UNIVERSITY OF CAMBRIDGE
Department of Engineering

IB Paper 8
Electrical Engineering

Lecture 11
Fabricating Devices: Patterning

https://www.vle.cam.ac.uk/course/view.php?id=69961

Introduction to Pattern Transfer

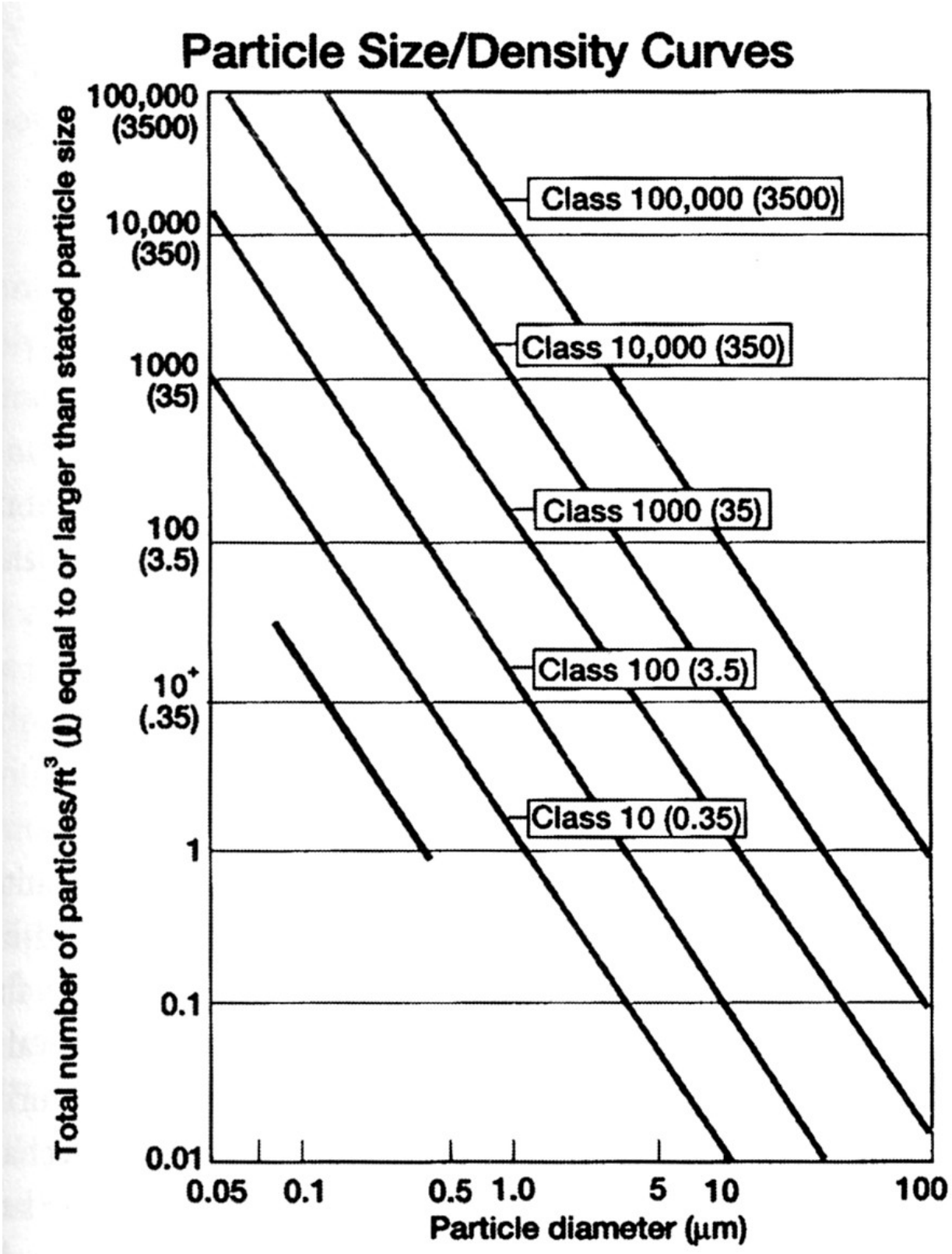
- Thus far in this course we have concentrated on the production and properties of materials over an indefinite area
  - In practice, of course, we need to be able to define certain areas where we do wish our material to be and certain area where the opposite is true
  - This is known as ***pattern transfer***
  - Traditionally, this has required the use of ***photolithography*** on a small scale in which a pattern is defined in a polymer on the surface of the sample, and this is used to create a pattern in the sample itself
  - Photolithography is a process which is, in effect, very similar to photography
  - A material that is sensitive to high energy (UV or X-ray) photons or electrons (known as a ***photoresist***) on the surface of a sample is exposed to a pattern of photons or electrons which causes a physical change in the exposed regions
  - The photoresist is then chemically developed causing regions of photoresist to be removed
  - In this way, a pattern can be produced on the surface of the sample, which can then be transferred to the sample itself

Environmental Cleanliness

- The fabrication of small scale patterns in a material presupposes that the material itself is ***clean and free from particulates*** at a similar length scale
  - It is for this reason that lithographic processing takes place in a Clean Room environment
  - The Clean Room is a controlled environment where both humidity and temperature are regulated and the air entering the environment has been passed through ***High Efficiency Particle Arrestors*** (HEPA filters)
  - The Clean Room environment is then classified according to ISO 14644 by a number *N*

$$C_n = 10^N \left(\frac{0.1}{D}\right)^{2.08} \qquad (11.1)$$

  - where C_n is the concentration of particles of diameter greater than than *D* (measured in µm)
  - This nomenclature is relatively new, and most Clean Room are still classified according to US Federal Standard 209b where the Class is the number of particles of 0.5 µm diameter or greater per cubic foot!


