located, whereas on ion-beam techniques the plasma is generated apart, where ions are obtained and directed towards the substrate. On ion-beam etching system (in which are included sputter/ion etching and ion-beam milling) the etch is basically due to a physical effect, namely momentum transfer between energetic ions and the substrate surface, that provides which vertical etch but with poor selectivity. A chemical reaction takes place in all other dry etching methods. In the physical/chemical case, impacting ions, electrons or photons induce chemical reactions that starts the etching process, obtaining directional etching and with good selectivity.

When selecting a dry etching process, the desired shape of the etch profile and the selectivity require careful consideration. In fig. 3.14, different possible etch profiles able to be obtained by dry etching are presented. Depending on the etching mechanism, isotropic, directional, or vertical etch profiles can be obtained. The difference between wet and dry processes is that these profiles can be generated in single crystalline as well as in polycrystalline and amorphous materials. The etching anisotropy is not a result of the single crystals anisotropy, as it was in the case of wet etching, but of the plasma conditions.

Between all possible dry etching systems, the most broadly used is the Reactive Ion Etching (RIE). It is based on a physical/chemical reaction that allows obtaining directional etching with high selectivity while providing very precise pattern transfer. The most significant features of this system can be seen in table 3.9

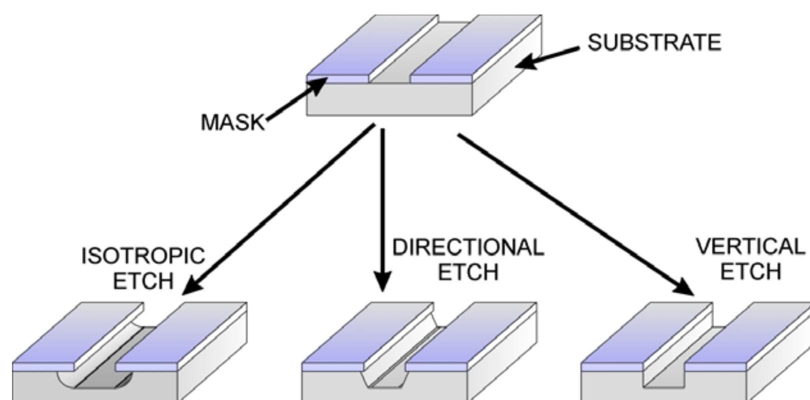
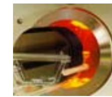


Fig. 3.14. Directionality of etching processes.



RIE (Reactive Ion Etching)

Temp. (ºC)	Pressure (Pa)	Reactor properties	Working regime	Advantages	Disadvantages
Room	0.1-100	Frequency: 13.56Mhz. Ion energy: >100eV. Chlorinated or Fluorinated gases.	Physical and chemical etching.	Directional etching. High selectivity and uniformity. High etching rates. Etch semiconductors, dielectrics and metals.	High ion damage. Complex.

Table 3.9: Standard configuration and general properties of a RIE system.

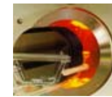
At low pressures, in the 0.1 to 0.01-Pa range, obtaining anisotropic etching with RIE is relatively easy, but achieving selectivity is difficult. On the contrary, at high pressures (100Pa) in plasma etching, chemical effects dominate, leading to a better selectivity but obtaining isotropic patterns. Thence, a compromise between both pressures must be reached.

The operation principle of a RIE system is the same of a PECVD. The single difference between them is the reverse in the polarity of the electrodes. A radio-frequency voltage is applied between the two electrodes causing the free electrons to oscillate and to impact with enough energy with gas precursor molecules so as to ionize them, leading to sustainable plasma. However, neutral species greatly outnumber the electrons and ions; the degree of ionization has a typical value around 10^{-4}-10^{-7}ion/cc for parallel plate gas discharges.

The more general mechanism consists on three different steps for ion-assisted etching. Firstly, ion bombardment induces a reaction by making the surface more

reactive for the neutral plasma species, mostly by creating surface damage. Secondly, ions clear the surface of by-products, allowing etching with reactive neutrals to proceed on the cleared areas. Finally, the energy required for the neutral species to have surface reaction is also supplied by the ion bombardment. Normally, their radicals are quickly absorbed at the surface and their reaction has very low activation energy.

The etching properties of the RIE system will strongly depend on the etching conditions, being the most important the following: **Discharge power:** An increase in the power discharge implies an increase of the electrons average energy and in electron density. This causes an increase of the ionic species in the gas, enhancing the surface ionic bombardment and allowing obtaining a more directional etching at a higher speed but with lower selectivity. **Temperature:** The increase of the temperature only affects to the surface reaction of the neutral species, increasing the rate of chemical interaction, being the process more isotropic and selective. **Total pressure:** If the total pressure is reduced, the mean free path increases, causing the electrons to be more energetic and causing a higher ionization which, in turn, provides a higher anisotropy although selectivity decreases, since the physical etching prevails. **Material of the cathode:** If the cathode is made of light metals (Al, Cu), it causes re-deposition of the metal particles, due to partial etching of the cathode during ion bombardment. In this case, cathode should be covered with a quartz plate, used as a substrate-holder, avoiding metallic contamination, but reducing the etching rate since the reactive species also react with the plate. Moreover, the oxygen released by quartz etching modifies the gaseous phase, affecting the final result. **Inert gases addition**: The dilution of the etching mixture with a noble gas increases the mean energy of the electrons, leading to a more anisotropic etching but at a lower rate due to a more diluted precursors. **Precursors:** Predominance of a certain mechanism and morphology also depends on the gas or gas mixture used for the etching. As an example, the most commonly used gas in the etching of silicon compounds by plasma are fluorocarbons; specially carbon tetrafluoride (CF_4). These gases are not easily absorbed at the surfaces, but their radicals, in the form C_x F_y and F, are. As a product of this reaction, volatile compounds are obtained (SiF_4 for silicon etching, SiF_4+ CO_2 for silicon oxide and SiF_4+ NF_3 for



