MME '95

Micromechanics Europe 1995

Sixth Workshop on Micromachining Micromechanics and Microsystems

Technical Digest

Copenhagen, Denmark

3 - 5 september 1995

A survey on the reactive ion etching of silicon in microtechnology

Henri Jansen, Han Gardeniers, and Jan Fluitman

MESA Research Institute, University of Twente, P.O.Box 217, 7500AE Enschede, The Netherlands
Phone: X-31-53-894438; Fax: X-31-53-309547; E-mail: H.V.Jansen@eltn.utwente.nl

Why plasma etching

Dimensional control in etching small geometry's -necessary for advanced micromachining- is an important topic in microtechnology. To etch these structures, dry plasma assisted etching is increasingly used. Although the basic investments are rather high, it was introduced rapidly due to 1) the achievement of etch directionality without using the crystal orientation, 2) the ability to faithfully transfer lithographically defined photoresist patterns into underlying layers, and 3) cleanliness and compatibility with vacuum-processing technologies.

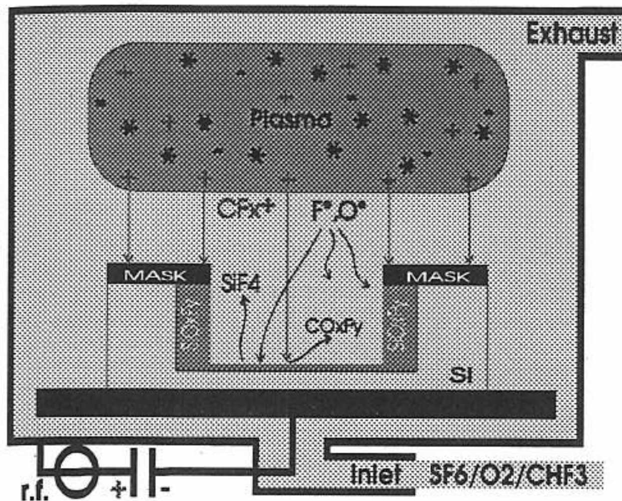
Micromechanics has its foundation in microelectronics and this has resulted in a tendency to use "IC compatible" materials as structural or mask materials. In addition, new methods are adapted a long time after its introduction in microelectronics. Yet, in micromechanics there is no word such as "S&A compatible" therefore, one should have a good reason to use IC compatible materials because they are giving many constraints. Unfortunately, most research dealing with plasma etching is done in IC technology, so it is necessary to start research within the S&A group. Special research topics are: 1) Profile control for deep Si trench etching, 2) high-speed etching when using bulk micromachining, 3) high-speed isotropic etching in sacrificial layer etching, 4) high-speed anisotropic etching for e.g. high aspect ratio combdrives, 5) high-selectivity etch masks for reliable pattern definition, 6) smooth surfaces after etching to avoid stress concentration, 7) plasma deposition of polymers for various applications, and 8) releasing of movable structures.

A large number of reviews on plasma etching have been published [1-12]. However above all, the author is charmed by "reactive ion etching" by Oehrlein and this reference is taken as a framework to treat all different plasma concepts [7]. This article is a brief review of dry etching as applied to pattern transfer, primarily in *silicon technology*. Rapid progress is being made in all aspects of plasma etching; therefore this review focuses on concepts, rather than listing data obtained on all different systems. Although the detailed plasma chemistry of r.f. discharges used for etching materials of interest in micromechanics is different, many of the basic processes are similar so they can be cautiously adapted to different plasma-substrate systems. In short, this article is intended to be a guide to the tremendous plasma jungle and it has tried to give an answer to the question:

"How and where to use what plasma chemistry and to what should I pay attention".

What is plasma etching

The basis of plasma-assisted etching is simple; use a gas glow discharge to dissociate relatively stable molecules forming chemically reactive species and choose the chemistry such that these species react with the solid to be etched to form volatile products. A basic reactive ion etch (RIE) system is illustrated in figure 1 with a list of typical parameters. The following processes take place in RIE [13]: *Generation:* A glow discharge is used to generate from a suitable feed gas (e.g. SF_6 for Si etching) by electron-impact dissociation/ionisation the gas phase etching environment which consists of neutrals, electrons, phonons, photons, radicals (F^*), and positive (SF_5^+) and negative (F^-) ions. *D.c. bias formation:* The Si wafer is placed on an r.f. driven capacitatively coupled electrode. Since the electron mobility is much greater than the ion mobility, after ignition of the plasma the electrode acquires a negative charge i.e. the d.c. self-bias voltage. *Diffusion/forced convection:* The transport of reactive intermediates from the bulk of the plasma to the Si surface occurs by diffusion. Positive ions from the glow region are forced to the substrate surface by way of the d.c. self-bias and will assist the etching. *Adsorption:* Reactive radicals adsorb on the Si surface. This step can be strongly enhanced by concurrent ion bombardment which serves to produce "active sites" since it aids in the removal of e.g. the SiF_x layer which otherwise passivates the Si surface. *Reaction:* A reaction between the adsorbed species and the Si must take place. In the case of fluorine-based etching of Si, chemical reactions between the F-atoms and the surface produces -spontaneously- either volatile species, SiF_4, or their precursors, SiF_x ($x<4$). However, in Cl-based etching Cl-atoms are known to adsorb readily on Si surfaces but the spontaneous etch rate is very slow. Ion bombardment makes it possible for adsorbed Cl-atoms to attack the backbones of Si more efficiently and form a volatile $SiCl_4$ molecule. This mechanism is called ion-induced RIE. *Desorption:* The desorption of the reaction product into the gas phase requires that the reaction product is volatile, thus it should have a high vapour pressure at the substrate temperature. Additionally, there should be no deposited blocking film at the surface. The removal of these films can be greatly accelerated by ion bombardment via sputtering. This mechanism is known as ion-inhibitor RIE. *Exhaust:* The desorbed species diffuse from the etching surface into the bulk of the plasma and should be pumped out, otherwise plasma induced dissociation of product molecules will occur and redeposition can take place.



Quantity	Typical value	
r.f. power density	0.05-1.0	Wcm^{-2}
r.f. frequency	0.01-27	MHz
pressure	1-30	Pa
gas flow	1-200	sccm
wafer temperature	100-1000	^oK
gas temperature	300-600	^oK
ion energy	bulk: 0.05	eV
	sheath: 10-1000	eV
electron energy	3-30	eV
gas number density	10^{14}-10^{16}	cm^{-3}
ion density	10^{9}-10^{10}	cm^{-3}
electron density	10^{9}-10^{10}	cm^{-3}
neutral flux	10^{18}-10^{20}	$cm^{-2}s^{-1}$
radical flux	10^{16}	$cm^{-2}s^{-1}$
ion flux	10^{14}-10^{15}	$cm^{-2}s^{-1}$

Figure 1: Basic RIE system and characteristics.
1 eV~8000 ^oK, 1 Pa~7.5 mTorr.

Plasma system configurations

Plasma etching can be divided into single wafer- and batch reactors. It is also common to differentiate between the three main groups (fig.2); 1) the *chemical* plasma etching (PE), 2) the *synergetic* reactive ion etching (RIE), and 3) the *physical* ion beam etching (IBE). Generally, IBE shows only positively tapered profiles, low selectivity and -etch rates, whereas PE gives rise to isotropic profiles, high etch rates and -selectivity. RIE enables the achievement of profile control due to the synergetic combination of physical sputtering with chemical activity of reactive species with high etch rate and -selectivity.

Single wafer vs. batch reactors: Batch reactors generally have lower etch rates and work at lower pressure- and power-density than single wafer reactors, therefore high throughput is achieved with large batch sizes. However, increases in wafer size and the demand for improved process control, such as individual end point detection, have made single wafer etching reactors more desirable for many etching applications. In order to achieve adequate throughput, high etch rates are required. Since the arrival rate of reactive species at the wafer surface controls the etch rate, a high reactive species generation is a prerequisite (e.g. by way of a high density plasma or a high gas pressure).

Plasma etching: Typical reactor types for PE include the barrel- and downstream etchers in which the plasma is excitated using microwaves. They are characterised by minimal ion bombardment and purely chemical etching. Such systems are often used for photoresist stripping and other applications where high selectivity and low radiation damage are key requirements and the isotropic nature of the etch is not a problem or even an advantage e.g. in surface micromachining, a buried layer can be removed by way of an isotropic etch. Sometimes symmetrical parallel plate reactors are used in PE. Because of the equal area of both electrodes there is no bias created between the two electrodes. When the pressure in the reactor is high (say 1 Torr) then the plasma potential and bombardment of ions will be low. Sometimes, it is more convenient to use an asymmetrical system, in which the r.f. powered electrode (where the wafers are situated) is large relative to the grounded surface area. In these cases the plasma potential will be high with respect to the grounded electrode, but will almost equal the target electrode potential. Hence, no highly energetic ion bombardment will occur at the substrates. Unfortunately, the wafer can easily be contaminated by material sputtered off the grounded counter electrode.

Reactive ion etching: In applications where ion bombardment is required, parallel plate reactors can be employed. In symmetrical low pressure systems, the plasma potential is high and both electrodes are bombarded by energetic ions. Due to the zero bias, this type of etchers is often confused with real PE (i.e. no bombardment). More commonly -in asymmetrical systems- the r.f. powered electrode is small relative to the grounded surface area. These systems are characterised by a low plasma potential (10-50 Volt) and a large bias on the r.f. driven electrode (10-1000 Volt). Because of the low plasma potential relatively little sputter contamination from the grounded surface occurs. In RIE it is difficult to control independently the temperature and fluxes of species. This is one of the reasons for the lack of consistence in the reports concerning the F-based RIE of Si. Nevertheless, RIE is the most important plasma technique.

