

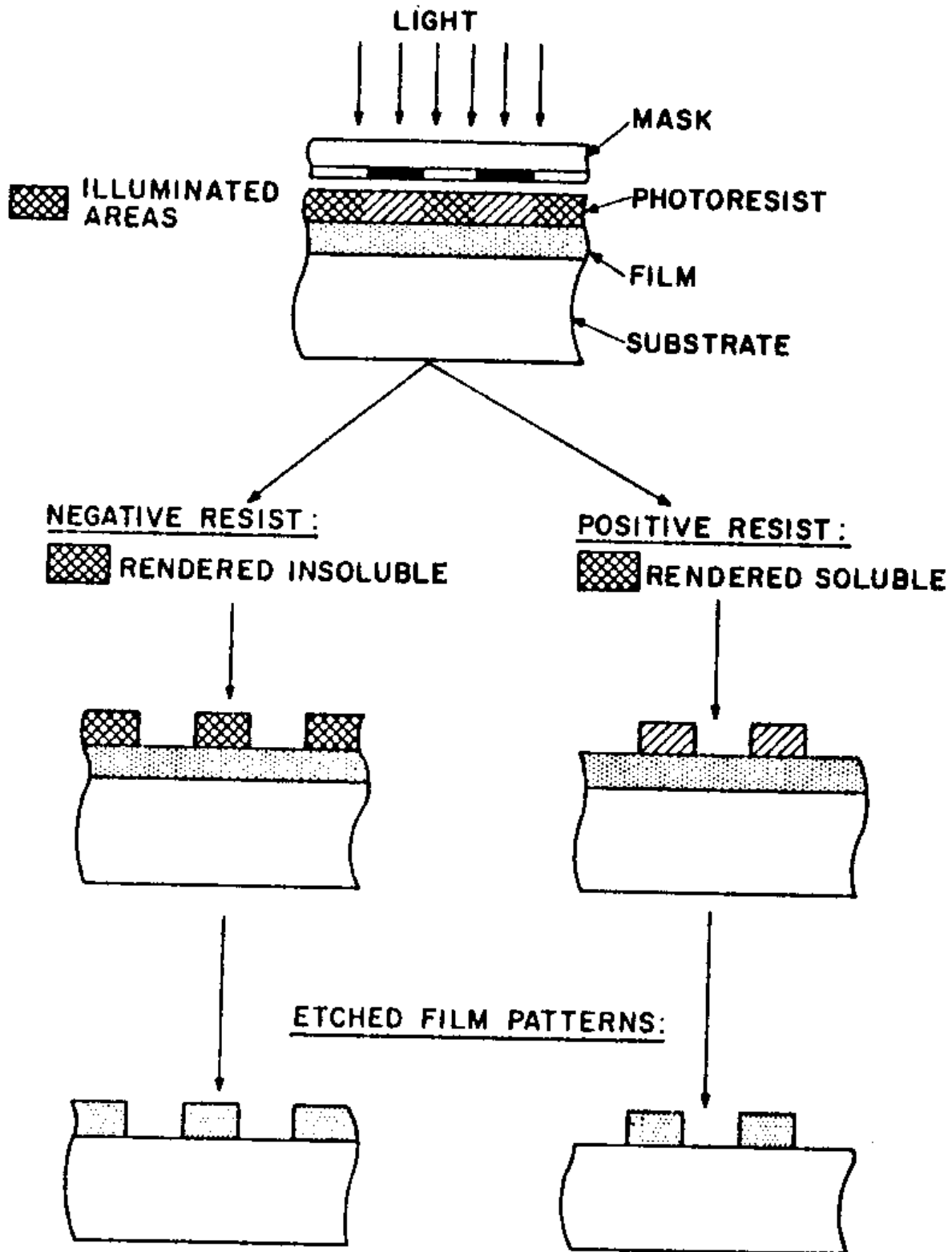
Photolithography

- Microcircuit fabrication requires that precisely controlled quantities of impurities be introduced into tiny regions of the silicon substrate, and subsequently these regions must be interconnected to create components and VLSI circuits.
- The patterns that define such regions are created by lithographic processes in which:
 - a) layers of photoresist materials are spin-coated onto the wafer substrate.
 - b) The resist layer is selectively exposed to a form of radiation, such as ultraviolet light, electrons, or x-rays using an exposure tool and mask to effect the desired selective exposure.
 - c) The patterns in the resist are formed when the resist is developed so that the areas of resist remaining after development protect the substrate regions which they cover.
 - d) Locations from which resist has been removed are subjected to one or more additive or subtractive processes that transfer the pattern onto the substrate surface.

