Plasma Etching

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1. Plasmas: useful but complex.

Plasma etching is a relatively new technique in the fabrication of integrated circuits. It was introduced in the seventies, mainly for stripping resists. In the eighties, plasma etching became a mature technique to etch layers and was introduced in the production of integrated circuits. Reactive Ion Etching was the main technology, but new techniques were developed. In the nineties new techniques, such as electron cyclotron resonance (ECR) ,and inductively coupled plasmas (ICP), were introduced, with mixed success. The use of plasma etching is widespread in the industry, but contrary to other techniques (e.g. lithography), the theoretical understanding of the different mechanisms involved in plasma etching is still very poor. This explains why no reliable (TCAD) simulator for plasma etching exists (yet).

The use of plasmas in general is also increasing for other applications. In the semiconductor industry, plasmas are used also for e.g. sputtering and PECVD. Other industries are relying increasingly on plasmas to improve their products. One of the newest applications of plasmas is in the reduction of air pollution, where plasmas neutralise the harmful components of certain exhausts.

As will become clear later in this text, plasmas are very complex “entities”, what makes them difficult to understand and to describe. The physical and chemical reactions in plasma etching, the electrical interaction between the different particles themselves and between electrically charged particles and electromagnetic fields are not simple. initially, literature described only the main reactions in plasma etching, as e.g. in [1,2]. The chapters on plasma etching in books on semiconductor manufacturing are in general quite easy to read, even for beginners in the field, but rather limited to the description of general principles. Classics in the literature on plasmas are [3] and [4]. Both books give very good basic information, deducing specific plasma phenomena, starting from basic physical laws. Students in their last year of engineering and physics find here very valuable information to understand the basics of plasmas and in some degree of plasma etching. This knowledge is sufficient to start development of processes and research in “common” plasmas used in the so-called “Reactive Ion Etching” and “Plasma Etching” techniques, where capacitively coupled plasmas are used, mainly at the 13.56 MHz frequency. Until the beginning of the nineties, these techniques were used in more than 90% of the applications of plasma etching. A very good overview of plasma etching techniques and characterizations was given in [5]. Plasma etch chemistry and diagnostics are the strong points of this book.

At the same time, specific etch processes were reported in specialized journals, such as the Journal of the Electrochemical Society, Journal of Vacuum Science and Technology, Applied Physics etc. The results reported in these papers were very difficult to reproduce, because the construction details of the reactor influence the final etch results very much. However, general information could be obtained from these papers. One should also be very careful with the mechanisms which were proposed in this era. The understanding of plasma etching was rather poor (it still is, in a certain way) and some conclusions are certainly not applicable in more general situations. A short review of the main characteristics of RF plasmas and how to develop processes for the most common layers in lC fabrication can be found in [6].

In the nineties, new techniques were introduced and more knowledge became available on the different process mechanisms in etching. Relatively successful techniques such as ECR and ICP employ magnetic fields to enhance the densities of the plasmas. The electrical characterization of the plasmas becomes much more complex in these systems. A very good, but rather complex overview can be found in [7]. All the basic interactions are treated in detail, what allows the authors to describe capacitively coupled plasmas, inductively coupled plasmas and wave-heated discharges.

At the same time, more results on basic etching mechanisms were reported in literature, such as the journals mentioned above.

In this text, we shall try to explain, briefly and simplified, the most used plasma etching techniques and give an overview of the basic etch mechanisms as they are accepted today.

2. Capacitively coupled RF plasmas

2.1 The formation of a DC voltage.

A plasma is a (partially) ionized gas. In the plasmas we deal with, free electrons collide with neutral atoms/molecules and, through a dissociative process, they can remove one electron from the atom/molecule, which gives a net result of 2 electrons and 1 ion. Depending on the energy of the incoming electron, this collision can result also in other species, such as negative ions, because of electron association, excited molecules, neutral atoms and ions. The light emitted by the plasma is due to the return of excited electrons to their ground state. As the energies between the electron states are well defined for each element, each gas will emit light at specific wavelengths, which will give us the possibility to analyse the plasma.

Capacitively coupled RF plasmas are still the most common plasmas used in dry etching. A typical reactor chamber is shown in figure 1. The power is applied to the lower or the upper electrode (or in some special cases to the reactor walls). In general the frequency of the applied power is 13.56 MHz. A so-called dark sheath is formed in the neighbourhood of all surfaces in the reactor, electrodes and wails. This dark sheath can be considered as some kind of dielectric or a capacitor. So one can consider that the applied power is transmitted to the plasma through a capacitor.