Particle Size/Density Curves
Total number of particles/ft³ (ℓ) equal to or larger than stated particle size
100,000 (3500)
10,000 (350)
1000 (35)
100 (3.5)
10⁺ (.35)
1
0.1
0.01
Class 100,000 (3500)
Class 10,000 (350)
Class 1000 (35)
Class 100 (3.5)
Class 10 (0.35)
0.05
0.1
0.5
1.0
5
10
100
Particle diameter (µm)

- Great care is taken to ensure that the fabric of a Clean Room assists in maintaining the classification desired
  - For example, only special furniture is used, and the room is kept under positive air pressure to ensure particulates do not enter through cracks around doors
  - However, it is people and the things that they bring in to the Clean Room which tend to present the greatest problems
    - Proper Clean Room suits must be worn
    - Ball point pens must be used – no pencils
    - Approved Clean Room writing paper must be used
    - Paper for wiping samples and surfaces must be lint free
    - Operators should avoid speaking where possible
    - Beard masks are essential
    - Makeup should be avoided
    - Smoking before entering the Clean Room should be avoided
  - Poor cleanliness is the easiest way to reduce yield!
  - However, users can help themselves avoid sample contamination by keeping samples vertically upright whenever possible

Substrate Cleanliness

- Substrates should also be cleaned prior to processing (and sometimes during processing)
  - **RCA Cleaning**
    - The RCA1 and RCA2 cleaning processes have become popular for removing contaminants from silicon wafers
    - RCA1 involves immersing the wafer for ten minutes in a solution of one part 25% aqueous NH_3 to five parts of DI water, which is allowed to boil before one part of H_2O_2 (and the wafer) is added to remove organics
    - RCA2 involves immersing the wafer in a solution of one part HCl to six parts of DI water, which is allowed to boil before one part of H_2O_2 (and the wafer) is added to remove metal ions
  - **HF Cleaning**
    - A 30 second dip in buffered hydrofluoric acid is commonly used to remove the native oxide layer from a silicon wafer and, in doing so, any surface contaminants, but this is a hazardous process
  - **Fuming Nitric Acid**
    - A wider range of materials may be cleaned by immersion in fuming nitric acid for 5 minutes
    - This removes organics, and is improved by ultrasonic agitation – a DI water rinse follows

- **Solvent Clean**
  - A somewhat gentler approach to sample cleaning is to use solvents
  - If the substrate is heavily soiled, then a 10 minute ultrasonic clean in an aqueous solution of degreasing agent (such as Decon 90) is required, followed by three 10 minutes ultasonic DI water baths to completely remove the degreasing agent
  - The sample may then be cleaned for 10 minutes in an ultrasonic bath of acetone (a more gentle degreasing agent, and this step is normally the first one used for substrates which are already nominally clean)
  - This is followed by a 10 minute ultrasonic bath in isopropanol (IPA) which is miscible with acetone, and so removes traces of this solvent
  - Finally, the sample undergoes a 10 minute ultrasonic bath in DI water to remove the IPA (acetone and water are not miscible directly) and is then spin dried and baked (30 minutes at 125° C is normally sufficient)
- The substrate is then ready for processing