Basic Photoresist Process

- The photoresist (PR) is applied as a thin film to the substrate (e.g. SiO_2 on Si or thin-film aluminum), and subsequently exposed through a mask (or reticle in step-and repeat projection systems).
- The mask contains clear and opaque features that define the pattern to be created in the PR layer in which areas exposed to the light are made either soluble or insoluble in a specific solvent known as a developer.
- In the case when the irradiated (exposed) regions are soluble, a positive image of the mask is produced in the resist (positive resist).
- If the nonirradiated regions are dissolved by the developer, a negative image results (negative resist)

- Following development, the regions of SiO_2 no longer covered by resist, are removed by etching, thereby replicating the mask pattern in that oxide or metallization layer.



- **The resist performs two roles in this process:**
 - a) **First, it must respond to exposing radiation in such a way that the mask image can be replicated in the resist.**
 - b) **Second, the remaining areas of resist must protect the underlying substrate during subsequent processing**
- **Although both negative and positive optical resists are used to manufacture semiconductor components, the higher resolution capabilities of positive resists have virtually made them the exclusive choice for VLSI applications.**
- **Conventional positive optical lithographic processes and resists are capable of producing images on VLSI substrates with submicron dimensions.**
- **For smaller features, however, diffraction effects during exposure may ultimately cause other higher-resolution techniques to replace optical lithography.**
- **Conventional optical photoresists are three-component materials consisting of:**
 - a) **the matrix material (also called resin), which serves as a binder, and establishes the mechanical properties of the film;**
 - b) **the sensitizer (also called the inhibitor), which is a photoactive compound (PAC);**
 - c) **the solvent (different than the developer solvent), which keeps the resist in the liquid state until it is applied to the substrate being processed.**
- **The matrix material is usually inert to the incident imaging radiation such that it does not undergo chemical change upon irradiation, but provides the resist film with its adhesion and etch resistance.**
- **It also determines other film properties of the resist such as thickness, flexibility, and thermal flow stability.**
- **The sensitizer is the component of the resist material that reacts in response to the actinic radiation.**

- The term actinic relates to the property of radiant energy (especially in the visible and ultraviolet regions) by which photochemical changes are produced.
- The sensitizer gives the resist its developer resistance and radiation absorption properties.

PHOTORESIST MATERIAL PARAMETERS

- A large group of material properties possessed by the resist play a role in how effectively these functions are performed which can be grouped into three categories:
 - a) optical properties, including, resolution, photosensitivity, and index of refraction;
 - b) mechanical/chemical properties, including, solids content, viscosity, adhesion, etch resistance, thermal stability, flow characteristics, and sensitivity to ambient (e.g. oxygen) gases;
 - c) processing and safety related properties, including, cleanliness (particle count), metals content, process latitude, and shelf life.

Resolution

- The resolution of a lithographic process is formally defined in terms of the modulation transfer function of the lithography exposure equipment and how well it is matched to the resist being utilized.
- The term is also used, in a more practical sense, to specify the consistent ability to print minimum size images under conditions of reasonable manufacturing variation.
- The resolution of a lithographic process can be limited by many aspects of the process, including:
 - a) hardware (e.g. diffraction of light, lens aberrations, and mechanical stability of the system);
 - b) optical properties of the resist material;
 - c) process characteristics (e.g. softbake step, develop step, postbake step, and etching step).

