Photolithography
Theory

1. Introduction

Optical lithography is the process of creating specific patterns on semiconductor wafers using a photosensitive material (known as photoresist, PR) and an ultraviolet light exposure system to transfer patterns from masks to wafers. Processes with direct patterning on the wafers are also possible, such as directly writing on a wafer with an electron beam or a laser beam, but at this time none are in use for high-volume semiconductor manufacturing.

Optical lithography technology determines the smallest transistor dimensions which can be manufactured on a semiconductor chip. As such, it has been the primary driver for the remarkable improvements in performance and reduction in cost per function, the hallmark of the microelectronics industry. Optical microlithography involves the practice of multiple disciplines: physics, chemistry, and engineering specialties [1]. During this module, students will learn the basic principles of optical microlithography, chemistry of the photoresists, and pattern replicator instruments.

2. Photoresists

2.1. Types of Photoresists

Photoresist (PR) is a radiation – sensitive compound that can be classified as positive or negative, depending on how it responds to radiation. For positive resists, the exposed regions become more soluble and are thus more easily removed in the development process. The net result is that the patterns formed (also called images) in the positive resist are the same as those on the mask. For negative resist, the exposed regions become less soluble and the patterns formed in the negative resist are the reverse of the mask patterns [2], as shown in Figure 1.

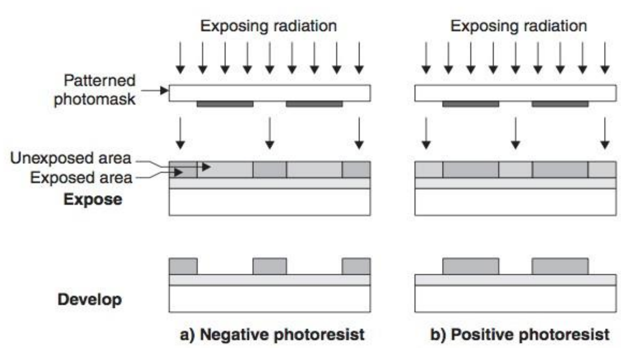

Figure 1: Negative and positive photoresist [3]

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2.2. Photoresist Chemistry

Positive Photoresists usually consist of four components: a photoactive compound (PAC), a polymer resin, an organic solvent and additives. Prior to exposure, it is insoluble in the developer solution; after development, the exposed areas are removed. An example of a **positive photoresist** is AZ®1512, which consists of Cresol-Novolak resin (polymer), Diazo Photoactive compound (PAC), Propylene Glycol Monomethyl Ester Acetate or PGMEA (solvent) and a few additives to tune the desired process parameters such as viscosity. Polymer by itself is highly soluble in a developer solution. However, its solubility is inhibited in the presence of PAC. On exposure to UV radiation, the PAC loses its N_2 to form carboxylic acid which is highly soluble in a developer solution (see Fig. 2). Thus, a spatial variation in light energy incident on the photoresist will cause a spatial variation in solubility of the resist in developer.

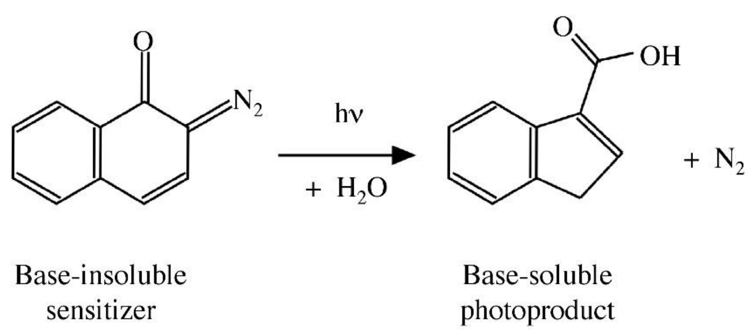

Figure 2: Chemistry of a positive photoresist PAC [12].

Negative Photoresists usually consist of isoprene monomers which on exposure to UV radiation undergo polymerization and crosslinking to form long chain polymers, as show in Figure 3. These polymers do not dissolve in the developer solution and thus the exposed region remains insoluble during development.

