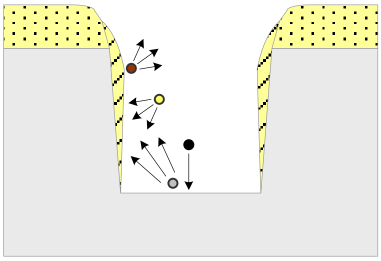
Semiconductor Technology

von A bis Z



Dry etching

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1 Dry etching

1.1 Overview

1.1.1 Abstract

In wet etching film stacks are generally etched isotropic, however, at small feature sizes an anisotropic profile is neccesary. Therefore dry etch processes are applicable which have a sufficient selectivity. Such methods allow reproducible uniform etching of almost all materials which are used in semiconductor manufacturing. Besides anisotropic processes, isotropic processes are possible as well. Despite the expensive production facilities and the single wafer processes, dry etching has established itself.

1.1.2 Major values in dry etching

Etch rate r: the etch rate is the abrasion per time and for example can be specified in nanometers per minute or Angstrom per second.

$$\mathrm{r} = \frac{\text{Etch removal } \Delta \mathrm{z}}{\text{Time } \Delta \mathrm{t}}$$

Anisotropism f: The anisotropism gives the ratio of horizontal etch rate $\mathrm{r_h}$ and vertical etch rate $\mathrm{r_v}$.

$$\mathrm{f} = 1 - \frac{\mathrm{r_h}}{\mathrm{r_v}}$$

For structuring high anisotropic processes are desired, which means an etching only in vertical direction, so that the resist mask is not underetched. For anisotropic etch processes $f \to 1$, and accordantly for isotropic processes $f \to 0$.

Selectivity S_{jk} of layer j and layer k: the selectivity is the ratio of the etch rates of two films, e.g. of the layer which should be structured (j; e.g. oxide) and the layer which should not (k; e.g. resist).

$$\mathrm{S_{jk}} = \frac{\mathrm{r_j}}{\mathrm{r_k}}$$

The value of the selectivity depends on the process. For structuring the value should be as high as possible, which means that the layer one wants to structure is etched much faster than a masking resist layer. In reflow back etching the selectivity should be about 1 to ensure a uniform surface.

1.1.3 Dry etch processes

In dry etching gases are stimulated by high frequency, which is primarily 13.56 MHz or 2.45 GHz. At a pressure of 1 to 100 Pa the mean free path is some millimeters to centimeters.

Primarily there are three types of dry etching:

- **physical dry etching:** physical abrasion of the wafer surface by accelerated particles
- **chemical dry etching:** chemical reaction of gas and wafer surface
- **chemical physical dry etching:** physical etch process with a chemical character

1.2 Dry etch processes

1.2.1 Ion Beam Etching

The ion beam etching (IBE) is a physical dry etch process. Thereby argon ions are radiated onto the surface as an ion beam with about 1 to 3 keV. Because of the energy of the ions, they strike out material of the surface. The wafer is held perpendicular or tilted into the ion beam, the etch progress is absolute anisotropic. The selectivity is low because there is no differentiation of the individual layers. The gas and the striked out material are exhausted by vacuum pumps, however, particles can deposit on the wafer or on chamber walls since the reaction products are not in gaseous state.