Positive Optical Photoresists

- **Positive photoresists for microelectronics applications are three-component materials (i.e. matrix, sensitizer, and solvent), whose properties are altered by the photochemical transformation of the photosensitive component, from that of a dissolution inhibitor to that of a dissolution enhancer.**
- **The matrix component of positive resists is a low-molecular weight novolac resin which forms the resist film properties.**
- **The generic term novolac (new lacquer) refers a type of adhesive first developed for plywood.**
- **The novolac resin dissolves or disperses in an aqueous base such as the developer.**
- **The sensitizers or photoactive compounds (PAC) in positive resists are photosensitive, but are insoluble in aqueous developer solution and also therefore prevent the novolac resin from being dissolved by the developer.**
- **Upon exposure to light, the sensitizers which prior to exposure act as dissolution inhibitors, photochemically decompose and allow the novolac resin to dissolve.**
- **Unexposed regions remain much less soluble in developer (~100 times less soluble) which is the primary mechanism for image formation in positive resists.**
- **Positive photoresists have become the dominant resists for VLSI applications because of their higher resolutions which arise because the unexposed film regions are not permeated by the developer.**
- **As a result they closely retain the size that they possessed after exposure, even after being immersed in developer.**
- **In negative resists, the developer permeates both the exposed and unexposed regions of the film.**
- **In the unexposed regions such penetration leads to film dissolution, but even in the exposed areas where little dissolution occurs, the solvent penetration causes the regions to swell and distort the pattern.**

Negative Optical Photoresists

- Negative photoresist has historically been the workhorse of the microelectronics industry, and was only been replaced when VLSI resolution requirements exceeded 3 μm .
- Their long predominance, however, stems from several attractive properties that negative resists possess for lithographic applications.
- It is predicted that these advantages will continue to make negative resist a widely used material for many lower resolution lithographic processes, especially on older wafer fab lines, where it would be prohibitively expensive to change masks to accommodate positive resists.
- The advantages of negative resist over positive resist include the following:
 - 1) better adhesion to some substrate surfaces;
 - 2) faster photospeed, which allows greater exposure throughput, and thus lower fabrication costs;
 - 3) somewhat greater process latitude in terms of developer concentrations and temperatures;
 - 4) less costly (about one-third as expensive as positive resists).
- Optical negative resists, like their positive counterparts, are three-component materials, although their chemistry and photoactive behavior is quite different.
- Most optical negative resists function by becoming less soluble in the regions exposed to light in which a photochemical reaction generates a cross-linked three-dimensional molecular network that is insoluble in the developer.
- The reactive component can undergo various reactions which result in the formation of more stable molecules, and the generation of a polymer-polymer linkage, or crosslinkage.
- Negative resists have several other disadvantages in addition to lower resolution which include:

- a) Light that is invariably scattered off the projection optics crosslinks a thin layer in the top surface of the negative which can slide down between the features and interfere with etching.
- b) In some negative resists, the sensitizer decomposes without crosslinking the polymer if exposure takes place in the presence of oxygen which may reduce the thickness of resist layers so much that not enough protection remains for the subsequent etch step.

Photoresist Inspection

- Following development, an inspection (sometimes referred to as an after-develop-inspection, or ADI) is performed to insure that the steps of the PR process up to this point have been performed correctly and to within the specified tolerance.
- Mistakes or unacceptable process variations can still be corrected, since the resist process has not yet produced any changes (e.g. through an etch step) to the wafer itself so that any inadequately processed wafers detected by this inspection (rejects) can have their resist stripped and reworked.
- In high production fab lines, individual reject wafers may be collected by device type and mask level, until enough are assembled to be reprocessed as a group.
- In lower volume production lines (or for special "hot lots", that need quick completion), the rejected wafers may be immediately re-run, while holding the acceptable wafers at the inspection station.
- The wafers at ADI are typically inspected with an optical microscope, although SEMs and laser-based systems are being introduced for performing some inspection tasks such as linewidth measurement.
- Some aspects of the resist process that are monitored by the inspection procedure include:
 - a) correct mask has been used;
 - b) resist film qualities are acceptable (i.e. resist is free from contamination, scratches, bubbles, striations, etc.);

- c) image quality is adequate (i.e. look for good edge definition, linewidth uniformity or indications of bridging);
 - d) critical dimensions are within the specified tolerances;
 - e) defect types and densities are recorded (and this data is used to correlate the occurrence of defects and product yield);
 - f) registration is within specified limits.
- On some microscopy-based inspection stations, all wafer handling and data processing functions have been automated.
 - Wafers are transported by belts or vacuum shuttle from an input cassette to a pre-aligner, then onto an inspection stage under the microscope.
 - Automatic handling allows the operator to concentrate on inspection, and to minimize the likelihood of airborne or human handling contamination.
 - In more automated systems, the human operator is completely removed from the defect inspection task with machine vision.
 - Defect detection is accomplished either by die-to-die or die-to-database comparison with defect detection sensitivities well into the sub-micron range.
 - Such instruments, however, often have difficulty detecting particles on substrates that have surface granularity, or on wafers containing surface topography because of difficulty in automatically analyzing textures.
 - In addition, for particles near the minimum-size detection limit, such machines can be prone to miss the presence of some particles, and signal the detection of others that may be non-existent.

