PHOTOLITHOGHRAPHY

Photolithography

- Photolithography is the process of transferring patterns of geometric shapes on the mask to a thin layer of photosensitive material (called ***photoresist***) covering the surface of a semiconductor wafer.

- These patterns ***define*** the various region in all integrated circuit such as:
  - *The implementation regions.*
  - *The contact window.*
  - *The Bonding-pad areas.*

- The resist patterns defined by the lithographic process are not permanent elements of the final device, but only replica of circuit features.

Photolithography (Cont.)

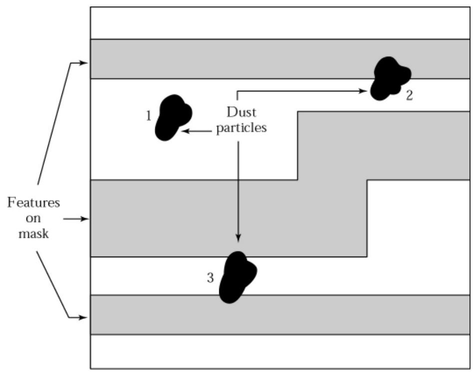
- To produce circuit features, these resist patterns must be transferred once more into the underlying layers comprising the device.
- Pattern transfer is accomplished by etching process that selectively remove unmasked portions of a layer.
- Covering subject:
  - The *Importance of a clean room* for lithography.
  - The most widely used lithographic method–photolithography- and its resolution enhancement techniques.
  - Advantages and limitations of other lithographic methods.

The Clean Room

- An IC fabrication facility requires a ***clean processing room*** especially in the area used for photolithography.
- The need for such a clean room arises because dust particles in the air can settle on semiconductor wafers and lithographic masks and can cause defects in the devices which result in circuit failure.
- For example a *dust particle* on a semiconductor surface can disrupt the single-crystal growth or an epitaxial film causing the formation of *dislocations*.
- A *dust particle* incorporated into the gate oxide can result in enhanced conductivity and cause device failure due to *low breakdown voltage*.

The Clean Room (Cont.)

- The situation is even worst critical in the Lithographic area. When dust particles adhere to the surface of a photomask, that behave as opaque patterns on the mask and these patterns will Be transferred to the underlying layer along with the circuit patterns on the mask.



Particle one → Pinhole
Particle two → Current leakage
Particle three → Short circuit

The Clean Room (Cont.)

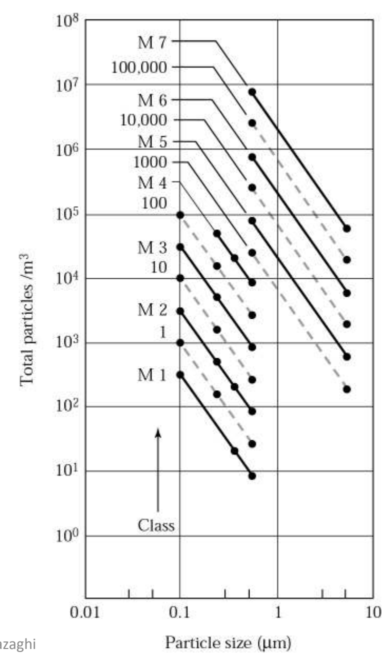
- In a clean room the total number of dust particles per unit volume must be **tightly con**trolled, along with the temperature and humidity.

- Two systems are used to define the classes of clean room. In the English system the numerical designation of the class is taken from the maximum allowable number of particles that are 0.5 um and larger per cubic foot of air. In the metric system, the class is taken from the logarithm (base 10) or the maximum allowable number of particles that are 0.5 um and larger per cubic meter.

The Clean Room (Cont.)

- Class 100 (English) = Class M 3.5 (metric)
- 100 particle/ft^3= 3500 particle/m^3
- For most IC fabrication areas, a class 100 clean room is required: that is the dust count must be about four order of magnitude lower than that of ordinary room air. However for the lithography area a **class 10** clean room or one with a lower dust count is required.
- Example

Particle-size distribution curve for English (---) and metric (——) classes of clean rooms.