The most popular types of RIE reactors are: 1) *Diode-reactors* with horizontal target platen for single wafer processing (fig.1), 2) *hexodes* designed for batch processing in which the cathode has the shape of a hexagon surrounded by the cylindrical chamber walls forming the anode, and 3) *triodes* used for increased ion bombardment: Most industrial RIE reactors use 13.56 MHz r.f. power which is higher than the ion plasma frequency. Consequently, ions can not follow the applied field and respond only to the time average cathode voltage. At a frequency of 100 kHz ions can follow the field and will bombard the cathode. In triodes, a 13.56 MHz is supplied to an annular electrode surrounding the chamber to produce reactive ions and a 100 kHz source is supplied to the cathode to maximise bombardment.

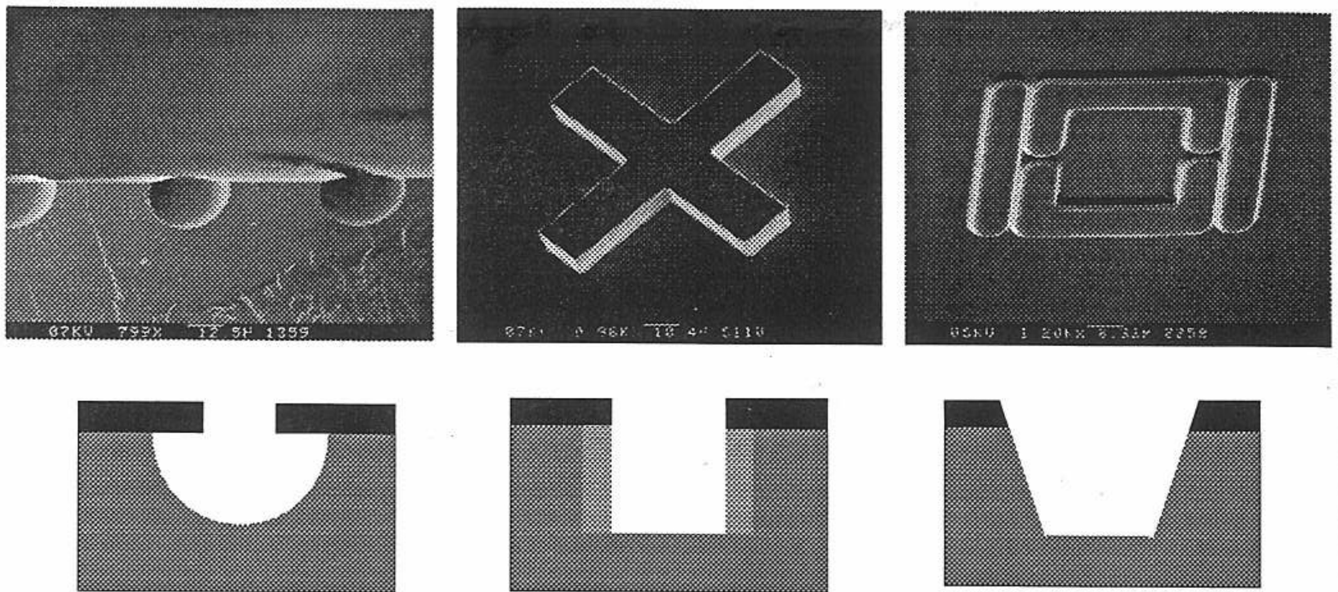


Figure 2: The three basic mechanisms of dry etching; chemical PE (left), synergetic RIE (mid), and physical IBE (right).

Ion beam etching: It is often hardly possible to etch a specific substrate material because there is no chemical etchant available. In these cases the patterning is fulfilled by sputtering the layer with a directed energetic flux. Redeposition is minimised by etching at low pressure (<1 mTorr). Because it is difficult to start at such low pressure a plasma, it is created in a remote small, higher pressure, chamber (Kaufmann-source). The inert (IBE) or reactive (RIBE) ions are extracted from this plasma with electrostatically controlled grids and directed to the substrate to be etched. Because physical etching is a slow process -typically 1-30 nm/min-, sometimes an extra reactive feed gas is led into the reactor. Such processes are known as chemical assisted (reactive) ion beam etching (CAIBE, CARIBE). In RIBE -and more in particular CAIBE- it is possible to manipulate important parameters in plasma-assisted etching e.g. temperature, electron- or photon-impact. For this reason, basic studies of the surface science aspects of plasma etching were initiated using CAIBE in the beginnings of the eighties in laboratories all over the world.

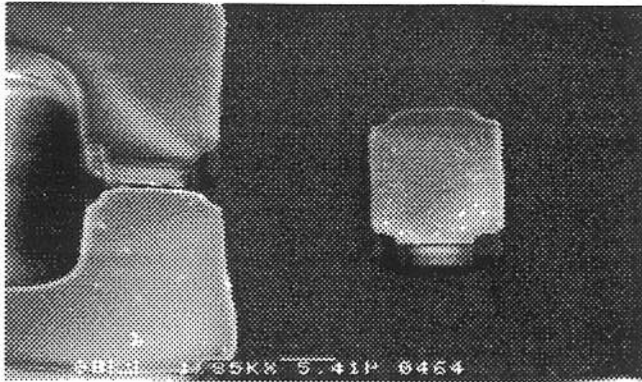
Etch directionality in RIE

Etch directionality is due to directed energy input into an etching reaction at a surface and can be accomplished by neutral, ion (i.e. RIE), electron, or photon bombardment of a surface exposed to a chemical etchant. An important clarifying experiment performed by Coburn and Winters was the exposure of a Si surface to a well-defined dosage of chemical etchants, XeF_2, and energetic ions, argon [9]. They found that the etch rate obtained for a Si surface exposed to both particle fluxes simultaneously is much greater than the sum of the etch rates for exposure to the ion beam and chemical etchant separately.

Ion-enhanced or ion-assisted etching can bedivided in two main groups; ion-induced (reaction controlled etching) and ion-inhibitor (desorption controlled etching) RIE.

Ion-induced RIE: This technique is used when the substrate is not etched spontaneously such as in the Cl_2/Si or O_2/polymer system. Ions do modify the surface reactions in one or another way (e.g. chemical sputtering, chemically enhanced physical sputtering, or lattice damage [7]) and make it possible for radicals to react with the substrate (see fig.3 left).

Ion-inhibitor RIE: (fig.3 right) In this technique the substrate is etched spontaneously and therefore an inhibiting layer is needed to achieve directionality. Sidewalls of trenches are not exposed to ion bombardment and will be covered by the film. However, the bottom of the trench is exposed to ion bombardment thus free from this deposit and etching can proceed. The passivating layer can be grown by [15]: a) Inserting gases which act as a Si oxidant forming siliconoxyhalogens, b) inserting gases which act as polymer precursors forming carbonhalogens [14], c) freezing the normally volatile reaction products of Si with radicals at the trench walls such as siliconhalogens, or d) erosion and redeposition of mask material such as metalhalogens. The deposition of a polymeric carbonhalogen film has the disadvantage that this film is thermally less stable than an inorganic siliconoxyhalogen film. The freezing of reaction products uses expensive cryogenic coolers and the redeposition of mask material is not acceptable because areas which should stay clean are also contaminated. Because the passivating film is very thin the incoming ions should not be highly energetic, so the mask/Si selectivity will be very high and the substrate damage will be low. Also, because of the low energy of the ions, trenching and faceting (typical IBE problems) are not found and it is very easy to change the direction of the impinging ions thus changing the etched profile [15].



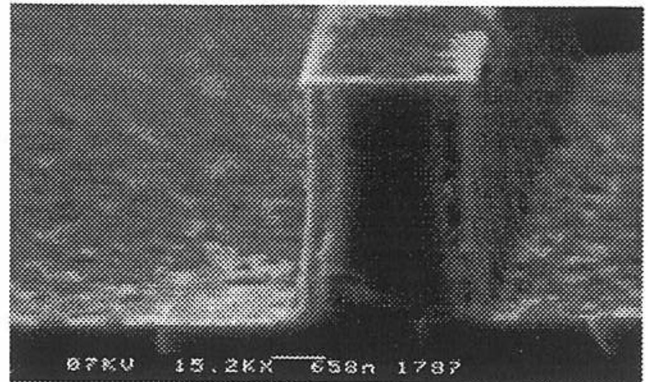


Figure 3: The two types of RIE etching. Left; ion-induced polymer etching. Right; ion-inhibitor Si etching with C_xF_y film at the beam-sidewalls.

Pure plasma chemistries

Because of their high etch rates, normally hydrogen- and halogen-based (i.e. F, Cl, and Br) plasmas are used for the RIE of Si and the etch products are volatile SiH_4, SiF_4, $SiCl_4$, and $SiBr_4$ respectively (table 1). Whereas F-based plasmas are generally used for isotropic etching, Cl- and Br-based plasmas such as Cl_2 are primarily used to achieve anisotropic etch profiles. Except for F-based mixes, these gases are particularly hazardous (Br_2 or Cl compounds) and special precautions are recommended.

Hydrogen-based: There has been extensive surface science activity in the H-Si system, most of which has been directed towards developing an understanding of the surface structure resulting from an exposure of single-crystal silicon to H-atoms. Because of the small size of the H-atom ion-induced RIE might be impossible (see "Chlorine-based").

Fluorine-based: Mogab studied the etching of Si in a CF_4 plasma and found a linear relation between the etch rate and F-atom density showing that F-atoms are directly involved in the etching process [17]. Etching of Si in F-based plasmas e.g. SF_6, CF_4, SiF_4, NF_3, XeF_2 or F_2 normally results in a large undercut of the mask. However, Tachi and his co-workers showed that the horizontal Si etch rate using an SF_6 plasma can be reduced dramatically by cooling the substrate to -120°C and near-ideal etch profiles can be obtained [18]. If anisotropy is due to an inhibiting Si_xF_y layer, the same effect should occur for the other gasses. Ion-assisted etching -dominating at the bottom of the trench- was not affected by the low substrate temperature although the vertical Si etch rate increased as the temperature was decreased, possibly due to condensation of etchant.

