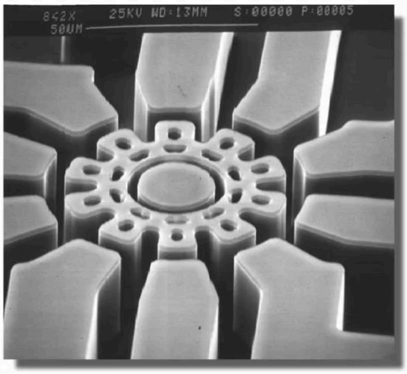
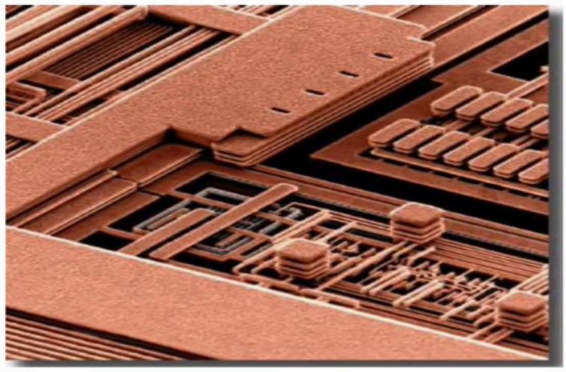


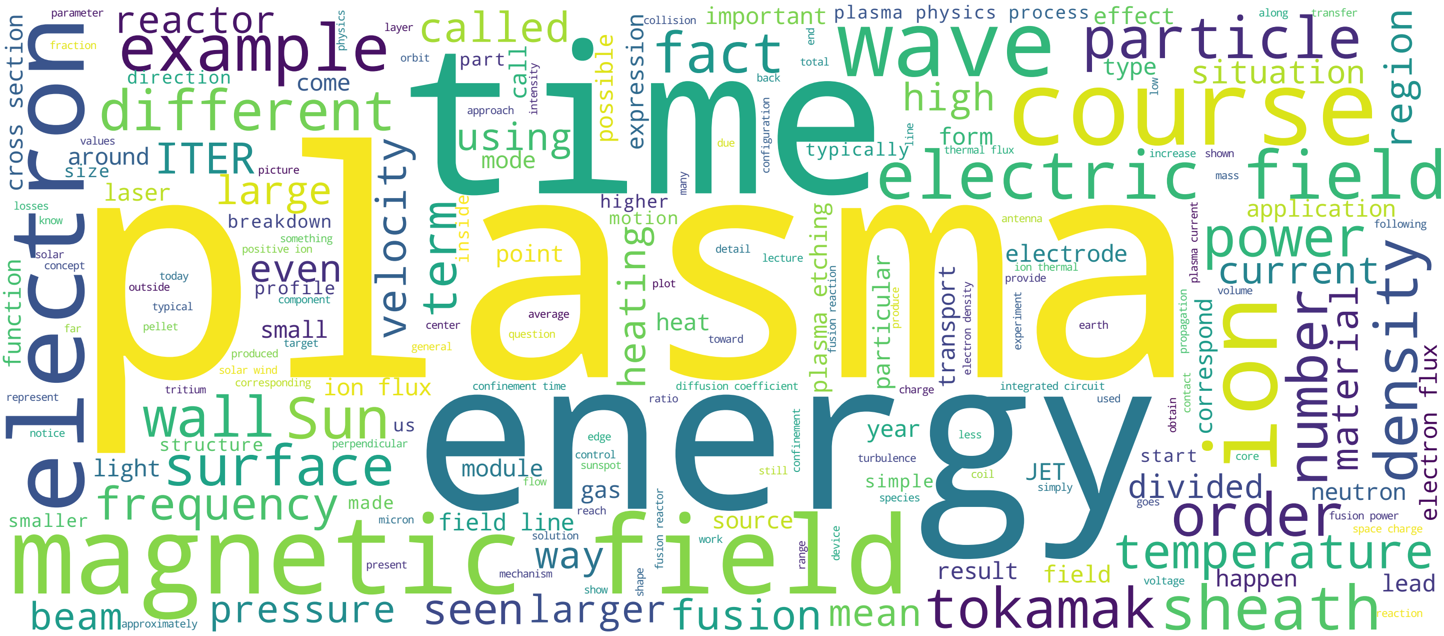


Sheaths and plasma etching: part I

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 5d

Alan Howling



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Introduction

Welcome to the course on plasma physics and applications. In these next two modules, we will consider sheath physics and plasma etching. We will show the plasma etching is the only way to make the complicated structures that you find in integrated circuits.