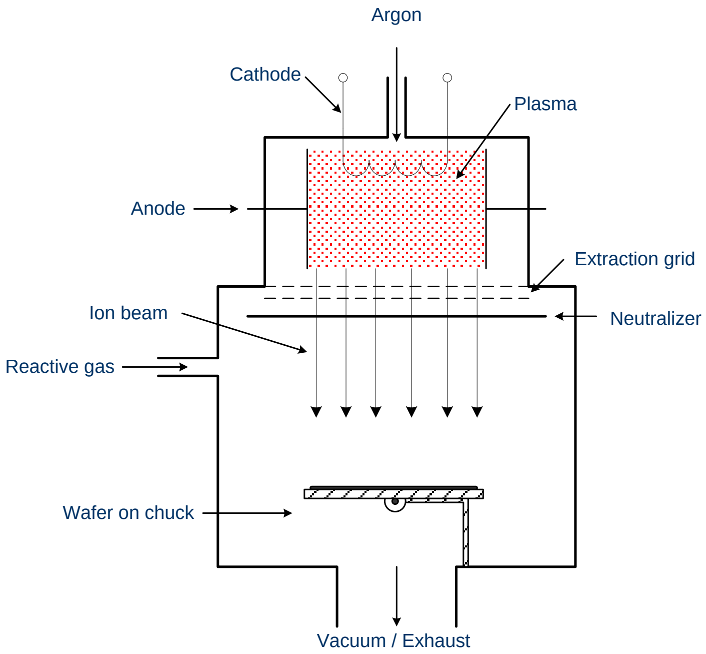

Fig. 1.1: Illustrationn of an ion beam etch reactor

To avoid particles a second gas is led into the chamber. This gas reacts with the argon ions and causes a physical chemical etch process. Partial the gas reacts with the surface but also with the striked out particles to form gaseous byproducts.

Almost every material can be etched with this method. Due to the perpendicular radiation the abrasion on vertical walls is very low (high anisotropism). However, because of the low selectivity and the low etch rate, this process is only used rare in todays semiconductor fabrication.

1.2.2 Plasma Etching

The plasma etching (PE) is an absolute chemical etch process (chemical dry etching, CDE). The advantage is that the wafer surface is not damaged by accelerated ions. Due to the movable particles of the etch gases the etch profile is isotropic, thus this method is used to remove entire film layers (e.g. back side clean after thermal oxidation).

One reactor type for plasma etching is the down stream reactor. Thereby a plasma is ignited at high frequency of 2.45 GHz through impact ionization, the location of the impact ionization is separated from the wafer.

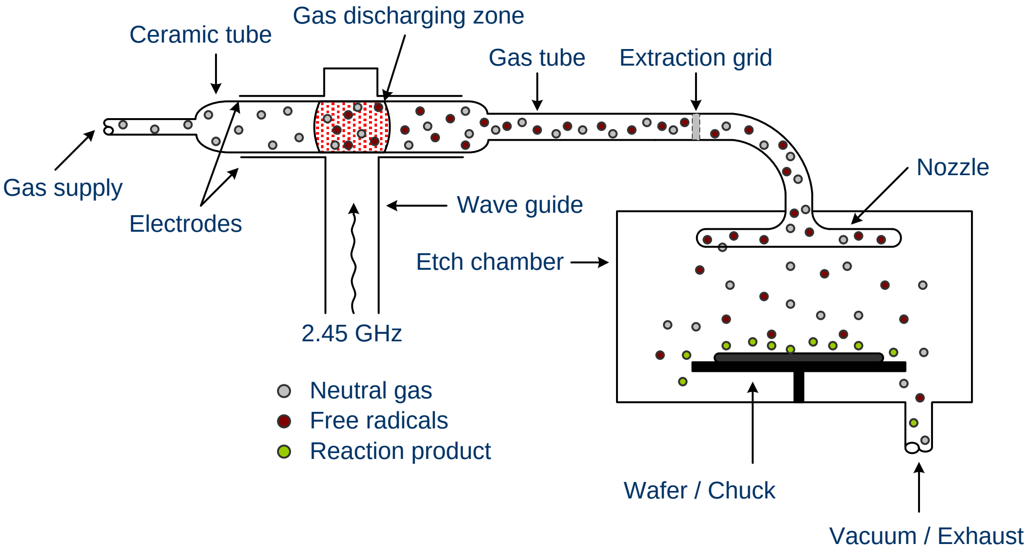
Gas discharging zone
Ceramic tube
Gas tube
Extraction grid
Nozzle
Gas supply
Electrodes
Wave guide
Etch chamber
2.45 GHz
Neutral gas
Free radicals
Reaction product
Wafer / Chuck
Vacuum / Exhaust

