Manufacturing Techniques for Microfabrication and Nanotechnology

BOOK 2 of The Fundamentals of Microfabrication and Nanotechnology, Third Edition, Three-Volume Set

Chapter 1: Photolithography

1.1:

Analyze each of the expressions for photolithography resolution and explain how to improve resolution in each case. What are the advantages and disadvantages of using e-beam lithography compared to typical photolithography using UV radiation? What is the most likely next-generation lithography?

Answer:

Photolithography resolution. The general equation for the theoretical resolution (R), i.e., the minimum resolved dimension b_{min} (for a line or a space), in case no lens is used is given by:

$$R = b_{min} = \frac{3}{2}\sqrt{\lambda\left(s + \frac{z}{2}\right)} \qquad 1.1.1$$

where s is the gap between the mask and the photoresist surface, λ is the wavelength of the exposing radiation, and z the photoresist thickness. In contact printing a photo mask is pressed against the resist-covered wafer and s, in Equation 1.1.1, is zero. Equation 1.1.1 in this case reduces to:

$$R = b_{min} = \frac{3}{2}\sqrt{\frac{\lambda z}{2}} \qquad 1.1.2$$

Equation 1.1.2 clarifies the need to use shorter wavelengths and thinner resist layers in order to achieve higher resolution. In proximity printing, spacing of the mask away from the substrate minimizes defects that result from contact. For proximity printing, Equation 1.1.1, with s >> z, can be rewritten as:

$$R = b_{min} = \frac{3}{2}\sqrt{\lambda s} \qquad 1.1.3$$

Resolution is higher at shorter wavelengths and with shorter distances between the wafer and the mask but it is not as good as in contact printing (see above) or with projection printing (see below). The most desirable fabrication processes involve *in situ* deposited masks, also called *self-aligned* or *conformable* masks. These may be regarded as an extreme case of contact printing—that is, s is zero with the mask in atomic contact over the whole device under construction.

The practical limiting resolution R in projection printing is given by:

$$R = \frac{k_1\lambda}{NA} \qquad 1.1.4$$

where k_1 is an experimentally determined parameter that depends on resist parameters, process conditions, and mask aligner optics; λ represents the wavelength of the light used for the pattern transfer; and NA is the numerical aperture of the imaging lens system. A small k_1 and short λ and a large NA will all improve resolution. The k_1 parameter fluctuates in practice between 0.3 and 0.75 (1.1 for reflective surfaces like aluminum). The NA of lenses in projection aligners ranges from ~0.16 to 0.60.

Comparison of e-beam lithography with UV lithography. E-beam lithography exhibits some very attractive attributes compared to UV photolithography. These include
- Precise control of the energy and dose delivered to a resist-coated wafer
- Deflection and modulation of electron beams with speed and precision by electrostatic or magnetic fields
- Imaging of electrons to form a small point of <100 Å as opposed to a spot of say 5000 Å for light
- No need for a physical mask, only a “software mask” is required
- The ability to register accurately over small areas of a wafer
- Lower defect densities
- Large depth of focus (DOF) because of continuous focusing over varying topography

Some of the disadvantages of e-beam lithography include:
- Electrons scatter quickly in solids, limiting practical resolution to dimensions greater than 10 nm.
- Electrons, being charged particles, need to be held in a vacuum, making the apparatus more complex than for photolithography.
- Slow exposure speed. An electron beam must be scanned across the entire wafer (for a 4-in wafer with a high feature density this might require ~1 h).
- High system cost.

The use of e-beam lithography has been limited to mask making and direct writing on wafers for specialized applications, for example, small batches of custom ICs.

Next-generation lithography. Extreme UV lithography (EUVL) is the favorite candidate for next-generation lithography (NGL). EUVL, using wavelengths in the 10 to 14 nanometer (nm) range to carry out projection imaging, is the most natural extension of optical projection lithography as in principle it only differs in terms of the wavelength. This type of radiation is also referred to as soft-x-ray radiation and vacuum UV. The technique is capable of printing sub-100-nm features while maintaining a DOF of 0.5 μm or larger and has k-values that make process control less demanding. EUVL is strongly absorbed in virtually all materials and consequently imaging must be carried out in vacuum. New resists and processing techniques must be developed as well.

1.2:

An exposure is performed with coherent light using a step-and-repeat projection printing system. The light source has a wavelength of 365 nm (I-line of a Hg arc lamp). The pattern is a grating with a line-to-line spacing of 1 μm.

