

# **Aspects of Plasma Processing:**

**A brief overview of plasma science in industry**

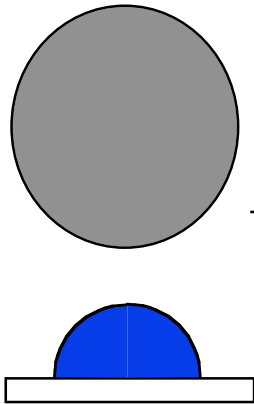


# Outline

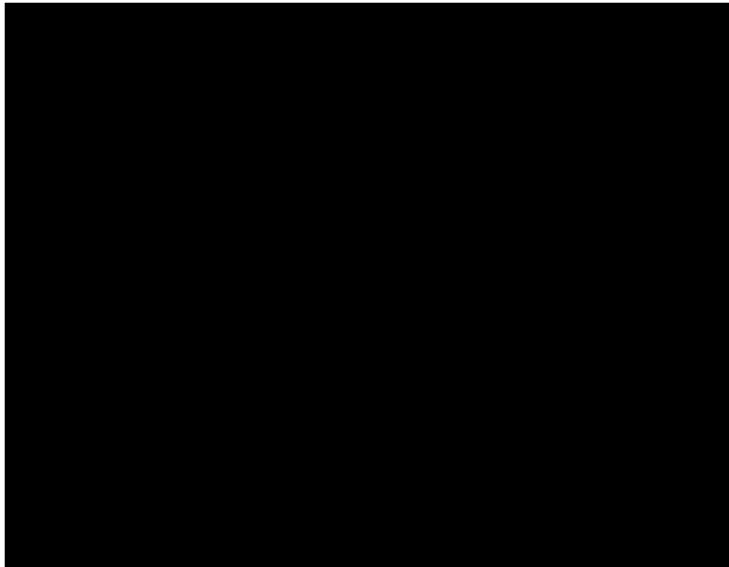
- 1) Why study plasma processing?
- 2) Diagnostic tools used to study processes
- 3) Overview of some plasma processes
- 4) Overview of some processing discharges
- 5) Opportunities in plasma processing

