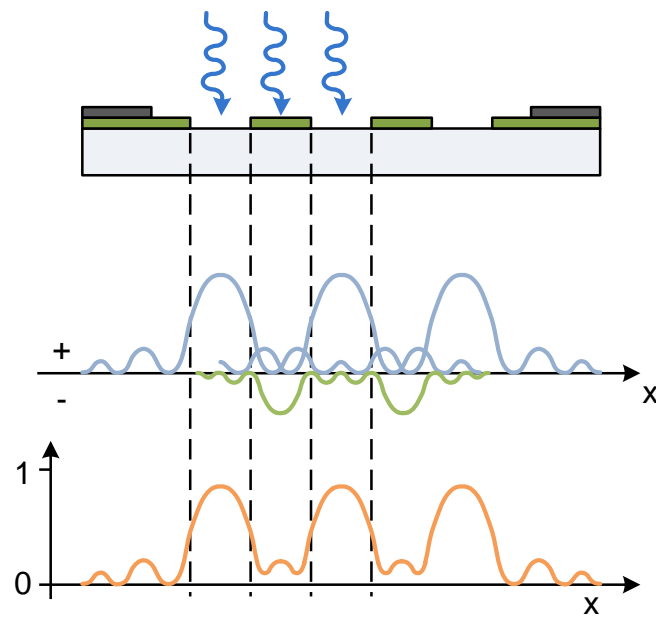


# Semiconductor Technology

from A to Z



## Photolithographie



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# 1 Photolithographie

## 1.1 Exposure and resist coating

### 1.1.1 Overview

In the manufacturing of semiconductors, structures are created on wafers by means of lithographic methods. A light sensitive film, primarily a resist layer, is coated on top of the wafer, patterned, and transferred into the layer beneath.

Photolithography consists the following process steps:

- adding adhesives and removing moisture from the surface
- resist coating
- stabilization of the resist layer
- exposure
- development of the resist
- curing of the resist
- inspection

In some processes, as the ion implantation, the resist serves as a mask to cover certain areas which should not be doped. In this case there is no transfer of the patterned resist layer into the layer beneath.

### 1.1.2 Adhesives

First of all the wafers are cleaned and annealed (pre-bake) to remove adhesive particles and adsorbed moisture. The wafer surface is hydrophilic and has to be hydrophobic before deposition of the photoresist. For this reason adhesives, hexamethyldisilazane

(HMDS) in general, are added to the surface. The wafers are exposed to the vapor of this liquid and are dampened.

Because of moisture in the atmosphere even after the pre-bake there are hydrogen H oder hydroxyl groups  $\text{OH}^-$  attached to the surface. The HMDS decomposits into trimethylsilyl groups  $\text{Si}-3\text{CH}_3$  and removes the hydrogen by forming ammonia  $\text{NH}_3$ .

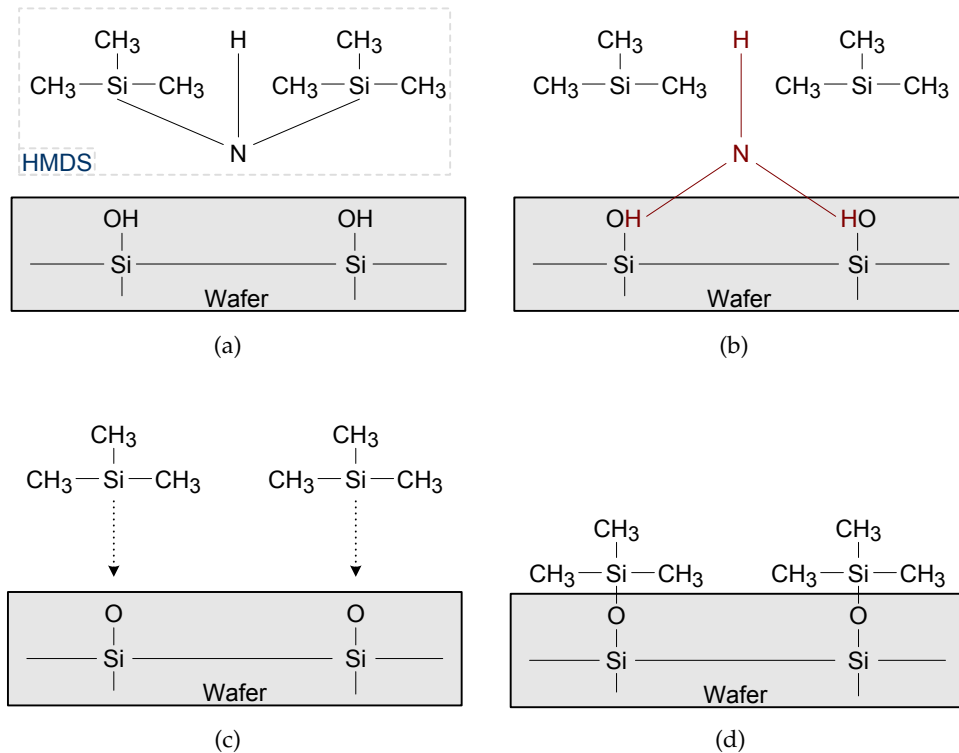


Fig. 1.1: Surface modification with HMDS

### 1.1.3 Coating

The coating of the wafer is done by spin on methods on a rotating chuck. On low rotation the resist is spun on and then planished at for example 2000 to 6000 rpm. Depending on the subsequent process the thickniss of the resist layer can be up to 2 microns. The thickness depends on the rpm and the viscosity of the resist.