(a) Calculate the minimum value of the numerical aperture (NA) which will provide contrast at the image plane (the plane of the resist).

(b) What is the maximum value of the numerical aperture, above which there will be no improvement in image quality?

(c) Calculate the depth of field of the image for cases (a) and (b).

Answer:

(a) At a fixed wavelength and resolution (R = 1 μm), the smallest NA value goes with the smallest value of k_1. The value of k_1 should not be much lower than 0.4 and based on:

$$R = \frac{k_1 \lambda}{NA} \qquad 1.2.1$$

the minimum NA equals 0.146 (a typical lens in projection lithography have an NA of 0.3-0.4).

(b) Using Equation 1.2.1 with $k_1 = 1$, the maximum NA value equals 0.365 (the largest lenses made by Nikon have an NA of 0.54 and 0.6).

(c) Using Equation 1.2.2 and assuming a k_2 value of 0.5:

$$DOF = \pm\delta = \pm\frac{k_2 \lambda}{(NA)^2} \qquad 1.2.2$$

the DOF is 8 μm for (a) and 1.4 μm for (b).

Thanks to Professor Kevin Kelly, Louisiana State University.

1.3:

Lift-off refers to the process of exposing a pattern into a photoresist, depositing a thin film such as a metal or dielectric over the entire area, and then washing away the photoresist to leave behind the film only in the patterned area. Why is it easier to obtain a lift-off profile with a negative resist than with a positive resist?

Answer:

In a lift-off process one can either use a negative resist which easily results in an undercut (retrograde profile) or modify a positive resist to exhibit the desired undercut. Using a negative resist and adjusting the exposure and development time, one can obtain a retrograde profile in one step. Because the light strikes the resist first at the surface the material there, only in the case of a negative resist, resists development better than resist deeper down. An undercut does not readily form with a positive resist so some “tricks” are in order. The first is to “pre-soak” the positive resist surface with an aromatic solvent (e.g., chlorobenzene) to convert a surface layer, which develops at a much slower rate than the bulk of the resist film thereby providing an undercut during development in alkaline solution. The second involves image reversal of a positive resist.

1.4:

Which statements are NOT correct?

(a) Short exposure wavelengths can create standing waves in a layer of photoresist.

(b) Regions of constructive interference create increased exposure.

(c) Standing waves can impair the structure of the resist, but they can be eliminated by use of multiple wavelength sources or postbaking.

(d) Standing waves effects are most noticeable at the center of the resist.

(e) The primary components of a positive photoresist are

1. Non-photosensitive base phenolic resin
2. Photosensitive dissolution inhibitor

3. Coating solvent

(f) Projection lithography resolution is limited by exposure wavelength, resist thickness, and diffraction and dispersion of light.

(g) Proximity lithography resolution is limited only by exposure wavelength and resist thickness.

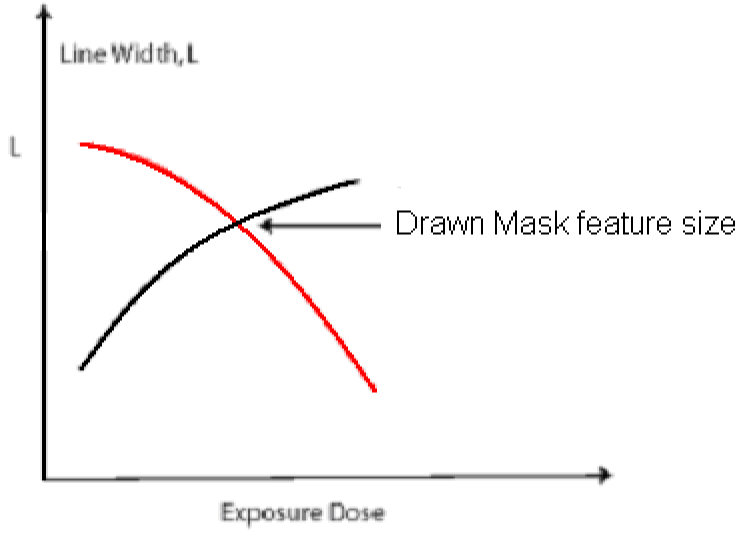
Answer:

d and g

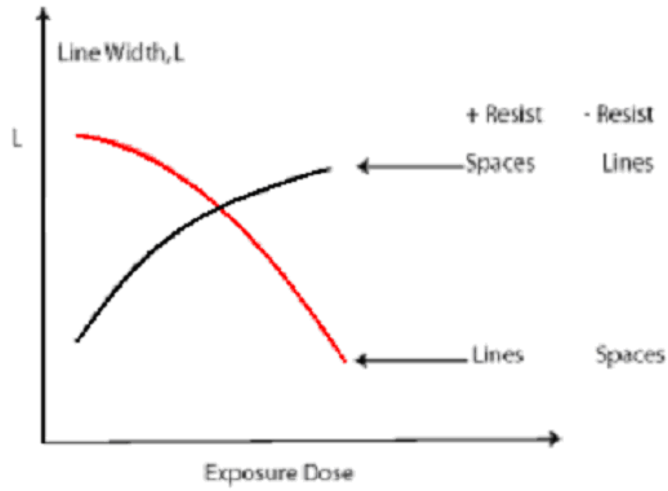
Thanks to Professor Karl Böhringer, University of Washington, Seattle.

1.5:

Indicate which line in this graph corresponds to **negative** photoresist and which corresponds to **positive** photoresist.



Answer:



Thanks to Professor Karl Böhringer, University of Washington, Seattle.

1.6:

Why is it easier to find good data from the literature on resist sensitivity than on lithographic sensitivity?

Answer:

In the literature, the values given for the lithographic sensitivity of a resist show a tremendous spread as a result of the complex relationship between the intrinsic resist sensitivity and the dose required to successfully process that resist. This relation involves not only the intrinsic resist sensitivity but also the bandwidth of the optical exposure system, baking conditions, resist thickness, developer composition, development conditions, etc. In order to reproduce a reported lithographic sensitivity, all these parameters need to be duplicated exactly.

1.7:

Sketch the lithography steps involved in generating a staircase resist pattern that is oriented in the same direction on both sides of a Si wafer. The steps of the staircase need to be aligned within 2 μm and your laboratory cannot afford a >$250,000 double-sided mask aligner.

Answer:

Gray-tone mask (GTM) technology might work. The challenge with GTM is the definition of zones of variable optical transmission that represent the various gray levels on the gray-tone mask. Gray levels may be created by the density of dots in a chromium mask. In the simplest, least-accurate approach, wafer flats can be used as reference for the double-sided alignment, but this approach offers at most a 5 μm accuracy. Using an inexpensive double-sided alignment system, developed by White and Wenzel and shown in Figure 1.62, staircases on either side of the wafer may be aligned with somewhat better accuracy (depending on the wafer size, 2 μm is feasible). In this approach, mask 1, containing alignment marks, is contact printed onto photoresist-coated mask 2 while both are positioned snugly against the three pins on a jig. After developing and etching the alignment marks on mask 2, individual alignment patterns from the two masks are transferred onto the opposite faces of the semiconductor wafer coated on both sides with photoresist. This latter is accomplished by sandwiching the resist-coated Si wafer between the two alignment masks (again set snugly against the three pins of the jig) and exposing each wafer surface (directly for one side and through the large hole in the jig for the other). The alignment patterns are then etched into the wafer and used in a conventional one-sided mask aligner. The wafers are exposed and the light intensity modulation by the gray-tone areas on the mask generates depth variations in the photoresist. A method that would work well for monolayer range step heights and an identical orientation for both staircases on either side of the wafer involves Langmuir-Blodgett film deposition as sketched in Figures 1.7.1 and 1.7.2 below.

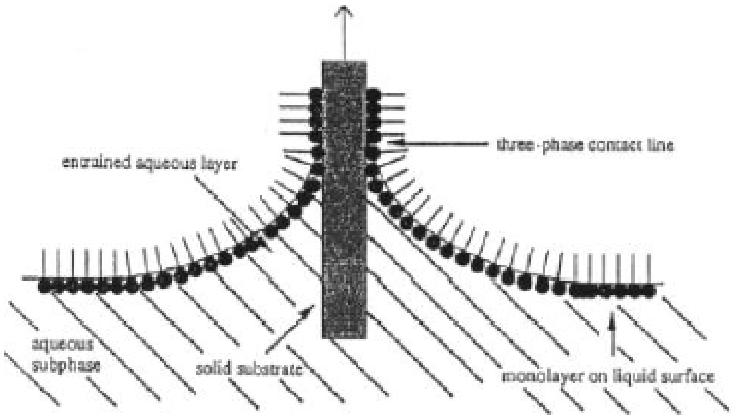


FIGURE 1.7.1 Langmuir-Blodgett deposition method.