Fig. 1.2: Illustration of a CDE reactor

In the region of the gas discharge there are various particles due to impacts, amongst others there are radicals. Radicals are neutral atoms or molecules with an unsaturated electron which are therefore very reactive. As a neutral gas e.g. tetrafluoromethane CF_4 is led in the gas discharge zone and separated into CF_2 as well as fluorine molecules F_2. Similarly fluorine can be splitted from CF_4 by adding oxygen O_2:

$$2\,CF_4 + O_2 \longrightarrow 2\,COF_2 + 2\,F_2$$

The fluorine molecules can now be splitted into two individual fluorine atoms by energy at the gas discharging zone: each fluorine atom is a fluorine radical, since each atom has seven valence electrons and wants to achieve the noble gas configuration.

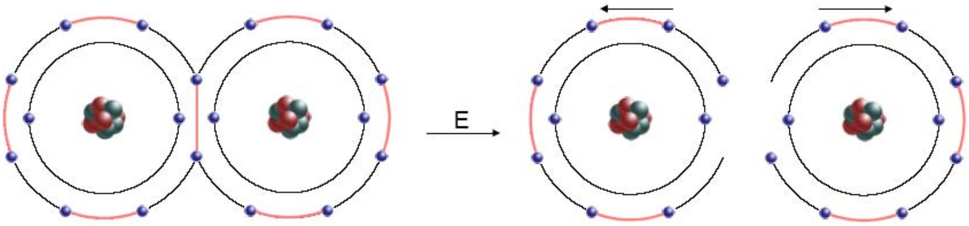

Fig. 1.3: Generation process of radicals

Besides neutral radicals there are several, in part charged particles (CF_4^+, CF_3^+, CF_2^+, ...). All the particles, radicals etc. are then led through a ceramics pipe into the etching chamber. Charged particles can be hold off from the etching chamber by an extraction grating or are recombining on their way to form neutral molecules. Also the fluorine radicals are partial recombining, but there are enough to reach the etching chamber which can react at the wafer surface and cause a chemical abrasion. Other neutral particles are not part of the etching process and are exhausted as well as the reaction products.

Examples for films that can be etched in plasma etching:

- **Silicon:** $Si + 4\,F \longrightarrow SiF_4$
- **Siliconn dioxide:** $SiO_2 + 4\,F \longrightarrow SiF_4 + O_2$
- **Silicon nitride:** $Si_3N_4 + 12\,F \longrightarrow 3\,SiF_4 + 2\,N_2$

1.2.3 Reactive Ion Etching

The etching characteristic - selectivity, etch profile, etch rate, uniformity, reproducability - can be controlled very precisely in the reactive ion etching (RIE). An isotropic etch profile is possible as well as an anisotropic. Therefore the RIE process, a chemical physical etch process, is the most important process in semiconductor manufacturing for structuring various films.

Inside the process chamber the wafer is placed on a high frequency electrode (HF electrode). By impact ionization a plasma is generated in which free electrons as well as positively charged ions occur. If the HF electrode is at a positive voltage the free electrons accumulate on it and cannot leave the elctrode again because of their electron affinity. Thus the electrode charges up to -1000 V (BIAS voltage). The slow ions which could not follow the fast alternating field are now moving towards the negatively charged electrode.