# How some view plasma processing

raw materials in



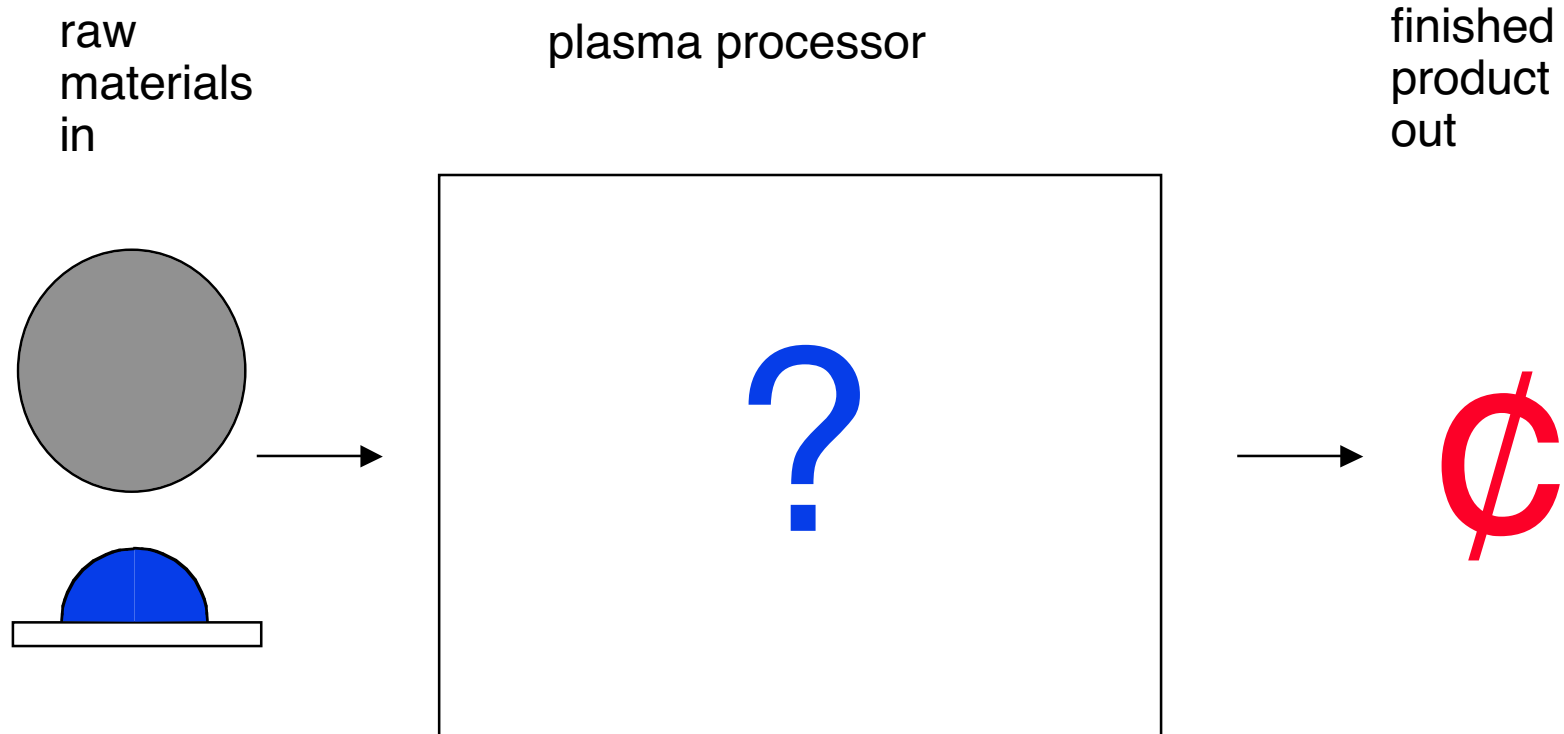
plasma processor



finished product out

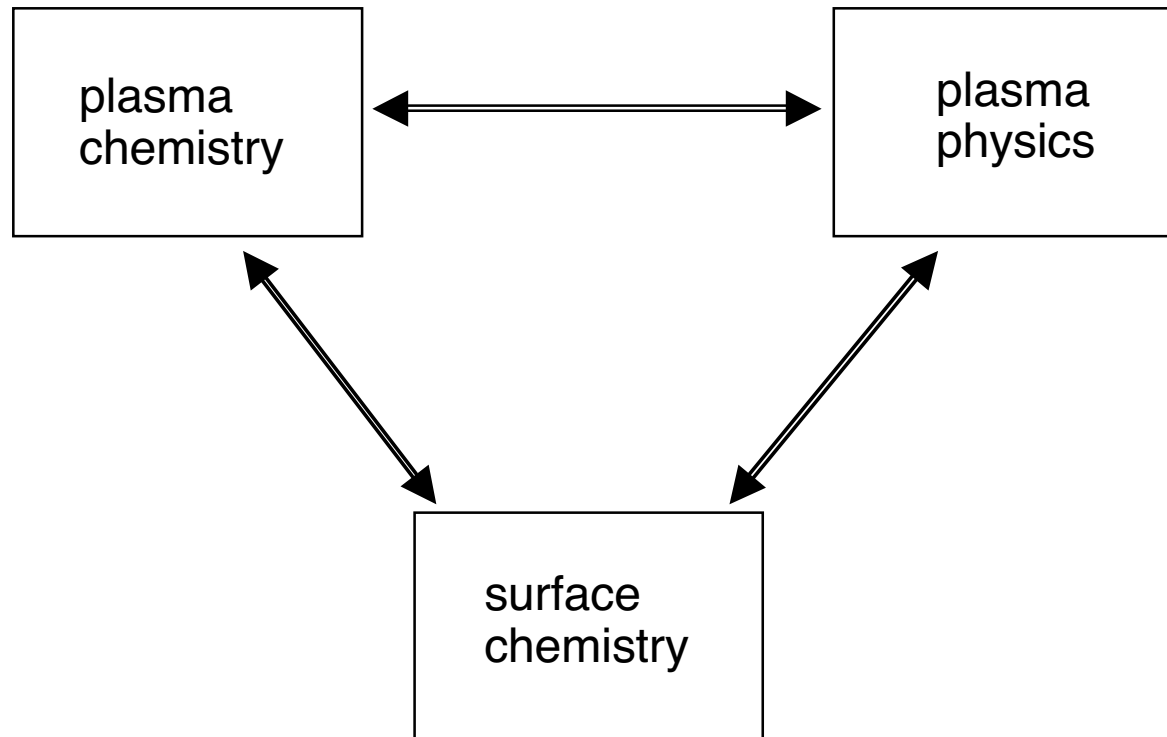


# How plasma processing really works



**One desires to understand the process so as to improve the value of finished product**

# Plasma processing

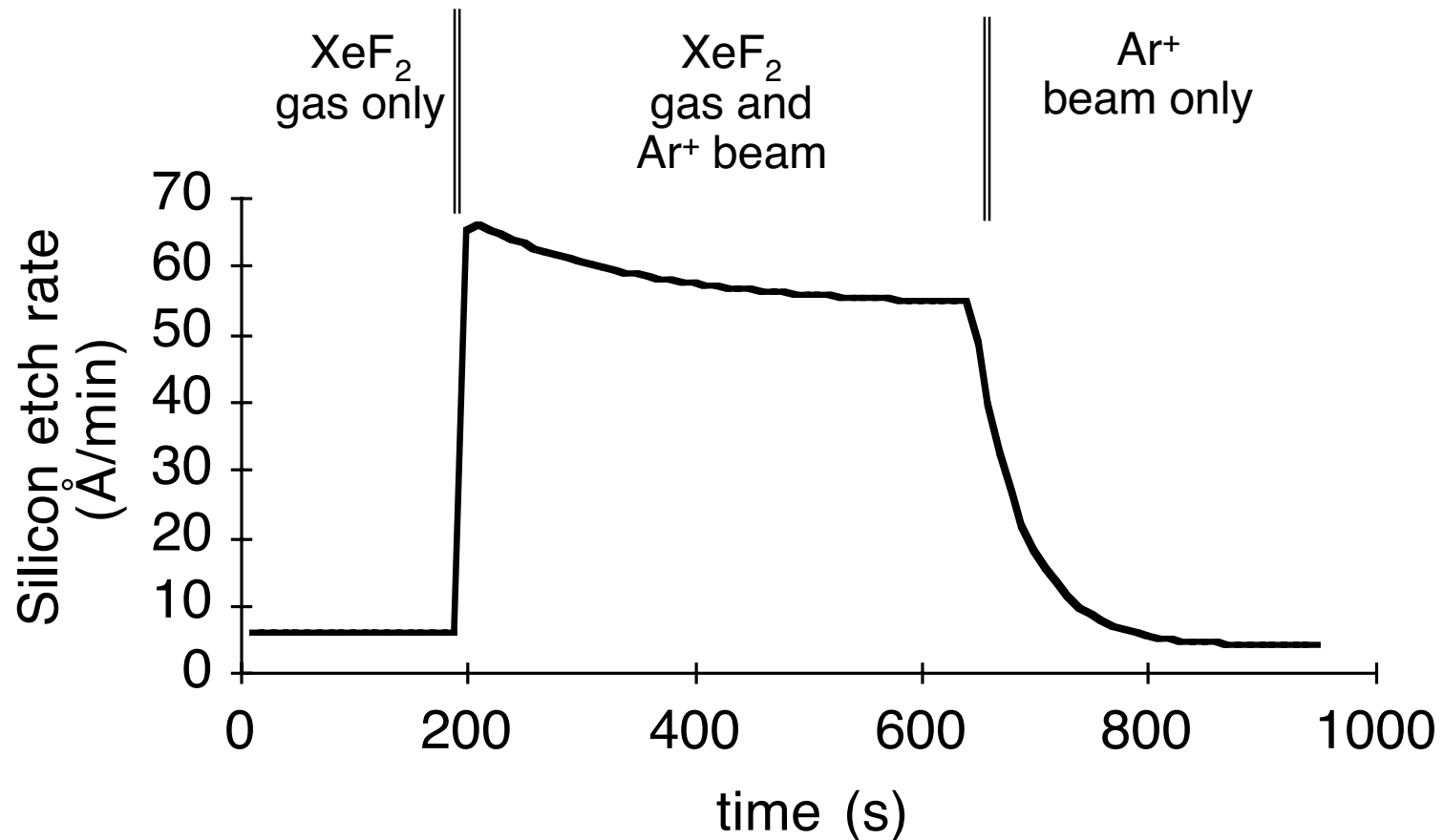


**Every process is a complex interaction between**

- **gas phase chemistry**
- **plasma conditions**
- **surface phase chemistry/conditions**

## Classic example

Silicon etching:



Work of Coburn and Winters in  
"Glow Discharge Processes" by Chapman (Wiley, 1980) p317

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# Plasma Physics

The basic plasma physics can be examined using probes

Langmuir probes give:

- $n_e$ ,  $T_e$ ,  $V_p$ , &  $V_f$

**Probes are quick and simple  
and give general information**

Certain details can only be obtained with more exotic diagnostic techniques

- laser-induced fluorescence,
- e-beam
- $\mu$ wave interferometer, etc.

**These other techniques are more difficult**

# Gas and Surface phase chemistry

To fully understand plasma processing one must understand the plasma and surface chemistry