To enable a homogeneous layer, the resist contains water and solvents which soften it. For stabilization reasons the wafer is annealed afterwards at about 100 °C (post-/soft-bake). Water and solvents are vaporized partially, some moisture has to remain

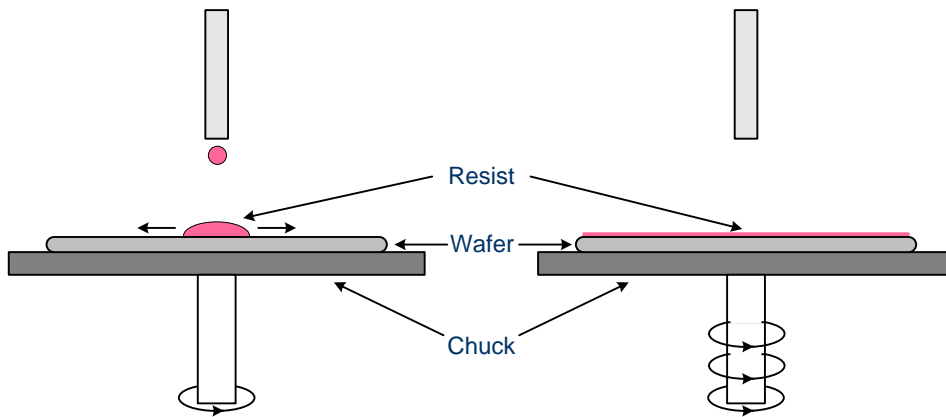


Fig. 1.2: Spin on coating

for subsequent exposure.

### 1.1.4 Exposure

In a lithographic exposure tool, there is a glass mask which is fractional covered with chrome to partial expose areas of the resist.

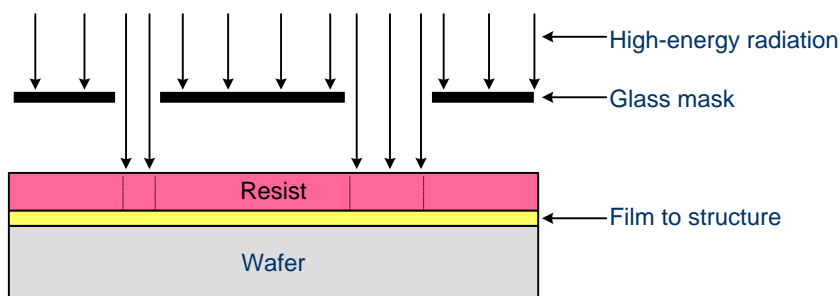


Fig. 1.3: Optical lithography

Depending on the type of the resist, exposed areas are solubly or insolubly. With a wet-chemical developer the solubly parts are removed, so that a patterned resist layer remains. The exposure time is a very important value to achieve the correct dimensions of the structures. The longer the wafers are exposed to the radiation, the larger the radiated area is. Due to fluctuating ambient temperatures a precise determination of the correct exposure time has to be investigated with one or more dummy wafers, because the characteristics of the resist can change with temperature.

An overexposure causes smaller resist patterns, and therefore smaller structures be-



neath, in contrast vias will be enlarged. With a too short exposure time the vias are not opened correctly, conductors are too wide or even in contact to each other (short circuit). In addition, a bad focusing leads to unexposed areas, so that vias can not be opened and conductors are in contact as well.

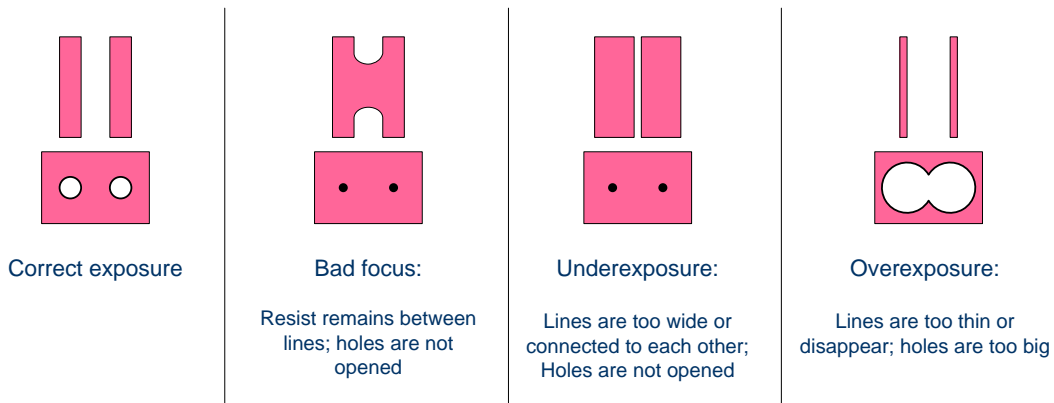


Fig. 1.4: Bad exposure due to focus issues, over exposure, or under exposure

Depending on the subsequent process, the width of the resist patterns or the diameter of the vias, respectively, has to be adjusted. In isotropic etch processes (etching in vertical and horizontal orientation) the resist mask is not transferred 1:1 into the layer beneath.

### 1.1.5 Exposure methods

For exposure there are different radiation sources, depending on the demands: ultra-violet radiation, electron beam, x-ray, and ion beams. The shorter the wavelength the smaller the possible structures.

For structures of 120 nm an argon fluoride laser is used, for ever smaller structures a nitrogen laser (wavelength 157 nm) or extreme ultra-violet radiation (EUV, wavelength 13 nm) is conceivable. X-rays do have a wavelength of 0.2 to 0.4 nm, electron beam writers about 0.02 nm and ion beams - in case of protons (hydrogen ions) - 0.0001 nm.