Notes

Summary

0m 05s

Introduction

- Formation of plasma
- Formation of a sheath
- Sheath properties
- Plasma etch applications

Plasma

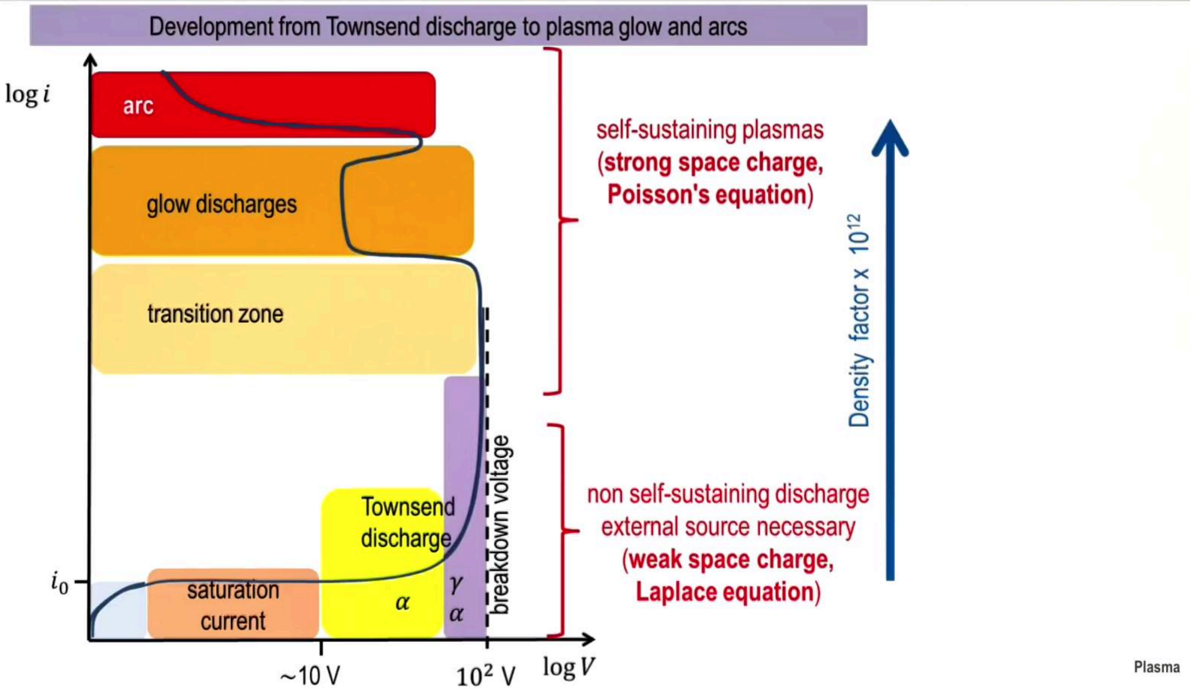
In this module we will see how a plasma forms. We will see how a sheath forms when a plasma is in contact with a wall. We will see some properties of the sheath and how we can apply these for plasma etching applications.

Notes

Summary

0m 23s

Formation of plasma



In modules 5.2 and 5.3, we saw how breakdown could lead to very high densities in the plasma and as the density increases the voltage drops down to a glow discharge and can eventually form an arc. This is the development from a Townsend discharge to a plasma glow and arc. In the Townsend region, this is a non self-sustaining discharge where only an external source can maintain the plasma. The plasma density is weak. The space charge therefore is weak and we can use the Laplace equation to calculate the electric field. But after breakdown the density increases by a factor of 10 to the 12 or more and then we arrive at self-sustaining plasmas. Where we have strong space charge and we have to include Poisson's equation for calculations of electric fields.

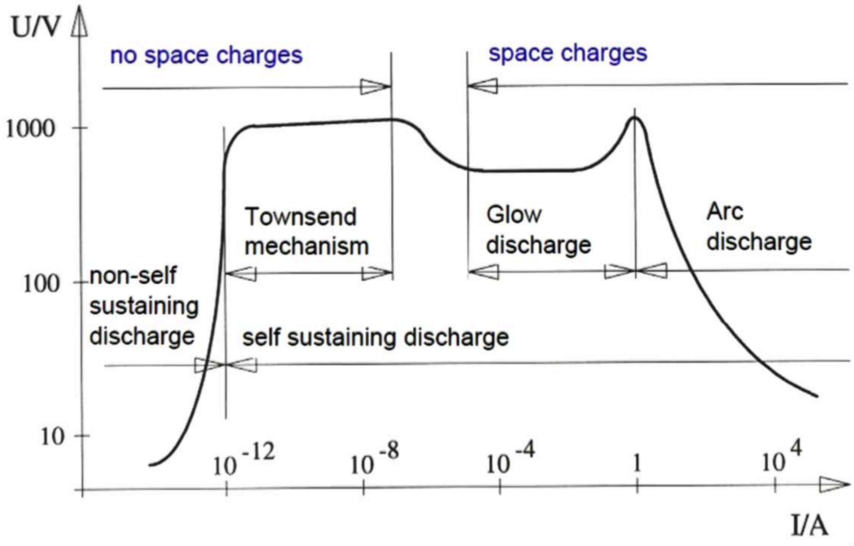
Notes

Summary

0m 41s

Formation of plasma

Development from Townsend discharge to plasma glow and arcs



This applies to parallel plates, NOT a universal curve!

Other types of plasma can form, such as sparks, corona and streamers, depending on electrode geometry and electric fields.