Chlorine-based: Etch directionality for Cl-based plasmas (Cl_2 or $SiCl_4$) may be explained by the observation that Si and SiO_2 are not etched spontaneously at room temperature by Cl-atoms making only ion-induced etching possible [19]. Cl-atoms chemisorb on Si and form an ordered Cl monolayer. In contrast to the Si_xF_y layer in F-based etching, this layer is barely influenced by temperature and will "inhibit" etching almost completely. Cluster calculations have shown that Cl-atoms on a Si-surface have to overcome a Van der Waals energy barrier of ~10 eV to attack the backbones of Si surface atoms to form $SiCl_4$ [20]. No energy barrier for F-atoms to the penetration of the Si-surface was found, indicating that sub surface SiF_x species will form spontaneously. The size of the halogen relative to the Si-Si interatomic distance plays an important role.

Bromine-based: Recently, the use of Br chemistry has received considerable interest in RIE process development, because of the low spontaneous etch rate of Si and SiO_2 with Br-atoms (Br-monolayer) [21]. Unfortunately, very little surface science activity has been reported for this system.

Oxygen-based: Oxygen plasmas are mainly used for polymer etching and are important in Si trench etching because they are able to remove polymeric residues afterwards. At elevated temperatures spontaneous etching (ashing) occurs. However, the RIE etching of polymers below the glass temperature is ion-induced thus the film is not removed at the sidewalls of a trench. This principle is used to release movable structures in MEMS applications (see "Multi-step plasma chemistries").

Mixed plasma chemistries

Mixed molecules (e.g. CCl_2F_2) and -gases (e.g. SF_6/Cl_2) containing halogens are often used for anisotropic etching (table 1). If the plasma chemistry is chosen such that etch inhibiting films can form at the sidewalls of a trench, directional etching is possible. By changing the relative atom density e.g. F/Cl in the feed gas, it is possible to vary the trench profile.

Mixed molecules: The strongest halogen-carbon bond is the F-C bond. Thus, electron impact dissociation of mixed halocarbons produces primarily Cl- or Br-atoms and the etch characteristics using these plasmas are Cl- or Br-like. For example, Matsuo used a 30 mTorr $CBrF_3$ plasma to etch Si directionally, whereas a CF_4 plasma using similar conditions resulted in nearly isotropic etching [22]. Directionality is due to an inhibiting Br-monolayer. On March 22nd 1985 in Vienna and September 16th in Montreal there were international commitments to reduce the use of chloro- and bromofluorocarbons in order to protect the ozone layer and to prevent the greenhouse effect. On the "forbidden list" are $CBr_xCl_yF_z$, $CCl_xF_{(4-x)}$, and $C_2Cl_xF_{(8-x)}$ for (x>1).

pure gas	radicals	products	inhibitor	mixed gas	radicals	products	inhibitor
H_2	H	SiH_4	Si_xH_y *	CHF_3	CF_2	HF, (SiF_4)	$Si_xC_yF_z$
CH_4	H, CH_3, CH_2	SiH_4, H_2	$Si_xC_yH_z$	CH_2F_2	CFH, C	HF	$Si_wC_xF_yH_z$
F_2	F	SiF_4	Si_xF_y *	CH_3F	CH_2, CFH	HF, H_2	$Si_wC_xF_yH_z$
NF_3	F, NF_2	SiF_4	$Si_xN_yF_z$ *	CF_4/O_2	CF_3, F, O	SiF_4, F_2, OF, O_2F, COF_2,	$Si_xO_yF_z$
SiF_4	F, SiF_3	SiF_4	Si_xF_y *	CF_4/H_2	CF_3, F, H	" ",HF, CHF_3	$Si_xC_yF_z$
CF_4	F, CF_3	SiF_4	$Si_xC_yF_z$	SF_6/O_2	SF_5, F, O	SiF_4, SOF_4	$Si_xO_yF_z$
SF_6	F, SF_5	SiF_4	$Si_xS_yF_z$ *	SF_6/H_2	SF_5, F, H	SiF_4, HF	$Si_xS_yF_z$ *
S_2F_2	F, S_2F	SiF_4	$Si_xS_yF_z$ *	SF_6/N_2	SF_5, F, N_2	SiF_4	$Si_xS_yF_z$ *
Cl_2	Cl	$SiCl_4$	Cl	SF_6/CHF_3	SF_5, F, CF_2	SiF_4, HF	$Si_xC_yF_z$
Br_2	Br	$SiBr_4$	Br	$CBrF_3$	forbidden	greenhouse	ozone
CBr_4	Br, CBr_3	$SiBr_4$	Br, $Si_xC_yBr_z$	CCl_4	forbidden	greenhouse	ozone

Table 1: Important gases for Si trench etching with their main plasma radicals, products, and inhibitor. *: Only with cryogenic cooling.

The most widely used mixed molecule is CHF3. It dissociates primarily into CF_2 and HF species. The CF_2 intermediates are responsible for polymer formation, C_xF_y, on surfaces (fig.3 and 5).

Mixed gases: A large variety of F-, Cl-, Br-, and O-based plasmas with profusion of gas additives are used in micromachining. In most cases a specific gas mixture or "recipe" is based on a great deal of empirical evidence obtained for a particular application rather than a real basic understanding of the relevant plasma chemistry. However, certain insights have proven to be helpful in formulating gas mixtures as is shown below.

Effect of oxygen addition: The addition of small amounts of O_2 (<5%) to a CF_4 plasma is known to increase dramatically the F-atom density, thus etch rate, in the discharge [23]. The CF_4/O_2 dissociates primarily in CF_3*-, F*-, O*-, and, in minority, CF_2**-radicals. The increase in F-atoms is due to reactions of O_2 with CF_x radicals forming CO_2 and COF_2, and CF_4 with O-atoms forming COF_2. This effect reduces also the recombination of F-atoms with CF_3* again increasing the F-atom density, although this effect is probably less important because the chance for two radicals to collide is rather small (Note that in a plasma there is no thermodynamic equilibrium). The consumption of unsaturated CF_x species by oxygen has the additional effect of suppressing polymer formation. At higher O_2 content (>7.5%) a passivating inorganic $Si_xO_yF_z$ film is formed on the Si surface and the etch rate is controlled primarily by the thickness of this layer rather than the F-atom density which increases up to ca. 15% O_2 addition. Too much O_2 will decrease the F-atom density due to dilution.

In summary, the Si surface changes from primarily Si-C to Si-F to Si-O bonding as the O_2 percentage is increased.

The effect of the addition of O_2 to an SF_6 plasma is practically the same as its addition to a CF_4 plasma. The mix primarily dissociates in SF_5* (little SF_4**), F*, and O*-radicals and the higher F-atom density is due to the reaction of O_2 with SF_x* forming SO_2 and SOF_4, and SF_6 with O* forming SOF_4. The vertical etch rate first increases because of the higher F-atom density and subsequently decreases due to a growing $Si_xO_yF_z$ film and F-atom dilution. A big difference is that there is no formation of a passivating S_xF_y film due to its high volatility at room temperature in contrast to the C_xF_y film in the CF_4 chemistry. In figure 4 SEM images of Si trenches using various percentages of O_2 are displayed. The horizontal etching is depending on the thickness of the passivating $Si_xO_yF_z$ layer and the F-atom density trying to etch the Si by penetrating this layer. The thickness of the $Si_xO_yF_z$ layer is a function of e.g. the O-atom density, the ion impact, and the local temperature. The F-atom density is a function of e.g. the SF_6 flow, power, and (micro)loading.

Adding O_2 to mixed halocarbon gases will increase the halogen-atom density also. For example, a $CBrF_3/O_2$ mixture will produce CF_3* (CF_2**), Br*, and O*-radicals. Subsequently, the reaction of $CBrF_3$ with O-atoms will form COF_2. Additionally, O_2 reacts with CFx* into COF_2 and CO_2. Both processes increase the Br- and F-atom density. The extra F-atoms are responsible for an increase in lateral etching. So, it will change the trench profile and may prevent the forming of grass (see "Roughness").

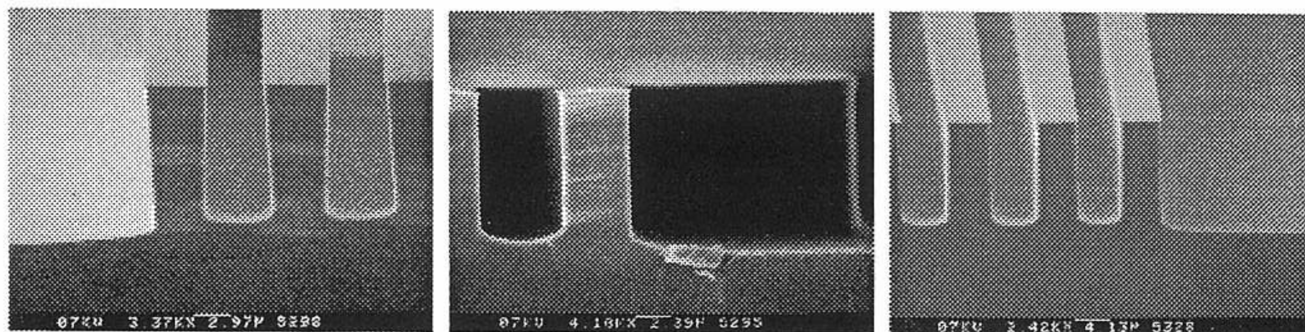


Figure 4: The effect of oxygen addition in an SF_6/O_2 plasma. Left=20%, Mid=25%, Right=30%.