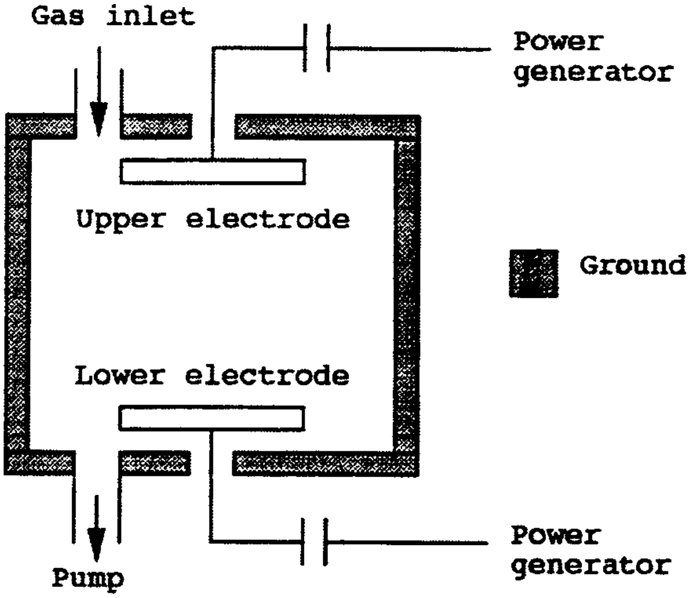


Figure 1 : Schematics of a simple plasma etch reactor.

At frequencies between 1 MHz and 100 MHz, the free electrons are able to follow the variations of the applied electric field and, unless they suffer a collision, they can gain considerable e energy, of the order of some hundred eV. On the other hand, in this frequency range, the movement of the much heavier (positive) ions is very little influenced (one may simplify that they are not influenced) by these electric fields: their energy comes completely from the thermal energy of the environment and is of the order of a few hundredths of an eV (i.e., ~0.01eV).

In the pressure range of these plasmas, from a few mTorr to a few hundreds of mTorr, the electrons will travel much longer distances than the ions, and in this way, they will much more frequently collide with the reactor walls and electrodes and consequently be removed from the plasma. This would leave the plasma positively charged. However, plasmas remain neutral. To guarantee this neutrality, a DC electric field has to be formed in such a way that the electrons are repelled from the walls. The capacitor between the power generator and the electrode, shown in figure 1, helps to form the DC charge. During the first few cycles, electrons generated in the plasma escape to the electrode and charge the capacitor negatively. In this way, a negative DC bias voltage is formed on the electrode, which repels the electrons. The AC voltage becomes then superposed on this negative DC voltage as shown in figure 2.

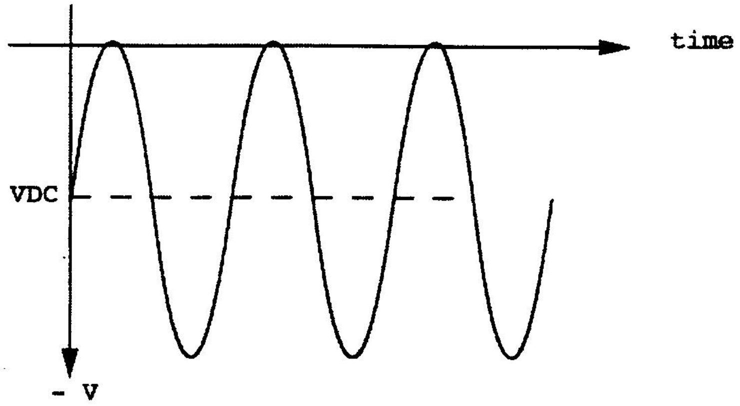


Figure 2: DC and AC voltage on the powered electrode.

What happens to the plasma in the neighbourhood of grounded conductive walls? Free electrons escape from the plasma in higher numbers to the walls than ions do. So, one also needs a certain DC voltage to repel the electrons from the walls. In this way, one can understand that the DC voltage of the plasma will always be the most positive of all the DC voltages in the reactor.

Figure 3 shows how the DC voltage varies between the lower and upper electrode. This figure indicates clearly how the electrons are repelled from the walls and electrode towards the plasma. The ions are attracted towards the wall. However, because of their large mass, only the ions which arrive “by coincidence” at the interface of the plasma with the dark sheath will be attracted towards the electrodes or the walls. Within the plasma, the ions are not influenced by the electric fields and move randomly.