Plasma

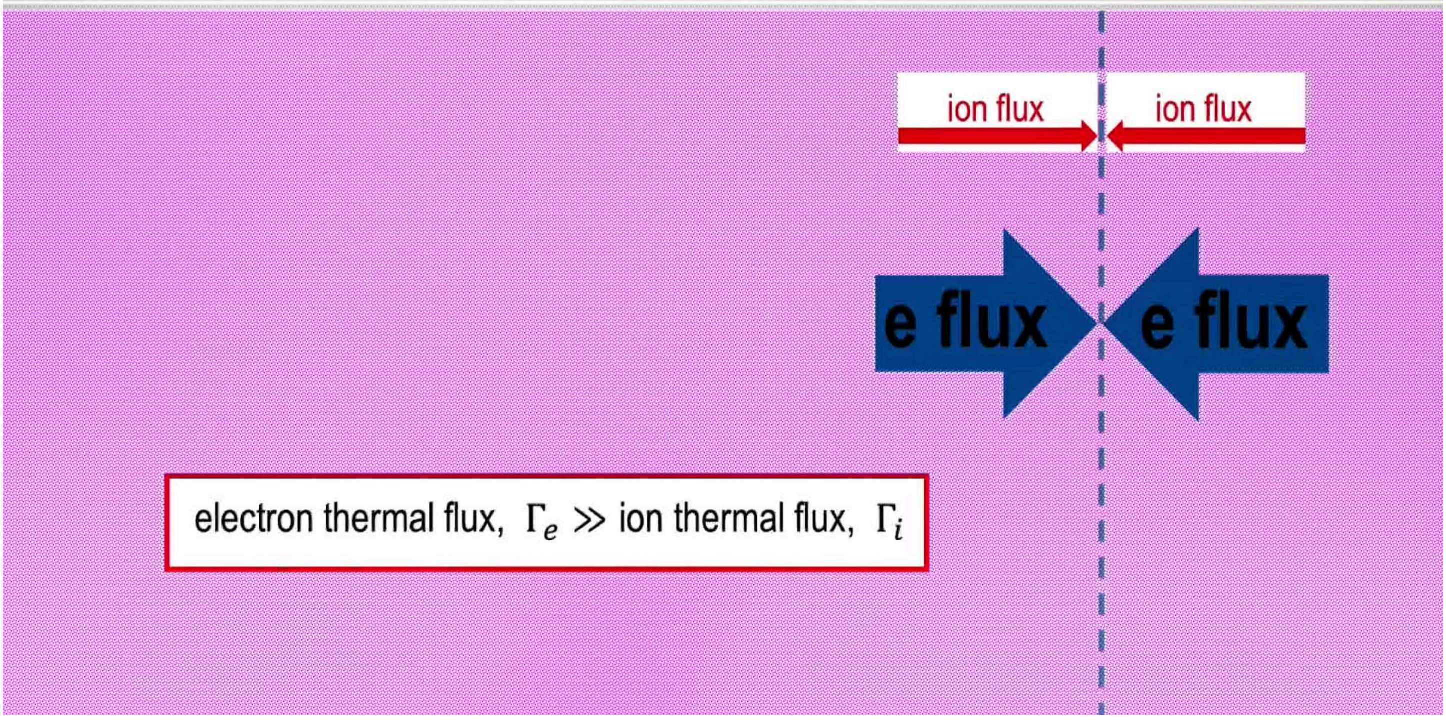
This is the same voltage current graph presented in a different orientation. This time with current along the X axis, the voltage on the vertical axis. This again, is the Townsend region. This is the glow discharge and arc region. Again, the vacuum field applies here and Poisson's equation applies here. Just note that this curve applies to parallel plates. It's not a universal curve because in other types of configuration, other types of electrodes, other shapes, other types of plasmas can form, such as sparks, coronas, and streamers depending on electrode geometry.

Notes

Summary

1m 34s

Formation of a sheath



Now let's consider in a simple way how a sheath can form in a plasma. First, let's consider a virtual or an imaginary surface in the plasma. There is an ion flux crossing this surface, whose value is given by the ion thermal flux given by the kinetic theory. This is simply the ion density times the ion thermal speed divided by four. The ion thermal speed is given by the root of eight, *eTi*. Remember the ion temperature is given in electron volts over π times the ion mass. This ion flux can cross this surface in a uniform plasma because simply there's the same ion flux coming back the other way. There is also an electron flux crossing this virtual surface. The electron thermal flux given by a similar expression to the ion thermal flux is in fact much larger than the ion flux, simply because the electron mass is much smaller than the ion mass. We also know that the electron temperature is generally higher than the ion temperature but the principle reason for the strong electron flux is that it has a higher mobility due to its low electron mass. To resume, the electron thermal flux is much bigger than the ion thermal flux. Of course, there's an equal and opposite electron flux crossing this same surface.

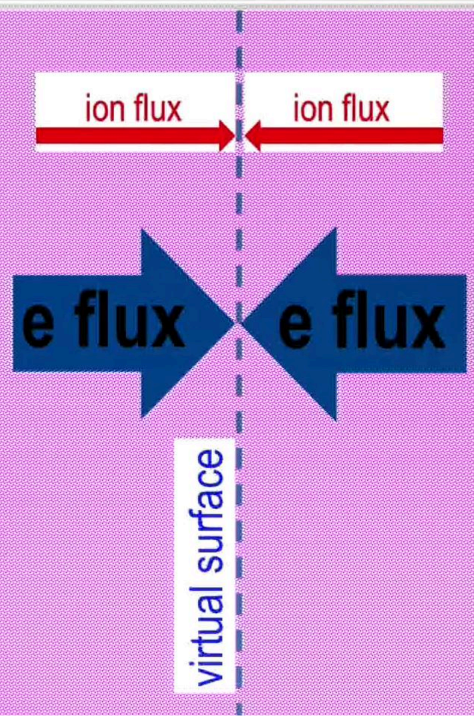
Notes

Summary

2m 15s

Formation of a sheath

What happens if the virtual surface is now replaced by a metal wall?