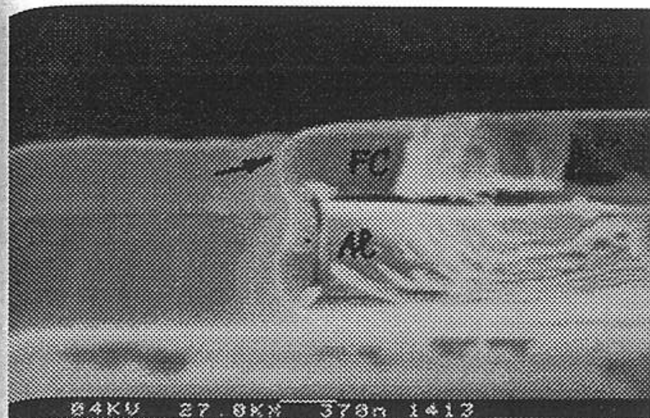


Figure 5: The effect of hydrogen addition; CHF_3 plasma ($\sim CF_4/H_2$).

Effect of hydrogen addition: The effect of small amounts of H_2 to CF_4 plasmas (CF_3*, F*, and H*) is twofold. 1) H_2 reduces the F-atom density because of -relatively inert- HF formation and the Si etch rate is consequently reduced. 2) More importantly, H_2 reacts with CF_3* forming polymeric precursors, such as CF***. As a result, a C_xF_y film will form on surfaces where ion bombardment fails such as the trench sidewalls (fig.3 right). If the H_2 concentration is high (>30%) polymerisation occurs on all surfaces and etching stops. Figure 5 shows a typical example of a deposited C_xF_y film covering an Al beam. At even higher H_2 content, the plasma becomes H-based and again etching is observed. As a useful indicator of the predominance of etching (F*) over deposition (CF_x*) the F/C ratio of the discharge is often used [24]. The F/C ratio is 4 for CF_4, 3 for C_2F_6, etc.. The ratio is lowered when extra Si which consumes F-atoms is added or when CF_4 is mixed with H_2 or CH_4. The changeover from deposition to etching is stimulated by ion bombardment. For a Si substrate, deposition is observed for small F/C ratios (<2). However, it is known that H-based plasmas (e.g. H_2) are etching Si and, identically, C_xH_y film formation might occur. The model is not accounting for this and should be modified with e.g. the HF/C(H+F) ratio.

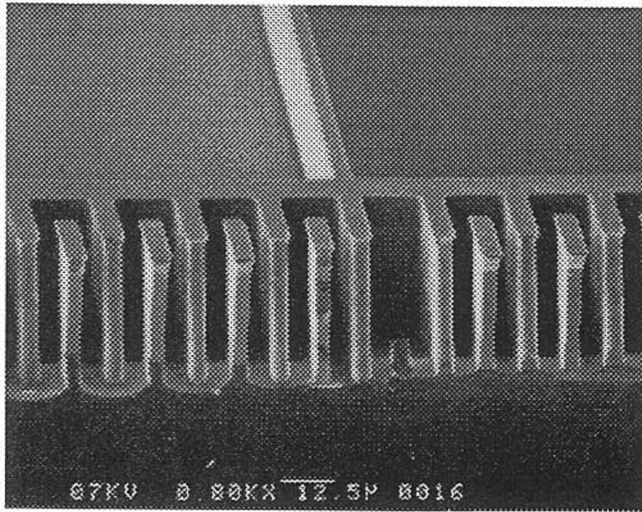
When H_2 is added into SF_6 no $S_xF_yH_z$ film formation occurs at room temperature, so directionality is not possible this way. As for CF_4 plasmas, SF_6 and H_2 react with radicals into 'inert" HF, thus decreasing the etch rate. The effect of H_2 addition on a mixed halocarbon plasma is similar to effects observed with CF_4/H_2; e.g. in a $CClF_3/H_2$ plasma the deposition of a $C_xCl_yF_z$ film is observed [25]. At the same time, the Cl-atom density decreases due to the stable HCl molecule thus decreasing the etch rate.

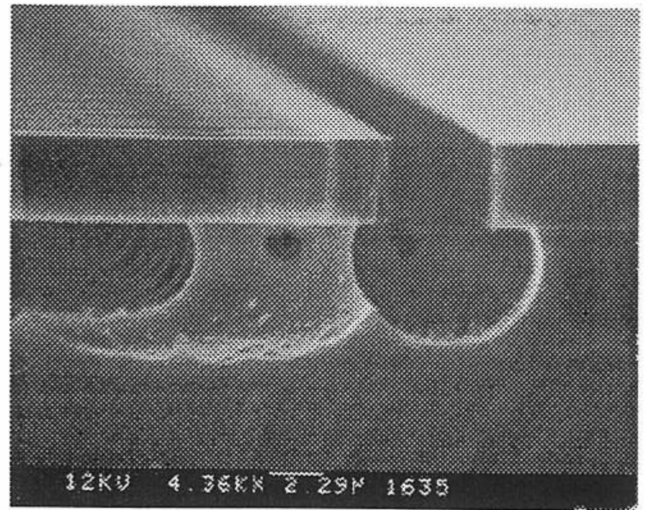
Effect of nitrogen addition: The addition of N_2 gas into a CF_4 or SF_6 plasma is another important mixture in etching Si because it increases the F-atom density. In contrast to most other gases, nitrogen doesn't dissociate on excitation [26]. Instead it is found in bound excited electronic states and not as atom or ion. These exitated molecules are more effectual in splitting SF_6 into SF_5* and F* radicals than the small electrons (In general, the electronic- and thermal dissociation of species is not the same [10]). Again, at higher N_2 content the etching will decrease due to dilution. SF_6/N_2 differs from SF_6/O_2 etching because relatively more SF_5 ions can respond to the bias and sputtering might increase. Adding N_2 into a CF_4 plasma has the additional effect that polymer forming is decreased because of volatile CN species. In the same way F/O-atoms react with bare Si into $Si_xO_yF_z$, F/N_2-radicals might turn Si into $Si_xN_yF_z$. This film is weakly passivating thus never used in ion-inhibitor processes. Instead, these F-rich plasmas are effective in fast isotropic etching of Si.

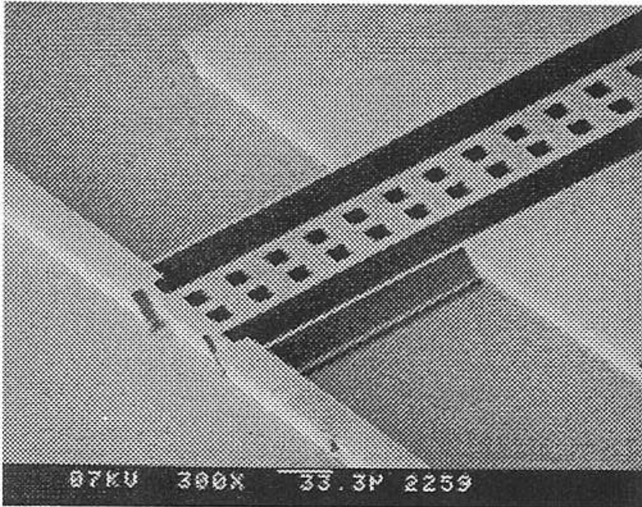
Effect of CHF_3 addition: The addition of CHF_3 gas does not play a special role in CF_4 mixes because the CF_4/CHF_3 system is almost identical with CF_4/H_2 mixes (fig.5). For CF_4+H_2 has a higher internal energy than CHF_3+HF, when CF_4 is mixed with H_2, CHF_3 and HF might be created spontaneously. In contrast, SF_6/CHF_3 and SF_6/H_2 plasmas are different. Unlike H_2 addition, when adding CHF_3 profile control is possible because CF_2 radicals, a product of the CHF_3 plasma, will form a blocking C_xF_y layer on the Si surface [14,27]. The film decomposes at much lower temperature than e.g. an inorganic $Si_xO_yF_z$ film. Thus for a vertical sidewall, ion bombardment, exothermic reactions, etc. should be sufficiently low to ensure the growing of a polymeric film. The SF_6/CHF_3 mixture differs from the SF_6/O_2 and SF_6/N_2 mixture because the F-atom density is barely increased resulting in a lower etch rate.

Other gas additives: Noble gases such as argon and helium are often added to stabilise plasmas or for cooling purposes (He in high pressure plasmas). Ar-addition can also cause inert ion bombardment of a surface and results in enhanced anisotropic etching (e.g. Cl_2/Ar RIE of Si [16]). The consequences of diluting a reactive gas with a noble gas are not easily understood. The addition of a chemically inert gas may significantly change the electron energy distribution in a plasma and alter the reactive species population in the discharge. This effect is observed when the ionisation potential of the chemically inert additive is very different from the ionisation potentials of the plasma species of the primary gas. An altered reactive species make-up of the discharge, e.g. enhanced dissociation, can also be due to more complex effects. Gottscho et al. examined the mixing of BCl_3 with He, Ar, and Kr and found that energy transfer from noble gas metastable states to BCl_3 states causes enhanced dissociation of BCl_3 [28].

Special mixes: In an $SF_6/O_2/CHF_3$ plasma, each gas has a known specific function and influence, so the etched profile is easily controlled just by changing the flow rate of one of these gases [15,34]. In such a plasma SF_6 produces the F* radicals for the chemical etching of the Si forming volatile SiF_4 (fig.1), oxygen creates the O* radicals to passivate the Si surface with $Si_xO_yF_z$, and CHF_3 (or SF_6) is the source of CF_x^+ (SF_x^+) ions, responsible for the removal of the $Si_xO_yF_z$ layer at the trench bottom forming the volatile CO_xF_y (or SO_xF_y).