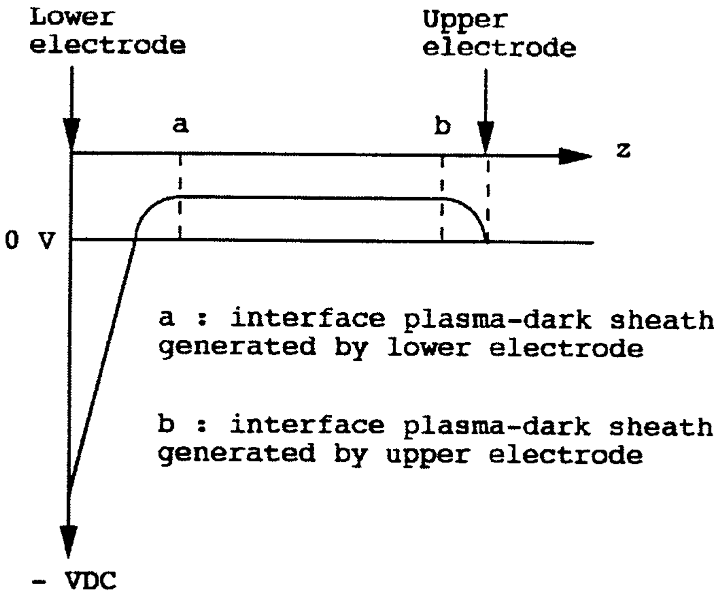


Figure 3: DC voltages in the plasma reactor in RIE mode.

In most reactors, one can clearly observe this so-called dark sheath as a region with less luminosity than the bulk of the plasma. In this region, the density and energy of the free electrons is lower. Therefore, less collisions with molecules will occur, causing less excitations of electrons (bound to molecules) and therefore less photons will be emitted from this region.

2.2 How to influence the DC voltage

The value of the DC voltage is influenced by many parameters. It depends in the first place on the dimensions of the etching reactor. It also depends on the plasma process parameters (gas, flow, pressure, power etc.). There are other second and third order influences (e.g. material of the reactor), which will not be treated in this text.

2.2.1 Influence of the dimensions of the reactor and etching mode

One can demonstrate that:

$$|V_{DC}| \sim (A_1/A_2)^n \qquad (1)$$

with:

V_{DC}: the voltage drop between plasma and electrode 2
A_1 the area of electrode 1
A_2 the area of electrode 2
n an exponential factor, which is typically between 1 and 2.

Formula (1) is valid for whatever electrode is powered. If electrode 1 is powered and electrode 2 is grounded, V_{DC} is in this case the DC potential of the plasma, see figure 3.

One can prove that $n = 1$ or that $n = 4$, depending on the (very reasonable) assumptions one makes about the plasma. Anyway, the modulus of the DC voltage will increase with the ratio of grounded surface area to powered surface area. In RIE systems, the powered electrode has in general much less area than the grounded surfaces, resulting in a large negative DC voltage on the lower electrode. The consequences on the etching results will be discussed later. In PE systems, the upper electrode is powered and the lower electrode is in general grounded, together with the walls. This results in general in a small voltage drop between plasma and lower electrode. One can decrease the voltage drop between plasma and electrode even more, when one leaves the electrode floating. i.e. no electrical connection is made to the lower electrode.

2.2.2 Influence of the plasma parameters

In general, the dimensions of the reactor are fixed. In this case, one can influence the DC voltage by the process parameters. One should remember that the DC voltage is created to repel electrons. Therefore, the higher the electron density and the higher the electron energy, the higher the modulus of the DC voltage will be: a more negative voltage is necessary to repel a larger number of electrons, with higher energies. Using this reasoning, one is able to predict the tendencies of the DC bias voltage.

2.2.2.1 Gases and flows

The electronegativity of used gas(es) is a determining factor. When all other process parameters remain constant, the electronegativity of the gas will determine the DC voltage. Gases with low electronegativity, such as O_2, N_2 etc. have very negative DC bias voltages. Fluorine, chlorine and bromine containing gases are much more electronegative: the atoms of group VII are very prone to absorb any free electron which passes nearby. In this way, these gases decrease the density of the free electrons in the plasma (increasing the number of negative ions). Fluorine containing gases are more electronegative than chlorine containing gases, which are more electronegative than bromine containing gases. SF_6 is a very electronegative gas: its main use is in fact as an insulator gas in places with high electric fields, e.g. around linear accelerators. When all other plasma parameters remain the same, the DC voltage of a SF_6 plasma can be a factor of 10 less than the DC voltage of a $\mathbf{N_2}$ plasma.