The chemistry can be examined with the following

- FTIR spectroscopy
- absorption spectroscopy
- microwave spectroscopy
- optical emission spectroscopy
- laser-induced fluorescence
- mass spectrometry
- ellipsometry
- etc.

Each has advantages and disadvantages

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# General Types of Plasma Processes

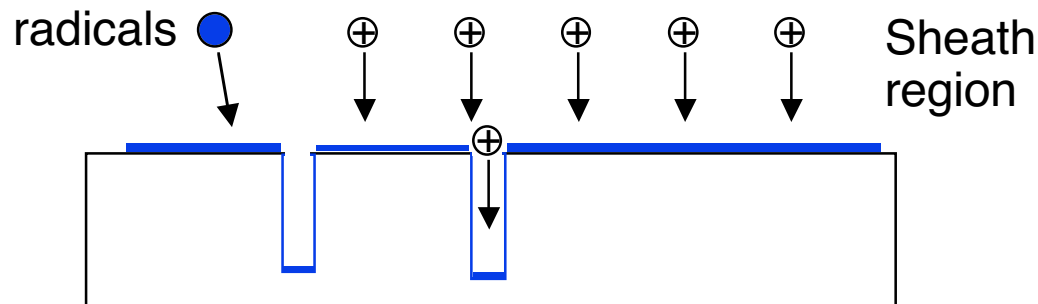
- 1) Etching
- 2) Chemical Vapor Deposition (CVD)
- 3) Sputtering/Physical Vapor Deposition (PVD)
- 4) Implantation
- 5) Sprays
- 6) Chemical Production/Destruction
- 7) Medical Sterilization (Johnson & Johnson)
- 8) etc.

# Plasma Assisted Etching

20 to 30 years ago most etching was “wet” chemistry

EPA and industrial requirements have almost reversed this

Plasma



Typical parameters

Gas:  $\text{Cl}_2$ ,  $\text{CF}_4$ ,  $\text{O}_2$  (ashing)

Pressure:  $\sim 10$  mT

Plasma density:  $\sim 10^9 - 10^{11} \text{ cm}^{-3}$

Electron Temperature:  $\sim 5-10$  eV

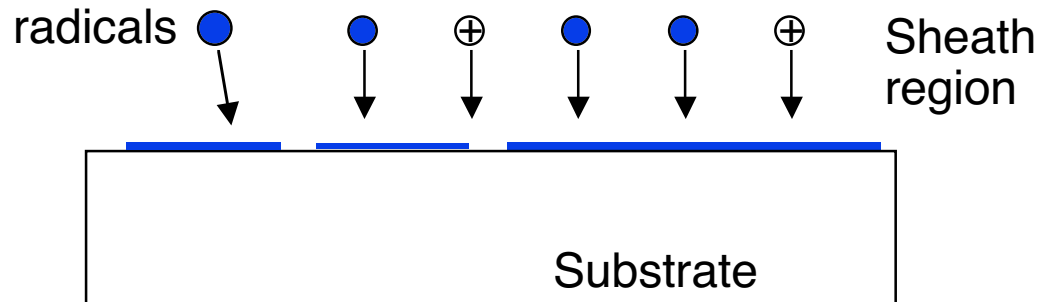
Radicals produced in the plasma will drift to the surface

Ions accelerated across the sheath deliver energy,  
driving the chemical reaction(s) between  
the radicals and the surface material