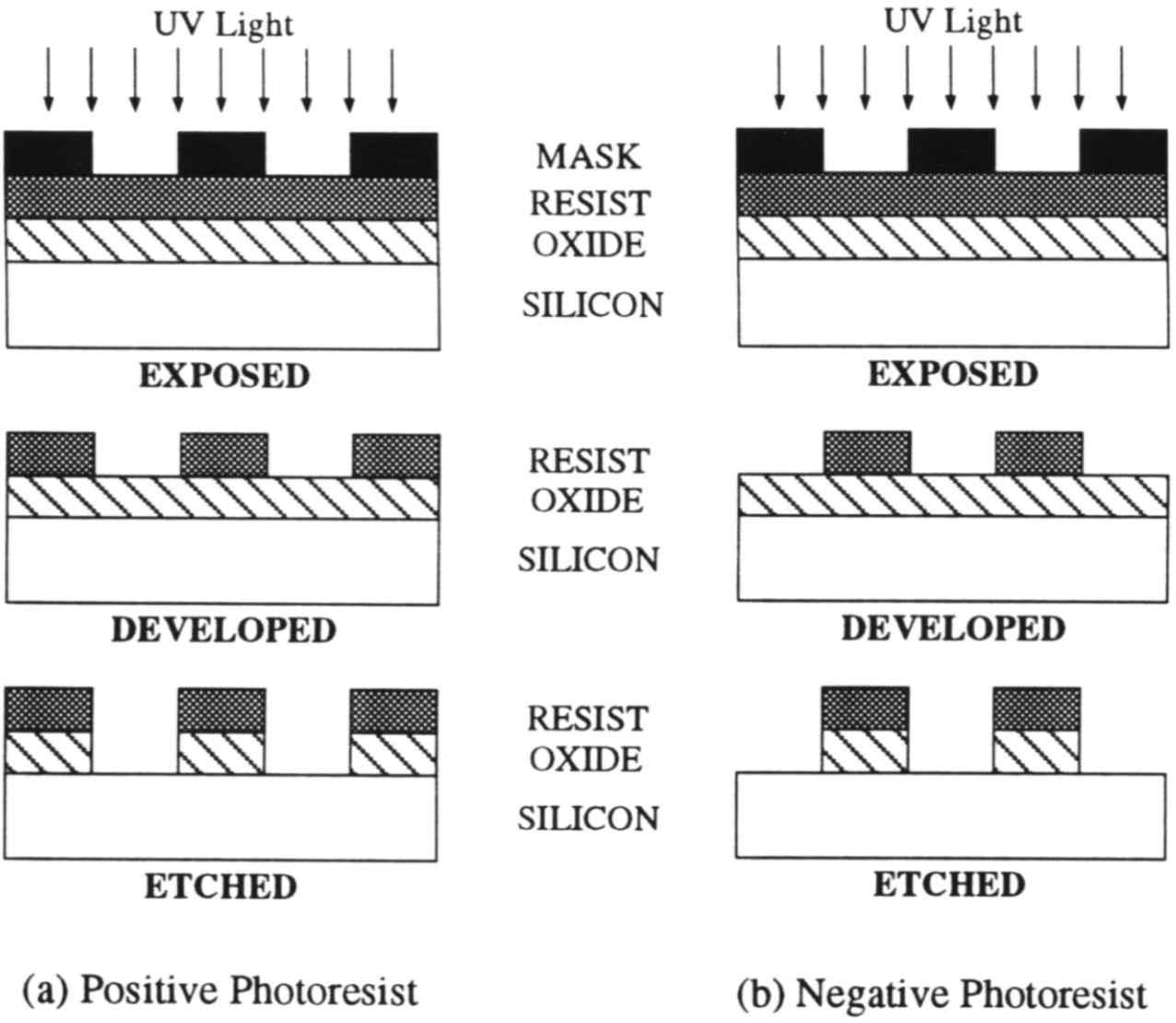
Photoresists

- The photoresist is an organic polymer resin, (with a sensitiser) in a liquid solvent
  - A thin coating of photoresist may therefore be formed by a process known as ***spin coating***
    - The sample is rotated about its middle at a speed between 1500 and 8000 rpm whilst the polymer solution is applied to the centre of the sample
    - Centrifugal forces then cause the liquid to spread out over the surface of the sample, producing a uniform (±0.3%) thin film which is typically between 0.5 and 5 µm thick
    - The empirical expression for the thickness, t, obtained is

$$t = \frac{KC^{\beta}\eta^{\gamma}}{R^{\alpha}} \qquad (11.2)$$

    - where C is the polymer concentration in g per 100 ml, η is the intrinsic viscosity, R is the number of rotations per minute, K is a calibration constant and α, β and γ are resist-dependent constants
  - Adhesion promoter (e.g. hexamethyldisilazane, HMDS) is sometimes employed to assist binding of the photoresist to the substrate, particularly if the latter is hydrophobic
  - A drying bake in an oven follows spinning

- Resists are broadly classified into two categories:
  - ***Positive tone resists***
    - Exposure of the resist to high energy photons or electrons causes scission of the polymers chains
    - The weakened polymer may then be removed by a developer solution (usually a weak base, such as KOH) in the exposed region
    - Positive resists may be completely stripped by strong bases
  - ***Negative tone resists***
    - Exposure of the resist either causes cross-linking of the polymer chains to create large molecular weight chains which are insoluble, or induce a photochemical change to an insoluble polymer
    - Water based developers are most frequently used, but a few organic based developers do still remain
- A few resists have the property that they can behave either as positive or negative resists, such AZ5214E
  - The first exposure causes the resist to behave in a positive fashion
  - This is followed by a flood exposure (high photon dose everywhere) which reverses the pattern before development