The absolute flow of the gases does in general not affect the DC voltage.

if a mixture of gases is used, the DC bias will be a monotonically increasing function of the relative flows of the gases. In general, the DC bias tends to become rapidly more negative when a small flow of a gas with low electronegativity is entered in the plasma. Small flows of electronegative gases do not influence the DC bias very much.

2.2.2.2 Pressure

The pressure of the plasma does also influence the DC bias voltage, but to explain its influence is a little more complicated.

At higher pressure, more molecules are available for the electrons to collide with and to generate a new free electron - and a positive ion. In this way, an increase in pressure would increase the number of free electrons, turning the DC voltage more negative.

On the other hand, an increase in pressure increases the density of species, i.e. it decreases the mean free path of the electrons before colliding. In this way, the electrons will gain less energy before colliding. This decrease in energy results in less formation of a new electron-positive ion pair. This mechanism decreases the formation of free electrons and ions.

So, one has two tendencies in opposite ways. In the pressure ranges used for plasma etching, one can observe that in the 1- (approximately) 100 mTorr range, the number of free electrons increases, the plasma becomes more dense with increasing pressure. At higher pressure, the plasma density decrease with pressure.

The DC voltage is also a function of the energy of the free electrons. At higher pressure, electrons suffer more collisions, therefore they gain less energy between collisions. The electron energy decreases with pressure.

Taking all these mechanisms in account, one can understand that the DC bias voltage becomes less negative with increasing pressure.

2.2.2.3 Power

The influence of power is straightforward: an increase of power increases both the density and the energy of the free electrons. Therefore, the DC voltage becomes more negative with increasing power.

2.2.2.4 Conclusions

When a wafer is placed on the lower electrode, one obtains a high voltage drop between wafer and plasma:

- when a gas with low electronegativity is used, or added to an electronegative gas (e.g. N_2 to SF_6)
- at low pressure
  - for high power
  - in RIE mode

To obtain a low voltage drop, the inverse conditions have to be used.

2.3 Etching mechanisms

The etching mechanisms explained in this chapter are valid for all types of plasmas, not only for RF capacitively coupled plasmas.

In general, plasma etching is a chemical etching, not a physical etching. This means : a chemical reaction takes place between the solid atom (from the film to be etched) and gas atoms to form a molecule, which is removed from the substrate. Because of the existing DC bias, there is always some sputtering. For the large majority of etching processes, this physical etching component is so small it can be neglected.

The main steps in the etching process are:

1) formation of the reactive particle
2) arrival of the reactive particle at the surface to be etched
3) adsorption of the reactive particle at the surface
4) chemisorption of the reactive particle at the surface, i.e. a chemical bond is formed
5) formation of the product molecule
6) desorption of the product molecule
7) removal of the product molecule from the reactor.

These 7 steps will be commented now in more detail. As an example, we shall take the etching of silicon using SF_6.

The gases enter the reactor in the form of molecules. In general, these molecules are not reactive enough to react chemically with the substrate. The plasma is able to dissociate the molecules into reactive atoms (radicals). For our example:

$SF_6 + e^- \rightarrow SF_5 + F + e^-$ (2)

$SF_5 + e^- \rightarrow SF_4 + F + e^-$ (3)

etc.

The fluorine has then to diffuse to the surface of the substrate. Only a part of the formed fluorine atoms will arrive, a part will recombine, another part can be lost to the walls or go to the pump etc.

The fluorine has then to adsorb (typically by the formation of a Van der Waals bond) and then to chemisorb (forming a covalent bond) with the silicon.

$\mathrm{Si} + \mathrm{F} \rightarrow \mathrm{SiF}$ (4)

SiF is not a volatile molecule: it will remain on the surface. At room temperature, the first volatile compound formed is $\mathrm{SiF_4}$. This compound can be formed or by reactions (5) to (7) or by reactions (5) and (8). What exactly happens is not completely understood. For more details, see references [5,8,9].

$\mathrm{SiF} + \mathrm{F} \rightarrow \mathrm{SiF_2}$ (5)
$\mathrm{SiF_2} + \mathrm{F} \rightarrow \mathrm{SiF_3}$ (6)
$\mathrm{SiF_3} + \mathrm{F} \rightarrow \mathrm{SiF_4}$ (7)
$\mathrm{SiF_2} + \mathrm{SiF_2} \rightarrow \mathrm{SiF_4} + \mathrm{Si}$ (8)

Once $\mathrm{SiF_4}$ is formed at the surface of the substrate, it can desorb form the surface and become a gas molecule, which is then removed from the reactor through the pump to the exhaust.

2.4 The influence of the DC bias on the etching characteristics

In a first approximation, one can consider that the etch rate of a film will be limited by the slowest process of the steps 1-6 of the etching mechanism explained in 2.3.