Exposure Tools

- The pattern transfer process is accomplished by using a lithographic exposure tool.
- performance of an exposure tool is determined by three parameters:
  - **Resolution** → *the minimum feature dimension that can be transferred with high fidelity to a resist film on a semiconductor wafer*.
  - **Registration** → *a measure of how accurately pattern on successive masks can be aligned (or overlaid) with respect to previously defined patterns on the wafer*.
  - **Throughput** → *the number of wafers that can be exposed per hour for a given mask level*.

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Exposure Tools (Cont.)

- There are basically two optical exposure methods:
  - Shadow printing
  - Projection printing
- Shadow printing
  - Contact printing → the mask and wafer in direct contact with one another
  - *proximity printing* → the mask and wafer in close proximity with one another

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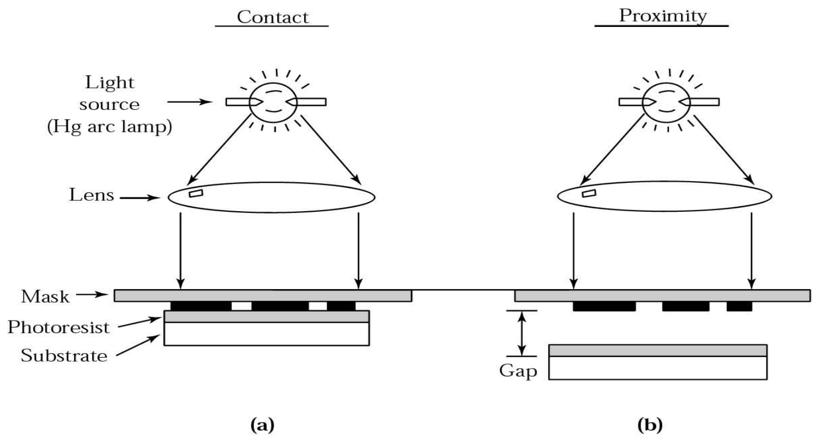

Schematic of optical shadow printing techniques. (a) Contact printing. (b) Proximity printing.

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Exposure Tools (Cont.)

- Contact printing
  - Major advantage → *resolution* → 1 um
  - Major drawback → *dust particle* → A dust particle on the wafer can be imbedded into the mask when the mask makes contact with the wafer. The imbedded particle causes permanent damage to the mask and results in defects in the wafer with each succeeding exposure.

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Exposure Tools (Cont.)

- Proximity printing
  - Major advantage → Minimum mask damage → there is a small gap (10-50 um) between the wafer and the mask during exposure.
  - Major drawback → lower resolution because of diffraction → (2 - 5 um)
- In shadow printing, the minimum linewidth [or critical dimension (CD)] that can be printed is roughly:

$$CD=(\lambda g)^{0.5}$$

- where λ is the wavelength of the exposure radiation and g is the gap between the mask and the wafer and includes the thickness of the resist. For λ to 0.25 um (a wavelength range of 0.2 to 0.3 um is in the deep UV spectral region) and g to 15 um, the CD becomes 2 um. *So the resolution can be changed by source wavelength and the proximity gap*.
- However, for a given distance g, any dust particle with a diameter larger than g potentially can cause mask damage.

Exposure Tools (Cont.)

- To avoid the mask damage problem associated with shadow printing projection printing exposure tools have been developed to project an image of the mask patterns onto a resist-coated wafer *many centimeters* away from the mask.
- To increase resolution, only a small portion of the mask is exposed at a time. The small image area is scanned or stepped over the wafer to cover the entire wafer surface.
- The small image field can also be stepped over the surface of the wafer by two dimensional translations of the wafer only, while the mark remains stationary.