That one can fabricate structures with a width of less than  $x$  nm with a radiation of  $x$  nm is possible due to special photomasks which utilize the phase shift of light. In addition the resolution can be increased with liquid films inside the optical system (immersion lithography). These techniques made it possible to fabricate today's structure sizes of 32 nm still with a radiation wavelength of 193 nm.

While ultra-violet radiation (generated with mercury bulbs) and gas lasers are used for the exposure of the wafer, x-ray or ion beam lithography is used in research. Electron beams are used for photomask manufacturing.

## **1.2 Exposition methods**

### **1.2.1 Overview**

There are different types of lithographic methods, depending on the radiation used for exposure: optical lithography (photolithography), electron beam lithography, x-ray lithography and ion beam lithography.

In optical lithography patterned photomasks (reticles) with partial opaque and partial translucent areas are used. The exposure with ultra-violet radiation or gas lasers is done in a scale of 1:1 or reducing in a scale of 4:1 or 10:1 for instance.

### **1.2.2 Contact exposure**

Contact exposure is the oldest used method. The photomask is in direct contact to the resist layer, the structures are transferred in a scale of 1:1. Thus disruptive scattering or diffraction effects only appear at the edges of the structures. This method allows only moderate feature sizes. Because all chips are exposed simultaneously the wafer throughput is very high, the construction of the lithographic unit is simple.

However, the disadvantages are obvious: the mask is contaminated because of its contact to the resist and can be scratched as well as the resist layer can be damaged. If there are particles between the mask and the resist, the optical imaging is degraded.

### **1.2.3 Proximity exposure**

In proximity exposure there is no direct contact of the photomask and the resist. Thus only a shadow image is projected onto the wafer which results in a much worse resolution of the structures, contact issues are prevented therefore.

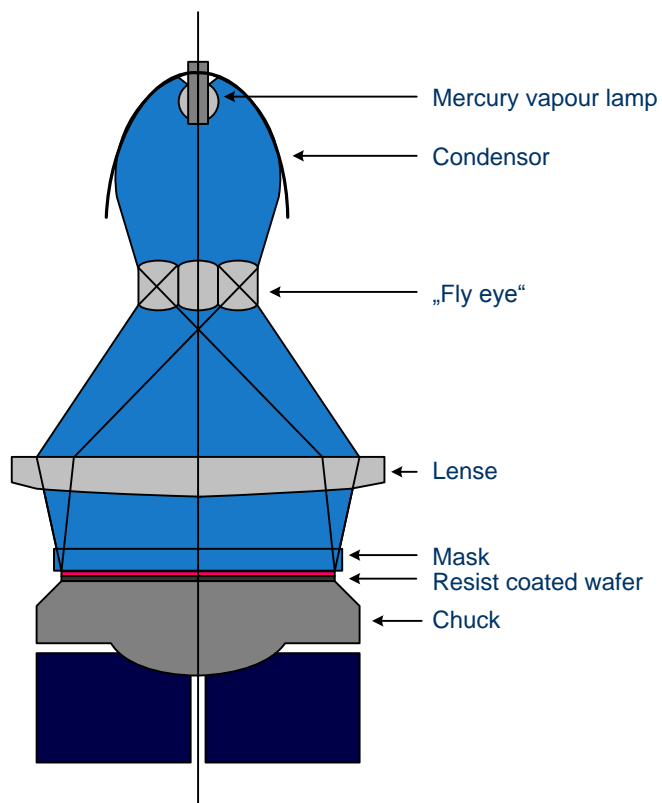


Fig. 1.5: Contact exposure

#### 1.2.4 Projection

The exposure via projection uses the so-called step-and-repeat technique. Thereby only one or a few dies were projected onto the wafer at a time. The entire wafer is exposed step by step - die by die.

The advantage of this method is that the structures on the reticle are enlarged 4-fold or 10-fold. If the structures are projected onto the wafer in reduced scale, also defects, like particles, are reduced. In contrast to other exposure methods the resolution is improved.