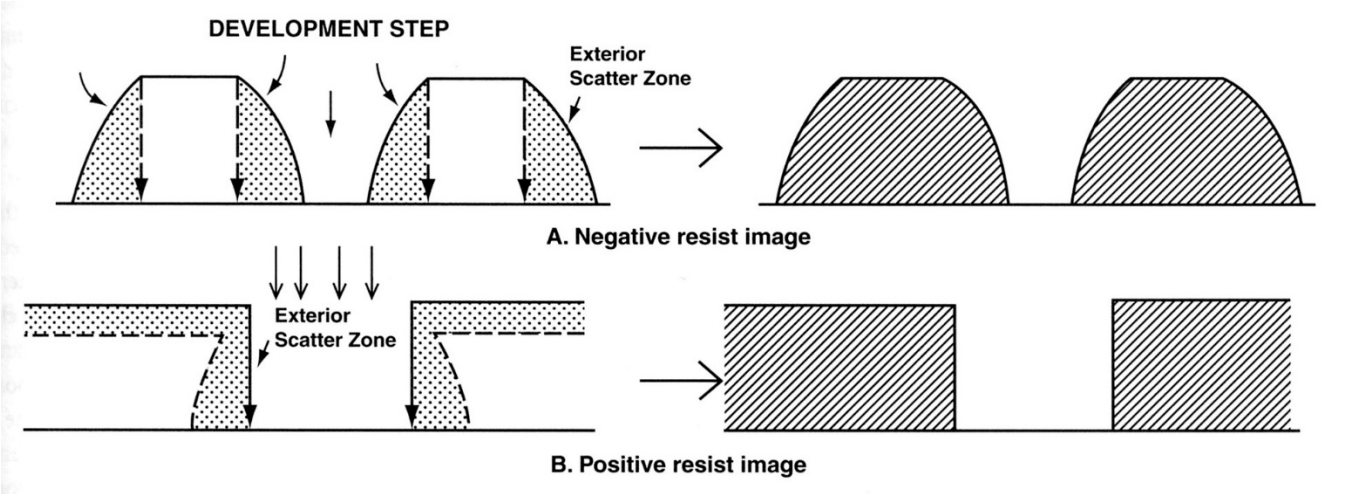


(a) Positive Photoresist

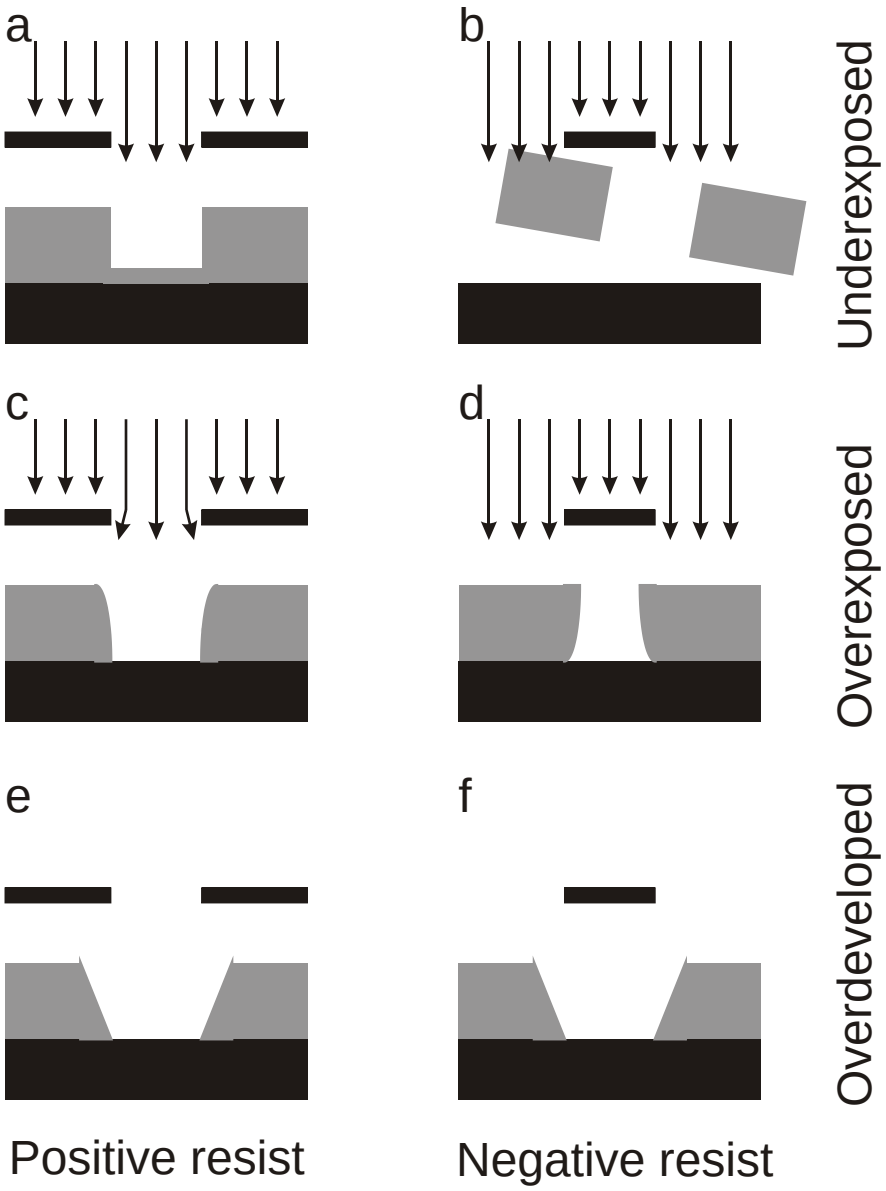
(b) Negative Photoresist

Characteristic	Positive Resists	Negative Resists
Adhesion to Si	Fair	Excellent
Available compositions	Many	Vast
Contrast, γ	High	Low
Developer	Aqueous	Aqueous / organic
Developer process window	Small	Wide (insensitive to over-development)
Influence of oxygen	No	Yes
Lift-off	Yes	Yes
Minimum feature	<0.5 µm	~2 µm
Opaque dirt	Low sensitivity	Causes pinholes
Photospeed	Slow	Fast
Pinhole count	Higher	Lower
Pinholes in mask	Printed	Low sensitivity
Plasma etch resistance	Low	High
Proximity effect	Good printing of isolated holes/trenches	Good printing of isolated lines
Residue after development	Mostly at <1µm and high aspect ratio	Problematic
Sensitiser quantum yield, Φ	0.2 – 0.3	0.5 – 1
Step coverage	Higher	Lower
Strippers	Acid / bases / solvents	Acid / solvents
Swelling in developer	No	Yes
Thermal stability	Good	Fair
Wet chemical resistance	Fair	Excellent

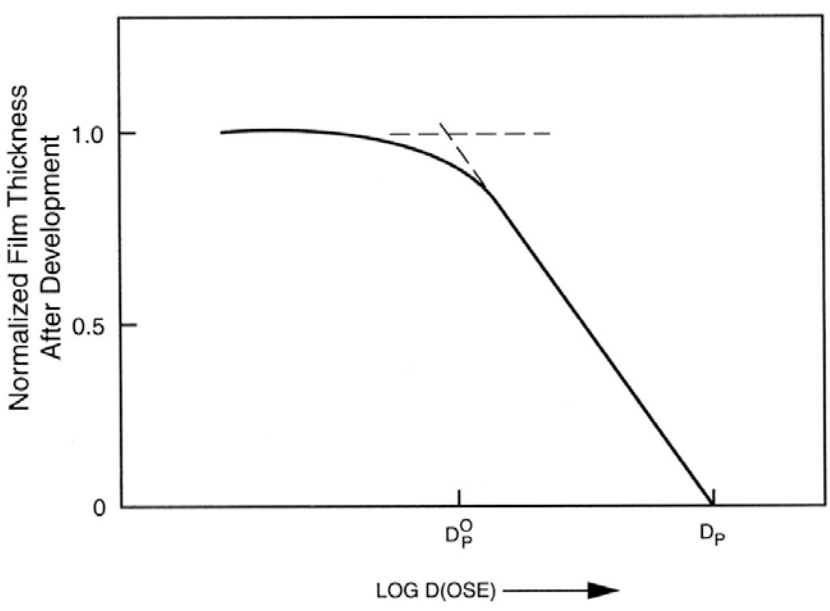
- It is clearly important that the correct photon dose is applied to a photoresist
  - If the dose is too low for a given thickness, then the lower layers of resist will not be developed
    - In the case of a positive resist, a layer of resist will remain at the bottom of exposed features, preventing pattern transfer
  - If the dose is too high, then diffraction of light into nominally 'unexposed' regions will become significant, with a resultant loss of resolution and increased size of exposed patterns
- The scattering of photons at the edge of features can never be fully avoided, and this results in developed features having characteristic profiles