Illumination Considerations for Photolithography

- UV illumination provides substantially better resolution than visible light although it has distinct limitations for deep submicron geometries.
- Mercury-vapor lamps are typically used as the illumination source for UV illumination over the range from 350 to 450 nm.

- To obtain maximum intensity, high power mercury-arc lamps are used (e.g. 200-1000W).
- In some systems, air jets cool the bulb, and the heated air is removed by an exhaust fan because heat will not only cause shifts in the spectral output of the lamp, but can also cause dimensional changes in the mask and optical path length of projection aligners.
- Collecting optics systems, which surround the lamp, are used to direct as much of the emitted light as possible onto the surface being exposed. Filters are also used to limit exposure wavelengths to the specified frequencies and bandwidth.
- The spectral output of the lamps vary with age, and together with variations in glass transmission and optical element coatings, exposure energy can change with time, or from machine-to-machine (even with the same lamp model).
- As a result, a spectral exposure meter must be used so that a correct and repeatable total energy dose is provided for each exposure.
- As the lamp output varies, the exposure time can be adjusted to maintain a constant incident energy dose onto each wafer.
- The meter must also be spectrally matched to the photoresist type being exposed using filters to set their spectral response, but the limited variety of transmission curves available in filters results in a relatively crude approximation of the response of actual photoresists.
- More recently, exposure meters which contain a complete UV spectrometer have been developed that can be adjusted to match the response of any photoresist over the wavelength range from 254-436 nm.

Contact Printing

- Contact printing was the earliest method used to produce patterns on silicon wafers. in which the mask containing the circuit pattern is first correctly positioned (aligned) relative to existing patterns on the wafer and clamped to the resist-coated wafer (while maintaining alignment), and exposed with UV light.

- This form of printing yields the most faithful image transfer and best resolution but as a result of the repeated mask-to-wafer contacting process, defects in the mask are generated which appear on subsequent wafers that are exposed through the mask.
- To minimize this effect, hard surface masks must be inspected and cleaned regularly.
- If the defects cannot be removed by cleaning, the mask must be replaced.
- Particles between the mask and wafer also prevent intimate contact which reduces resolution in the local area and has led to the virtual abandonment of contact printing for VLSI, and the development of techniques in which the wafer and mask do not make contact.

Proximity Printing

- The next form of pattern transfer to evolve was proximity printing, in which the mask and wafer are placed close to one another during exposure, but do not make contacts.
- By introducing such a gap between the mask and wafer, the defect problem of contact printing is avoided but as the gap size is increased, the resolution rapidly degrades.
- The use of this technique also requires extremely flat masks and wafers.
- In spite of the fact that many of today's wafers are flat enough to allow the use of a 10 μm gap, many VLSI circuits require features smaller than 2 μm so this technique is also not adequate for VLSI.

Projection Printing

- In projection printing, lens elements or mirrors are used to focus the mask image on the wafer surface, which is separated from the mask by large distances.
- Several types of projection printing techniques have been developed, including:
 - a) 1:1 projection scanners (based on reflective optics);

- b) reduction step-and-repeat projection aligners (based on refractive optics);**
- c) non-reduction (i.e. 1X) step-and-repeat projection aligners (based on a reflective /refractive system).**

1:1 Scanning Projection Aligners

- A typical 1:1 wafer scan projection system uses a reflective spherical mirror to project the image onto the wafer surface in which a narrow area of radiation is imaged from the mask to the wafer, with the light traveling along an optical path that reflects it 5 times, most importantly by a spherical mirror.**
- The wafer and mask are scanned through this area of radiation by means of a continuous scanning mechanism which minimizes mirror distortions and aberrations by keeping the imaging illumination in the "sweet spot" of maximum optical correction.**
- These systems use Hg lamps over a spectral range of 240 to 440 μm .**
- A resolution of better than 1.50 μm is reportedly attainable when 350-400 nm light is used.**
- At deep UV (240 nm), exposure resolution submicron resolutions can be achieved.**
- A throughput of 100 150 mm wafers/hr can be obtained.**