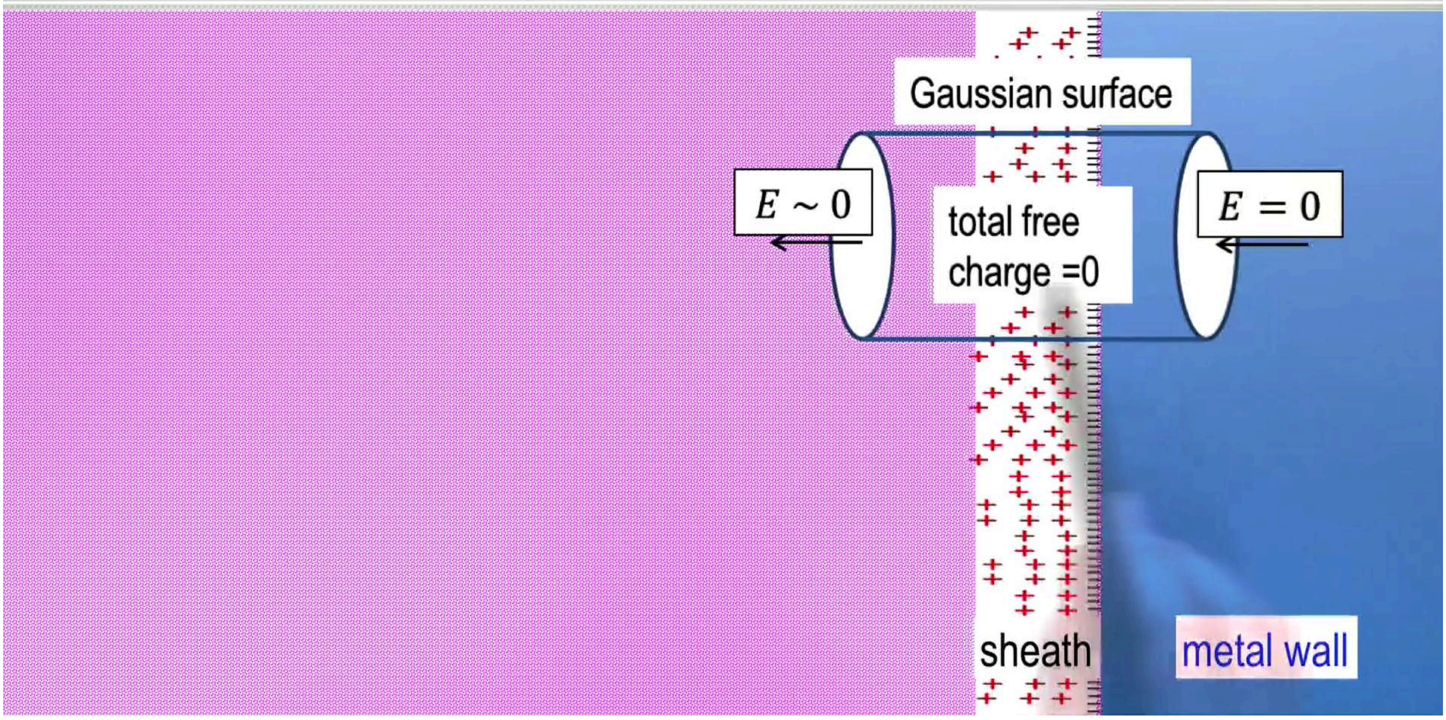
Now in all the courses up until now, the plasma has always been considered in isolation from its environment. That is, the plasma has never been in contact with any walls or electrodes in this course so far. However, if you want to make any devices, that is, any plasma applications. Then plasma wall interaction will of course be necessary because it's the only way you can make deposition, etching, or surface modification. So now we have to consider what happens if the virtual surface is replaced by a metal wall.