The resulting molecules leave in gaseous form

# Plasma Assisted Chemical Vapor Deposition (PCVD)

Plasma



Typical parameters  
Gas:  $\text{SiH}_4$  [Silane], for  $\alpha$ -Si  
 $\text{SiH}_4/\text{O}_2$ , for  $\text{SiO}_2$   
 $\text{Si}(\text{OC}_2\text{H}_5)_4$ [TEOS]/ $\text{O}_2$  [1%/99%]  
Pressure:  $\sim 200$  -  $1000$  mT  
Temperature:  $100$ - $800^\circ\text{C}$   
Plasma density:  $\sim 10^7$  -  $10^9$   $\text{cm}^{-3}$   
Electron Temperature:  $\sim 5$ - $10$  eV

Radicals produced in the plasma and the supplied feed gas drift to the surface

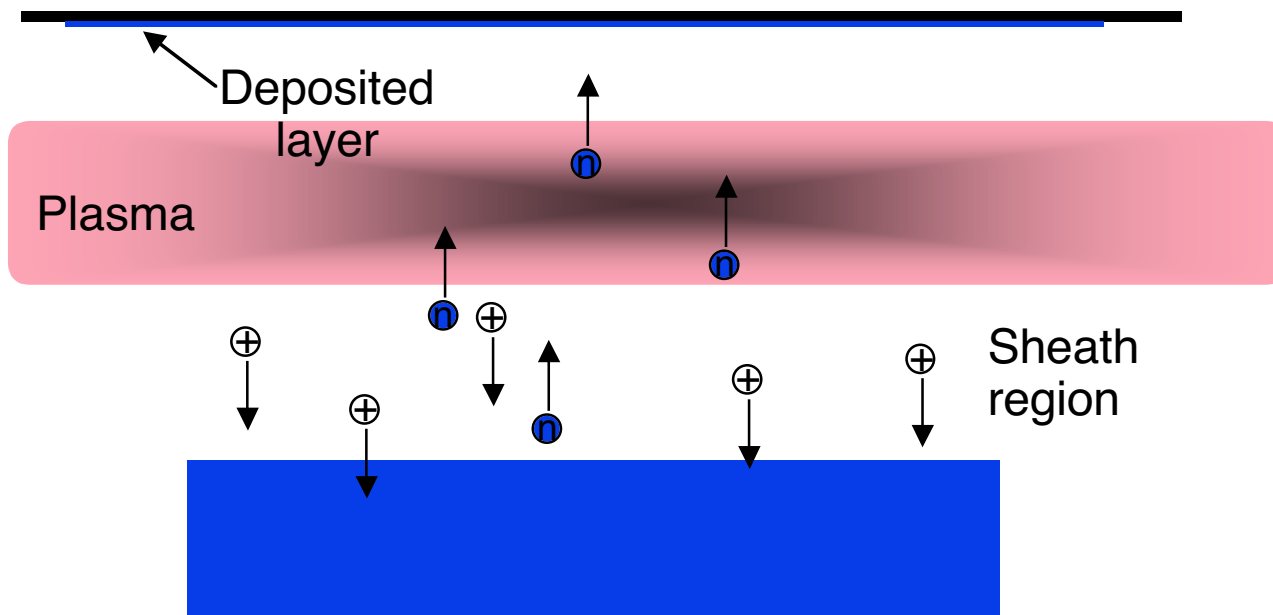
The radicals do not chemically react with the substrate

Instead the radicals combine to form stable chemicals (Solids!)

Ions accelerated across the sheath deliver energy that tends to "cross-link" these chemical bonds

Growth pattern is very complex

# Sputtering



Typical parameters  
Gas: Ar, N<sub>2</sub>, O<sub>2</sub> (reactive)  
Pressure: ~100 mT  
Plasma density: ~10<sup>9</sup> - 10<sup>10</sup> cm<sup>-3</sup>  
Electron Temperature: ~5-15 eV

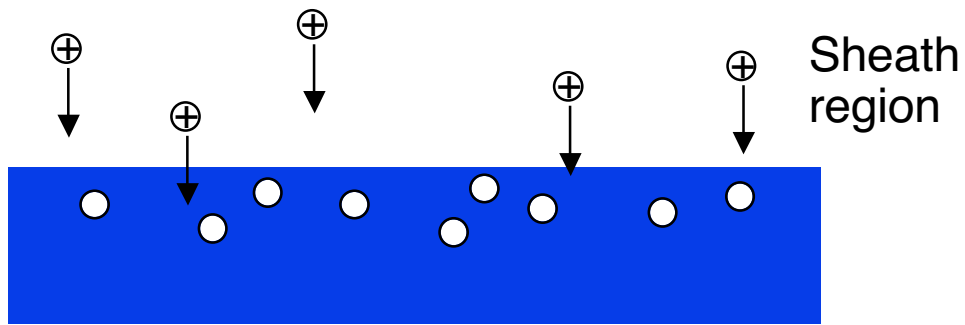
Ions are accelerated into target

Some of the surface atoms are sputtered off of the target.

These sputtered atoms “flow” across the chamber to where they are deposited

# Implantation

Plasma



Typical parameters  
Gas:  $\text{BF}_3$ ,  $\text{AsH}_3$ , (Si Doping)  
 $\text{N}_2$ ,  $\text{O}_2$  (Metal hardening)  
Pressure:  $\sim 10$  mT  
Plasma density:  $\sim 10^9 - 10^{10} \text{ cm}^{-3}$   
Electron Temperature:  $\sim 5-15$  eV

Ions are accelerated (Typically in a pulsed mode)

Upon impact, they drive deep into the cathode,  
where they are trapped

These implanted ions change the surface structure

This results in a change of the surface characteristics  
(Hardness, friction, wear resistance, etc)

