 1, and k_2 was thought to be 0.5. Numerical aperture (NA) is defined as $\sin \theta$ when the angle of luminous flux spread for imaging a point on a wafer in air (the maximum angle of incidence) is $\pm\theta$. Accordingly, although the value of NA never exceeds 1 theoretically, the problem here is that there is a trade-off because NA is in both formulas (1) and (2); thus, increasing NA to reduce the resolution in Formula (1) will simultaneously reduce the DOF in Formula (2).

According to Henderson (1995), at the start of the 1980s, semiconductor manufacturers wanted a DOF three times bigger than

the resolution. Thus, when we insert that larger DOF in formulas (1) and (2), we obtain the following formula:

$$(k_1 \times \text{wavelength}/\text{NA}) \times 3 = k_2 \times \text{wavelength}/\text{NA}^2 \quad (3)$$

Considering $k_1 = 1$ and $k_2 = 0.5$, by solving this formula, we can obtain $\text{NA} = 1/6 \approx 0.167$.¹ In this way the theoretical limit of 0.167 for high NA was predicted.²

Before 1980, photolithography equipment used super-high pressure mercury lamps as light sources. Among the bright line spectra with sufficient strength, photolithography equipment used the g-line, having the shortest wavelength in the visible spectrum (436 nm = 0.436 μm), and the h-line (405 nm = 0.405 μm) and i-line (365 nm = 0.365 μm) in the ultraviolet spectrum (Okazaki et al., 2003, p. 25). Because the resolution is equal to wavelength/0.167, the wavelength of the g-line at the end of the 1970s rendered a resolution of 2.6 μm , and the resolution of the shortest wavelength i-line was 2.19 μm (according to Henderson, 1995, p. 636, this was thought to be the limit at the time). This resulted in the conclusion that detail finer than 2 μm was difficult to achieve.

This is how predictions of limits in resolution came to be formed based on the Rayleigh criterion. However, the predicted limits have been exceeded, and photolithography equipment with greater detail has been developed. Changing the architecture from {mirror system, equal magnification, batch exposure} to {lens system, reduction, divided exposure} led experts to repeat “a set of recurrent and quasi-standard illustrations” (Kuhn, 1962, p. 43) in order to improve the resolution using the Rayleigh criterion, previously used to make

¹ Henderson (1995) has many errors in its explanations, including the derivation of these figures. For more details, see Taguchi and Takahashi (2010).

² Technical limits are actually said to be determined by social factors (Kikuchi, 2016; Ogami, 2015, 2016).

predictions about limits. This process is what Kuhn (1962) referred to as the “community’s paradigm”, by which improvements to resolution are achieved by (a) increasing NA, (b) shortening wavelength, and (c) reducing the k_1 factor.

Improvement of NA

Even if the limits of NA via DOF constraints were eased beyond 0.167, in actuality it was difficult to achieve NA greater than 0.167 in a mirror system (Okazaki et al., 2003, p. 30). In 1978, US company GCA began selling a photolithography stepper that used a lens system in its optical system that enabled higher NA. At the beginning of the 1980s Japanese camera manufacturers Nikon and Canon leveraged their extensive experience with lenses to start stepper manufacturing, which led to breakthroughs (Hirota, 2001).

Actually, divided exposure as used in steppers greatly eased the requirements imposed by DOF. Photolithography equipment up to that time used equal magnification, or used a batch exposure method for the entire wafer surface, making it difficult to control the flatness of the entire wafer and creating even stronger demand for a larger DOF. Meanwhile, later photolithography equipment used a reduction exposure method with a lens system. Because the size of one projection is limited, divided exposure came to be used rather than batch exposure. A stepper is a device that uses the step-and-repeat technology, which was used to create masks, for exposing the wafer. By using a divided exposure, manufacturers only needed to worry about the flatness of the section being exposed each time, which significantly eased the constraints of DOF. Moreover, a scanner creates an image by scanning each exposed area via a slit, requiring an even smaller screen size, and further easing the constraints of DOF (Okazaki et al., 2003, pp. 30–33).

Henderson (1995) states that semiconductor manufacturers, who

up to that point had demanded a DOF three times the resolution, eased their demands and allowed a DOF equal to the resolution, resulting in a modified limit, $NA = 0.5$, calculated as the solution of Formula (3). In actuality, however, a major factor in this case was that a batch exposure was superseded by a divided exposure and the dominant architecture did not really require a high level of wafer flatness. Further, chemical mechanical polishing (CMP) of wafer surfaces made sudden advances in the 1990s, which reduced demands for DOF (Doi, Hiyama, Fukuda, & Kurokawa, 2007; Doi, Kasai, & Nakagawa, 1998; Sato, 2016, p. 188). The easing of the constraints of Formula (2) (where DOF gets smaller as NA gets larger), pointed the way towards higher NA, and higher NA was achieved by adopting a lens system (Taguchi & Takahashi, 2010).