- The actual profile of the side walls of a feature will, in practice be dependent on both the exposure and development
  - Of particular importance is the ratio of the development rate of the exposed to unexposed regions, R/R_0, and the contrast, γ



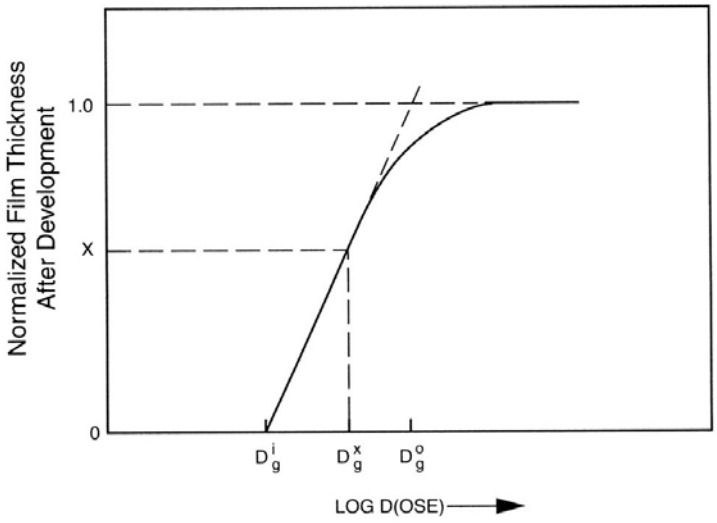
- For positive resists, the resist contrast is dependent upon the rate of chain scission and the rate of change of polymer solubility with molecular weight
  - Photon doses below a certain level, D_P^0, will have no effect upon the resist
  - As the photon dose, D, applied to resist increases, the resist thickness after development will decrease until the critical dose, D_P, is reached, at which point the resist is completely removed



  - The contrast may then be determined from the gradient of normalised resist thickness against log(D),

$$\gamma = \frac{1}{\log D_P - \log D_P^0} = \left[\log\left(\frac{D_P}{D_P^0}\right)\right]^{-1} \qquad (11.3)$$

- For negative resists, the contrast is dependent upon the rate of cross-linked network formation
  - The onset of cross-linking required a certain minimum dose, known as the interface gel dose, $D_g{}^i$, below which all of the resist will be removed by development
  - Above this, the resist thickness after development will increase with dose, until the full thickness is preserved at the required dose, $D_g{}^0$



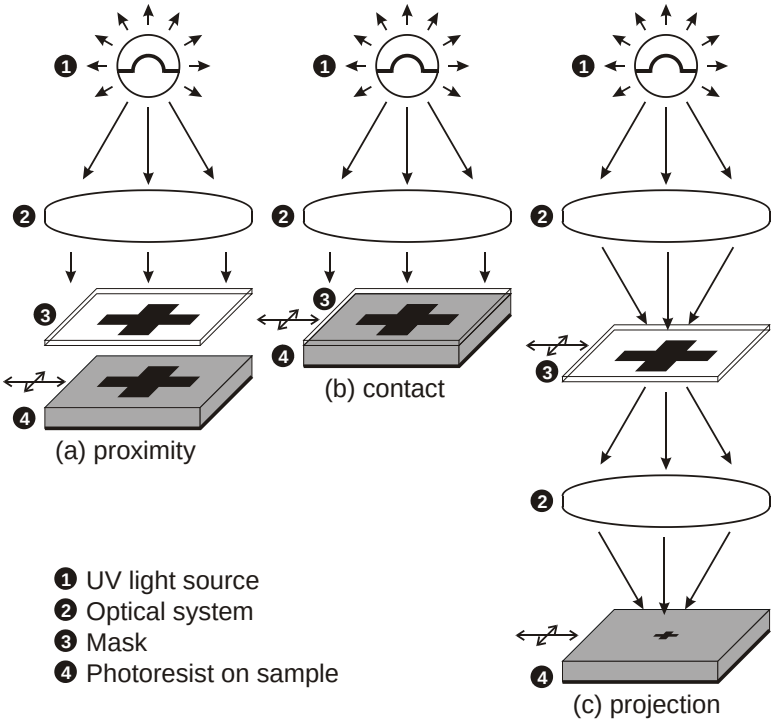
  - The contrast is then given by

$$\gamma = \frac{1}{\log D_g^0 - \log D_g^i} = \left[\log\left(\frac{D_g^0}{D_g^i}\right)\right]^{-1} \qquad (11.4)$$