Fig. 1.6: Proximity exposure

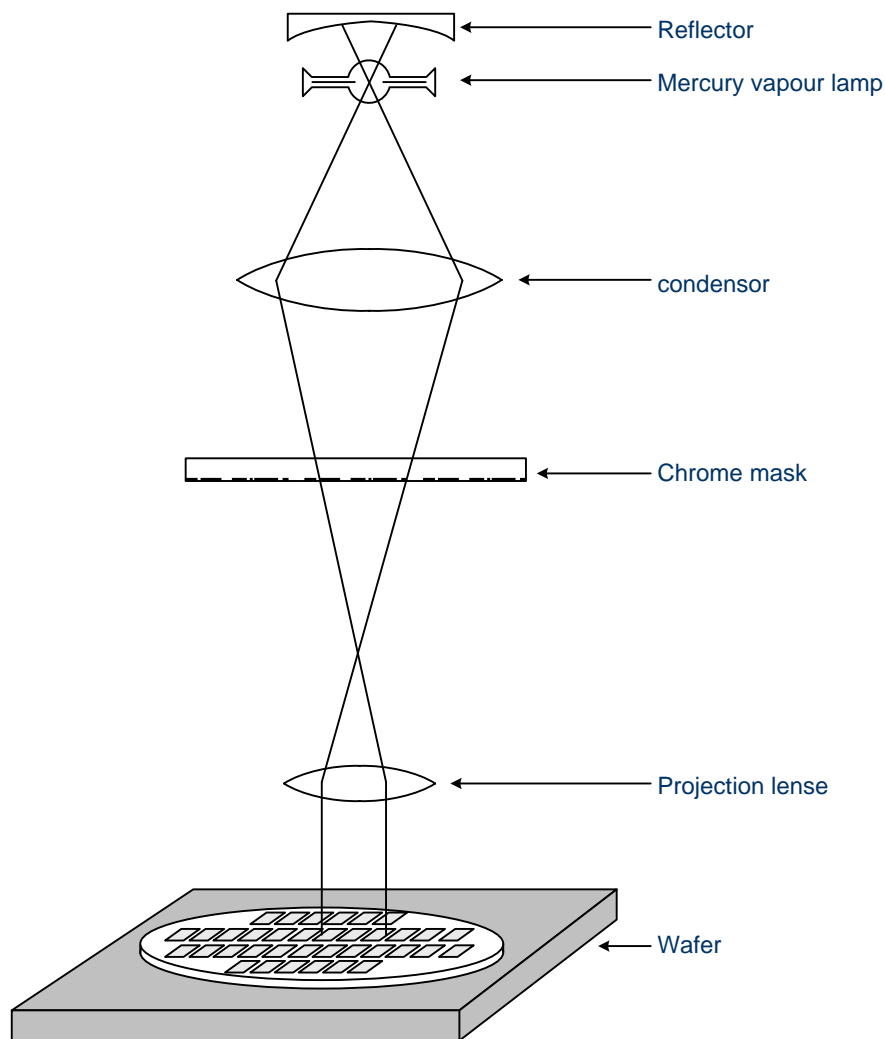


Fig. 1.7: Step and repeat technique

In addition a thin foil - pellicle - is attached to the mask, and therefore particles will be held off the mask and are out of focus during projection.

Besides the projection with lenses also a projection with a complex system of mirrors can be used (scale 1:1). Compared to lenses there are no color aberrations and thermal expansion of the photomask can be adjusted. However, mirror images can be distorted or warped. The resolution is limited due to the scale of 1:1.

### 1.2.5 Electron beam lithography

As in photomask manufacturing a focused ion beam is scanned across the wafer, the scan is done line by line. Each structure has to be written one after the other which takes a lot of time. The advantage is that there is no need of photomasks which reduces the costs. The process is done under a vacuum.

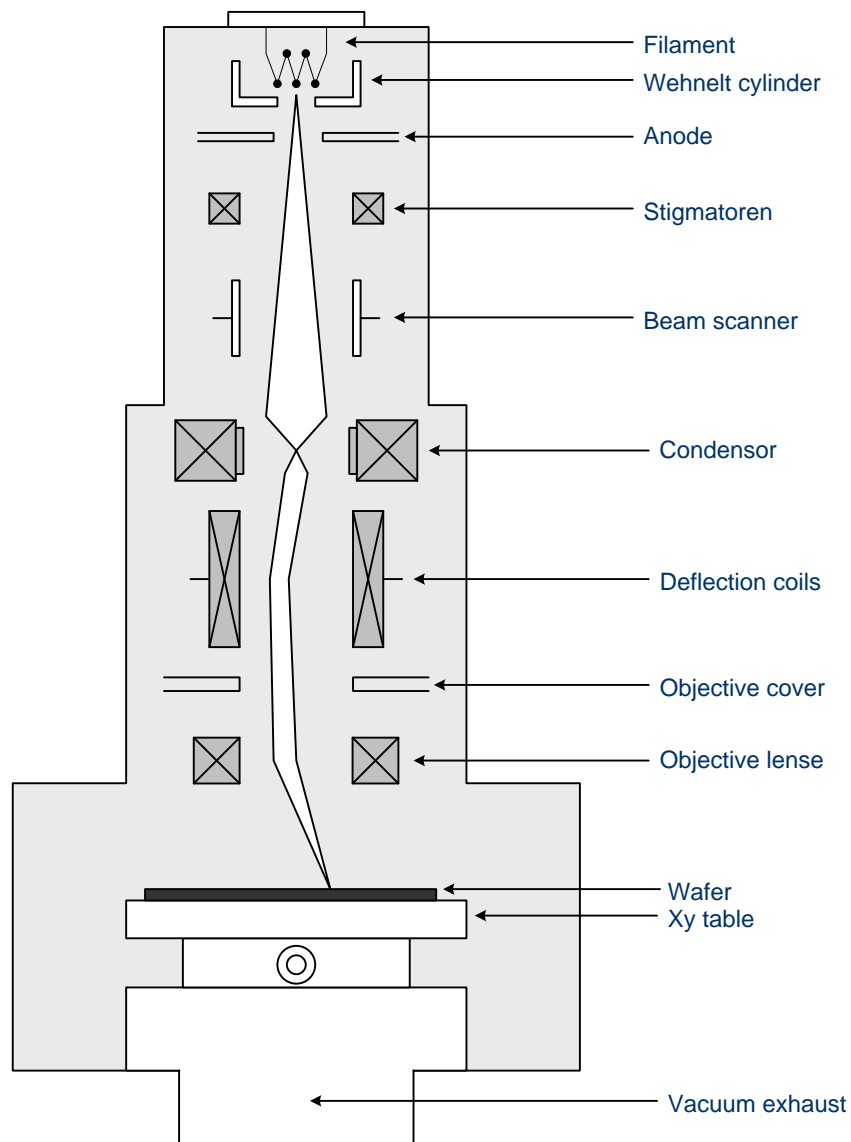


Fig. 1.8: Electron beam lithography

### 1.2.6 X-ray lithography

The resolution of x-ray lithography is about 40 nm. The imaging is done in step-and-repeat technique in a scale of 1:1 in atmospheric pressure or low pressure in helium atmosphere (about 10.000 Pa). The x-ray source can be a plasma or a synchrotron.

Instead of chrome coated glass masks, thin foils made of beryllium or silicon are used. To adsorb x-rays heavy elements like gold are necessary. The facility as the photomasks are very expensive.