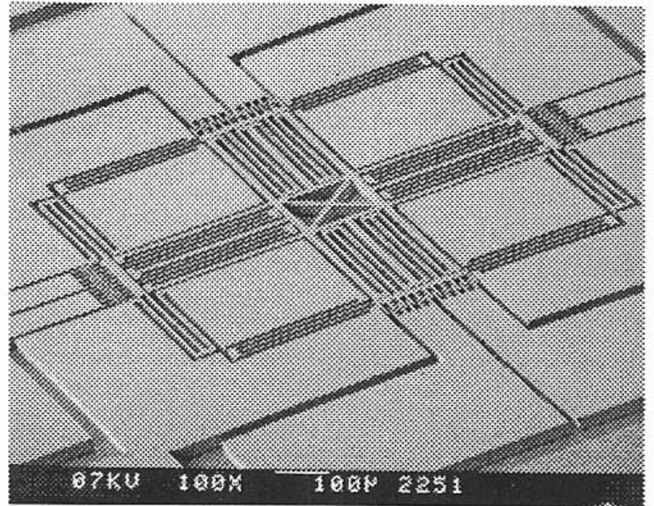


Figure 6: One-run multi-step RIE process [29]. Top-left: After anisotropic etching the top Si of an SOI wafer. Top-right: After etching the insulator, sidewall passivation, and isotropic etching of the base Si. Bottom: Typical finished MEMS products.

Multi-step plasma chemistries

After the successful (anisotropic) etching of micromechanical structures, they have to be released. In bulk micromachining some very useful dry release techniques have been proposed such as the SIMPLE and SCREAM processes [30,31]. The BSM multi-step one-run process is a more sophisticated dry release technique [29]. The technique starts with commercially available silicon-on-insulator (SOI) wafers. After the deposition of a (lift-off) mask for the pattern definition, the movable structures can be fabricated in only one RIE run with four individual steps. These are (fig.6): 1) The (an)isotropic RIE ($SF_6/O_2/CHF_3$) of the top Si, 2) the RIE (CHF_3) of the insulator together with the passivation (C_xF_y film) of the sidewalls of the structures (fig.3 right), 3) the RIE ($SF_6/O_2/CHF_3$) of the floor, and 4) the isotropic RIE (SF_6) of the bulk Si. Eventually, the process can be finished with a conformal step coverage of a C_xF_y film to protect the released structures from the environment [14]. For instance, these fluorocarbon films have an extremely low surface tension and therefore they repel water and other liquids. With this technique it is possible to release very long thin Si beams successfully.

Plasma parameters/influences

Probably the biggest disadvantage of plasma etching is its extreme sensitivity to many variables. Partly, these parameters are well-known such as pressure, power, and flow. However, more often influences such as target/reactor materials and cleanliness are unintentionally disregarded. Strangly, number one on this list, temperature, is almost never accounted for enough. Therefore, many times etch results are, not surprisingly, inconsistent and irreproducible.

Doping: In contrast to undoped Si, highly doped Si etches spontaneously in a Cl_2 discharge. N-type Si (e.g. P- or As-doped) etches faster than intrinsic Si which etches faster than p-type Si (e.g. B- or Ga-doped) and this effect is not chemical in nature since it is absent if the dopants are not electrically activated [32]. Thus, the etch rate depends on the electronic properties of the substrate and this has been explained by band bending effects at the Si surface [33]: Coulomb attraction between uncompensated donors (n-type), e.g. As^+, and chemisorbed halogens, e.g. Cl^-, enhances the etch rate, whereas Coulomb repulsion in p-type Si inhibits the etch rate.

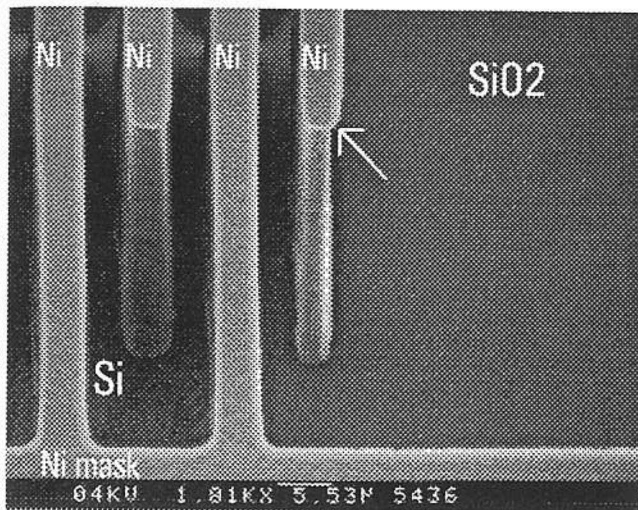


Figure 7: The influence of microloading.

Schwartz et al. observed horizontal etching of a buried highly As-doped layer in a low pressure (10 mTorr) Cl_2 discharge [16]. However, for a CCl_4 discharge (C_xCl_y film) or intrinsic Si (Cl monolayer) the etching was perfectly directional. Mogab et al. observed that etching of doped poly-Si in a 300 mTorr Cl_2 plasma resulted in an isotropic profile [32]. Directional etching could be achieved by adding C_2F_6 to Cl_2 which formed a sidewall passivation layer. A detailed study of the doping effect for Si has recently been completed by Winters et al. [35].

The etching of poly-Si by Br-atoms has been measured in an afterglow experiment [36]. No etching at room temperature was observed even for n^+ poly-Si and a very large doping effect was seen.

The doping effect decreases with ion bombardment and is difficult to observe for RIE conditions as a doping dependence of the vertical etch rate [37]. Its technological significance lies in the fact that it makes the control of profile shapes in trench etching possible [31]. Since the lateral etch rates (chemical etching only) of the different doped Si layers are not the same, dry release of movable structures for MEMS applications is possible.

Temperature: Needless to say, temperature is the most important parameter in RIE etching. Together with the entropy and enthalpy it rules every energy step in the reactor such as adsorption and reaction. Many sources are known to increase the temperature at the substrate surface such as: 1) ion bombardment, 2) exothermic reactions at the substrate surface, 3) r.f. heating due to Eddy currents, and 4) gas heating.

Commonly, to stabilise the surface temperature the target is cooled by circulating water (or other liquids) through the target platen. Of course, the wafer has to be clamped sufficiently (e.g. mechanically, electrically, or vacuum grease) to maximise the heat transfer from the substrate to the target. Alternatively, gases like helium, may be added to the plasma to cool the substrate from the front side or helium backside cooling can be utilised.

Loading: Loading occurs whenever the reactant density is depleted due to an excessive substrate load. As a result, the etch rate will decrease inversely proportionally to the Si area which is exposed to the plasma glow [38]. Moreover, the etch rate/volume depends on the Si shape; a long small structure etches faster than a square. The importance of this effect depends strongly on the radical life-time. At the same time, the etched profile in e.g. SF_6/O_2 etching will change while increasing the loading because the F/O density ratio and ion impact (or d.c. bias) is decreasing. The bias decreases because of the increase in reaction products which increases the plasma impedance. At higher loading there will be less underetching due to the smaller F-atom density.

Depending on the gas phase mean free path and the number- and structure of specimens being etched the loading effect may be both global, i.e. the reactant concentration in the reactor is uniformly lowered, and local, i.e. microloading. Thus, microloading is formally equivalent to loading and it describes the etching rate dependency on pattern density. Structures in the locality of big Si areas are etched at a slower speed than those situated in nonetching areas. In figure 7 an example of microloading is given. In this picture four poly-Si combfingers on top of a SiO_2 layer are etched. Because of RIE lag (see 'ARDE'), the open area at the right is etched faster than the areas between the fingers where there is still some Si left. At the moment that the SiO_2 surface is reached for the open area, the local F-atom density increases resulting in an enhanced chemical underetching, indicated by the arrow.

The importance of the (global) loading effect is decreased by consuming etchant species through processes other than reaction with the wafer load, e.g. rapid pumping or a Si target. Another possibility is making the synergism such that ions -and not radicals- control the etching rate. In other words, ion-induced etching (e.g. Cl_2-Si) is less sensitive for loading than ion-inhibitor etching (e.g. SF_6-Si). Additionally, the shorter life-time of Cl-atoms with respect to F-atoms will decrease the loading effect in Cl-based etching. The effect of microloading is minimised by changing the original mask pattern density into a more uniform pattern density.

Reactor cleanliness: The addition of small amounts of contaminants to a plasma may alter an etch result significantly. For example: 1) The etching of native oxide is made irreproducible if small amounts of water are present in the chamber; the water will react with oxygen scavengers or oxidise the substrate e.g. $Al \rightarrow Al_2O_3$ in Cl- and $Si \rightarrow SiO_2$ in F-based etching. Since the presence of water is primarily due to exposure of the chamber to room ambient load locks eliminate this problem. 2) Small concentrations of N_2- or O_2-gas due to leakage can noticeably change the plasma chemistry. It can be caused when particles are trapped in the rubber seal during closure of the reactor or because seals are etched by long living reactive atoms like fluorine.

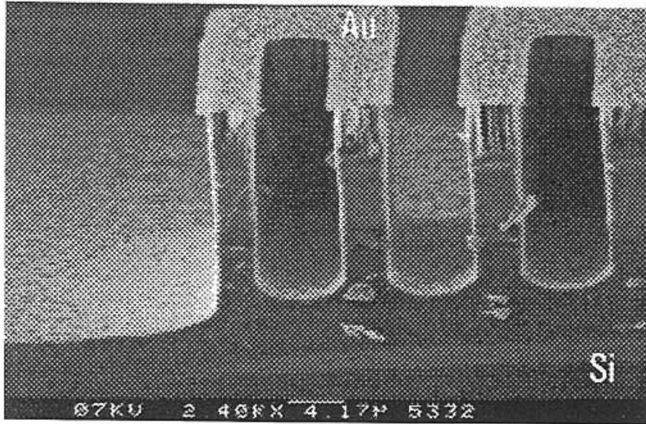


Figure 8: Mask erosion for a gold mask layer at 40eV.