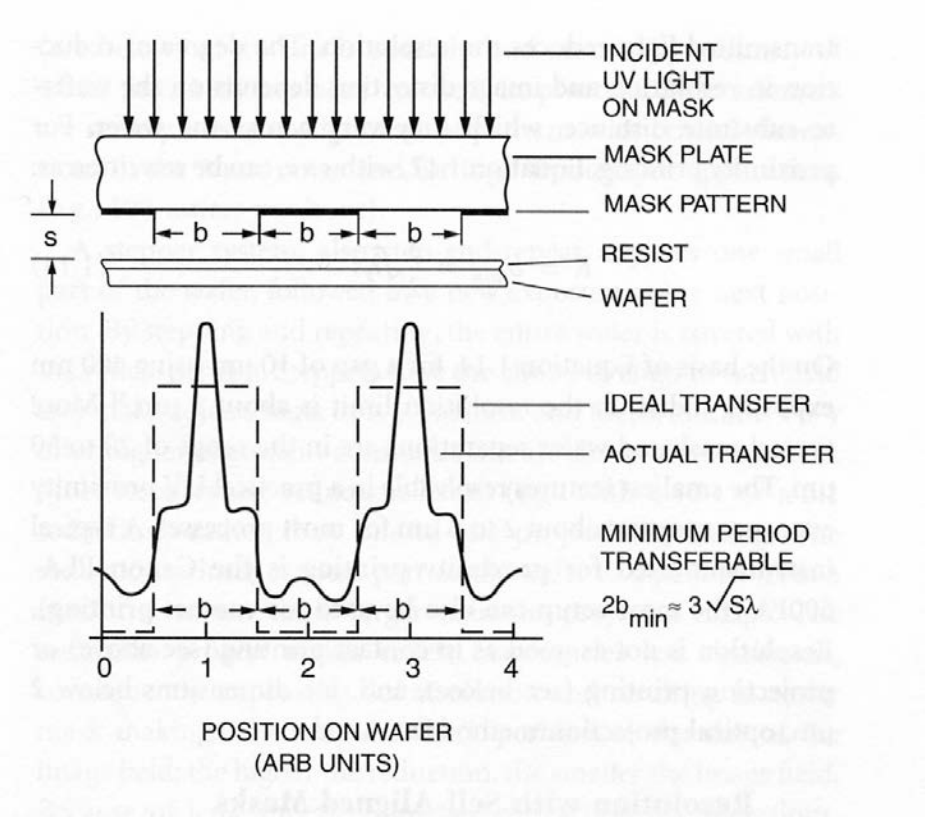
- In general, a higher contrast will result in improved resolution and pattern transfer

UV Photolithography

- A method is required for actually producing a UV image on the photoresist, and three basic methods exist:
  1. Proximity printing
     - A mask produces a shadow on the sample which is separated from the mask by a few µm
  2. Contact printing
     - A mask produces a shadow on the sample which is in contact with the mask
  3. Projection printing
     - The pattern on a large mask is projected onto the sample, and stepped over the full area



- The ***critical dimension*** of a particular lithographic process is the minimum feature size which can be reliably produced, and is a measure of the resolution of the process
- In the case of shadow printing techniques (contact and proximity printing), resolution is limited by the diffraction of light around the edge of opaque features
  - The typical light intensity as a function of position on a sample after passing through a simple grating of opaque and transparent features with a pitch $2b$ is shown below

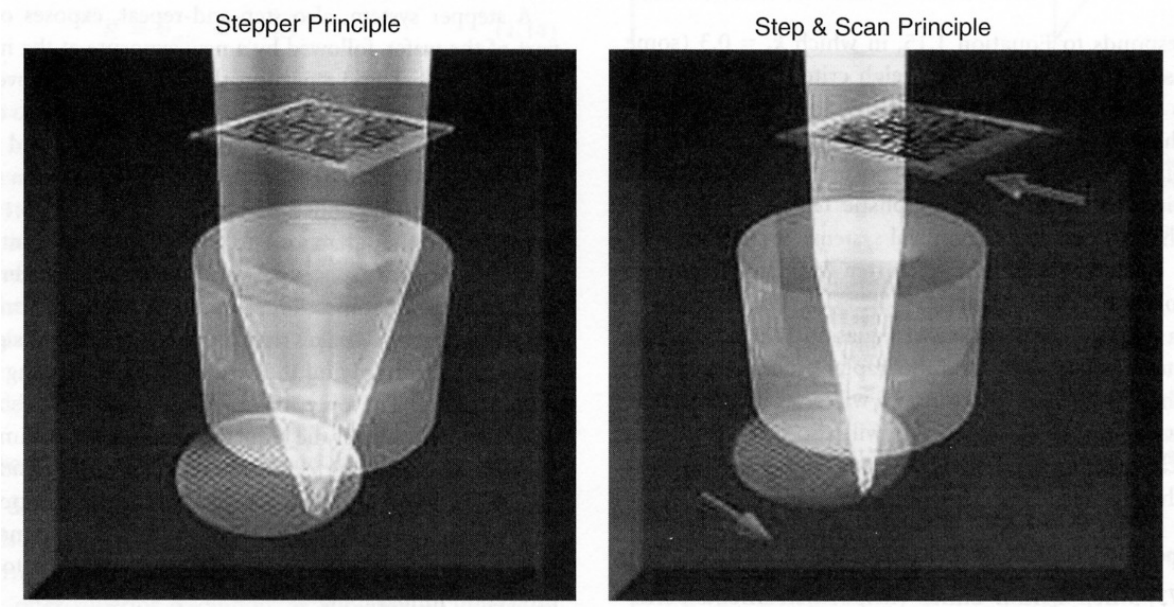


- The resolution for shadow printing using a conventional resist of thickness *z* and with a print gap between the mask and the resist surface of *s* is given by

$$R = \frac{3}{2}\sqrt{\lambda\left(s + \frac{z}{2}\right)} \qquad (11.5)$$

  - where λ is the wavelength of the light
- For contact printing, *s* is effectively reduced to 0, and so at first sight it is not clear what the point of proximity printing is at all!
  - To understand this, it is necessary to remember that contact printing required some pressure to be exerted between the mask and the sample to hold them in contact
    - In soft contact, gravity is used to keep the mask in place
    - In hard contact, a mechanical pressure is applied to press the mask and sample together
    - In vacuum contact, a vacuum is generated between the sample and the mask to produce a pressure of 1 atm to hold the two together (vacuum & hard contact may be used simultaneously to generate up to 3 atm of pressure