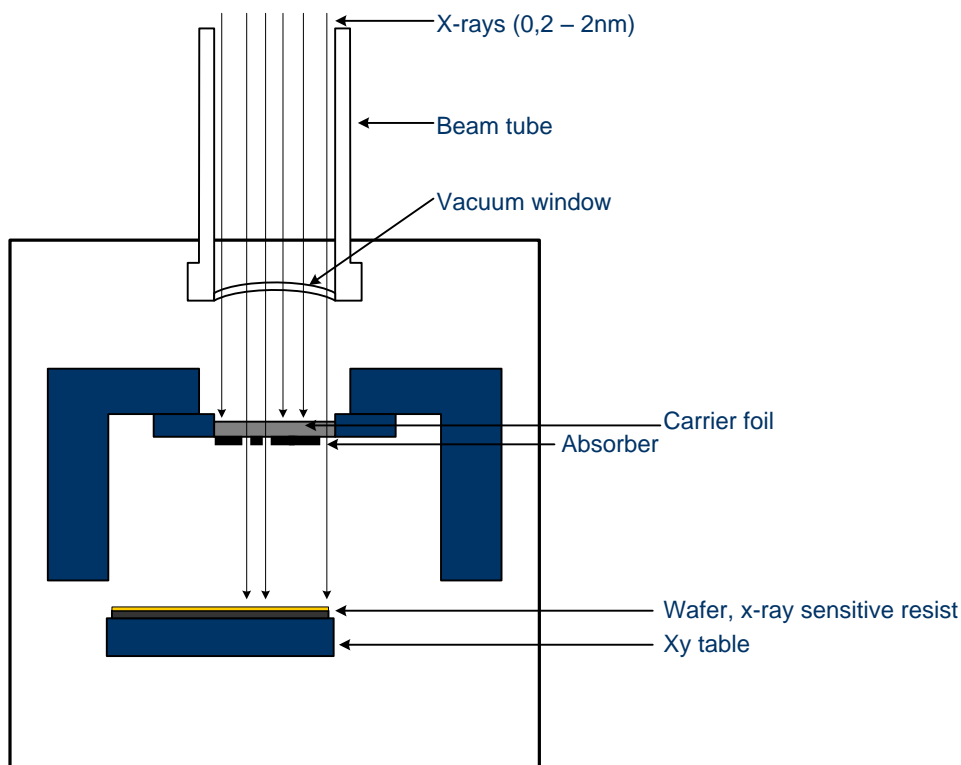


Fig. 1.9: X-ray lithography

### 1.2.7 Additional methods

An additional method of lithography is the use of ion beams. The wafer can be exposed with a photomask or, like in electron beam lithography, without a mask. In case of hydrogen ions the wavelength is about 0.0001 nm. Other elements allow a direct doping of the wafer without the use of masking layers.

## 1.3 Photoresist

### 1.3.1 Photoresist

There are two types of photoresist, positive and negative resist, which are used in different applications. In positive resist, the exposed areas are solubly, in negative resist the exposed areas are insolubly for wet chemical development.

Characteristics of positive resists:

- + excellent resolution
- + stable against developers
- + can be developed in aqueous developers
- bad resistance in etching or implantation processes
- bad adhesion on the wafer

Characteristics of negative resists:

- + high sensitiveness
- + fair adhesion
- + excellent resistance against etch or implantation processes
- + cheaper than positive resists
- lower resolution
- organic developers are needed (toxic)

For patterning of wafers in manufacturing, almost only positive resists are used. Negative resists were primarily used as a passivation which can be cured by ultra-violet radiation. If there is no specification in the text, a positive resist is the subject.

### 1.3.2 Chemical composition

Photoresists are composed of adhesive agents, sensitizers and solvents.

- **Binders ( 20%):** As a binder Novolac is used, which is a synthetic resin to control the thermal characteristics of the resist.

- **Sensitizer ( 10%):** Sensitizers define the photosensitivity of the resist. Sensitizers are composed of molecules which affect the solubility of the resist if it is exposed to energetic radiation. Thus the lithography has to take place in areas with ambient light which has a low energy.
- **Solvents ( 70%):** Solvents define the viscosity of the resist. By annealing, the solvent is vaporized and the resist is stabilized.

A resist, as it is provided from vendors, has a defined surface tension, density and viscosity. For this reasons the thickness of the resist layer in wafer fabrication depends on the temperature and the rpm of the coating tool.

## 1.4 Development and inspection

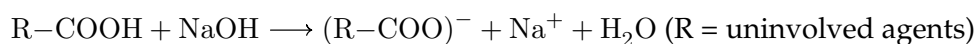
### 1.4.1 Development

The exposed wafers are developed in dipping baths or in spray processes. While dipping baths allow the development of multiple wafers at a time, in spray development one wafer is processed after another. As in resist coating processes the wafer is placed on a chuck and sprayed with developing chemicals while rotating at low rpm. Subsequent the wafer development process is stopped with water.