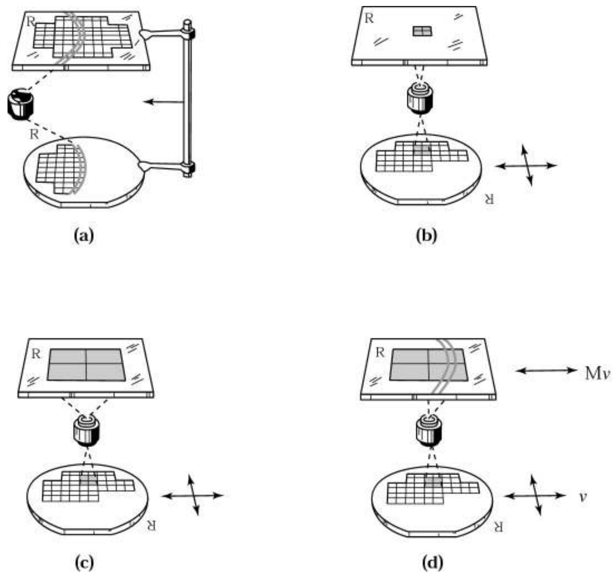

Image partitioning techniques for projection printing. (a) Annual-field wafer scan. (b) 1:1 step-and-repeat. (c) M:1 reduction step-and-repeat. (d) M:1 reduction step-and-scan.

Exposure Tools (Cont.)

- The demagnification ratio is an important factor in our ability to produce both the lens and the mask from which we wish to print.
- The 1:1 optical systems are easier to design and fabricate than 10:1 or 5:1 reduction systems. but it is much more difficult to produce defect -free masks at 1:1 than it is at a 10: 1 or a 5: 1 demagnification ratio.

Exposure Tools (Cont.)

- Reduction projection lithography can also print larger wafers without redesigning the stepper lens as long as the field size (i.e. the exposure area onto the wafer) of the lens is large enough to contain one or more IC chips.
- The step-and-scan system yields two-dimensional translations of the wafer with speed v and one dimensional translation of the mask with a speed M times than of the wafer speed.
- The *resolution* of a projection system is given by:

$$l_m = k_1 \times \lambda / NA$$

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

$$NA = n_r \sin\vartheta$$

- Where n_r is the index of refraction in image medium (usually air, where $n_r = 1$)

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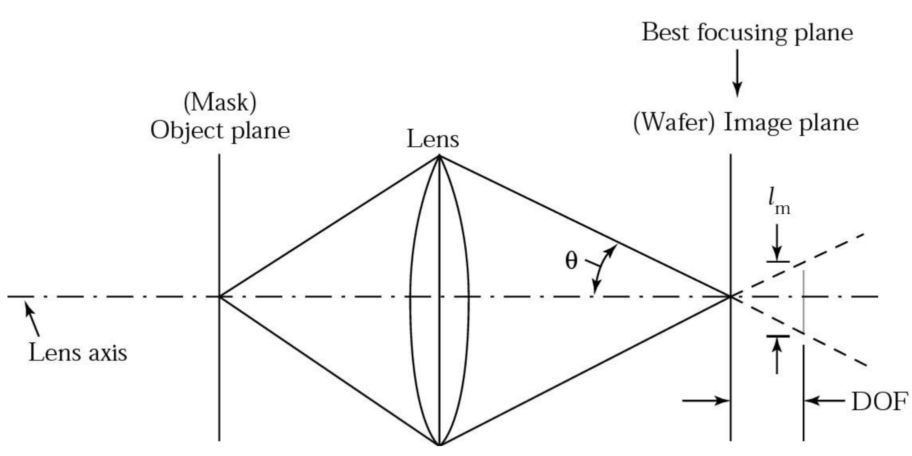

Simple image system.