One major drawback of a negative PR is that in the development process, the whole resist mass swells by absorbing the developer solvent. This swelling action limits the resolution of negative PRs [2].

Properties of the positive and negative photoresists are compared in Table 1.

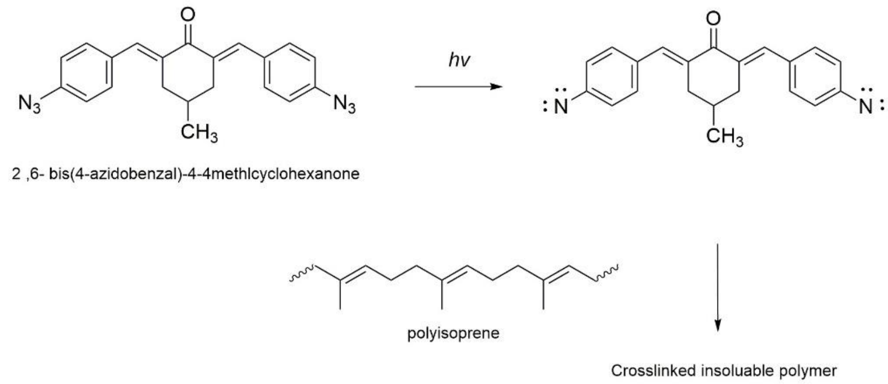

Figure 3: Chemistry of a negative photoresist PAC [12].

Characteristic	Positive PR	Negative PR
Adhesion to Silicon	Fair	Excellent
Relative Cost	More Expensive	Less Expensive
Developer Base	Aqueous	Organic
Solubility in the developer	Exposed region is soluble	Unexposed region is soluble
Minimum Feature	0.5 µm and below	2 µm
Step Coverage	Better	Lower
Wet Chemical Resistance	Fair	Excellent

Table 1 Comparison of positive and negative photoresists [10]

The polymer is the backbone of the PR. The most common polymers and monomers used in the semiconductor and Micro-Electro-Mechanical Systems (MEMS) industries are:

- Poly(methyl methacrylate) (PMMA),
- Poly(methyl glutarimide) (PMGI)
- Phenol formaldehyde resin (DNQ/Novolac),
- SU-8 (epoxy).

3. Optical Lithography

Photolithography is the process of transferring patterns of geometric shapes on a mask (or reticle) to a thin layer of PR covering the surface of a semiconductor wafer. The resist patterns defined by the lithography process are not permanent elements of the final device, but only replicas of circuit features [2]. The pattern transfer process is accomplished by using two kinds of lithography exposure tools: Pattern Generators and Pattern Replicators.

A pattern generator is an exposure tool that accepts pattern input data from a database and directly creates a physical image on a wafer using beams of either charged particles or photons. These tools are used extensively to create photomasks and reticles for pattern replicators. They are also used in limited volume for direct patterning on semiconductor wafers.

The main disadvantage in using pattern generators for general purpose high-volume lithography is the slow imaging on the wafer. The required patterning density is on the order of $10^{13}/cm^2$ discrete pixels for a feature size of ~65 nm. The achievable speeds for electron or photon pattern generators are less than 1010 pixels/s, leading to imaging rates of no more than one 200 mm wafer per hour. The general rule for economical semiconductor production requires a wafer patterning tool to process on the order of 100 wafers per hour or higher, and existing direct pattern generators simply cannot come close to achieving this speed [1].

The solution to the throughput limitation of pattern generators is to create a master pattern image in the form of a photomask or reticle and then replicate the pattern in a massive parallel fashion onto wafers. Photomasks consist of a fused-silica substrate covered with a chromium layer [2]. Photomask fabrication is performed with electron beam and photon beam tools, while repair of mask pattern defects is performed with ion beam and photon beam tools.