Notes

Summary

3m 47s

Formation of a sheath



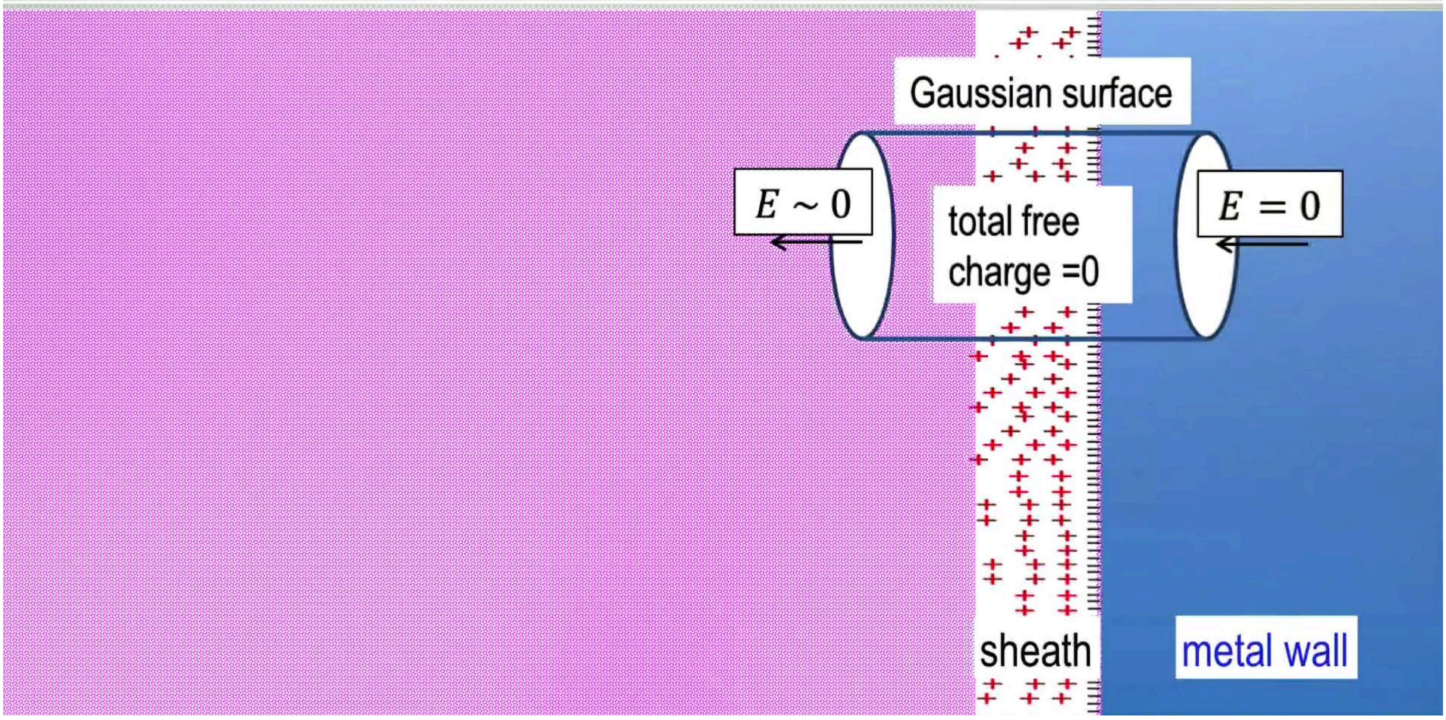
In a very short time the electron flux will flow quickly to the wall and form a negative charge on the surface. This will leave behind a layer of positive ions. This is called the sheath. The sheath forms in contact of a plasma with the metal wall. Now what happens when the electrons rush to the wall and the ions are left behind is that the plasma potential rises until the fluxes become equal. Now as you can see on this voltage distance graph, the plasma potential now rises this potential drop across the sheath brakes the electrons to reduce the electron flux and electric fields now accelerate the positive ions across the sheath potential drop to the voltage of the wall. So to resume, the ion flux is increased by the voltage drop, the electron flux is decreased due to the voltage drop, and the fluxes are equalized in equilibrium if there's no net current to the wall. Of course, this positive space charge in the sheath causes electric field towards the wall and there's a directional ion flux to the wall due to the sheath electric field. We can learn a bit more about the sheath by drawing a Gaussian surface, which straddles the sheath. On the righthand side, the electric field metals zero.

Notes

Summary

4m 25s

Formation of a sheath



The electric field in plasmas is very small because it's quasi-neutral. Therefore, we see that the total free charge in the sheath is zero. That is, that the positive charge in the sheath layer is equal and opposite to this surface charge of the electrons of the metal surface.

Notes

Summary

6m 02s

Some sheath properties

- Sheath provides the transition between plasma and wall.
- Positive space charge equal and opposite to negative surface charge.
- Guarantees dynamic equilibrium of ion and electron fluxes to wall.
- Plasma potential is always positive with respect to the most positive surface.
- Thin layer, several Debye lengths thick, due to Debye screening of sheath potential.
- Dark layer, because of strongly-reduced electron density.
- Strong electric field, and a positive ion flux, normal and directed towards the wall.