If the mean free path of the ions is high, the particles impact on the wafer surface in almost perpendicular direction. Thus material is striked out of the surface by the accelerated ions (physical etching), in addition some of the particles are reacting chemically with the surface. Lateral sidewalls are not affected, so that there is no abrasion and the etch profile remains anisotropic. The selectiviy is not too small, however, due to the

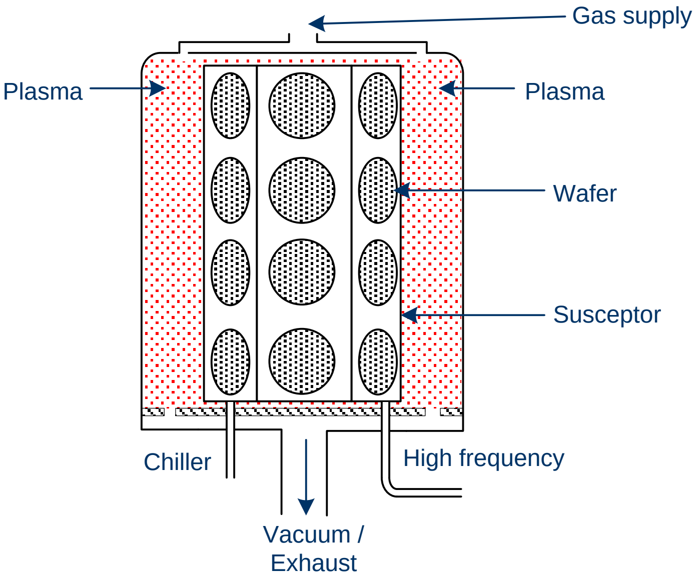

Fig. 1.4: Illustration of a RIE reactor in hexagonal construction

physical etch progress it's not to large either. In addition the wafer surface is damaged by the accelerated ions and has to be cured by thermal annealing.

The chemical part of the etch process is done by the reaction of free redicals with the surface and also with the physical milled out material in such a way that it can not redeposit onto the wafer or the chamber walls as in ion beam etching. By increasing the pressure in the etching chamber the mean free path of the particles is reduced. Therefore there are much more collisions and thus the particles are heading into various directions. This causes a less directed etching, the etch process gets a more chemical character. The selectivity increases, the etch profile is more isotropic.

By a passivation of the sidewalls during silicon etching, an anisotropic etch profile is achieved. Thereby oxygen inside the etch chamber reacts with milled out silicon to form silicon dioxide which deposits an vertical sidewalls. An oxide film on horizontal areas is removed due to the ion bombardement so that the etch progress in lateral direction proceeds.

The etch rate depends on the pressure, the power of the HF generator, the process gases, the real gas flow and on the wafer temperature.

The anisotropism increases with increasing HF power, deacresing pressure and decreasing temperature. The uniformity of the etch process depends on the gases, the

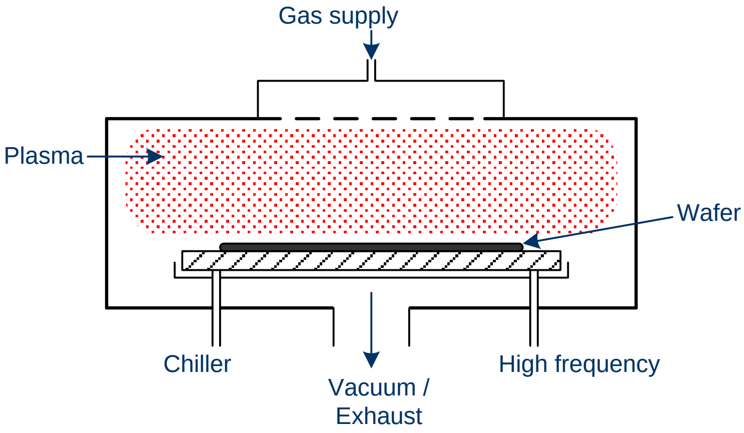
Gas supply
Plasma
Wafer
Chiller
Vacuum / Exhaust
High frequency