- Therefore, any debris on the mask or photoresist will be pressed into the mask and sample, resulting in mask degradation as a function of use
- This is not the case for proximity printing as the mask is not in contact with the sample, and should remain largely undamaged by the printing process
- A good rule of thumb is 'the greater the pressure that is applied during contact printing, the better the resolution achievable, but the shorter the life of the mask
- Daughter masks may be made from the Master and used for contact printing for a limited period each, but these will always have a reduced resolution due to inaccuracies in the copying process
- Projection printing allows high resolution without contact



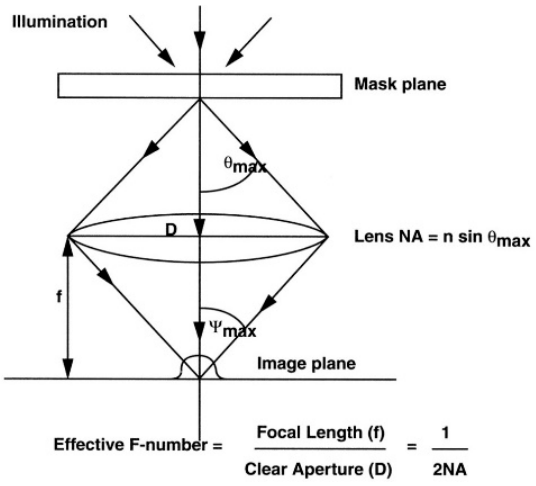
- In the case of projection, resolution is again limited by the diffraction of light
  - The ***Rayleigh Criterion*** again provides a measure of when two projected features can be resolved (see Lecture 8, Slide 4)
  - Using this concept, the resolution of a projection printing system is approximated by

$$R = \frac{k_1 \lambda}{N} \tag{11.6}$$

  - where λ is the wavelength of the light and *N* is the numerical aperture of the system

$$N = n \sin \theta_{max} = D/2F \tag{11.7}$$

  - The constant k_1, which must be determined experimentally, incorporates the Rayleigh criterion, process conditions
  - and resist parameters
  - For high quality projection printing systems using standard photoresists, k_1 ~ 0.3, although may be significantly higher than this if the sample is, for example, highly reflective, and may be as high as 1.1