Pattern replicators use a variety of image transfer techniques, including photons and charged particles. The most common pattern transfer agent is a well-conditioned beam of monochromatic photons. Exposure wavelengths used in photolithography are from the Far UV (100nm to 290nm) and Near UV (320nm to 450nm) portions of the electromagnetic spectrum (see Fig. 4). Systems with broad spectrum lamps or "broadband" systems typically emit wavelengths that span roughly the 350 nm to 450 nm wavelength range (or some subset of this range) [15]. Example of such a system is a high-pressure mercury-arc lamp; its spectrum is shown in Figure 5. The first practical step- and-repeat imaging tools used the so-called G-line of mercury, at 436 nm wavelength (see figure 5). Second generation stepper tools used the I-line of mercury, at 365 nm. **In our lab, we also use the I-line[1].**

[1] Lithographers often refer to monochromatic exposure systems as "I-line", "G-line", DUV etc. as opposed to specifying the actual wavelength emitted

More recently, as the need for higher resolution drove the requirement for wavelength down, mercury arc lamps were replaced by excimer lasers. The lasers provide both very high intensity and very narrow bandwidth. The most advanced exposure tools in semiconductor manufacturing employ a short wavelength of 193 nm, generated with the help of ArF excimer lasers [1].

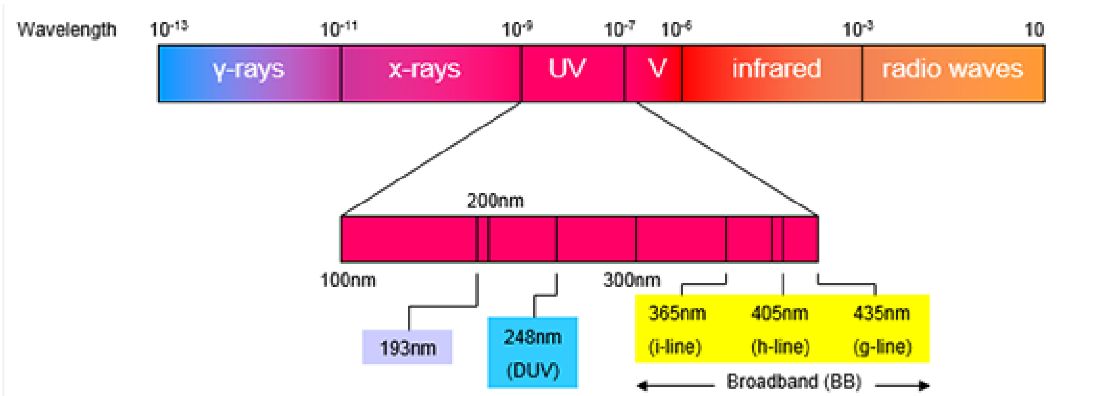

Figure 4: Photoresist exposure wavelengths [15].

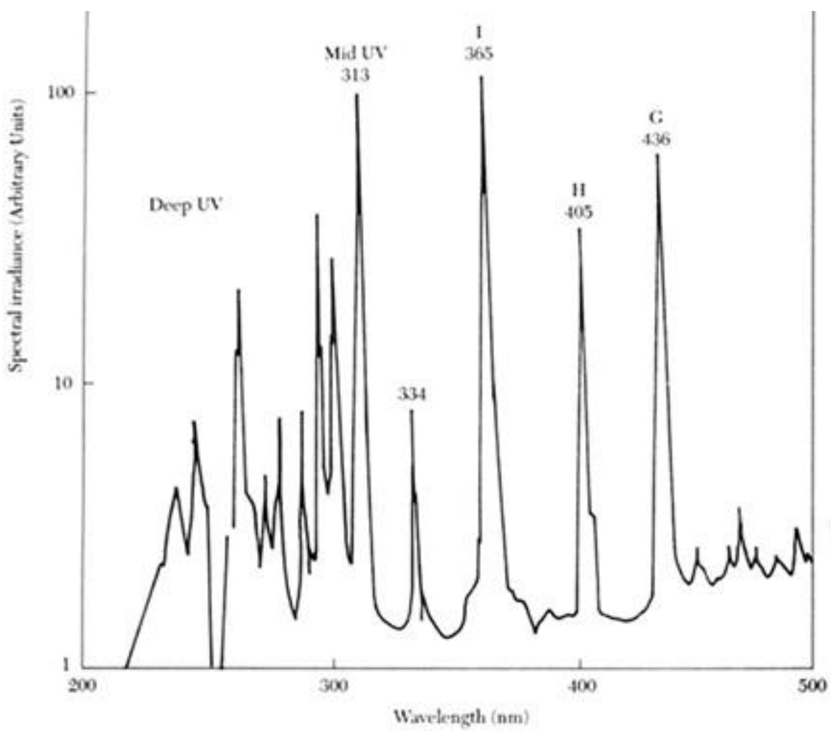

Figure 5: Typical high-pressure mercury-arc lamp spectrum.