silicon nitride). A problem inherently associated to these compounds is the production of polymers due to the ionization of the fluorocarbon products, which are deposited on the surface and are non-etched by the radicals, causing the etching to stop. This problem can be overcame using CF_4/O_2 mixtures or pure SF_6 as precursors. The latter provides several advantages as compared to the fluorocarbons: low surface contamination and high etching rate with good selectivity, although it also has drawbacks, mainly its over-etching and low anisotropy due to chemical mechanism prevail.

If all the previous parameters are optimized, it is possible to obtain accurate morphologies for silicon and silicon oxide layers. Figure 3.15 shows the definition of an accelerometer bridge by RIE. As can be seen, walls obtained are nearly vertical. In this case, however, selectivity was not essential, since accelerometers were fabricated using 450µm BESOI (Bond and Etch back Silicon On Insulator), which basically consists on a 2µm thermal silicon oxide layer buried 15µm deep from the silicon surface. Bridges were defined on the first 15µm of silicon and silicon oxide was wet etched to free the accelerometer.

Another interesting case can be observed in figure 3.16, where dry etching of plasma silicon oxide can be observed. Here, process parameters have been optimized so as to enhance selectivity while keeping a reasonable anisotropy value. As can be seen, walls are not completely vertical, but have a certain tilt. The effect of this non-verticality over the overall guiding properties will be studied in the following chapter. It can also be observed the trenching effect on the core edges due to forward ion reflection during the dry etching process.

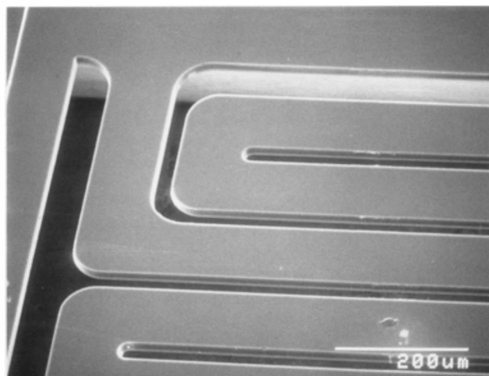


Fig 3.15 Silicon bridges from an optical accelerometer obtained by RIE dry etching. Whole structure was free using wet chemical etching.

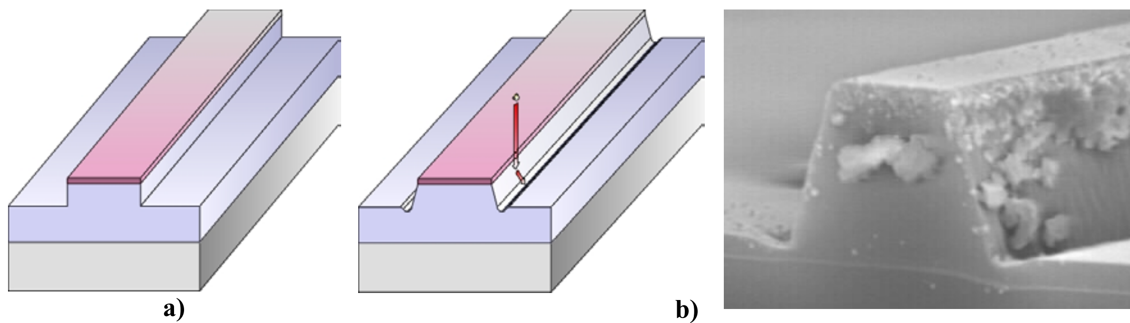


Fig 3.16 Rib etching on a silicon oxide waveguide a) ideal transference pattern, b) real transference pattern, where directional etching and trenching due to forward ion reflection is observed.

Summing up, dry etching offers several advantages as compared to wet etching, which are summarized in table 3.10. Still both techniques are extremely useful and complementary in some fields. Where high selectivity is required and anisotropy is not required, wet etching is preferable. If the contrary is a requirement, dry etching should be used.

Parameter	**Dry Etching**	**Wet etching**
Directionality	High with most materials	Only with crystal materials
Production-line automation	Good	Poor
Environmental impact	Low	High
Masking film adherence	Not as critical	Very critical
Cost chemical	Low	High
Selectivity	Moderate	High
Etchable materials	Not all (Not e.g., Fe, Ni)	All
Radiation damage	Can be High	None
Process scale-up	Difficult	Easy
Cleanliness	Good with adequate conditions	Very good
Critical dimension control	Very good (<0.1µm)	Poor (>2µm)
Equipment cost	Expensive	Cheap
Submicron features	Applicable	Not applicable
Typical etch rate	0.1-6µm/min	~1µm/min
Theory	Very complex	Relatively simple
Operating parameters	Many	Few
Control of etch rate	Good for slow etching	Difficult

Table 3.10. Comparison of dry and wet etching.