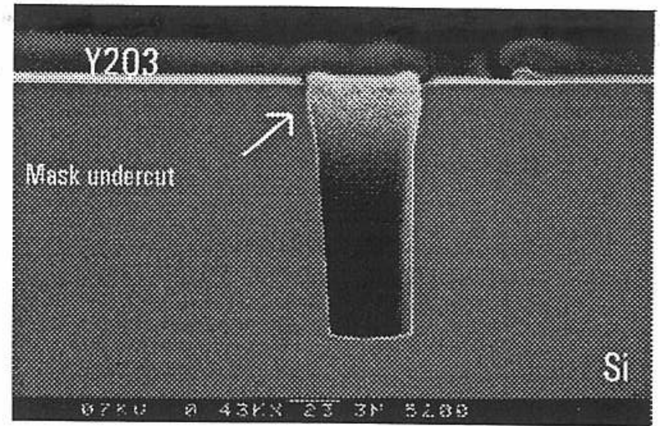


Figure 9: Undercutting of an Y_2O_3 mask due to ion bowing.

A solution for this problem is to check the base pressure periodically. 3) The etching process itself can lead to chamber contamination e.g. in CF_4 etching a C_xF_y film is deposited at the reactor walls which may loose adhesion and cause particles. The film is recycled or will alter the F- or O-atom concentration in a next run. The best procedure appears to be to clean e.g. an O_2 plasma and "condition" the chamber by running the process until equilibrium is reached.

Reactor materials: The choice of the reactor/ target materials is of critical importance and may result in (un)desirable etch characteristics such as 1) depletion of reactant e.g. graphite, Si or quartz targets consume F-atoms, graphite or Teflon consume O-atoms, and Al consumes Cl-atoms, 2) generation of active species *directly* e.g. Teflon produces F-atoms, CF_2+O→2F+CO, and quartz produces O-atoms which may prevent polymer building and *indirectly* e.g. Al may increase the F-atom density due to catalytic reactions, 3) generation of polymer precursors e.g. graphite or Teflon produces C_xF_y, 4) micro-masking due to redeposition resulting in surface roughening during processing e.g. SF_x^+ ions may sputter Al forming involatile AlF_3 particles, and 5) the secondary electron emission coefficient of electrode surfaces may influence the nature of the discharge.

Mask materials/influences

In order to copy a pattern into a Si substrate a mask is needed. It is therefore important to know the influence of this mask on the etch result such as the etchability.

Etchability: In general, an etching mask will influence the Si trench profile because the mask is retarding when its profile is not fully vertical. Almost infinite selectivity is possible in using metal(oxide) masks (except e.g. Ti, Mo, W, Nb, and Ta for F-based plasmas and Al or Cr for Cl-based plasmas) as long as the ion bombardment is sufficiently low (e.g. the C_xF_y deposit at the sidewalls of Si trenches in a CHF_3 plasma is not attacked by F* radicals). Important parameters to consider are the sputtering threshold (generally between 10 and 40 eV) and -yield (0.01-10 atoms/ion, fig.8) [39]. Sometimes a layer of 10 nm is enough to etch through a Si wafer due to the low volatility of the metal(oxy)fluorides.

Film formation: Sometimes, redeposition of mask material will prevent spontaneous etching. This inhibitor may be a metal fluoride (e.g. AlF_3 from an Al mask) or a polymer (e.g. $C_xH_yF_z$ from a resist mask).

Selectivity: Etch selectivity, i.e. the etch rate ratio between two materials, is required when a film is being etched with respect to an etch mask or -stop layer. It is due to: 1) Selective formation of an etch inhibiting layer e.g. C_xF_y on top of Si in a CF_4-based plasma. This film will not grow on SiO_2 because its oxygen produces volatile CO_x and COF_2. 2) Non-reactivity of one of the materials e.g. Si etching with an AlF_3 mask in a F-plasma. The AlF_3 layer is not attacked by F-atoms, but Si will volatilise by forming SiF_4 species. 3) Non-volatility of reaction product e.g. Si etching with an Al mask in a F-plasma. Now the Al reacts into involatile AlF_3. 4) Selective formation of an electrostatic screen at the mask surface e.g. Al_2O_3 on top of Si. When an insulating layer is bombarded with impinging ions, the layer will charge up and, subsequently, this charge will repel new incoming ions thus decreasing synergetic etching. Si cannot be charged to a different potential and therefore maximal ion bombardment will proceed. 5) Loading, e.g. in F-based etching the Si etch rate decreases with loading whereas the SiO_2 etching is barely loading dependent. In other words; the selectivity is increased while decreasing the Si loading.

Conductivity: An insulating mask might be charged to the plasma potential [38], thus creating strong local electrical fields at the edge of a mask giving rise to ion bowing and therefore an undercut directly beneath the mask surface (fig.9). Additionally, there will be a lower mask erosion due to this charge.

Catalytic reactions: Fedynyshyn and co-workers found an increase in the Si etch rate when using specific mask materials (e.g. Al or Ag) in F-plasmas [40]. They proposed that catalytic reactions at the mask surface are responsible for the higher etch rate. For instance, Al would dissociate SF_6 forming more F-atoms leaving the Al unaffected. However, at this moment we believe that an increase in substrate temperature, not these catalytic reactions, is more likely to be responsible for increasing the etch rate.

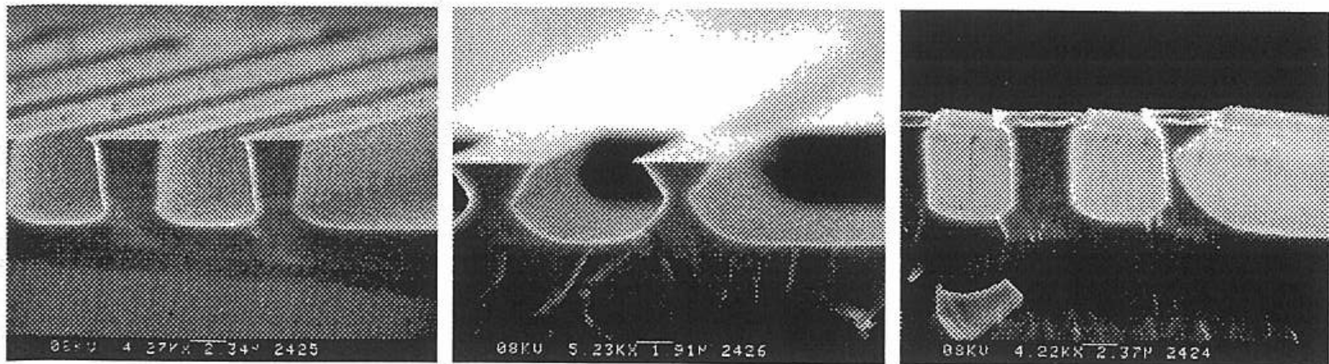


Figure 10: The influence of mask material on the profile. Left=copper. Mid=platinnum. Right=aluminium.

Temperature: The local temperature of sidewalls should be constant when etching deep Si trenches because surface reactions (adsorption or desorption) are temperature dependent. Eddy currents in the mask and ion bombardment increase the local temperature of sidewalls. This alters the adsorbility of oxygen thus changes the thickness of the inhibitor and this will change the profile. To demonstrate the influence of the mask (and temperature) we examined the etched profile for three different materials during the same RIE run (fig.10). A Cu-mask resulted in a nearly anisotropic profile, a Pt-mask showed a negatively tapered profile and an Al mask, a well-known material giving rise to Eddy currents, resulted in trench-opening-depending profiles. Cooling the substrate by grease-clamping, this difference almost vanishes. More experiments have to follow...

Materials: **Photoresist** (PR) is the most straightforward mask material. Unfortunately, the PR/Si selectivity is never very high and difficult to control, especially when there are O- and F-atoms in the plasma present. F-atoms react with polymer into HF and leave a reactive polymer surface behind which may react with oxygen gas. During etching PR and Si a lot of heat is produced and therefore the temperature rises and the selectivity decreases (this has its origin in the low glass temperature of PR, making the etching thermo-synergetic). When the temperature is low enough (20 ^{0}C) the only etch mechanism is due to impinging ions; a typical ion-induced (synergetic) etch mode. The etching of PR can be suppressed when e.g. CF_x monomers from a CHF_3 additive are allowed to adsorb at the PR mask. In short: The etching of PR can be suppressed by 1) cooling the substrate by clamping, cryogenically, or the addition of a cooling gas (e.g. He) in the gas mixture, 2) lowering the bias voltage by changing the reactor geometry (showerhead), an insulating target, or extra dummy Si in the chamber, or 3) additives such as CF_x which don't etch but only compete with the other radicals. **Silicon oxide** is etched synergetically and therefore the selectivity is limited. The etching is ion-induced and the selectivity to Si can be increased by suppressing the bias. When hydrogen is added to a CF_4 plasma, a decrease in SiO_2/Si etch selectivity is found as a result of the growing of a C_xF_y film on the Si surface. The addition of too much oxygen will form a $Si_xO_yF_z$ layer and thus decrease the selectivity also. The highest SiO_2/Si selectivity is reached when there is no passivating film grown at the Si surface. **Siliconnitride** is even less attractive as a mask than SiO_x, especially when it is not stoichiometric (i.e. Si_3N_4), mainly because it can be etched chemically. Thus nitride takes an intermediate position between Si and SiO_2. Nitride reacts faster with F-atoms than oxide because of the intrinsically weaker Si-N bond, although not as fast as Si. It also appears to react with CF_2 precursors into volatile CN species, as it is etched in CF_4/H_2 at roughly the same rates as SiO_2. **Aluminium** is IC compatible but there is mask erosion (sputtering) visible after greater etch depth giving rise to roughening of Si adjacent to the Al protected regions even at relatively low ion energies (<40eV). The high erosion rate may be explained by the low sputtering threshold of Al (13eV) together with the existence of Eddy currents in Al. Nevertheless, the Al/Si etch selectivity is extremely high for low ion energy and can easily exceed 100,000. **Chromium** and **nickel** seem to be perfect mask materials. They are minimally sputtered at bias energies up to 200eV. The noble metal **platinum** is strongly sputtered at low bias voltage and the soft noble **gold** is even worse (fig.8). Their use therefore is limited to extremely low bias voltages (<20eV). **Yttrium** is easily oxidised into the strong insulator Y_2O_3 giving rise to mask undercut, thus it should not be used in plasmas containing oxide atoms. **Zincoxide** is a semiconductor which is etched, although not heavily, so its use is limited to low voltages. **Palladium**, an expensive rare earth, seems to be OK. **Copper**, although noble, is easily oxidised but gives good results.