These etching mechanisms can be influenced by ion bombardment. Ion bombardment is caused by positive ions which arrive at the interface plasma / dark sheath and are then accelerated by the negative DC voltage towards the electrode and the wafer placed on this electrode.

The effect of the ion bombardment depends on the quantity of ions which arrive at the sheath, i.e. on the density of ions in the plasma, and on the energy the ions, which is determined by the DC voltage.

This ion bombardment can influence steps 1, 3, 4, 5 and 6. In general, several of these steps are simultaneously influenced by ion bombardment [9]

The plasma itself influences step 1: the denser the plasma, the higher the density of reactive particles, in our example fluorine atoms. For special gases, e.g. $\mathrm{XeF_2}$, some of the fluorine atoms are not formed in the plasma: $\mathrm{XeF_2}$ molecules adsorb on the surface and an incoming ion dissociates the molecules into Xe and 2 F atoms. In this case, the DC voltage will also influence the generation of the reactive particles.

Ion bombardment can influence the adsorption rate. It is possible that impinging ions break some Si-Si bonds, in this way forming active sites, which can more easily be "filled" with fluorine. The adsorption 01 the fluorine is accelerated by the ion bombardment (step 3).

The incoming ions can also deliver the necessary energy to form the covalent bond of the fluorine to the silicon (step 4).

Reaction (4) occurs more easily than reactions (5), (6) (7) or (8) [8] mainly because the first bond can be formed at the top of the surface while the other bonds occur "under" the silicon atom. The ion can furnish enough energy to rearrange the silicon and fluorine atoms, so the incoming fluorine can more easily form the remaining bonds to finally form $\mathrm{SiF_4}$ (step 5).

The product molecule remains initially at the surface of the substrate : it needs a certain energy to be removed. An incoming ion can furnish this energy.

The influence of the incoming ions on the etch rate was first demonstrated in [10] : the resulting etching is called ion bombardment enhanced etching. Its main importance is not as much in the fact that the etch rate is increased, but that the vertical etch rate is increased, while the horizontal etch rate remains constant. For this reason, it is possible to obtain an anisotropic etching with plasmas, even for noncrystalline structures, what is not possible with wet etching.

The most common mechanism to obtain an anisotropic etch process is through the use of a passivation layer at the vertical surfaces.

The plasma parameters are chosen in such a way that together with the etching process occurs the deposition of a polymer. Where the ions bombard the surface, this polymer is being removed and the (chemical) etching can continue, the bombardment only occurs on horizontal surfaces (or surfaces parallel to the electrode) and not on vertical surfaces, therefore, only etching in the vertical direction occurs, resulting in the (desired) anisotropic etching.

The polymer is normally formed by C and H and/or F atoms, resulting in a $C_xF_yH_Z$ polymer. To form this polymer, one needs a certain amount of carbon atoms. These carbon atoms can proceed from the feed gases, such as CF_4, CH_4 etc., from a graphite electrode or from the resist itself. One has to find a compromise: one should form enough polymer to protect the sidewalls, but one should not form too much polymer, if not, even the vertical etching could be stopped. With a more negative DC bias voltage, there is more ion bombardment, so it is easier to obtain a vertical profile.

The formation of polymers does not occur only on the wafers, but on all the reactor surfaces. This can result in bad consequences, such as the excessive formation of particulates, which can redeposit on the wafer and locally prohibit the etching, resulting in a rough surface, or sometimes even in incomplete removal of the etched layer. In these cases, the reactor walls have to be cleaned regularly, which reduces the uptime of the equipment and increases the cost of ownership. But very often, the formation of this polymer is the only way to obtain vertical etching.

One can conclude that to obtain a vertical wall profile, a large DC bias voltage is preferred.

Unfortunately, a large DC bias voltage has some negative consequences.

In the first place, the selectivity between the etched film and the underlying film will decrease. In the same way, the resist etch rate will also increase considerably with larger DC voltages. Another consequence is the introduction of several types of damage by ion bombardment [11,12]. The resulting roughness in the etched film will also increase when the ion bombardment energy is higher.

Ali these examples show that one must tailor carefully his process, that each application has its specific characteristics and that the etch process must be adapted to those characteristics.

2.5 Limitations of capacitively coupled RF plasmas

Capacitively coupled RF plasmas have been used for decades as the main tools for plasma etching. Their big advantage is that the reactors to generate these plasmas are (very) simple to manufacture. With a good knowledge of vacuum fundamentals, one was able to design and fabricate an RF reactor. But on the other hand, these types of plasmas suffer considerable limitations.