- The depth of focus (DOF) can be expressed as:

$$DOF = \pm l_m / \tan\vartheta = k_2 \times \lambda / (NA)^2$$

- where k_2 is another process dependent factor

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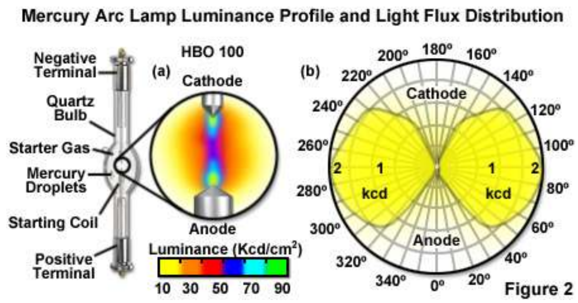
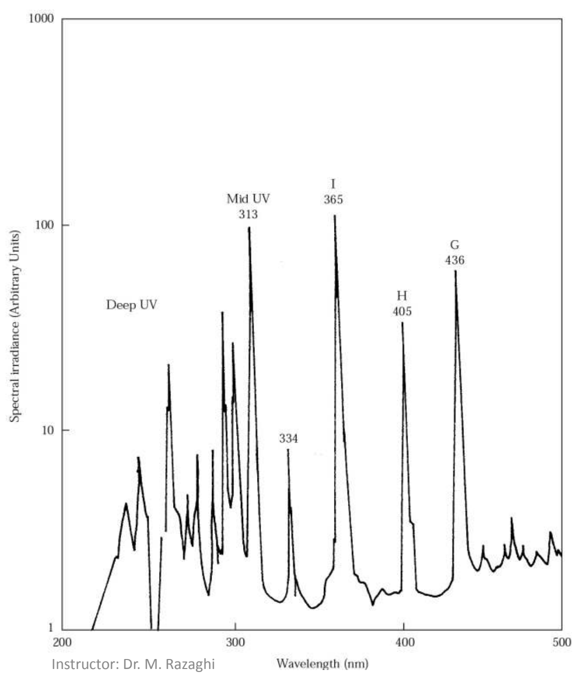
Exposure Tools (Cont.)

- By decreasing the λ both resolution and DOF enhances. Thus technology trends keenly goes towards shorter wavelength sources for optical lithography.

- The high-pressure mercury-arc lamp is widely used in source tools because of its high intensity and reliability.



Typical high-pressure mercury-arc lamp spectrum.



Exposure Tools (Cont.)

- Resolution:
  - Mercury arc → 0.3 um using I line (365 nm) and 5:1 step and repeat projection scheme.
  - KrF (Krypton fluoride)laser (248 nm)→ 0.18 um
  - ArF laser (193 nm)→ 0.1 um
  - F2 laser (157 nm)→ 0.07 um

Photoesist

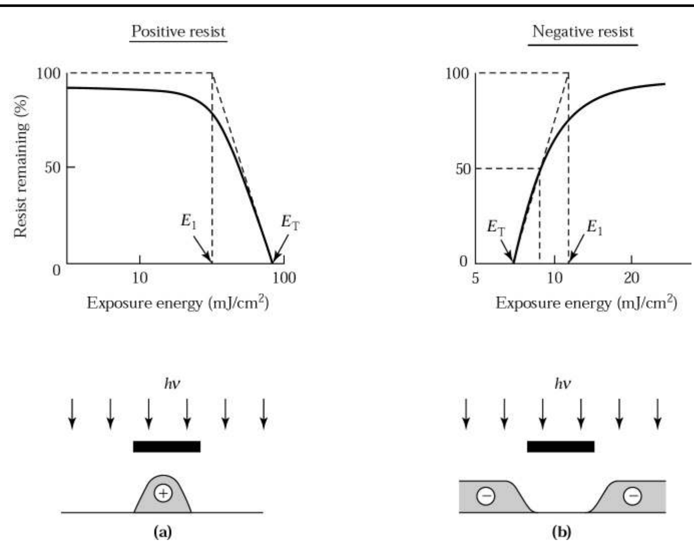
- Photoresist is a radiation sensitive compound that can be classified as positive or negative depending on how it responds to radiation. For positive resist the exposed regions become more soluble and are thus more easily removed in the development process.
- The net result is that the patterns formed in the positive resist are the same as those on the mask.
- For the negative resists the exposed regions become less soluble and the patterns formed in the negative resist are the reverse of the mask patterns.

Photoesist (Cont.)

- One major drawback of a negative photoresist is that in the development Process, the whole resist mass swells by absorbing developer solvent. This swelling action limits the resolution of negative photoresists.