# Outline

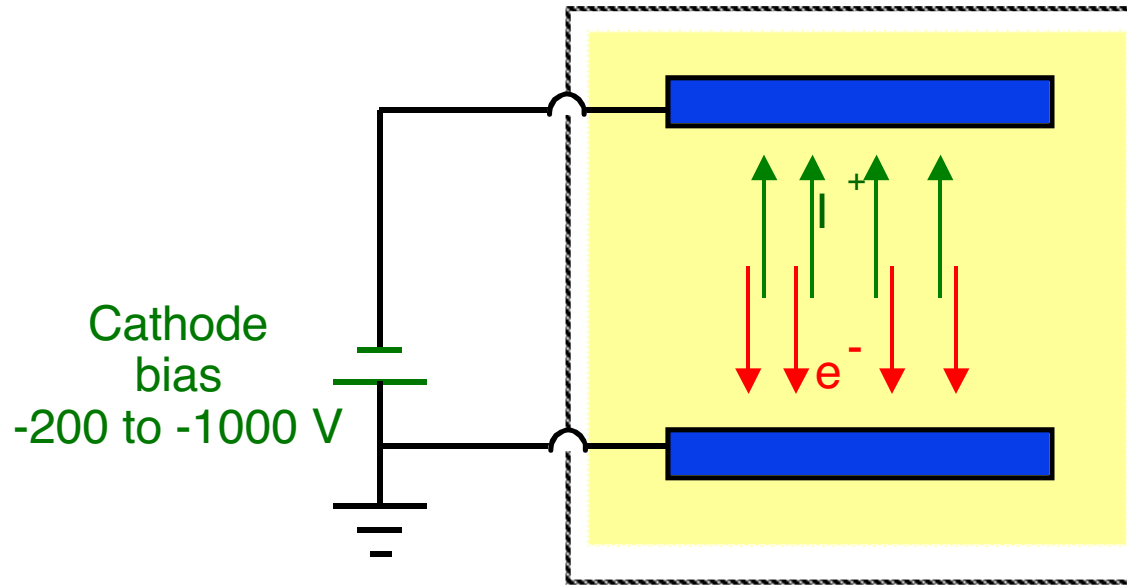
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# General types of processing discharges

- 1) DC Glow
  - Cold Cathode
  - Hot Cathode ('Filament' discharge)
  - Magnetron (Magnetized cold cathode)
- 2) Radio Frequency (~0.1 - 100 MHz)
  - Capacitively Coupled (rf)
  - Inductively Coupled Plasma (ICP)
  - Helicon (Magnetically enhanced wave coupling)
- 3) Microwave (~1 - 20 GHz)
  - Microwave
  - Electron Cyclotron Resonance (ECR)  
(Magnetically enhanced wave coupling)
- 7) Neutral Beams
- 8) Thermal Plasmas
  - Arcs
  - Torches
- 9) etc.

The choice of source depends on the desired process.  
We will look at some of the major sources for Si Processing  
(and a few others).

## Cold Cathode (DC/ Pulsed DC discharge)



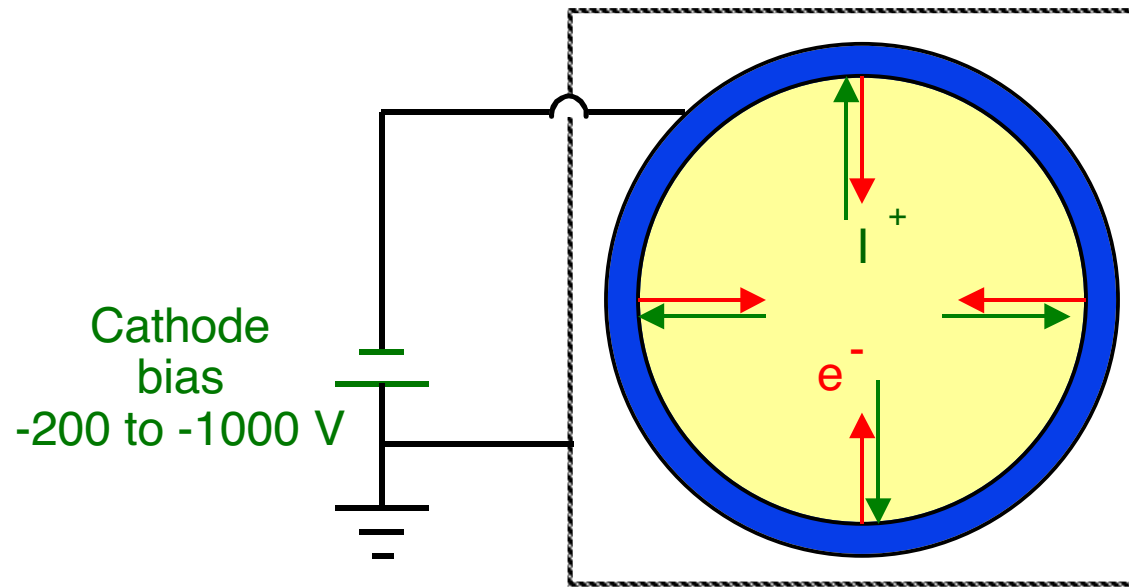
Ions are accelerated to the cathode

~10% of the impacts produce a secondary electron

These secondary electrons are accelerated back across the plasma  
Impact with neutrals produces additional ion/electron pairs  
which sustains the discharge