Some advantages of the spray development in contrast to dipping baths are:

- smallest structures can be developed
- the chemical is renewed steadily
- the amount of chemicals is much less

Depending on the type of resist - negative/positive - exposed areas are solubly or insolubly in developing chemicals and a patterned wafer remains after development. The exposure causes a chemical reaction in the resist thus that the sensitizer forms an acid which is neutralized by the developer like follows:





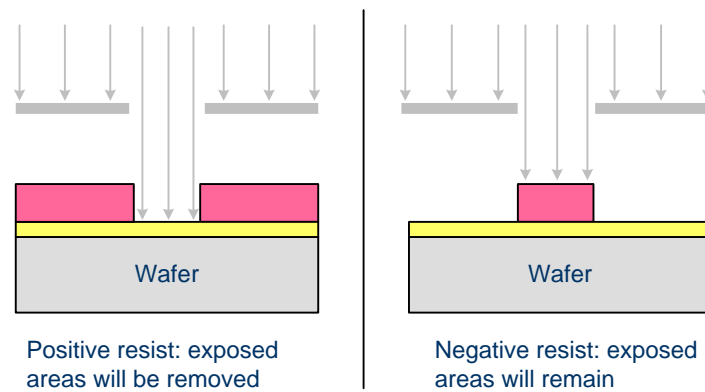


Fig. 1.10: Illustration of positive and negative resist after development

Because potassium hydroxide or sodium hydroxide leave residuals on the wafer, chemicals without metal ions, like TMAH (tetramethylammonium hydroxide), are used. An additional annealing (hard-bake) hardens the resist to be resistant to subsequent etch processes or ion implantation.

### 1.4.2 Inspection

The resist has to be inspected afterwards. In angular incidence of light the uniformity of the layer can be inspected as well as bad focusing or agglomeration of resist. If structures are too thin or too wide the resist has to be removed and the process has to be repeated. The resist pattern has to be adjusted precisely to the layer beneath or the process has to be repeated as well. Different alignment marks are used to investigate the adjustment and the line width.

The line width is inspected with a microscope: light rays incidence in perpendicular direction onto the wafer and will not be reflected into the objective from edges. Thus the edges appear as dark lines which can be used to calculate the line width and distance to adjacent lines.

### 1.4.3 Resist removal

After the pattern has been transferred into the layer beneath in etch processes, or after the resist mask was used in ion implantation, the resist has to be removed. This is done with abrasive chemicals (remover), in a dry etch step or with solvents. As solvent acetone can be used since it does not corrode other layers on the wafer. Due to a dry

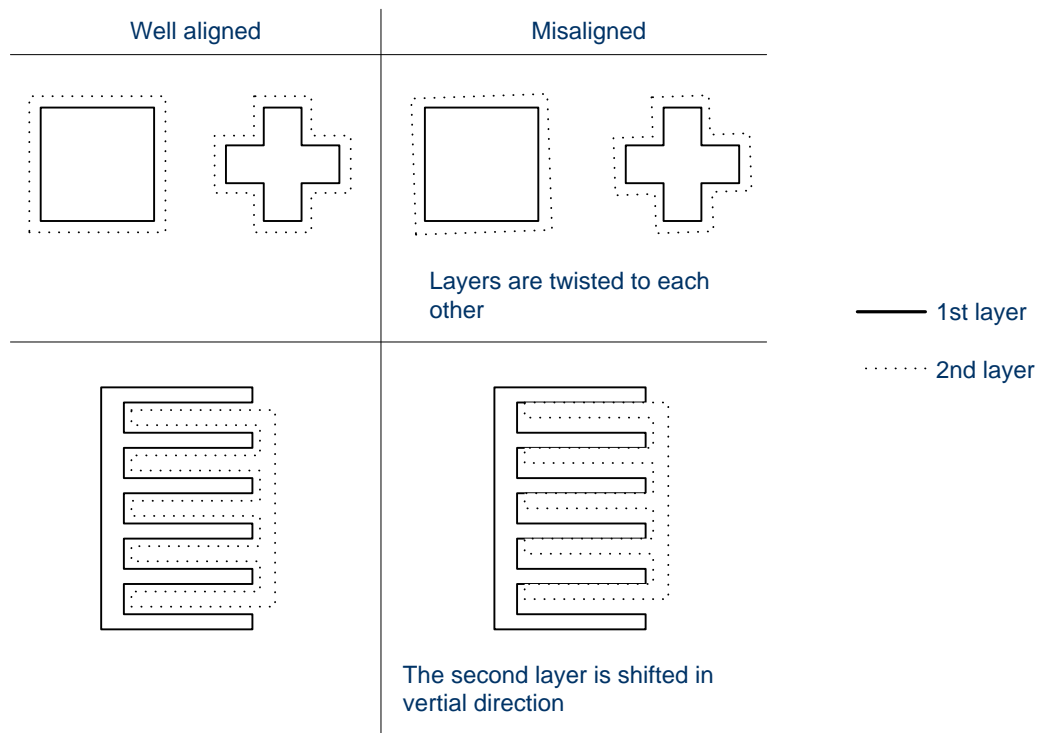


Fig. 1.11: Illustration of alignment marks

etch process or ion implantation the resist could be hardened, so that solvents can't remove it.

In this case the resist can be removed with a remover dilution at about 80 °C in a dipping bath. If the resist has been heated above 200 °C even the remover can't remove it. In this case the resist has to be removed in an ashing process.

Under oxygen ambient a gas discharge is ignited by high frequency, thus energetic oxygen atoms are generated. These atoms can ash the resist residue-free. However, charged particles can be accelerated in the electric field and cause damage to the wafer surface.

## 1.5 Photomasks

### 1.5.1 Introduction

Photomasks used for optical lithography contain the pattern of the integrated circuits. The basis is a so called *blank*: a glass substrate which is coated with a chrome and a resist layer. The resist is sensitive to electron beams and can be transferred into the chrome layer via etch processes. The chrome represents opaque areas on the photomask which are responsible for the casting of shadow during exposure of the silicon wafers.

The photomasks are directly exposed with electron beams under hard vacuum. With this method a resolution far below 100 nm is possible.

Due to wave optics (e.g. diffraction) there can be aberration during the exposure of wafers. Thus the optical proximity correction (OPC) has been introduced in semiconductor manufacturing, which can eliminate or reduce image defects.