The first limitation is that the reactive particle density is directly coupled to the ion energy. If one wants a dense plasma, rich in free atoms (which are in general the particles which react with the surface atoms), one has as a consequence also lots of ions with high energies. To obtain high densities of reactive particles, one has to increase the power in the plasma. This increase of power will also increase ion density and energy. Increasing the pressure can increase the reactive particle density and decrease ion density and energy somewhat, but not to a great extent: in general the effect of increasing the pressure is much lower than the effect of increasing the power.

So, if one desires a highly reactive plasma, with little bombardment, to attain a mainly chemical etching process, these types of plasmas are not very adequate. Neither will they be very useful for the “inverse” type of plasma: a (chemically) low density plasma with very high ion density and ion energy.

A second drawback is that it is not possible to generate plasmas at low pressures: 10 mTorr is typically the lowest pressure at which a plasma can be sustained. At lower pressures, there are not enough collisions to generate enough free electrons to generate/sustain the plasma. (Of course, the “real” value of the lowest attainable pressure depends on reactor design, gas, power etc.). To attain the lowest possible pressure without losing the plasma, one can strike the plasma at a higher pressure and then slowly decrease the pressure: striking a plasma is more difficult than keeping the plasma on.

In today’s plasmas, very high aspect ratios are required. These can only be obtained if the ions come in at (nearly) perpendicular angles. To obtain this condition, little or no collisions should take place in the dark sheath : a large mean free path is needed. Therefore, the pressure must be reduced as much as possible. At low pressures, less sidewall passivation is necessary to obtain a vertical profile. At the same time, the microloading effect is less pronounced.

Inductively coupled plasmas and electron cyclotron resonance plasmas are 2 types of plasmas which combine the quality of a high density plasma at a low pressure.

3. Inductively coupled RF plasmas

There exist two types of inductively driven sources : using cylindrical or using planar geometries, as shown in figures 4 and 5. The use of multipole permanent magnets is not indispensable, but their presence will increase the plasma density and mainly the uniformity of the plasma. An RF voltage is applied to the coil, resulting in an RF current which induces a magnetic field in the reactor. Therefore, the wall has to be a dielectric, it must not be “magnetically conductive”. It is possible to apply an extra (RF, low frequency or DC) bias voltage to the substrate holder, as shown in both figures, to increase the ion bombardment on the substrate. This voltage is small, in general, and does not “generate” the plasma: the ions and electrons are mainly generated by the inductive coupling. In this way, it is possible to “control” independently the plasma density and the energy of the incoming ions. This gives the process engineer an extra parameter with which he can optimise the process characteristics.

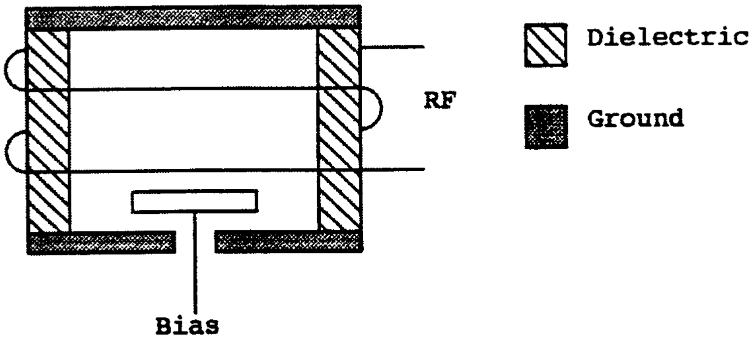


Figure 4 : Inductively coupled plasma reactor, using a cylindrical coil.

The most common geometry for production equipment is with the planar coil, which, together with multipole magnets, results in high density and uniform plasmas [7,13]. Besides, it requires less dielectric, which turns this geometry easier to fabricate. Quartz would be a good dielectric, would it not be etched, as when using e.g. fluorine containing plasmas. Therefore, the preferred dielectric material is alumina $(A1_20_3)$, which has excellent electric characteristics, but is hard and expensive to manufacture.