3.1 Image Resolution and Depth of Focus

The relationship of wavelength to image resolution and depth of focus in a projection optical system has been understood for more than 100 years. The simple relationship defined by the so-called Rayleigh equations is

$$l_m = k_1 \frac{\lambda}{NA},$$

where λ is the exposure wavelength, k_1 is a process-dependent factor, and NA is the numerical aperture, which is given by:

$$NA = \bar{n}\sin\theta$$

Where $\bar{n}$ is the index of refraction in the image medium (usually air, where $\bar{n}$=1), and θ is the half-angle of the cone of light converging to a point image at the wafer, as shown in Figure 6. Also shown in the figure is the Depth of Focus (DoF), which can be expressed as:

$$DoF = \frac{\pm\frac{l_m}{2}}{tan\theta} \approx \frac{\pm\frac{l_m}{2}}{sin\theta} = k_2 \frac{\lambda}{NA^2},$$

where k_2 is another process-dependent factor [2].

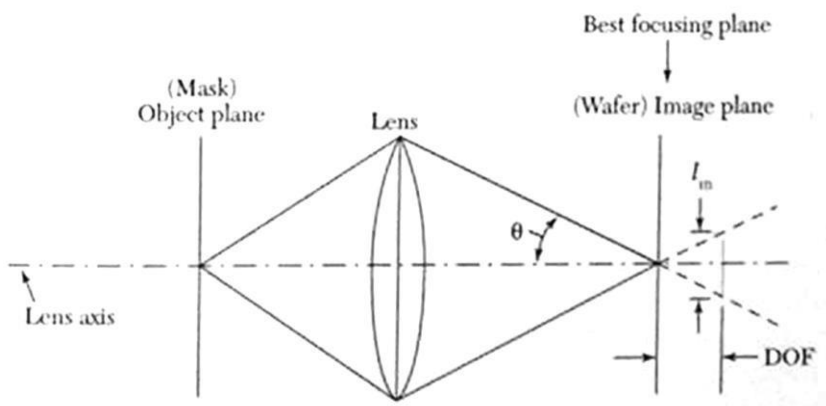

Figure 6: Simple image system [2]

3.2. Exposure Methods.

Pattern Replicators can be classified by two exposure methods: shadow printing and projection printing. Shadow printing may have the mask and wafer in direct contact with one another (contact printing) or in close proximity (proximity printing), as illustrated in Figure 7. In this module, we will use the contact printing method. As shown in Figure 7a, in contact printing a resist-coated wafer is brought into physical contact with a mask. Resist is then exposed with a nearly collimated beam of ultraviolet light through the back of the mask for a fixed time [15].

The intimate contact between resist and mask provides a resolution of approximately 1µm. It is important to realize that the contact printing suffers a major drawback caused by dust particles. The imbedded particles cause permanent damage to the mask and result in increasing defects in the wafer with each exposure [2].