Plasma

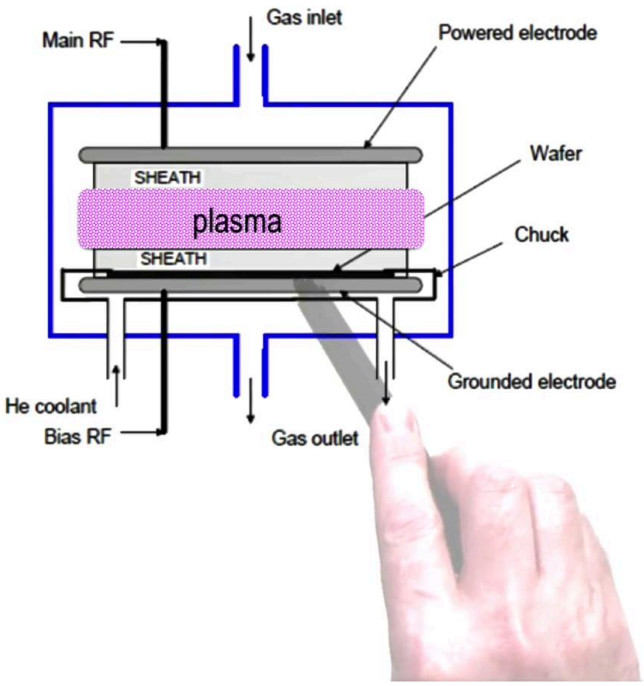
Therefore, with these very simple qualitative arguments we can already make a list of sheath properties. The sheath provides the transition between the plasma and the wall. Positive space charge is equal and opposite to the negative surface charge. The sheath guarantees a dynamic equilibrium of ion and electron fluxes to the wall. Plasma potential is always positive with respect to the most positive surface. The sheath layer is thin, it's only several Debye lengths thick due to Debye screening of the sheath potential. The sheath is a dark layer because there is a strongly reduced electron density in the sheath. Not because the electrons are colder but because there are very few electrons in the sheath and as we've already seen there is a strong electric field and therefore positive ion flux, which is perpendicular and directed towards the wall.

Notes

Summary

6m 24s

Plasma etch applications



Plasma

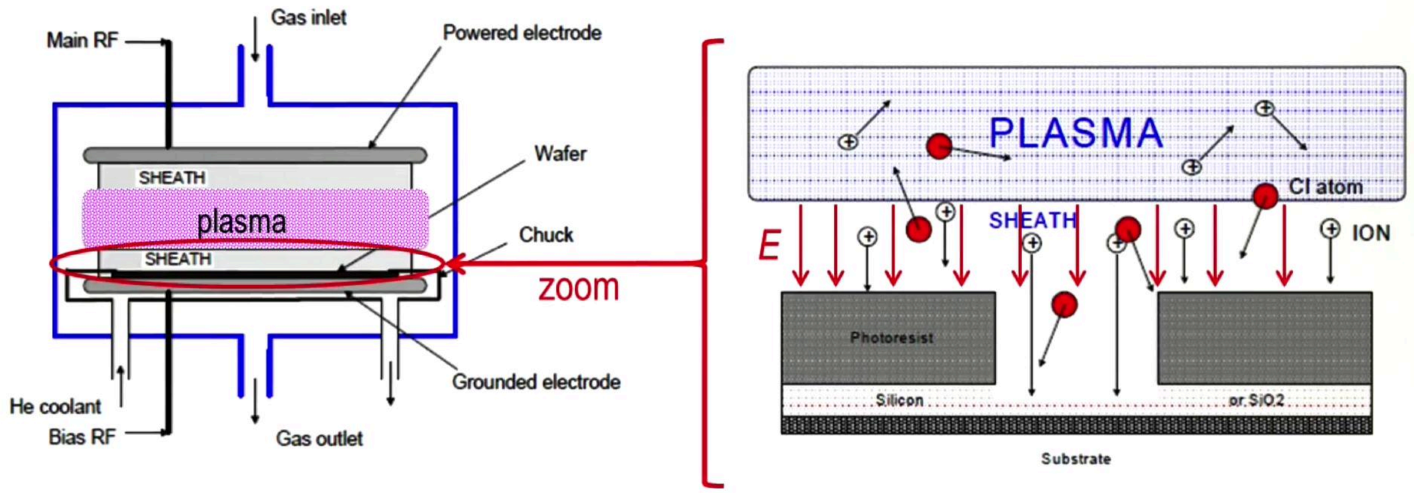
Let's see how our understanding of the sheath properties can help explain the applications of plasma etching. This is a plasma etch reactor. The vacuum chamber is blue. There are two electrodes and a plasma forms between the electrodes. Therefore there's a sheath in contact with each electrode. Let's look in more detail at the sheath region.

Notes

Summary

7m 33s

Plasma etch applications



- Uniform electric field above a substrate
- Vertical flux of ions
- Photoresist feature (0.1μm)<< sheath width (mm)

We zoom in on the sheath and we see that we have a plasma in contact with a Photoresist on a silicon substrate. The electric field in the plasma accelerates ions normally to the surface. The ions arrive perpendicular and go straight through the gaps in the Photoresist down to the silicon substrate. To resume, we have a uniform electric field above a substrate, vertical flux of ions. The Photoresist feature here is at the order of fractions of a micron, which is much less than a sheath width, therefore, the ions always arrive perpendicularly.