- For positive photoresist:
  - Note that the resist has a finite solubility in its developer, even without exposure to radiation. *As the exposure energy increases* the solubility increases until at a threshold energy E_T the resist becomes completely soluble. The Sensitivity of a positive resist is defined as the energy required to produce complete solubility in the exposed region. Thus corresponds to the sensitivity.

γ=[*ln*(



Exposure response curve and cross section of the resist image after development. (a) Positive photoresist. (b) Negative photoresist.

Photoesist (Cont.)

- A larger γ implies a higher solubility of the resist with an incremental increase of exposure energy and results in sharper images.

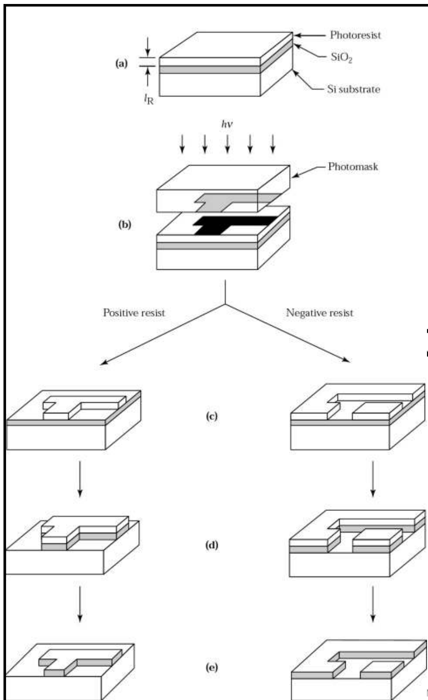
- The diffraction made different along photoresist length. Therefore the photoresist edge will not be vertical.

- The parameter γ is the same as before for negative photoresist except the interchange.

Photoesist (Cont.)

- For deep UV lithography (e.g. 248 nm to 193 nm), we cannot use conventional photoresists because the resist require high-dose exposure in deep UV which will cause lens damage and lower throughput.

- Chemical amplified resist (CAR) has been developed for the deep UV process. CAR is very sensitive to deep UV radiation and unexposed region differ greatly in their solubility in the developer solution.



:ern Transfer

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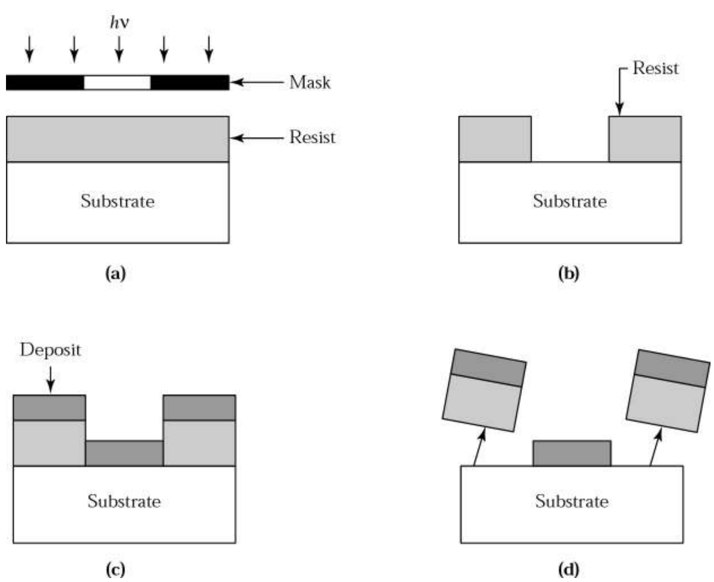

The liftoff process for pattern transfer.

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NEXT-GENERATION LITHOGRAPHIC METHODS

- Why optical lithography is still used?
  - high throughput, good resolution, low cost, and ease in operation
- But in deep submicron IC fabrication we should find an alternate method with very high resolution.
- Electron beam lithography, extreme UV lithography , x-ray, lithography, and ion beam lithography are considered.

