Semiconductor Technology from A to Z

Dry Etching

Overview

General

In wet chemical etching, layers are generally removed isotropically, yet an anisotropic etch profile is particularly important for small structures. Dry etch processes are well suited for this, offering sufficient selectivity. These processes enable reproducible, uniform etching of most layers used in semiconductor manufacturing. Besides anisotropic etch profiles, isotropic ones can also be achieved. Despite the high equipment costs and sequential single-wafer processing, dry etching has established itself over wet chemical etching.

Key parameters in dry etching

Dry etch processes are described by a small number of key parameters, which are also the target parameters of every process development effort.

Etch rate r

> The etch rate describes the material removed per unit time and is expressed, for example, in nanometers per minute or Ångström per second.

$$r=\frac{Etch\ removal\ \Delta z}{Etch\ time\ \Delta t}$$

Anisotropy factor f

> The anisotropy factor describes the ratio of the horizontal etch rate r_h to the vertical etch rate r_v.

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

For pattern transfer, strongly anisotropic processes are desired, i.e. etching only in the vertical direction, so that the resist mask is not undercut. For anisotropic etch processes, $f \rightarrow 1$, and correspondingly, for isotropic processes, $f \rightarrow 0$.

Selectivity S_{jk}

> The selectivity S_{jk} between material j and material k describes the ratio of the etch rates of two materials, e.g. of the layer to be patterned (j) and the resist mask (k).

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

Whether a high or a low selectivity is desired depends on the particular process. When patterning layers, the value should be as high as possible, i.e. the layer to be patterned is removed faster than the resist mask. In reflow etchback, the selectivity has to be 1 in order to planarize topographies uniformly.

Uniformity *U*
: Uniformity describes how evenly the material removal occurs – across a single wafer, from wafer to wafer, and from batch to batch. It is expressed as the spread of the etch rate relative to its mean value.

$$U=\frac{r_{max}-r_{min}}{r_{max}+r_{min}}\cdot 100\,\%$$

Aspect ratio *A*
: The aspect ratio is the ratio of etch depth z to feature width b. It describes how slender a trench or hole is.

$$A=\frac{z}{b}$$

As the aspect ratio increases, the etch rate decreases, because the etch species have more difficulty reaching the bottom of the structure and the reaction products are less readily transported away. This effect is known as aspect ratio dependent etching (ARDE), or RIE lag. Today it is the decisive limitation when etching deep structures, such as the memory holes in 3D NAND flash, which have aspect ratios exceeding 50:1. Typical profile defects in such etches include bowing (bulging widening in the upper region), twisting (deep holes tilting relative to one another), and microtrenching (excessive removal at the bottom corners).

Loading effect
: The etch rate depends on the total exposed area: a large area to be etched consumes more reactive species, so the etch rate decreases. Macro-loading affects the entire wafer or batch, while micro-loading affects the immediate vicinity of a single structure.

Since the etch rate depends on the state of the equipment, the gas flow, and the loading, an etch process in manufacturing is not controlled by a fixed time, but by endpoint detection. For this purpose, a spectrometer monitors the optical emission of the plasma (optical emission spectroscopy, OES) – when a layer is etched through, the intensity of characteristic lines changes because different reaction products are formed – or an interferometer measures the remaining layer thickness. Once the endpoint has been detected, a short, defined overetch time follows to reliably remove residues across the entire wafer.

Dry etch processes

In dry etch processes, gases are excited by high-frequency alternating fields, typically at 13.56 MHz and 2.45 GHz. At a pressure between 0.1 Pa and 100 Pa, the mean free path of the particles is a few millimeters to centimeters.

Modern tools separate the generation of the plasma from the acceleration of the ions: a high-frequency generator (e.g. 13.56 MHz or 60 MHz, coupled in inductively or via microwaves) sets the charge carrier density and thus the etch rate, while a second, low-frequency generator (e.g. 400 kHz to 2 MHz) at the wafer electrode sets the ion energy and thus the physical component of the etch. This allows both quantities to be adjusted largely independently of one another. In addition, the plasma is frequently pulsed to reduce charge buildup and profile defects in deep structures.

There are generally three different types of dry etching, which are described in more detail on the following page:

- Physical dry etching: physical removal of the wafer surface by accelerated particles
- Chemical dry etching: reaction between gas and the wafer surface
- Chemical-physical dry etching: physical etching with a chemical component

A more recent development is atomic layer etching (ALE). Here, the chemical activation of the surface and the actual removal step are separated in time and repeated cyclically, so that only one or a few atomic layers are removed per cycle. The amount removed is thus controlled not by the etch time but by the number of cycles – a prerequisite for devices whose layer thicknesses are only a few nanometers, such as gate-all-around transistors.