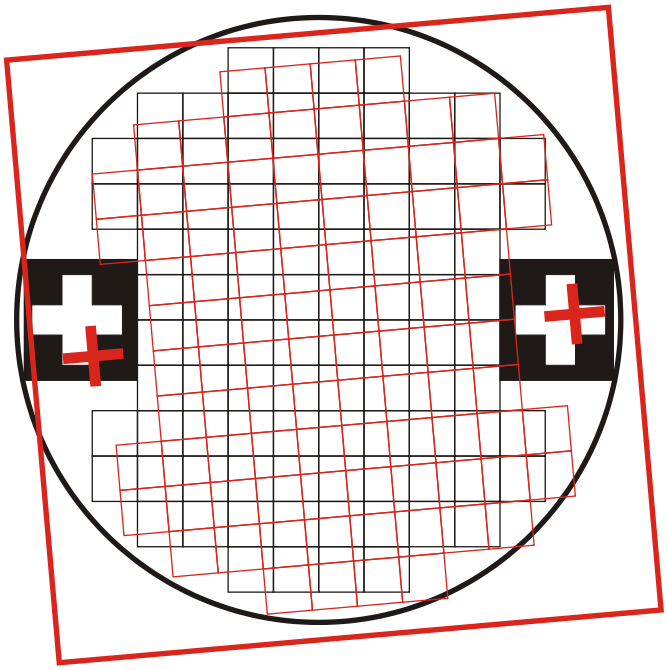


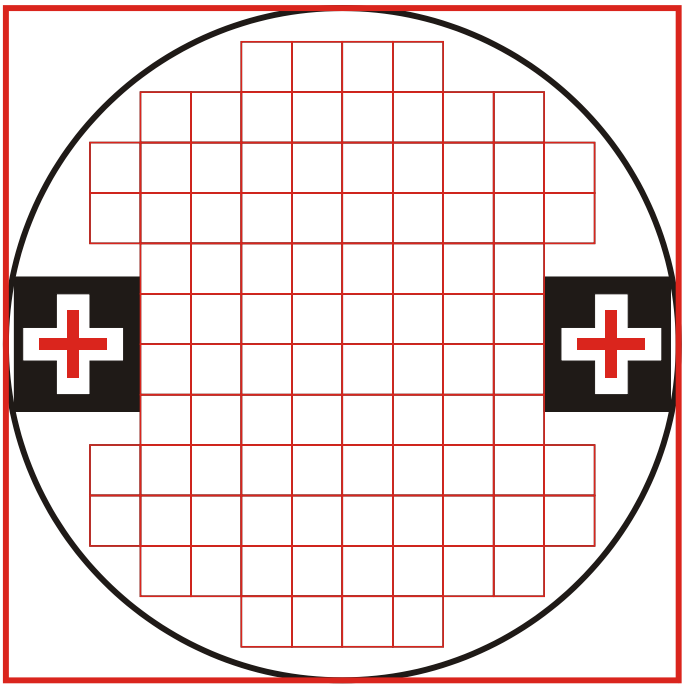
X-Ray and Electron-Beam Lithography

- X-ray lithography is an extension of UV photolithography
  - The exposing wavelength is in the range of 0.4 to 5 nm
  - X-ray lithography is limited to proximity printing as x-ray optical elements are not available
  - The mask and wafer are separated by ~40 µm and a full wafer is exposed in ~1 minute
  - X-ray lithography allows much higher resolution to be achieved without compromising on throughput
  - Also, X-rays are not absorbed by low atomic number dirt so the process is more resilient
- In e-beam lithography no mask is required
  - Instead, a beam of electrons is steered onto the photoresist to produce the pattern required
  - The technique is very versatile, and is used to make masks for UV lithography, but it is very slow (hours per wafer) and very expensive to operate
  - The technique was born out of electron microscopy, and so the technique for producing and steering the electron beam onto the surface is very similar to that seen in Lecture 10

Alignment

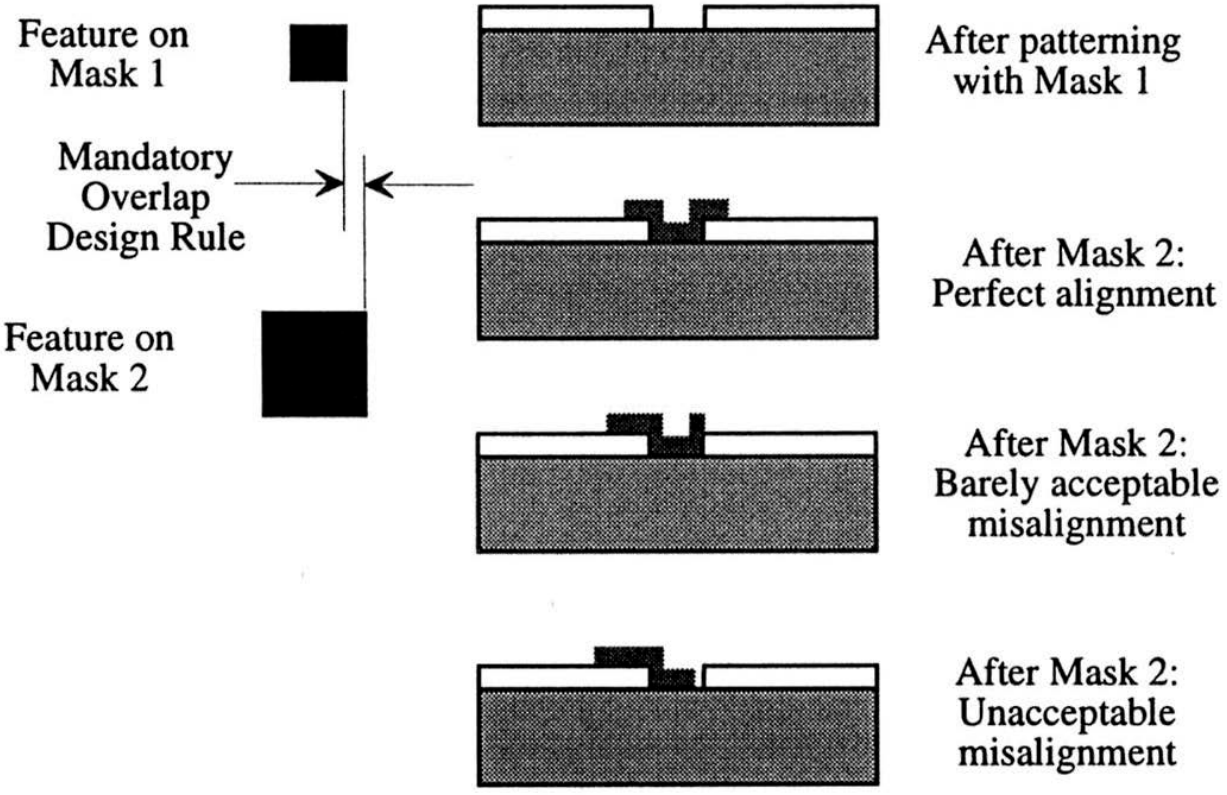
- It is usually the case that the construction of a full device requires the patterning of many layers, and each layer must be correctly ***aligned*** with previous layers
  - This is achieved through the use of alignment marks on each mask
  - These are normally a set of inverted and non-inverted crosses which are regularly repeated over the mask and the sample (from previous patterning stages)
  - A split view microscope allows a view of two points towards either edge of the mask





- The sample is moved relative to the mask until the two sets of crosses are aligned
  - When two points on a plane are aligned, the whole plane is aligned
  - During this movement, the distance between the mask and sample is larger than when printing occurs, and is called the ***alignment gap***
  - A larger gap is required to prevent damage to the mask by particulates which can cause the two to be dragged laterally together, preventing alignment
  - The limited depth of focus of the microscope limits the alignment gap to be normally < 30 µm

- In practice, it is never possible to perfectly align two layers to each other
  - A tolerance therefore needs to be allowed for in the mask design which will depend on the capability of the alignment tool



  - Self-alignment provides a cunning way of reducing this problem by using the pattern on the substrate to act as the mask itself for the next stage of patterning
  - This requires illumination through the sample from the back side, and requires a transparent substrate