Pulsed version used for Plasma based ion implantation

## Hollow Cathode (DC/ Pulsed)



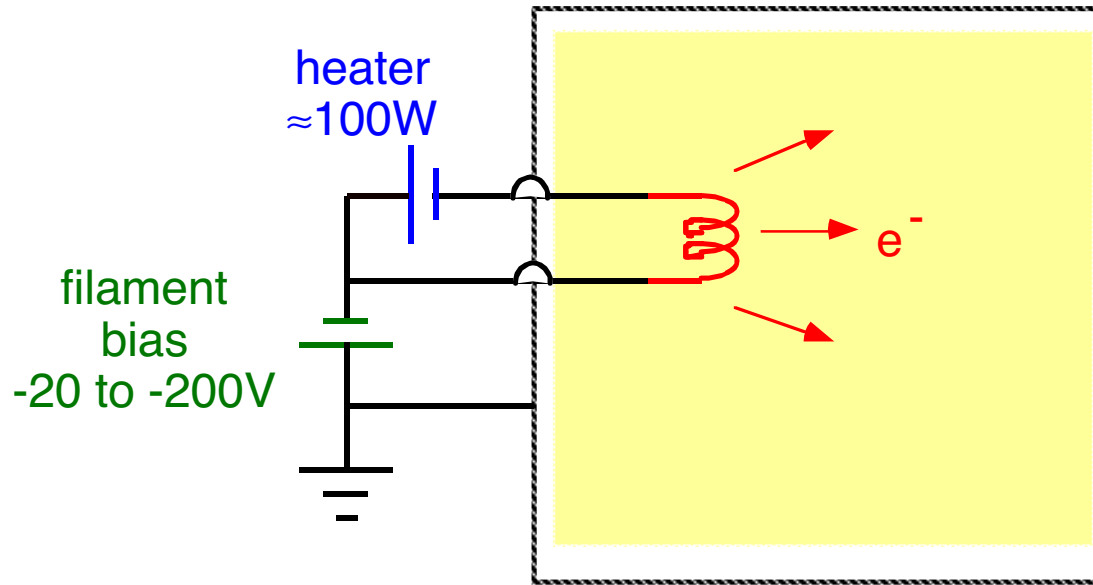
Hollow cathode are a variant of the planar cold cathode

Major advantage is that the electrons are better confined

Result is a denser plasma

Pulsed version used for Plasma based ion implantation  
Patent pending (Goeckner et al.)

## Hot DC Cathode (Filament discharge)



A heating current is drawn through a filament  
(Typically Thoriated Tungsten - Looks like a light bulb)

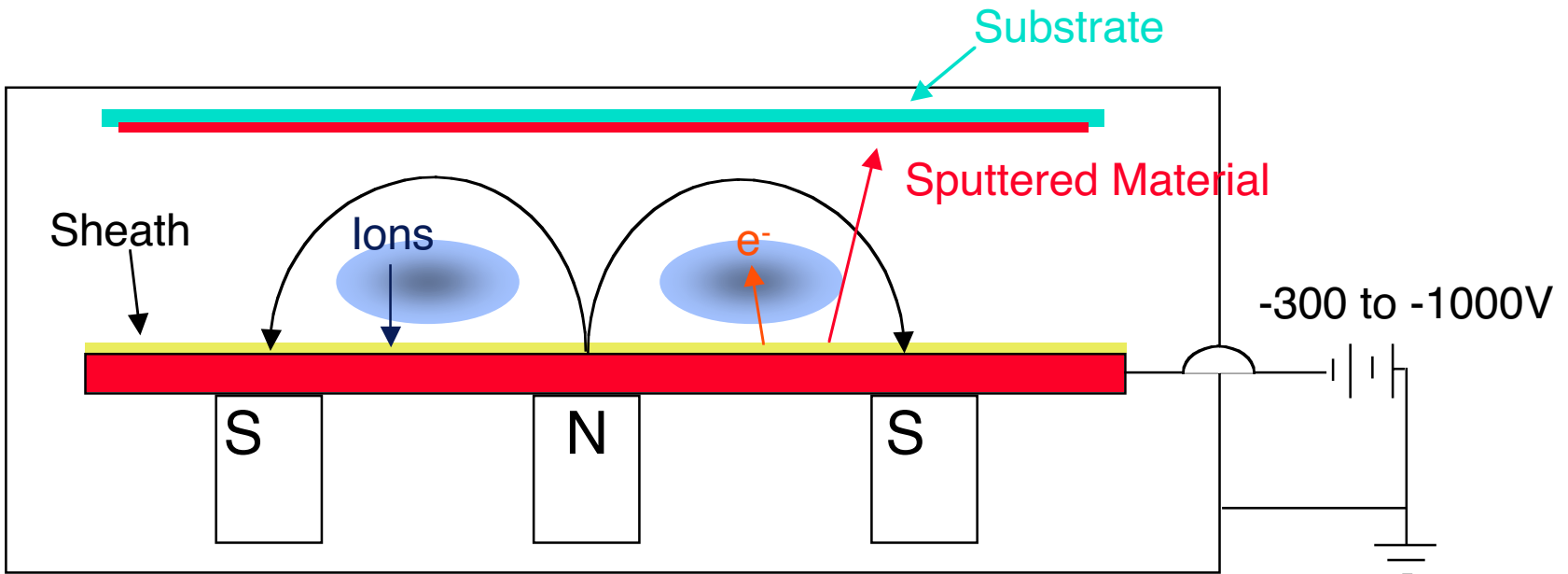
At about  $1800^{\circ}\text{C}$  the filament emits electrons