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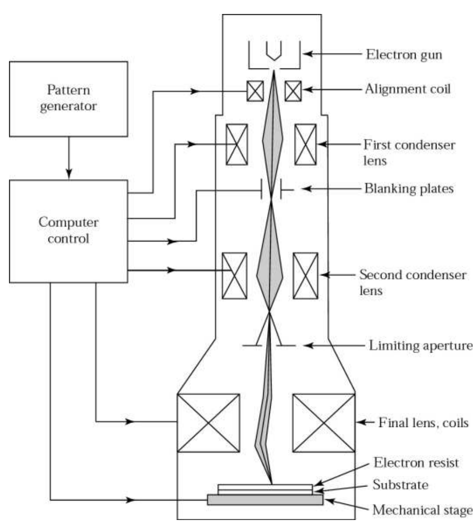
Electron Beam lithography

- Electron beam (e-beam) lithography is primarily used to produce photomasks.
- Condenser lenses are used to focus the electron beam to a spot size 10 to 25 nm in diameter.



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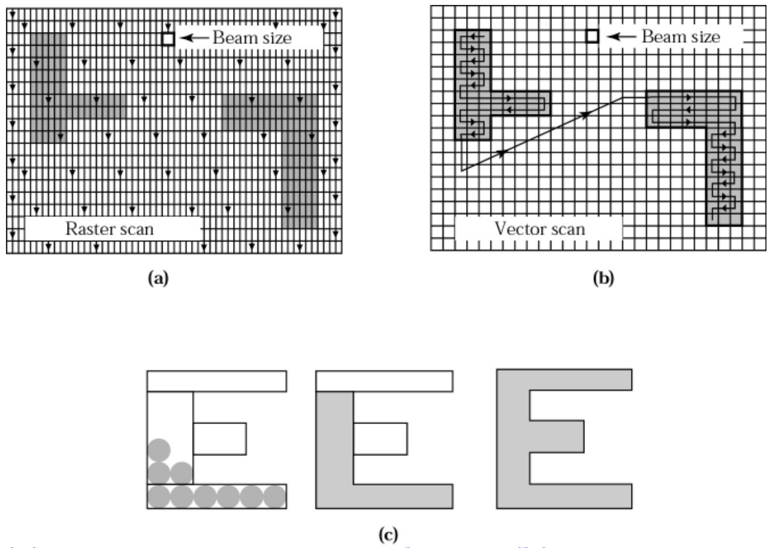

(a) Raster scan writing scheme. (b) Vector scan writing schemes. (c) Shapes of electron beam: round, variable, and cell projection.

Electron Resist

- Electron resists are polymers. The behavior of an electron beam resist is similar to that of a photoresist; that is a chemica1l or physical change is induced in the resist by irradiation.
- For the positive electron resist. The polymer-electron interaction causes chemical bonds to be broken (chain scission) to form shorter molecular fragments.
- As a result, the molecular weight is reduced in the irradiated area, which can be dissolved subsequently in a developer solution that attacks the low-molecular-weight material.
- For a negative electron resist the irradiation causes radiation-induced polymer linking. The cross linking create a complex three-dimensional structure with a molecular weight higher than that of the non-irradiated polymer.

Electron Resist

- Common e-resist material and resolution
  - Positive → poly-methyl methacrylate (PMMA) and poly-butene –I sulfone (PBS) → 0.1 um resolution.
  - Negative → Poly-glycidyl methacrlate-co-ethyl-acrylate (COP) → 1 um resolution.