OPC means to modify the structures on the mask in such a way that the shape of the image on the wafer looks like desired. Furthermore there can be additional structures just for minimizing aberration which do not have any function for the integrated device itself.

### 1.5.2 Photomask manufacture

The manufacturing of photomasks is basically equal to the wafer fabrication. The difference is the exposure of the resist which is done by electron beams (photomasks) or with optical lithography (wafer).

1. First step is the exposure of photoresist with electron beams (or laser).

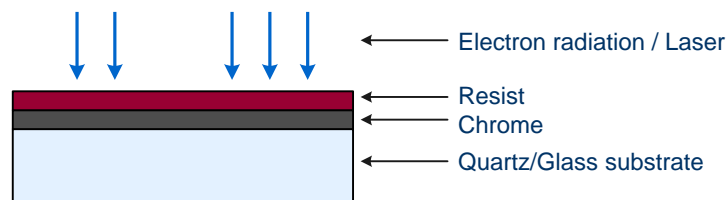


Fig. 1.12: Basic film stack of a chrome on glass mask (COG)

2. Subsequent the resist is developed to form a pattern.

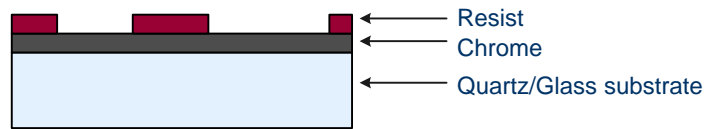


Fig. 1.13: Development of the resist layer

3. The resist acts as a masking to transfer the pattern into the chrome layer by etch processes.

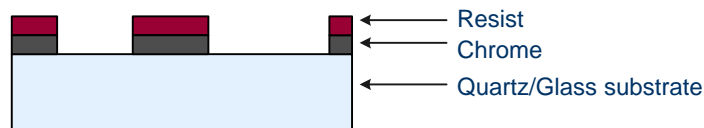


Fig. 1.14: Chrome etch

4. Subsequent the resist is removed.

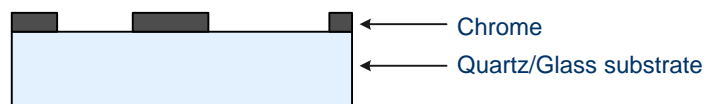


Fig. 1.15: Resist strip

5. Finally a pellicle is montaged on top to prevent contamination of the glass/chrome

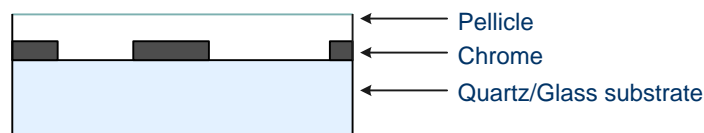


Fig. 1.16: Attached pellicle

### 1.5.3 Photomasks

Besides the traditional chrome on glass mask (COG) there are various types of photomasks which enhance the optical resolution of the structures. The central issue of COG masks is the diffraction of the light on edges. Thus the light will not only impact in perpendicular direction but will be deflected into areas which must not be exposed.

With different means which are described below the intensity of the diffracted light should be reduced.

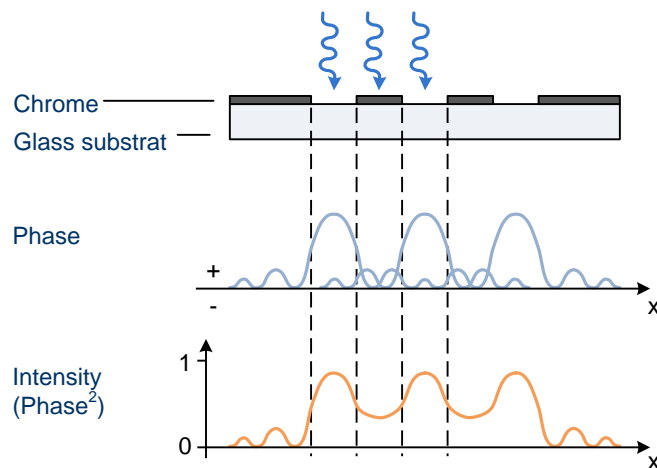


Fig. 1.17: Spectral intensity of a COG mask

#### Attenuated Phase Shift Mask (AttPSM):

The attenuated phase shift mask (AttPSM; also half tone mask) uses a patterned layer of molybdenum silicide (MoSi) which represents the structures of the circuit. The molybdenum silicide has a thickness which causes a phase shift of the transmitted light of  $180^\circ$ . Thus the phase shifted light and the radiation which transmits through glass only interfere destructively. In addition the molybdenum silicide is dense (6 % or 18 % @ 193 nm wavelength). On the one hand the light is attenuated and on the other hand the light waves which are in opposite phase erase each other almost completely, this results in a higher contrast. A chrome layer can be added to areas which are not used for exposure to mask unused regions. This photomasks are named tritone masks.