If no plasma is formed in the reactor, the magnetic field generated by the coil, enters the reactor. If a plasma is formed in the reactor, an electric field can be formed in the reactor, because of Faraday’s law:

$X E = \mu_o (\delta H/\delta t)$ (9)

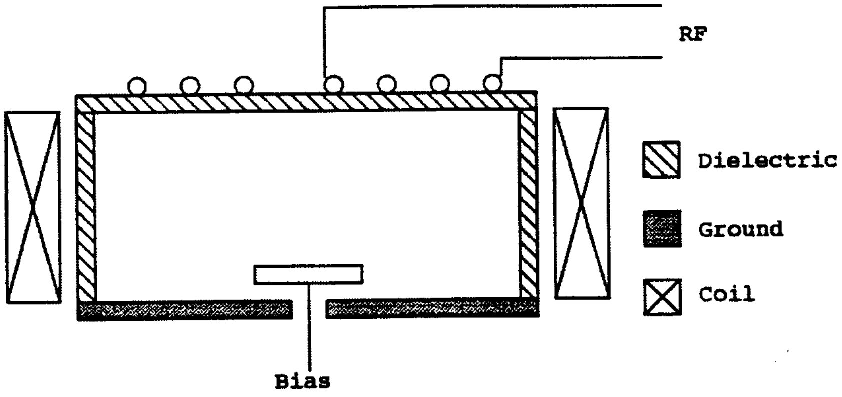


Figure 5 : Inductively coupled plasma reactor, using a planar coil.

This electric field creates a current in the plasma, and the resulting total magnetic field will be null in the reactor. The absorbed power in the plasma is then proportional to the real part of the product of the vectors of the current and the electric field in the plasma.

Ion densities of the order of 10^{11} to 10^{12} per cm^3 at pressures lower than 20 mTorr, can be obtained in these discharges. This is one to two orders of magnitude higher than for traditional capacitively coupled plasmas. Note however, that a RF power of at least 100 W is needed to sustain the inductively coupled plasma.

Beside the inductive coupling, there is also a small capacitive coupling: the dielectric serves as the dielectric of a capacitor formed between the lower part of the coil and the plasma. At the high voltage end of the coil, RF voltages of the order of 2000 V have been measured. Therefore, a capacitively coupled plasma is also formed. This capacitive coupling can help to strike and sustain the plasma. On the other hand, a local DC voltage can be formed, which results in sputtering of the dielectric. The presence of dielectric material in the plasma can induce serious contamination on the wafer, or chemical changes in the plasma, and has to be avoided. Therefore, it is necessary that the dielectric plate is thick enough to reduce the capacitive coupling. Another way to decrease the capacitance of the coil, is to place it a few millimeter above the dielectric, although this makes the manufacturing a little bit more difficult.

Since the beginning of the nineties, inductively coupled plasmas have been increasingly applied in the industry. The most sold aluminium etcher in this decade uses an inductively (or as the manufacturer baptised it a transformer) coupled plasma source. The fact that high density, uniform plasmas can be obtained at low pressures, and that the electron and ion density can be controlled independently from the energy of the ions which collide with the substrate, make this power source much more powerful than a capacitively coupled source.

Etch rates of the order of 1 µm per minute can easily be obtained at pressures around 10 mTorr. At this low pressures, it is easier to obtain walls with a well controlled, vertical profile [14].

Inductively coupled plasmas are here to stay.

4. Electron Cyclotron Resonance plasmas

The basic mechanism for the generation of Electron Cyclotron Resonance (ECR) plasmas is the possibility of the coupling of an AC electric field, E, with a frequency which matches the frequency at which the electrons rotate in the constant magnetic field, B.

When applying a constant magnetic field, B, electrons rotate at the electron cyclotron frequency, f:

$$2\pi f = eB/m \qquad (10)$$

with: e : the electron charge
m : the electron mass

If a variable electric field has the same frequency, f, the electrons gain energy during the whole cycle, as shown in Figure 6. The energy gained by the electron is proportional to the time between collisions. Therefore, ECR works only at low pressures, typically below 10 mTorr.

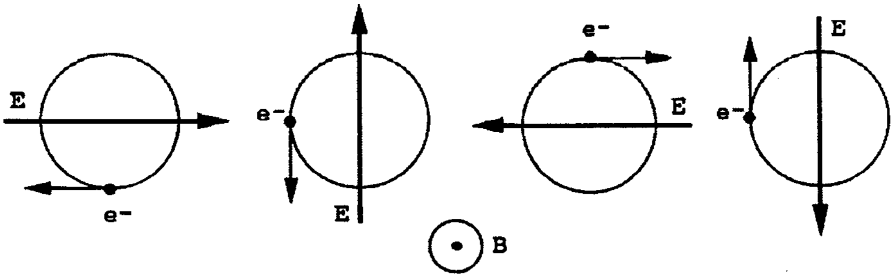


Figure 6 : Basic principle of ECR continuous energy gain.