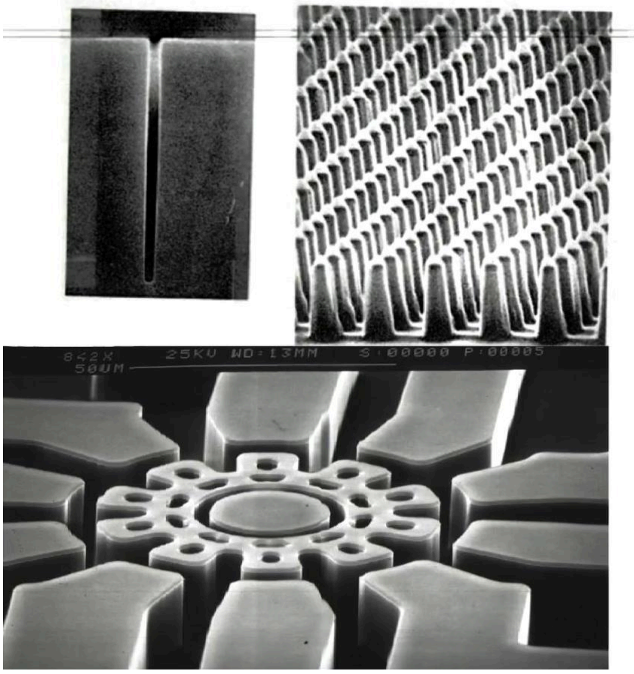
Notes

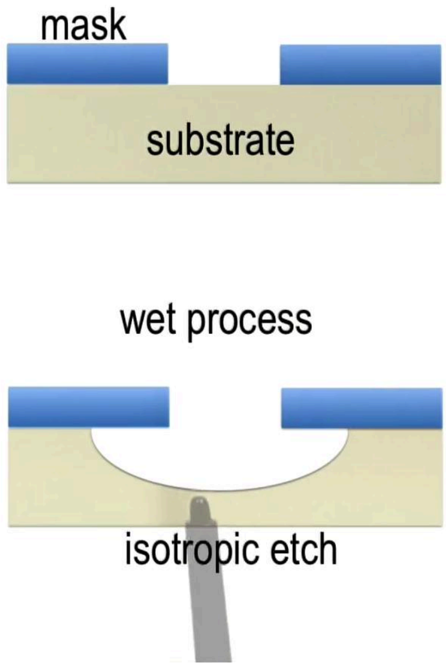
Summary

8m 04s

Plasma etch applications

Examples of high-aspect-ratio etching:





Plasma

If we want to make these type of structures using plasma etching with a high aspect ratio then we have to transfer the mask features in a faithful way, high fidelity onto the substrate. If we use a wet process, like in the early days of micro circuits, then the liquid will cause isotropic etch of the silicon wafer and not give a high fidelity reproduction of the photolithographic mask.

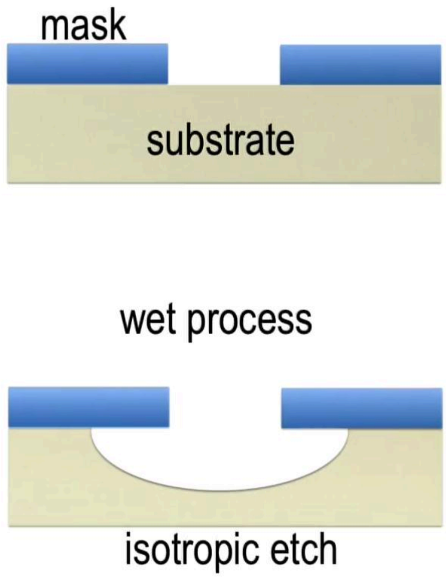
Notes

Summary

8m 48s

Plasma etch applications

Examples of high-aspect-ratio etching:



Plasma

And therefore these type of structures cannot be made using a wet process.

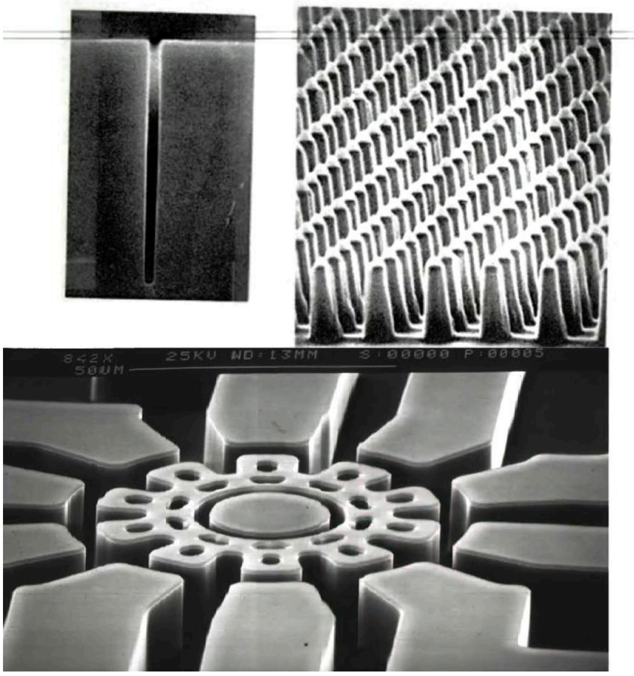
Notes

Summary

9m 18s

Plasma etch applications

Examples of high-aspect-ratio etching:



In plasma, the directionality of ions crossing the sheath provides anisotropic etching.