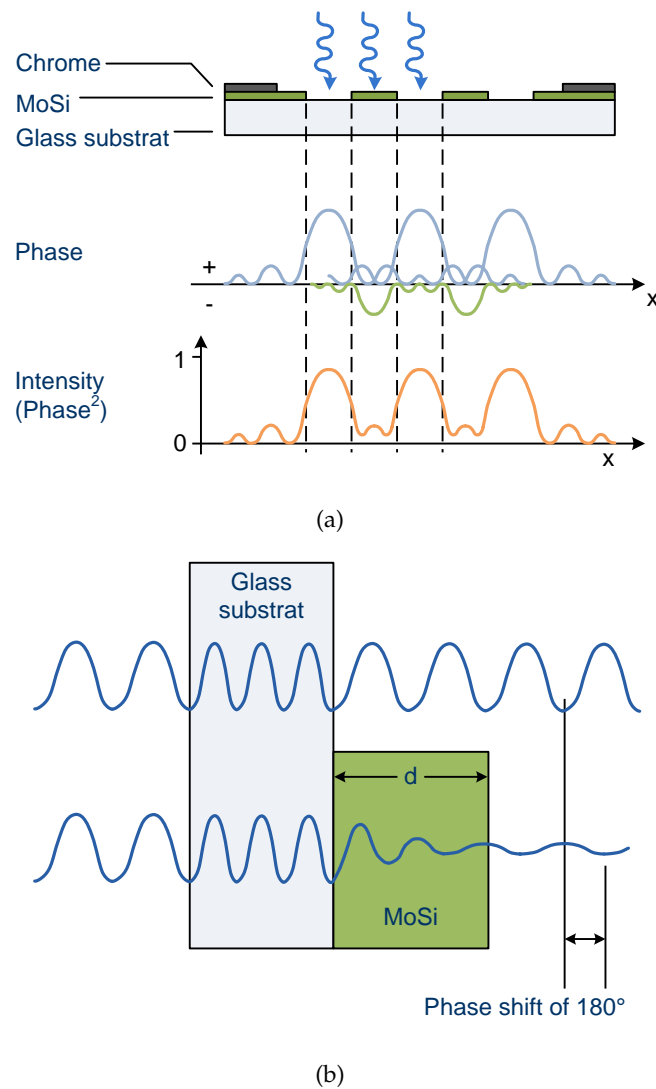


Fig. 1.18: (a) Spectral intensity of an Attenuated Phase Shift Mask, (b) principle of the phase shift with molybdenum silicide

#### Chrome less Phase shift mask:

Chrome less phase shift masks don't use opaque films. The phase shift is achieved by trenches which are directly etched into the glass substrate. The manufacturing of these masks is difficult, since the etch approach has to be stopped in the middle of the glass. In contrast to etch processes where one layer is completely etched till the layer beneath is reached - which causes changes in the etch plasma, so that one knows when the process is finished -, there is no indication when the exact depth in the substrate is reached.

### Alternating Phase Shift Mask (AltPSM):

The alternating phase shift mask also uses trenches which are etched into the glass substrate alternating to non-etched areas. In addition there are areas which are covered with a chrome layer to decrease the intensity of radiation in this regions.

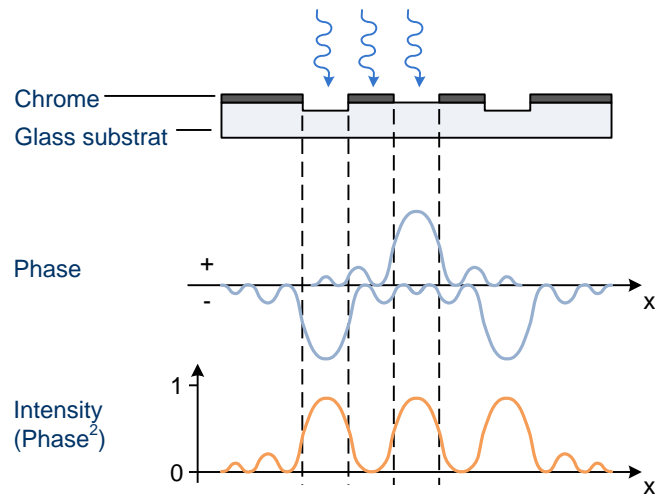


Fig. 1.19: Spectral intensity of an Alternating Phase Shift Mask

However, there are regions with an undefined phase shift, so that one has to exposure twice with different masks. One mask contains the structures which run in x-direction, while the second mask contains the patterns which are orientated in y-direction.

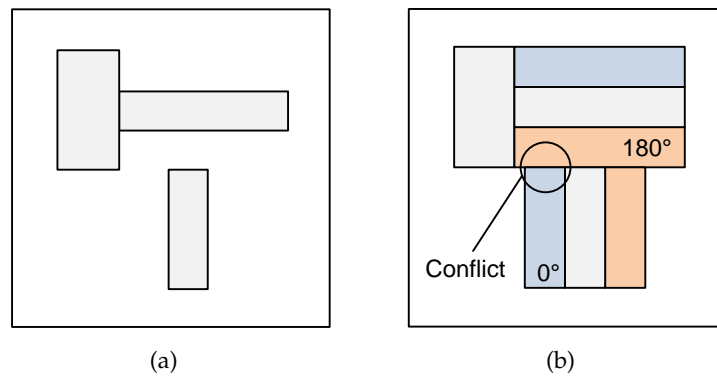


Fig. 1.20: Desired structures on the wafer and conflict on the mask

#### **1.5.4 Next generation lithography**

In the future there has to be a complete change-over which means, that the traditional lithography tools and the photomasks have to be replaced. Next generation lithography is expected to use extreme ultra-violet radiation (EUV, wavelength 13.5 nm) which is absorbed in normal atmosphere as well as in glass. For this reason EUV processes have to take place under vacuum and instead of optical lenses mirrors have to be used for focusing. The photomasks will have a reflective surface instead of translucent glass.

Also because of the tremendous effort (technical as well as of money matters) the traditional lithography is kept alive as long as possible, and new inventions as phase shift masks or immersion lithography have pushed the conventional lithography. Thus today's feature sizes of only 32 nm can still be exposed with a wavelength of 193 nm. Sometimes there was a thought of the introduction of radioation sources with 155 nm, however, because of the immense costs it is foreseeable that subsequent to argon fluoride lasers (193 nm) EUV sources will be established instantly.