Fig. 1.5: Illustration of a RIE reactor

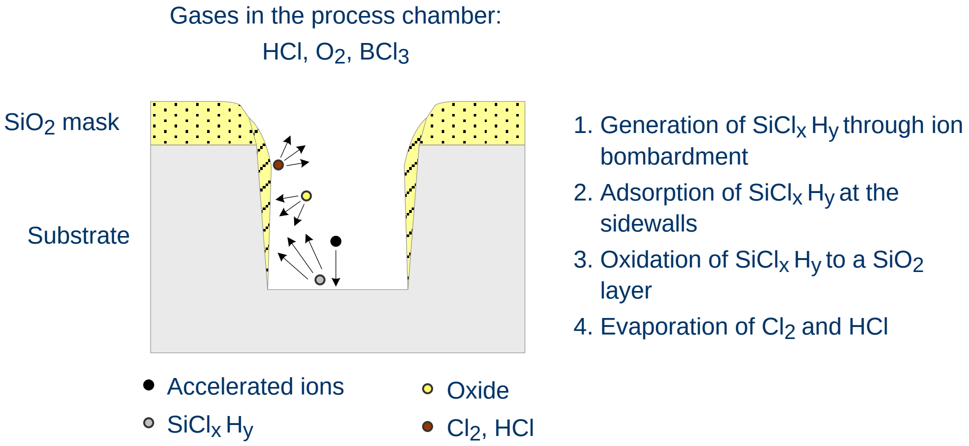
Gases in the process chamber:
HCl, O2, BCl3
SiO2 mask
Substrate
1. Generation of SiClx Hy through ion bombardment
2. Adsorption of SiClx Hy at the sidewalls
3. Oxidation of SiClx Hy to a SiO2 layer
4. Evaporation of Cl2 and HCl
Accelerated ions
SiClx Hy
Oxide
Cl2, HCl

Fig. 1.6: Sidewall passivation during RIE etching

distance of the two electrodes and on the material the electrodes are made off. If the distance is to small, the plasma cannot be dispersed unfiformly and thus leads to inhomogeneity. If the distance of the electrodes is increased, the etch rate decreases because the plasma is distributed in an enlarged volume. For the electrodes carbon has proven itself as the material of choice. Since fluorine and chlorine gases attack carbon as well, the electrode causes an uniform strained plasma and thus the wafer edge is affected in the same way as the wafer center.

The selectivity and etch rate depend very strong on the process gases. For silicon and silicon compounds fluorine and chlorine gases are used primarily.

An etch process is not limited to one gas, a mixture of gases or to fixed process pa-

Tab. 1.1: Overview of process gasses used in dry etch processes

Material	**Process gasses**	**Annotation**
SiO_2, Si_3N_4	CF_4, O_2	F etches Si, O_2 removes carbon (C)
	CHF_3, O_2	CHF_3 acts as polymere, enhanced selectivity on Si
	CHF_3, CF_4	
	CH_3F	enhanced selectivity of Si_2N_4 on SiO_2
	C_2F_6 / SF_6	
	C_3F_8	enhanced etch rate compared to CF_4
Poly-Si	BCl_3, Cl_2	no contamination with (C)
	$SiCl_4$, Cl_2	
	HCl, O_2	
	$SiCl_4$, HCl	
	O_2 / $SiCl_4$, HCl	
	HBr / CL_2 / O_2	enhanced selectivity on Fotolack and SiO_2
	SF_6	high etch rate, fair selectivity on SiO_2
	NF_3	high etch rate, isotropic
	HBr, CL_2	
monokrist.	HBr, NF_3, O_2 / CF_3Br	enhanced selectivity on SiO_2
Silicium	BCl3, CL2 / HBr, NF3	
Aluminium-	Cl_2	isotropic etch process
Legierungen	BCl_3	low etch rate
	BCl_3 / CL_2 / CF_4	anisotropic etch process
	BCl_3 / CL_2 / CHF_3	enhanced sidewall passivation
	BCl_3 / Cl_2 / N_2	enhanced aetch rate, no contamination with

rameters. For example native oxide on polysilicon can be removed at first with a high etch rate and low selectivity, while the polysilicon is etched subsequent with a higher selectivity against the layer beneath.