Plasma processing is the only commercial technology capable of such control, it is indispensable for modern IC manufacturing.

dry process

vertical etch

Plasma

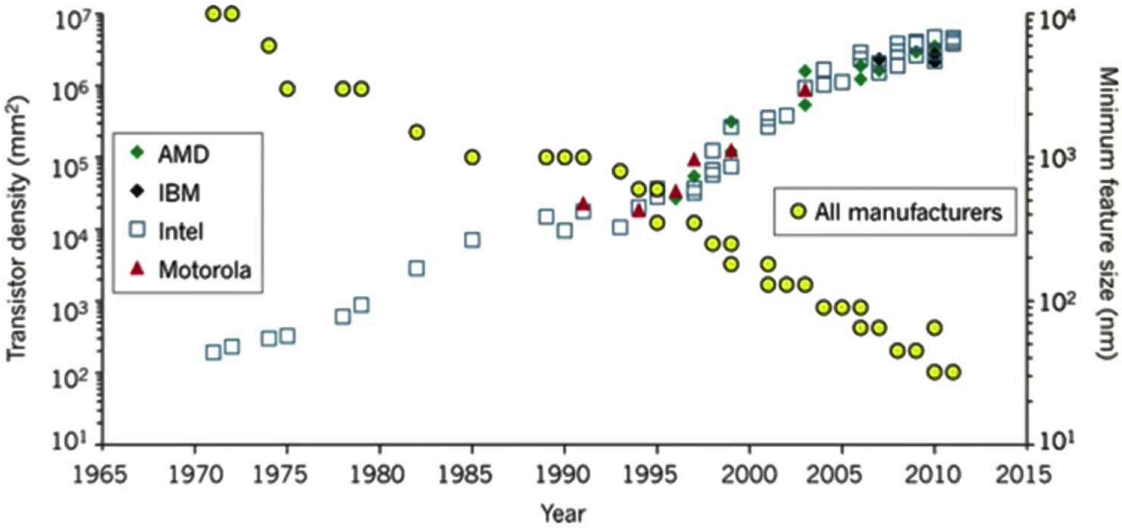
However, with the plasma, since the ions come down directly through the Photoresist then we get a vertical etch. This is called "dry process" or "plasma etching". So we see that in a plasma the anisotropic etching is given by the directionality of ions crossing the sheath. A very important result is that plasma processing is the only commercial technology capable of such control. Plasma is indispensable for modern integrated circuit manufacturing.

Notes

Summary

9m 25s

Plasma etch applications



- First p-n junction transistor – Shockley, Sparks, Teal - ~1951
- Basis for integrated circuits invented by Kilby and Noyce
- Early integrated circuits (1961 Fairchild camera) had 25 - 40 μm feature sizes
- Number of transistors per circuit doubles every couple of years (Moore's law, 1965)

Plasma

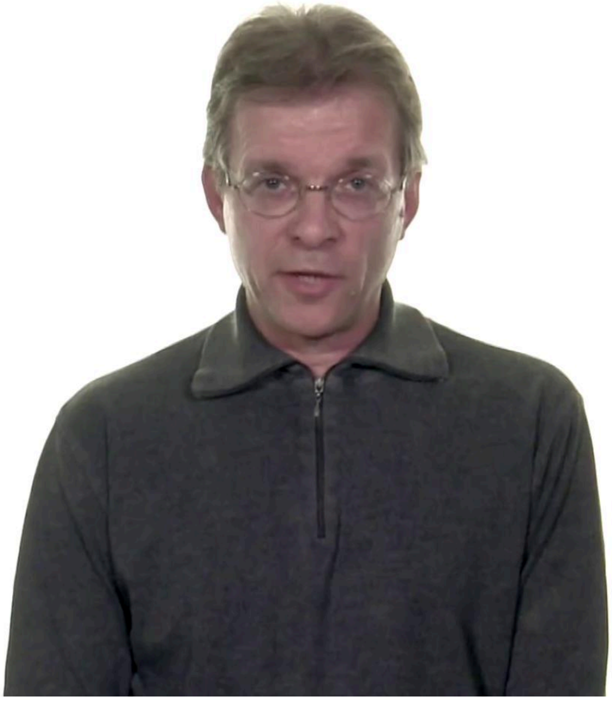
On this graph we see how micro electronics has improved during the years. This is the date. This is the number of transistors on a square millimeter of silicon. This is the minimum feature size on the integrated circuit in nanometers. So we see that during the years, the number of transistors on a square millimeter has increased strongly now coming up to 10 million transistors per square millimeter and the Photoresist size has come down to a few tens of nanometers as the control of plasma etching has improved. Historically the first p-n junction transistor was made in the 50's. The basis for integrated circuits was invented by Kilby, Noyce, and others. The very first integrated circuits, for example, in 1961 Fairchild camera. The feature sizes were of order of tens of microns. This graph shows how the number of transistors per circuit has almost doubled every few years and this is the famous Moore's law, which he formulated back in 1965.

Notes

Summary

9m 59s

Summary



- Sheath formation due to fact that electron mobility >> ion mobility
- Deduce basic properties of a sheath
- Directional ions in plasma etching indispensable for IC manufacturing

Plasma

To summarize this module, we have seen that sheath formation is due to the fact that the electron mobility is much greater than the ion mobility. From this we were able to deduce the basic properties of a sheath. And we've seen that the directional ions crossing a sheath is indispensable for integrated circuit manufacturing.

Notes

Summary

11m 19s