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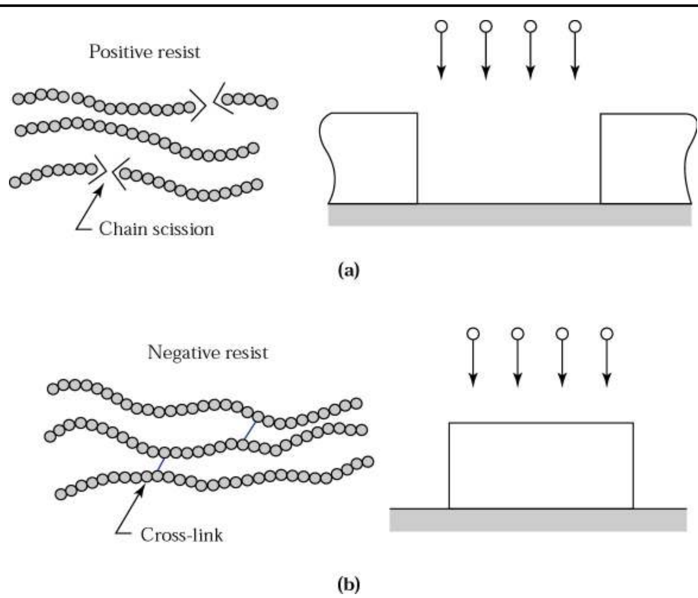

Schematic of positive and negative resists used in electron beam lithography.

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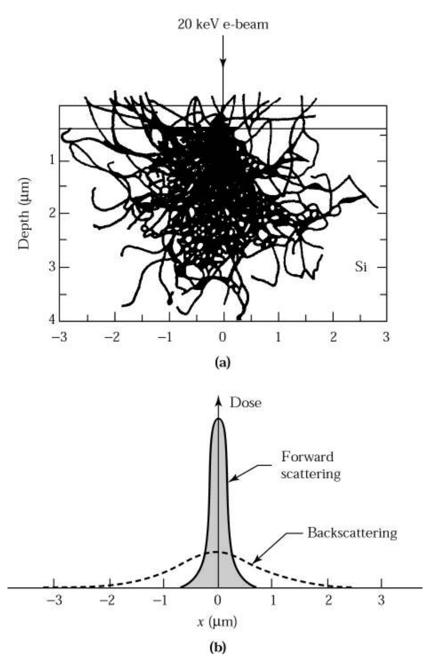
The Proximity Effect

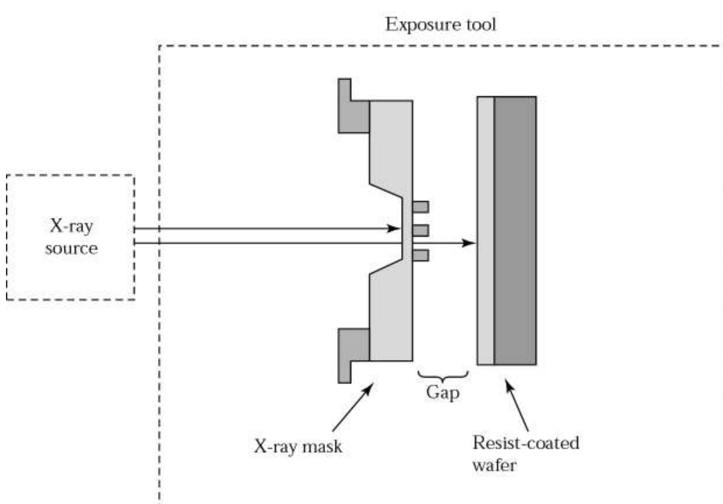
- In optical lithography the resolution is limited by diffraction of light. In electron beam lithography the resolution is not limited by diffraction but by electron scattering.
- When electrons penetrate the resist film and underlying substrate they undergo collisions. These collisions lead to energy losses and path changes. Thus the incident electrons spread out as they travel through the material until either all of their energy is lost or they leave the material because of backscattering.



(a) Simulated trajectories of 100 electronics in PMMA for a 20-keV electron beam.
(b) Dose distribution for forward cattering and scattering at the

X-Ray Lithography

- X-Ray lithography (XRL) is the potential candidate to succeed optical lithography for the fabrication of integrated circuits at 100 nm.
- XRL uses shadow printing method similar to optical proximity printing. The x-ray wavelength is about 1 nm, and the printing is through a 1-x mask in close proximity (10-40 um) to the wafer.
- Since X-Ray absorption dependent on the atomic number of the material and most materials has-low transparent at $\lambda = 1$ nm. The mask substrate must he a thin membrane (1-2 um thick) made of the low-atomic-number material such as silicon carbide or silicon. The pattern itself is defined in a thin (0.5 um) relatively high atomic-number material such as tantalum tungsten, gold or one of their alloys which is supported by the thin membrane.