Problems & solutions

It should now be obvious that RIE is an incredibly complex technique and takes quite some time before one is familiar with it. Unfortunately, it is not yet over; RIE has its own specific problems and this chapter will examine a few of them.

Uniformity: The uniformity, global as well as local, of an etch result depends completely on the loading and the ARDE effect and the solution for this problem is found in the corresponding chapters.

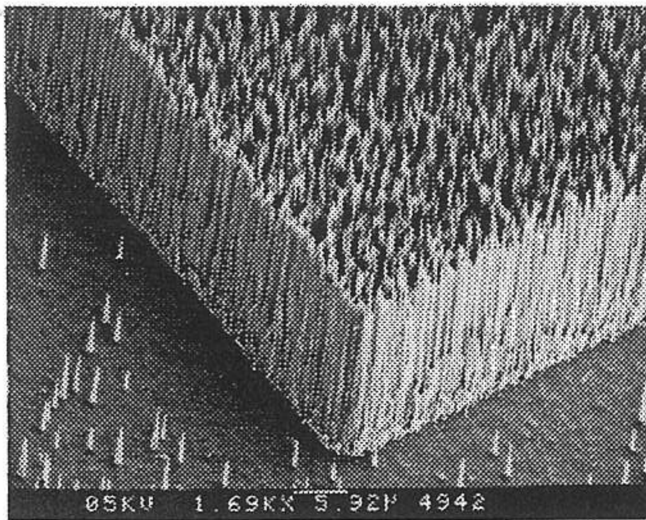


Figure 11: The forming of micrograss or black silicon.

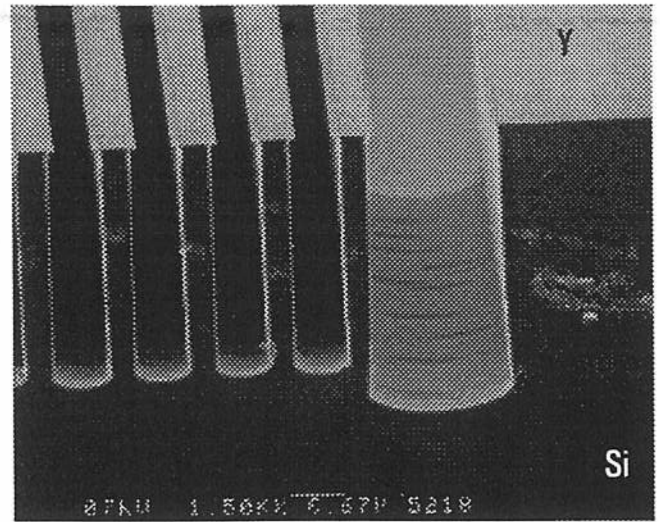


Figure 12: The influence of ion bowing on the profile.

Roughness: A major problem during etching Si vertically is the forming of "grass" or "black silicon" on the surface, because of all kinds of micro masks deposited or grown on the Si (fig.11). The origin of micro masks is caused by native oxide, dust, etc. which is already on the wafer before etching. But, it is also formed during etching due to redeposition of mask material from imparting ions or passivation of the surface together with angle dependent ion etching of this inhibitor.

Spikes formed due to dirty wafers before etching are easily controlled by giving the wafer a precleaning step, the redeposition of mask material decreases for low ion energies (thus low self-bias), and the growing of inhibitor particles is excellently controlled when a slightly lateral etching is allowed.

ARDE: Currently, in micromechanics the etch depth of trenches increases while the trench width (or opening) stays the same or will become even smaller. The aspect ratio (depth/width) therefore increases and aspect ratio dependent etching (ARDE) will become important. ARDE is a collective noun for 1) sidewall bowing i.e the deflection of ions to sidewalls during their trajectory along these walls, 2) feature size dependency of profiles i.e. different tapered profiles are observed for different trench openings, and 3) RIE lag i.e. the effect that smaller trenches are etched slower, positive lag, or faster, negative lag, than wider trenches. They are well known phenomena observed while etching trenches into a conducting substrate, as shown in figure 10 and 12, and seem to be strongly correlated by the effect of ion bowing. Ion bowing is caused by the diffraction of ions while entering a trench or by the negative potential of trench walls with respect to the plasma glow resulting in a deflection of ions to the walls. Ions are the main etching specimen of the passivating $Si_xO_yF_z$ layer in an SF_6/O_2 plasma and are controlling the etched profile by their direction. The etch rate decreases almost linearly as the aspect ratio increases and is determined by the aspect ratio, regardless of the opening size. This phenomenon has been attributed to a diverging electric field in the trench [41], diffusion effects on the supply of reactant to the bottom of the trench, and consumption of reactant at the trench sidewalls. However, in reference [38] the authors have made a plausible explanation that the physical ion depletion and bowing, are responsible for the ARDE phenomena observed. It was demonstrated that the effect of RIE lag could be suppressed while changing the plasma chemistry. Figure 13 gives an example of a "RIE-lag-free" etched structure.

RIE damage: The impact of RIE on properties of devices is thought to be due to RIE related surface contamination and substrate displacement damage [7]. The term "RIE damage" has been used for a variety of undesirable RIE effects such as: 1) Surface residues such as halocarbon films, which can be removed by an oxygen PE, or AlF_3 on top of Al in F-based etching which dissolves in e.g. KOH but not in standard Al etch. 2) Impurity implantation or penetration such as hydrogen diffusion. 3) Lattice damage due to energetic ions or radiation. Heat treatments can anneal out this damage. 4) Dopant loss due to e.g. hydrogen-boron interactions. 5) Heavy metal contamination from e.g. the reactor walls diffusing readily into Si. This effect reduces with the plasma potential. 6) Surface roughness as treated before. 7) Oxide breakdown as the r.f. power is turned off and the "oxide" capacitor discharges. 8) Mobile ion contamination such as sodium from Teflon electrodes. 9) Post RIE corrosion as in e.g. chlorine-based etching of Al. Upon exposure to atmosphere HCl is formed and corrosion of the Al takes place. The chlorine-containing residues are removed by post-RIE plasma/wet cleaning treatments.

The residual damage is a strong function of e.g. the maximum ion energy or -flux, but particularly of the Si etch rate. Upon exposure of a sample to a RIE plasma, damage will be introduced into the substrate and accumulate. At the same time however, the etching will consume the damaged layer. Thus for high etch rates little residual damage should be observed.

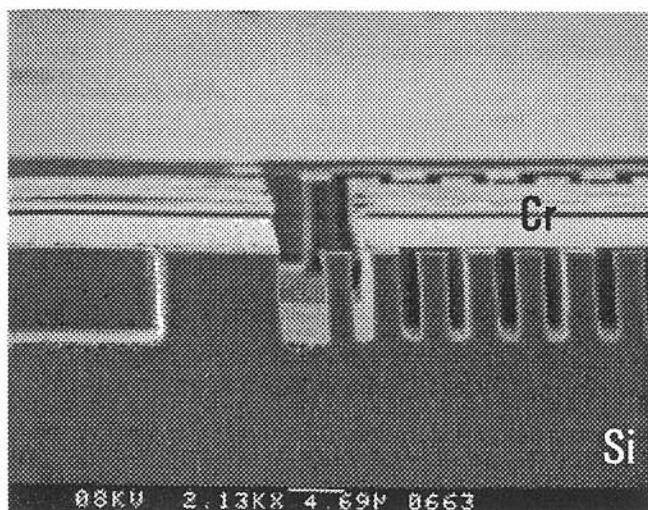


Figure 13: The BSM for suppressing RIE-lag.

Data acquisition

The result of a RIE process e.g. etch rate or -profile depends in a non-linear way on a great number of parameters e.g. power, pressure, flow, or residence time. This situation requires extensive experimentation in the development of suitable etching processes. It is expected that accurate computer models of plasma etching processes based on an improved understanding of the science of r.f. discharges will aid significantly in optimising their use for materials processing. A three-fold approach is being pursued in order to reach this goal.

Experiments: Firstly, non-intrusively, real-time, and in-situ measurements on real RIE systems are being performed. Significant progress has been made in determining species densities and their energy distribution. More direct techniques are looking at selectivity, surface texture, or profiles such as response surface methodology (RSM, [42]) and the black silicon method (BSM, [15]).

Modelling: Secondly, RIE models are studied since real glow discharges make well-controlled experiments difficult. Due to the coupling of most parameters, a controlled change in one quantity invariably, and often irreversibly, changes other quantities and it is difficult to asses the relative importance of the change of a specific quantity in producing a new result. The goal of the model system studies is to investigate the interaction of fluxes of species with well-specified surfaces.

Implementation: The third component needed is numerical modelling. Values of the controllable plasma operating parameters and the results of the model system approach on cross sections, reaction rates, etc. are used as inputs of a computer model of a glow discharge for a specific application. The output of the numerical model can be compared to the results of measurements performed on real systems. For prototypical plasma processes, such as Si etching using SF_6, numerical models are already quite advanced and increasingly accurate.

Species	λ (nm)	Species	λ (nm)
O	777; 843	CO	484
F	704	CN	387
N	674	HO	309
H	656	SiF	440; 777
N_2	337	SiCl	287

Table 2: Emission lines of some species.