Microwave energy is often used to generate plasmas. These plasmas are, in general, denser than RF plasmas, certainly in cavities. On the other hand, these cavities are located at a considerable distance from the wafer. Therefore, reactive particle densities at the wafer level are often lower than for RF plasmas, and the uniformity of the etching is in general rather poor. Using an ECR equipment, as shown in figure 7, the densities of electrons, ions and other reactive particles can be increased, and the uniformity will be much better than for a simple microwave reactor.

Figure 7 shows that the electron cyclotron resonance does not occur all over the reactor, because the magnetic field is not uniform over the reactor: only in a relatively small region, the magnetic field will match the electric field frequency to generate the resonance.

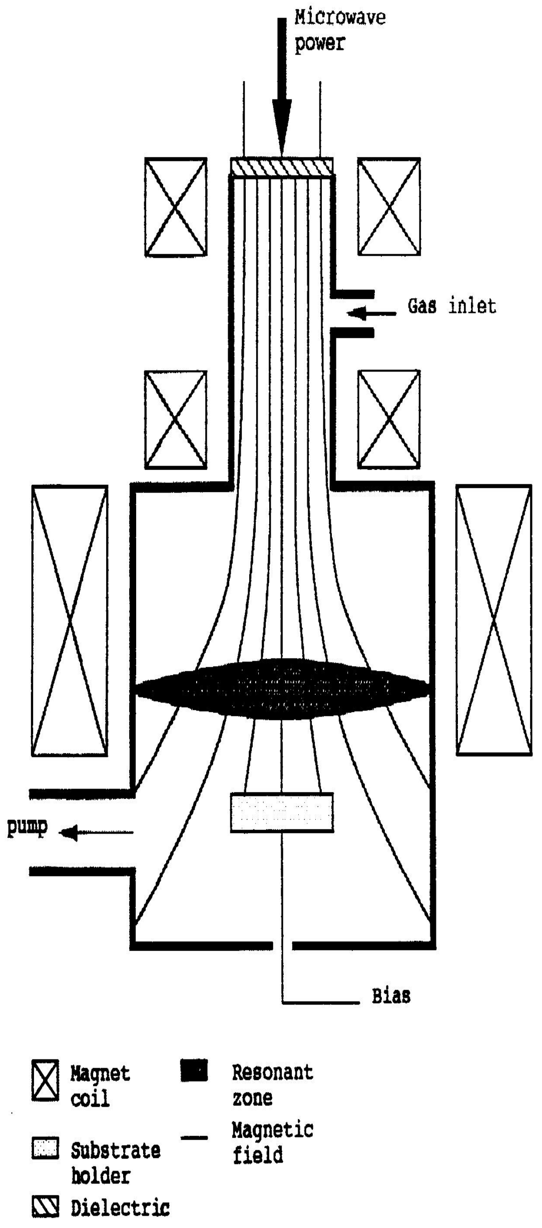
There exist several types of ECR reactors [7], but it is not within the spectrum of this paper to discuss the different configurations.

The drawback of using microwave plasmas, is that the applied magnetic field has to be large : for a frequency of 2.45 GHz, the magnetic field to obtain resonance, is approximately 875 G. For RF plasmas, an electron cyclotron resonance can be obtained at much lower magnetic fields. Equation (11) shows that the applied magnetic field is linearly proportional to the frequency, f:

$$B \sim f/2.8 \qquad (11)$$

with B in Gauss and f in Mhz.

Over the last few years, several papers appeared on the electrical characterization of ECR plasmas, mainly using Langmuir probes [15,16]. These papers show that high ion and electron densities can be generated. High etch rates, with good anisotropy can be obtained at low pressures. The main drawback of ECR etching is still the low uniformity of the etching as the plasma is generated at some distance from the wafer and it then spreads out, as shown in figure 7, so that it is hard to obtain good uniformities over large wafer diameters. As the tendency of silicon wafers is to grow ever larger, it is the opinion of the author that ECR will be used less and less for these applications. On the other hand, for other substrates, with (much) smaller diameters, ECR is a good technique.



5. Conclusions.

Plasma etching will remain an important technique in the fabrication of integrated circuits and microsystems for years to come. For several applications, the use of (simple) capacitively coupled RF plasmas will remain the best option. For specific applications, mainly where a high aspect ratio is required, plasmas at low pressures deliver a better solution. In this text, ECR and Inductively Coupled plasmas have been discussed as two options. ECR plasmas have serious limitations when large substrates are used, but for smaller samples, they can be an excellent solution. Inductively coupled plasma systems, mainly with a planar coil, together with an extra bias at the substrate holder, have proven to be very versatile, which deliver already excellent results in production. For low pressure plasmas, this kind of equipment seems to be the most promising.

6. Acknowledgements

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