A second power supply is used to accelerate the electrons off of the filament

These energetic electrons ionize the local neutral gas

Used for standard ion implantation and Plasma based ion implantation

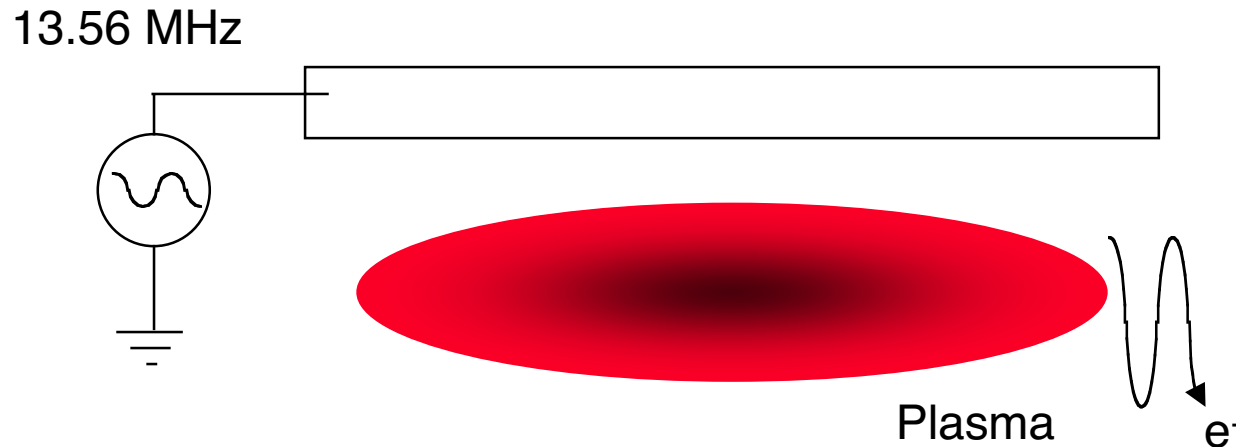
# Sputtering Magnetrons (Magnetized cold cathodes)



The sputtering process  
Ions accelerated across sheath to surface  
material sputtered  
secondary electrons produced

The plasma source  
Secondary, created by ion bombardment of the cathode  
are trapped between the sheath and B field and produce more ions

# Radio Frequency (RF) Plasmas (Capacitively coupled)



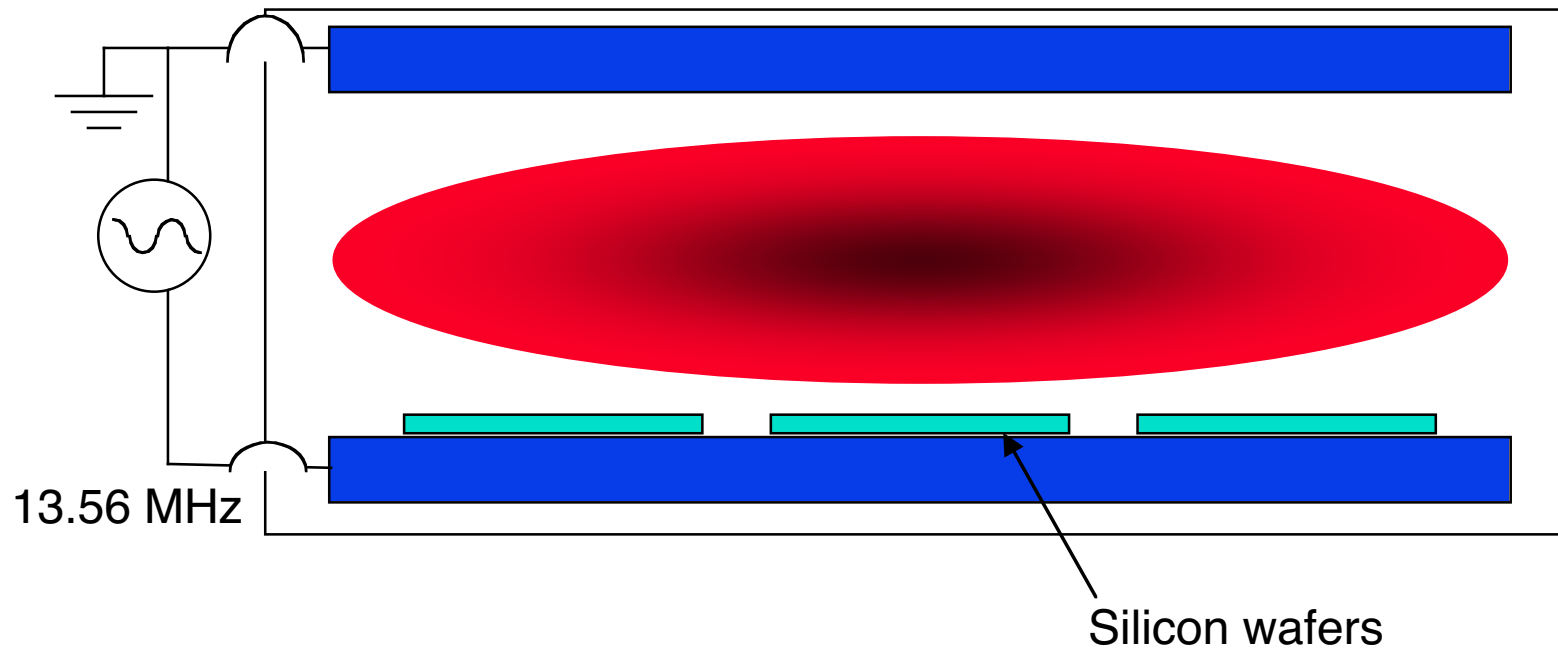
The RF signal is used to setup a time varying electric field between the plasma and the electrode