In addition, as was previously noted, NA should theoretically never exceed 1 in air; however, in immersion lithography in recent years, the space between the lens and the wafer (properly termed as “resist”) is filled with pure water. Pure water has a higher refractive index than air, allowing for the formation of light at greater angles within the resist and making $NA = 1.436 \sin\theta$, which is 1.436 times larger than the NA of air. In actuality, $NA = 1.35$ is achieved in the immersion lithography that uses an ArF excimer laser, which will be explained in a subsequent section herein (JEITA, 2009, p. 216).

Improvement of Wavelength

Shortening wavelengths requires the development of a light source, but the change to an architecture using a lens system brought about the need to develop glass material for lenses simultaneously with the light source. Although photolithography equipment using mirror systems already utilized short wavelengths in the ultraviolet i-line (365 nm), in steppers using lens systems, the wavelengths were pushed back to the g-line (436 nm) in the visible spectrum because

the glass material for the ultraviolet spectrum was immature. Advances in glass-material development for lens systems in the ultraviolet spectrum enabled the lens-system equipment to skip the h-line (405 nm) and adopt the i-line (365 nm). As a next step, even shorter wavelengths meant a move to quartz as the glass material; thus, wavelengths jumped to the ultraviolet KrF excimer laser (248 nm) in order to maintain the superior transmittance of quartz (Okazaki et al., 2003, p. 30). Further, instead of using quartz, which can be damaged by a ArF excimer laser (193 nm), a fluorite (CaF_2) was developed as a glass material to allow the use of the ArF excimer laser (Okazaki et al., 2003, p. 55).

Improvement of k_1 Factor

In the world of photolithography equipment, the initial selection of wavelength is said to decide the subsequent research and development. This is because changing the wavelength also requires physical and chemical changes, such as lens materials and the resist process, placing a huge load on development of an overall system. The k_1 factor is determined by multiple factors such as physics and chemistry; therefore, it is not uniquely determined. Although, generally, the value of k_1 was formerly thought to be almost equal to 1, it has been shrunk as far as 0.3 through the following combinations of fundamental technologies (Okazaki et al., 2003, p. 74, Table 2.2).

- (A) Photolithography equipment: modified illumination method (Horiuchi, 1993; Wakamiya, 1998), double patterning (Takahashi, 2006)
- (B) Resist process technologies: PEB (post-exposure bake), thinning
- (C) Mask technologies: OPC (optical proximity correction) (Kotani,

Mashita, & Uno, 2012), phase-shifting mask (Horiuchi, 1993; Wakamiya, 1998)

The modified illumination method since the beginning of the 1990s, phase-shifting masks since the mid-1990s, and double patterning from the latter half of the 1990s, along with the aforementioned immersion lithography from the first part of the 2000s, were developed as means to extend the life of existing steppers and scanners that cost billions of yen (Takahashi, 2006), and contributed to improvements to the k_1 factor.

Discussion

Light includes wavelengths much longer than X-rays or electron beams; therefore, it is natural to turn to the development of shorter-wavelength X-rays or e-beams if you improve resolution based on the Rayleigh criterion. In actuality, most experts in the 1970s predicted that visible light and ultraviolet light are replaced by X-rays and e-beams focusing on only the wavelengths in Rayleigh criterion formula. Thus, according to Henderson (1995), investment in developing technologies to use X-rays and e-beams as light sources began prior to 1970, with IBM investing more than a billion dollars in X-ray based photolithography devices. Articles about X-ray and e-beam photolithography equipment began to appear in journals in 1977, and prior to that time at least one company was using e-beam photolithography devices.³

However, when changing the architecture from {mirror system, equal magnification, batch exposure} to {lens system, reduction, divided exposure}, the Rayleigh criterion, which had been used to

³ Equipments using e-beams are used even today to make masks, though they are not in widespread use for semiconductors because of their low throughput compared to photolithography equipment.

make predictions on limits, was then repeatedly used in “a set of recurrent and quasi-standard illustrations” (Kuhn, 1962, p. 43) as means to improve resolution. The Rayleigh criterion itself was what Kuhn (1962) termed a “community paradigm,” and the Rayleigh criterion allowed for the realization of improvements to resolution through (a) increasing NA, (b) shortening wavelengths, and (c) reducing the k_1 factor.

However, (a) if you use immersion lithography and an ArF excimer laser, $NA = 1.35$, which is said to be the limit of NA. (b) Shortening wavelengths beyond those using an ArF excimer laser (193 nm) does not allow light to pass through lenses. (c) Even though the resist process may produce the maximum amount of contrast, an image cannot be focused into when the k_1 factor is $1/4$ of the wavelength ($k_1 = 1/4 = 0.25$ is called the limit of resolution), and cannot in actuality be made smaller than 0.3. Thus, many engineers claim that 43 nm is the limit of resolution (Higashiki & Onishi, 2012). When the age of the lens system architecture comes to an end after approximately forty years, will the paradigm change?

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