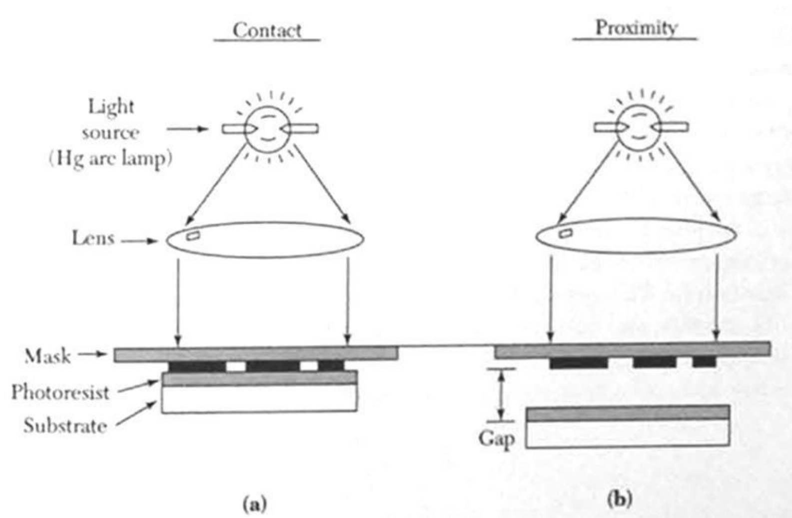

Figure 7: Schematic of optical shadow printing techniques: (a) contact printing; (b) proximity printing [2].

4. Steps Involved in the Photolithography Process

Every PR has its own instruction manual (datasheet or recipe) generally provided by its manufacturer. However, it is necessary for every laboratory to test the recipe offered by the manufacturer and create its own recipe adapted to the specific laboratory conditions (i.e. temperature, humidity, process interests and equipment characteristics). A general flow chart of the microlithography process can be seen in Figure 8. The students are encouraged to review some websites of PR manufacturers and vendors, such as the ones suggested in Section 5 of this module.

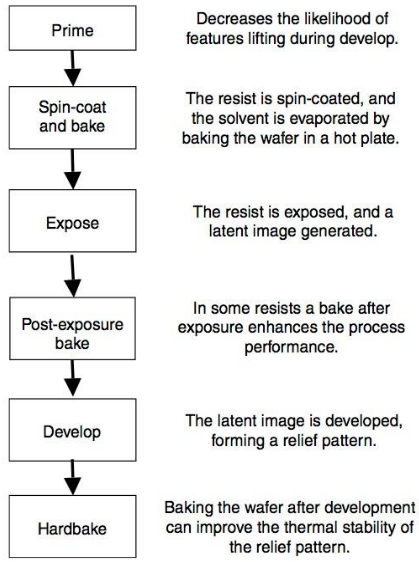

Figure 8: Flowchart of the photolithographic process. The post-exposure and hard-bake steps can be omitted, depending on the process [1].

4.1. Wafer priming: consists of a dehydration bake to remove water, organic and inorganic contaminants from the surface. However, the wafer surface readily reacts with moisture after dehydration bake at room temperatures to form a thin layer of silanol group (Si-OH). Silanol layer is hydrophilic and causes lower adhesion of PR to the wafer in the subsequent steps. This results in premature PR lift off, which is a serious problem. To prevent this from happening, the wafer is coated with Hexamethyl disilizane (HMDS) to improve PR adhesion to wafer surface since it is highly hydrophobic [11], as shown in Figure 9. In our lab we skip this step, but it remains a very crucial step in the industry.

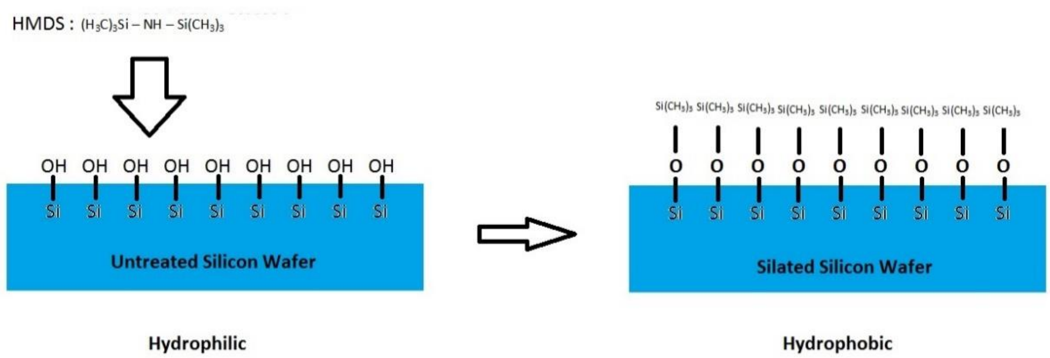

Figure 9: Generation of a hydrophobic wafer surface [13]

4.2. Spin Coating: In a typical spin coating process, the photoresist is applied to the center of rotating wafer and the spin speed is then increased rapidly to spread the resist evenly from the center to the edges, as illustrated in Figure 10. This “spread step” is then followed by a fixed

RPM spin step which sets the final coat thickness and allows solvent to evaporate, partially stabilizing the film. Higher spin speeds during this step will result in thinner resist films and lower RPM will yield thicker resist films [15]. In this module, we will be spinning wafers with speeds in the 2000-4000 RPM range.