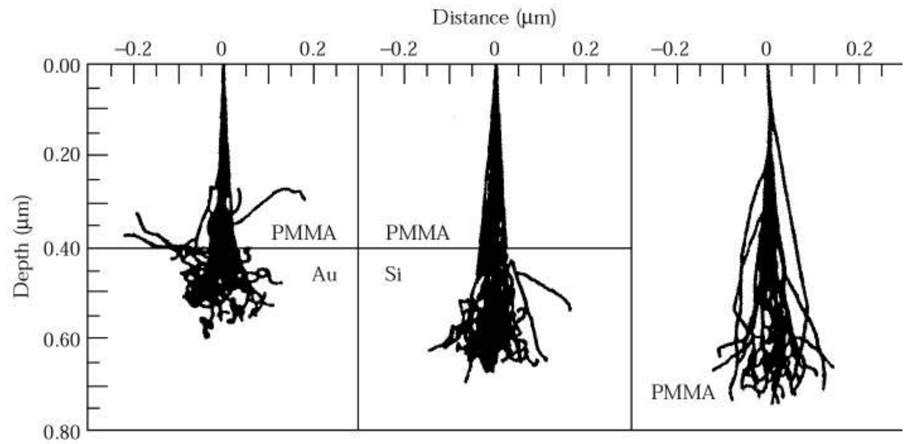
Schematic representation of a proximity x-ray lithography system.

X-Ray Lithography (Cont.)

- Masks are the most difficult and critical element of an XRL system, and the construction of an x-ray mask is much more complicated than that of a photomask. To avoid absorption of the x-ray between the source and mask the exposure generally takes place in a helium environment. The x-ray are produced in the vacuum.
- The mask substrate will absorb 25% to 35% of the incident flux and must therefore be cooled. An x-my resist 1 um thick will absorb about 10% of the incident flux.
- We can use electron beam resists as x-ray resists because when an x-ray is absorbed by all atom the atom goes to an excited state will the emission of an electron in the excited atom returns to its ground state by emitting an x-ray having a different wavelength than the incident x-ray . This x-ray is absorbed by another atom and the process repeats. Since all the processes result in the emission of electrons, a resist film under x-ray irradiation is equivalent to one being irradiated by a large number of secondary electrons from any of the other processes. Once the resist film is irradiated chain cross linking or chain scission will occur depending on the type of resist.

Ion Beam lithography

- Ion beam lithography can achieve higher resolution than optical. x-ray. or electron beam lithography techniques because ions have a higher mass and therefore scatter less than electrons.
- However ion beam lithography may suffer from the random space charge effects causing broadening of the ion beam.
- Backscattering is completely absent for the silicon substrate and there is only small amount of back scattering for the gold substrate.



Trajectories of 60-keV H* ions traveling through PMMA into Au, Si, and PMMA.

TABLE 4.1 Comparison of Various Lithographic Technologies

	Optical 248/193 nm	SCALPEL	EUV	X-ray	Ion Beam
Exposure Tool					
Source	Laser	Filament	Laser plasma	Synchrotron	Multicusp
Diffraction limited	Yes	No	Yes	Yes	No
Optics	Refractive	Refractive	Refractive	No optics	Full-field refractive
Step and scan	Yes	Yes	Yes	Yes	Stepper
Throughput of 200-mm wafers/hr	40	30–35	20–30	30	30
Mask					
Demagnification	4×	4×	4×	1×	4×
Optical proximity correction	Yes	No	Yes	Yes	No
Radiation path	Transmission	Transmission	Reflection	Transmission	Stencil
Resist					
Single or multilayer	Single	Single	Surface imaging	Single	Single
Chemical-amplified resist	Yes	Yes	No	Yes	No

SCALPEL, Scattering with angular limitation projection electron beam lithoraphy; EUV, extreme ultraviolet.