End point detection & plasma diagnostics

The most direct need for plasma diagnostic techniques arises in the determination of the etch end point for a given process. In addition, plasma diagnostic techniques are employed for process monitoring and provide information on the types of species present in a RIE plasma, their energy content, concentration, and so forth. The most commonly used techniques for etch end point and plasma diagnostics are laser-, spectroscopic-, and probe-measurements [7,10]. Less important are electron-spin resonance and microwave diagnostics.

Laser interferometry/reflectance & ellipsometry: In this technique light reflected from an etching surface is measured. For transparent films, e.g. SiO_2, an oscillating signal is observed for the reflected laser light intensity due to interference of the reflected light from the film surface and the substrate surface. Etch rates can be determined in real time. For nontransparent films, e.g. metals, a change in reflectivity is observed upon complete removal of the metallic film.

Spectroscopy: In optical emission/absorption spectroscopy (OES/OAS) the change in emission from a characteristic species is monitored or observed (with bare eyes) as etching is completed. Table 2 lists for some important plasma species emission lines. The sensitivity of this technique depends on how much etchant is consumed or how much film material is etched per unit time. Other spectroscopic measurements are laser-induced fluorescence-(LIFS), coherent anti-Stokes Raman (CARS), mass/energy- and optogalvanic-spectro-scopy.

Probes: The self-bias and/or plasma potential are changing with substrate material. For example, the amount of Si etched in a F-based RIE has a strong influence on the created self-bias. So, it can be used as an end point detector for a layer of Si on top of SiO_2 or vice versa. Other probe techniques are Langmuir, double, and emissive-probes.

Current & future trends

Currently, a great deal of development effort has gone into producing low pressure (p<10mTorr) single wafer etchers with adequate throughput, such as RIE or ECR, which would perform tasks normally accomplished in RIE batch reactors. Anisotropic etching is easier to achieve in low pressure reactors because of a high ion-to-neutral flux ratio and the reduced probability of ion-neutral collisions in the sheath region at low pressure.

Low pressure reactors are much more demanding in terms of pumping equipment and wafer cooling than conventional RIE systems. For RIE a

Roots blower and a turbopump is required to maintain pressures down to 10mTorr at adequate gas flows. The pressure for MIE processing is near 1mTorr and for ECR etching it can be even lower. Moderate gas flows at these low pressures demand very high pumping speeds, e.g. for a flow of 30 sccm a 1500 litres/sec turbopump may need to be employed. Wafer cooling is a critical issue because of the achievement of high etch rates, significant ion bombardment, and low pressure operation. Backside helium cooling using a wafer clamp or an electrostatic chuck is necessary in order to control the etching process.

Magnetron ion etching (MIE): Magnetic fields from magnets parallel- and electric field lines normal to the cathode surface (self-bias) confine electrons on cycloidal trajectories near the cathode [43]. The probability of an electron undergoing collisions with gas phase species is thus enhanced and the ion/neutral ratio can be 50 times greater in MIE than in RIE. The mobility of electrons towards the cathode is decreased because of this confinement, causing the self-bias to be lower than conventional RIE. A large flux of low energy ions is thus produced in magnetrons at low pressure whereas in RIE a small flux of high energy ions is produced for the same input power.

Electron cyclotron resonance (ECR): In ECR a discharge is produced by microwave excitation (commonly 2.45 GHz) [44]. When a magnetic field of B=875 Gauss is applied resonance between the cyclotron motion of the electrons in the magnetic and microwave field occurs. Electrons at resonance convert efficiently microwave energy into dissociation of gas species. The wafer is placed below the discharge chamber and can be r.f. or d.c. driven to control the energy of impinging ions and radicals. This enables far greater control of the etching process than possible in RIE.

Others: Other interesting new techniques are: Microwave multipolar plasma reactors equipped with confinement magnets which surround the etching chamber and use ECR sources [45], r.f. driven double cathode etcher [46], inductively coupled plasma (ICP), hallow cathode (HC), DECR, and MCRIE.

Clustering: RIE process-integration is introduced to effectively integrate RIE into the overall fabrication sequence, e.g. by connecting deposition and etching chambers by clean, evacuated transport chambers. At the same time, real-time process monitoring equipment will detect process/equipment malfunctioning. The near future may see the utilisation of computer models to scale-up the RIE reactors and to control the etching process.

Acknowledgements

The authors gratefully acknowledge the contributions of M.de Boer for performing the laborious work on mask preparation and etching, Johannes Burger for doing confusing experiments, B.Otter for taking all the beautiful SEM pictures, G.Roelofs for keeping the RIE machine alive, C.Eykel for aresting his eyes at the right moments and the Dutch Technology Foundation (FOM) for supporting our money waste.

References

[1] S.M.Irving, U.S.Patent 3,615,956 (1971), assigned to Signetics.
[2] A.Reinberg, Proc.Symp.Etching, Electrochem. Soc. (1976) 91.
[3] B.Chapman, Glow Discharge Processes, John Wiley & Sons, New York, USA (1980).
[4] D.L.Flamm and V.M.Donnelly, Plasma Chemistry and Plasma Processing, Vol.1, No.4 (1981) 317.
[5] J.A.Mucha and D.W.Hess, Plasma Etching, American Chemical Society (1983) 215.
[6] R.A.Morgan, Plasma Technology Vol.1: Plasma etching, edited by L.Holland, Elsevier, Amsterdam, The Netherlands (1985).
[7] G.S.Oehrlein, Reactive ion etching: Handbook of Plasma Processing Technology edited by S.M.Rossnagel, Noyes Publications, Park Ridge, New Jersey, U.S.A. (1990) 196.
[8] H.W.Lehmann, Thin film processes II: Plasma-assisted etching, edited by J.L.Vossen and W.Kern, Academic Press, Inc., San Diego, USA (1991) 673.
[9] H.F.Winters and J.W.Coburn, Surface science aspects of etching reactions, Surface Science Reports 14, North-Holland (1992) 161.
[10] M.Konuma, Film Deposition by Plasma Techniques, Springer-Verlag, Berlin Heidelberg, Germany (1992).
[11] AEDEPT (Automatic Encyclopedia of Dry Etch Process Technology), Du Pont Electronics, Wilmington, Delaware (1989).
[12] R.d'Agostino, Plasma deposition, treatment, and etching of polymers, Academic Press, Inc., San Diego, USA (1990).
[13] H.F.Winters, J.Appl.Phys.49 (1978) 5165.
[14] H.V.Jansen et al., Applications of fluorocarbon polymers in micromechanics and micromachining, Sens.&Act. A 41-42 (1994) 136.
[15] H.Jansen et al., The Black Silicon Method, Proc.Micro Mechanics Europe, MME'94, Pisa, Italy, (1994) 60.
[16] G.C.Schwartz and P.M.Schaible, J.Vac.Sci.Tech.16 (1979) 410.
[17] C.J.Mogab, J.Electrochem.Soc. 124 (1977) 1262.
[18] S.Tachi, K.Tsujimoto and S.Okudaira, Appl.Phys.Lett. 52 (1988) 616.
[19] R.A.Haring et al., Appl.Phys. Lett. 41 (1982) 174.
[20] M.Seel and P.S.Bagus, Phys.Rev. B23 (1981) 5464.
[21] G.C.Tyrrell et al., Appl.Surf.Sci. 43 (1989) 439.
[22] S.Matsuo, Appl.Phys.Lett. 36 (1980) 768.
[23] R.D'Agostino et al., J.Appl.Phys. 52 (1981) 1259.
[24] J.W.Coburn and H.F.Winters, J.Vac.Sci.&Tech. 16 (1979) 391.
[25] G.S.Oehrlein et al., Appl.Phys.Lett. 46 (1985) 686.
[26] W.R.Harshbarger, Analysis of N_2 plasma to characterize plasma etching systems, Solid State Tech. (1982) 126.
[27] E.Gogolides et al., Microelectronic Engineering 27 (1995) 449.
[28] G.C.Schwartz and R.A.Gottscho, The Electroc.Soc., Pennington (1987) 201.
[29] M.de Boer et al., The black silicon method V, accepted for Transducers/Eurosensors, Stockholm (1995).
[30] K.A.Shaw et al., Scream I, Sens.&Act. A 40 (1994) 63.
[31] Y.X.Li et al., Fabrication of a SCS..., Proc.IEEE MEMS (1995) 398.
[32] C.J.Mogab and H.J.Levinstein, J.Vac.Sci.&Tech.17 (1980) 721.
[33] Y.H.Lee and M.M.Chen, J.Vac.Sci.Tech. B4 (1986) 468.
[34] H.Jansen et al., The black silicon method IV, Proc.IEEE MEMS (1995) 488.
[35] H.F.Winters and D.Haarer, Phys.Rev.B36 (1987) 6613.
[36] Z.H.Walker and E.A.Ogryzlo, J.Appl.Phys. 69 (1991) 2635.
[37] Y.H.Lee et al., Appl.Phys.Lett. 46 (1985) 260.
[38] H.Jansen et al., The Black Silicon Method II, Microelectronic Engineering 27 (1995) 475.
[39] G.K.Wehner, General Mills Report 2309, Litton Industries, Beverly Hills, USA (1962).
[40] T.H.Fedynyshyn et al., Mask dependent etch rates II, J.Elect.Soc., Solid-State Sc. and Techn. Vol.134, No.10 (1987) 2580.
[41] D.Chin et al., J.Elect.Soc. 132 (1985) 1705.
[42] R.Legtenberg et al., Anisotropic RIE of Si using $SF_6/O_2/CHF_3$ chemistry, J.Elec.Soc. (1995).
[43] H.Okano and Y.Horiike, Plasma Processing, Electrochem.Soc., Pennington, USA, (1982).
[44] K.Suzuki et al., Vacuum 34 (1984) 953.
[45] Y.Arnal et al., Supplement a la Revue, Le Vide, les Couches Minces 237 (1987) 73.
[46] R.W.Boswell et al., Supplement a la Revue, Le Vide, les Couches Minces 237 (1987) 78.