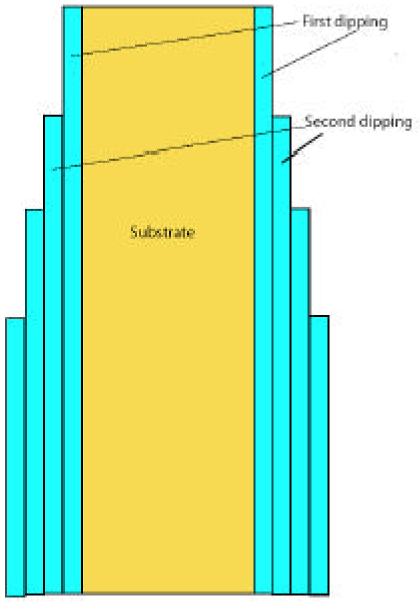


FIGURE 1.7.2 Staircase on both sides of a glass slide by repetitive Langmuir-Blodgett deposition.

1.8:

Present a comparison of negative and positive photo resists. Also explain what a permanent resist is. Describe what happens chemically to positive and negative resists when exposed to UV radiation.

Answer:

Resist tone comparison. In the simplest positive resists, photon irradiation breaks polymer backbone bonds, leaving fragments of lower molecular weight. A solvent developer selectively washes away the lower molecular weight fragments, thus forming a positive tone pattern in the resist film. Negative resists work by cross-linking the polymer chains together, rendering them less soluble in the developer. Negative resists tend to have less bias (often zero) than positive resists. However, they tend to have problems with scum (insoluble residue in exposed areas), swelling during development, and bridging between features. Advantages of positive resists include lack of swelling, possibility of higher resolution, higher contrast, and resistance to most chemical agents and procedures used in micro fabrication (wet etching and dry etching). Advantages of negative resists include swelling during development (good for lift-off), less expense, and good adhesion to Si.

Permanent resist. A permanent resist (e.g., SU-8 by MicroChem Corp.) is a resist that becomes a permanent part of a device after lithography and may serve a role such as a structural element, a dielectric, an optical waveguide, etc.

Photochemical reactions in positive and negative resists. If the photoresist is of the type called *positive* (also *positive tone*), the photochemical reaction during exposure weakens the polymer by rupture or scission of the main and side polymer chains, and the exposed resist becomes more soluble in developing solutions (say ten times more soluble). In other words, the development rate, R, for the exposed resist is about ten times faster than the development rate, R_0, for the unexposed resist. If the photoresist is of the type called *negative* (also *negative tone*), the reaction strengthens the polymer by random cross-linkage of main chains or pendant side chains, becoming less soluble (slower dissolving). See also comparison table below:

	Positive resist	**Negative resist**
Polarity	Duplicates the pattern on the mask	Pattern obtained is the reverse of the mask pattern
Polymerization	In the exposed regions the resist breaks down in to smaller segments	In the exposed regions the resist polymerizes further
Fidelity	Fidelity of structures somewhat lower	Fidelity of structures somewhat higher
Solvents	Water-based, more environmentally friendly	Used to be more organic solvents
Lift off profile	More difficult to obtain lift-off profile	Easier to obtain lift-off profile

1.9:

A polyimide photoresist requires 100 mJ/cm^2 per micron of thickness to be developed properly. If a lamp provides 1000 W/m^2, how long does it take to expose a 20 µm thick film?

Answer:

The answer is 20 seconds; 1000 W/m^2 = 1000 Js^{-1}/m^2 or 100 mJs^{-1}/cm^2 or every second 1 µm receives the necessary dose. In practice one could measure the power level of the UV light source with a photometer by placing the detector in the center of the mask aligner wafer chuck and sliding it underneath the UV source. The output power level should be between 10 and 12 mW/cm^2 for typical thin resist layers; with the thick resist used in this case, 100 mW/cm^2 is more appropriate. The exposure time to obtain the exposure dose as required for the resist is given as: exposure or dose (mJ/cm^2) = power level (mW/cm^2) × shutter opening time (sec).

1.10:

List four major factors in which IC technology differs from MEMS or miniaturization science.