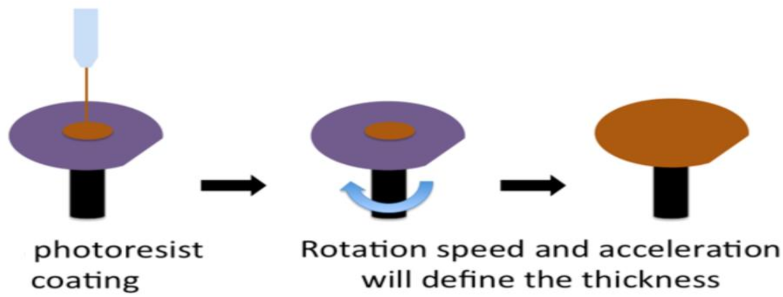

Figure 10: Spin coating [14]

4.3. Prebake/Soft Baking: After spin-coating, our resist film will contain solvent 20-40% by weight. Prebaking involves removing this excess solvent through drying by baking our wafers. By baking the wafer, majority of the solvent is removed and the adhesion between wafer surface and PR film is improved. Prebakes are commonly performed on hot plates or in exhausted ovens and typical temperatures range from 90 to 110^{o}C [11]. In the lab, we will be performing prebake for about 60 s. Higher temperatures or longer bake times will lead to the decomposition of PR.

4.4. Exposure: After prebaking, the wafer is exposed to a pattern of radiation, as described in Section 3. This exposure results in a chemical change in the photoresist as described in Section 2.2.

4.5. Post-exposure bake (PEB): For conventional resists, PEBs are carried out to reduce standing wave patterns resulting from interference of light (see Fig. 11). Diffusion during the bake helps in the reduction of standing waves. For another class of PRs called "Chemically Amplified" PRs, PEB is an essential part of the chemical reactions that create the solubility differentials between exposed and unexposed regions. These resists are used for Deep-UV lithography processes where wavelengths of 248 and 193 nm are used for exposure (we use 365 nm in this lab) [11]. We will not be performing PEB as we are not building any devices in our modules.

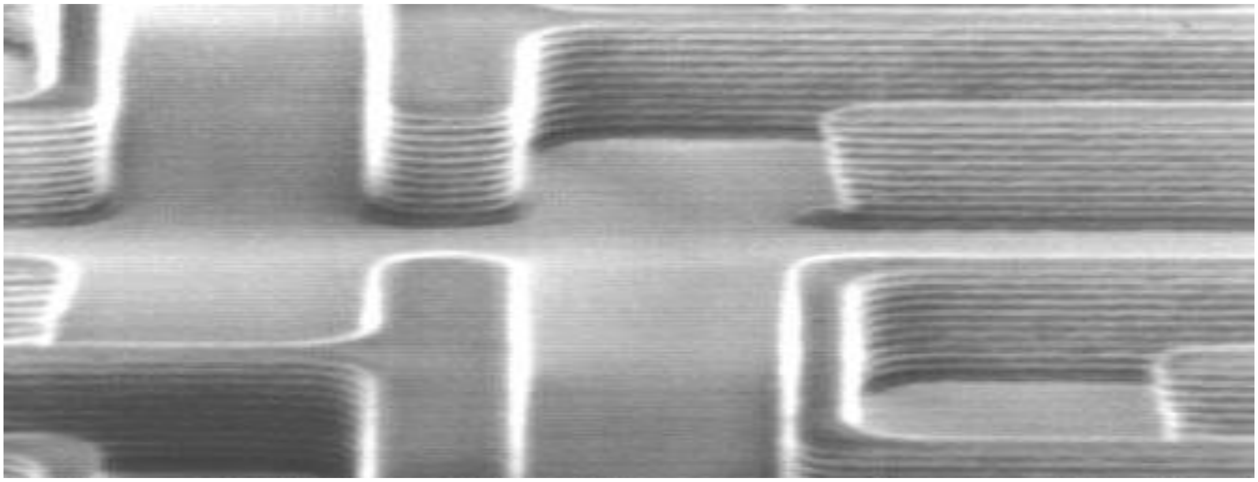

Figure 11: Photoresist pattern on a silicon substrate showing prominent standing waves [11]

4.6. Development: Once exposed, the photoresist must be developed. The vast majority of photoresists in use today require aqueous base solutions for developing the exposed image. Most commonly used PR use aqueous bases as developers such as Tetramethyl ammonium hydroxide (TMAH) in concentrations of 0.2 - 0.26 N. Development is undoubtedly one of the most critical steps in the photoresist process. The characteristics of the resist-developer interactions determine to a large extent the shape of the photoresist profile and, more importantly, the linewidth control [11]. The development process will proceed as described in section 2.2

4.7. Hard baking: A post develop bake (or hard bake) of the photoresist pattern is a common method for stabilizing the printed features to provide optimum performance at etch. This final bake step ensures complete removal of solvent, improving adhesion in wet etch (or plating) processes and resistance to plasma etches [15].

5. Recommended Websites

- http://www.microchem.com
- http://www.microchemicals.eu
- http://memscyclopedia.org
- https://snf.stanford.edu/SNF/processes/process-modules/photolithography/standard-resists-at-snf

References

[1] R. Doering and Y. Nishi, *Handbook of Semiconductor Manufacturing Technology*, 2nd ed. (CRC Press, 2008).

[2] G.S. May and S. M. Sze, *Fundamentals of semiconductor fabrication* (Wiley, 2004).

[3] Scotten W. Jones, *Photolithography*, http://www.icknowledge.com/misc_technology/PhotoChapter.pdf ed.: ICKnowledge LLC, 2008.

[4] J. Pulecio. (2012, April) Nanofabrication Group. Brookhaven National Laboratory. [Online]. http://www.bnl.gov/cfn/groups/Nanofabrication/cleanroom/SOPs/KarlSussMJB3_User-SOP.pdf

[5] Micro Chem. (2012, April) Shipley Microposit S1800 Series Photo Resists. [Online]. http://www.microchem.com/Prod- LithographyOverviewPosNeg.htm

[6] Micro Chem. (2012, April) LOR Lift-Off Resists. [Online]. www.microchem.com

[7] H. Lorenz et al., "SU-8: a low-cost negative resist for MEMS," *J. Micromech. Microeng.*, vol. 7, pp. 121-124, 1997.

[8] P. Rai-Choudhury, Ed., *SPIE Handbook of Microlithography, Micromachining and Microfabrication. Volume 1: Microlithography*, http://www.cnf.cornell.edu/cnf_spietoc.html ed., vol. 1.

[9] Micro Chem. (2012, April) SU-8 2000. Permanent Epoxy Negative Photoresist. [Online].

http://www.microchem.com/pdf/SU-82000DataSheet2000_5thru2015Ver4.pdf

[10] Madou, Marc (2002). *Fundamentals of Microfabrication*. Boca Raton, Florida: CRC Press. p. 9. ISBN 0-8493-0826-7

[11] Chris A. Mack, Fundamental Principles of Optical Lithography: The Science of Microfabrication , John Wiley & Sons, (London: 2007).

[12] S. J. Moss and A. Ledwith, The Chemistry of the Semiconductor Industry , Blackie&Son Limited, Glasgow (1987).

[13] Pabo, E.F. (7–9 December 2011). "Advances in spray coating technologies for MEMS, 3DICs and additional applications". Electronics Packaging Technology Conference. 13: 349–353. Retrieved June 3, 2012.

[14] https://www.elveflow.com/microfluidic-tutorials/soft-lithography-reviews-and-tutorials/introduction-in-soft-lithography/pdms-membrane-thickness-of-a-spin-coated-pdms-layer/

[15] Integrated Micro Materials. Lithography Process Overview. [Online].http://www.imicromaterials.com/technical/lithography-process-overview