This electric field accelerates the electrons in and out of the plasma

The electrons gain energy and ionize the local gas

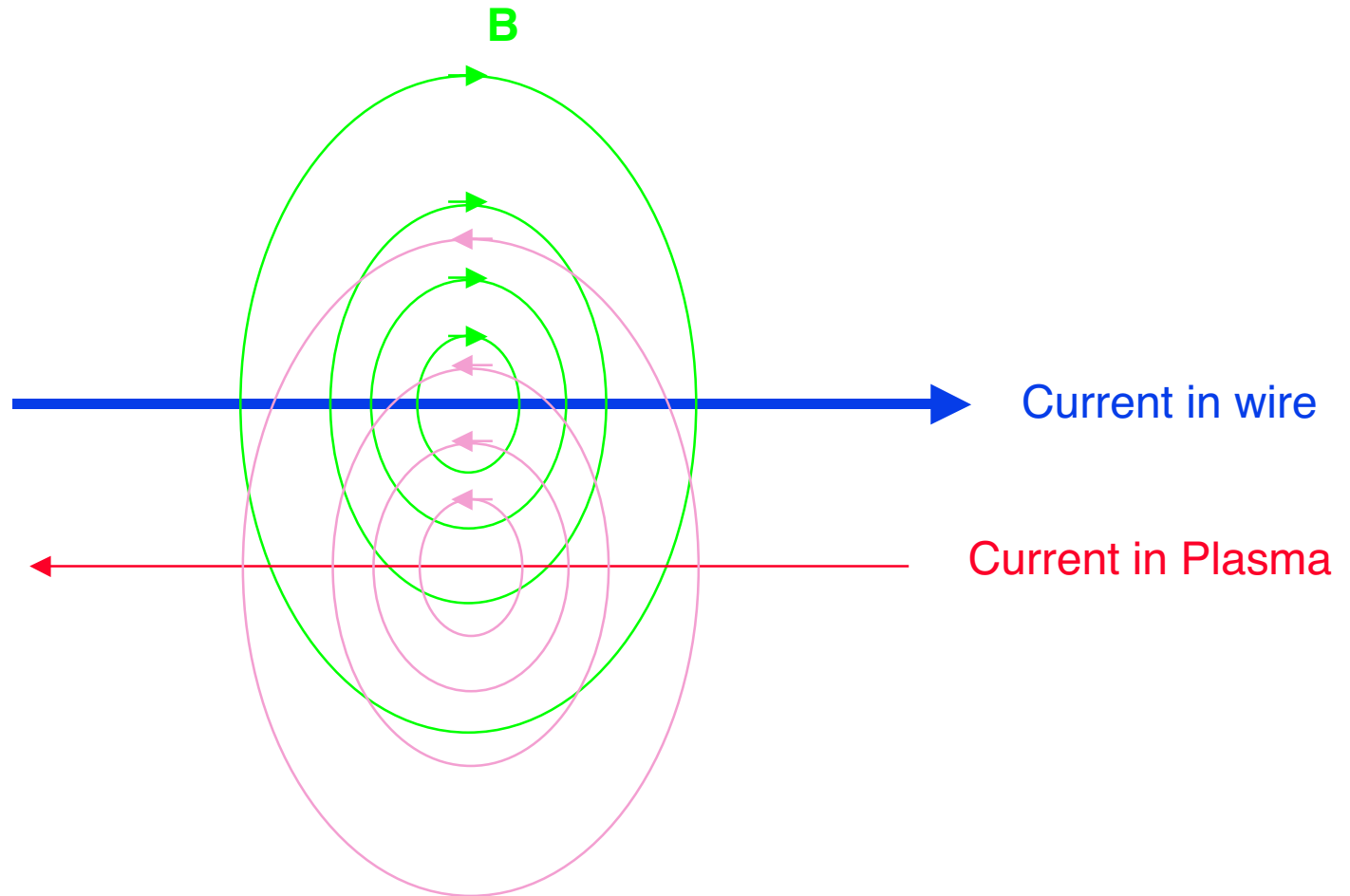
# Example configuration of an RF discharge

Reactive Ion Etcher (RIE)



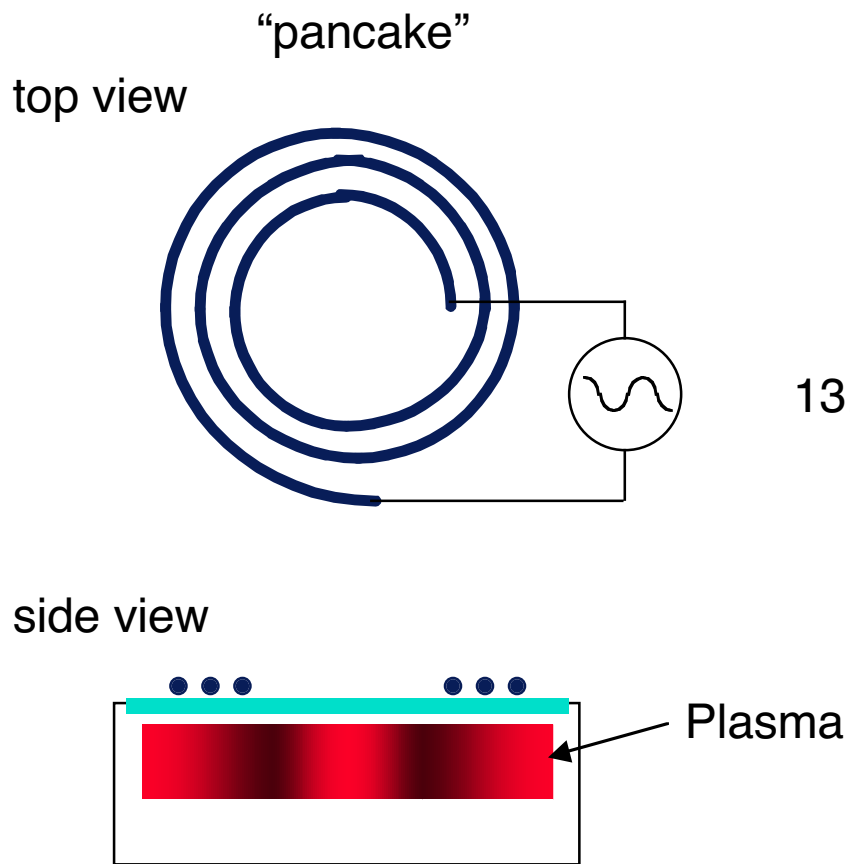
This was the most common configuration in the semiconductor industry

# Inductively coupled plasmas (ICP)

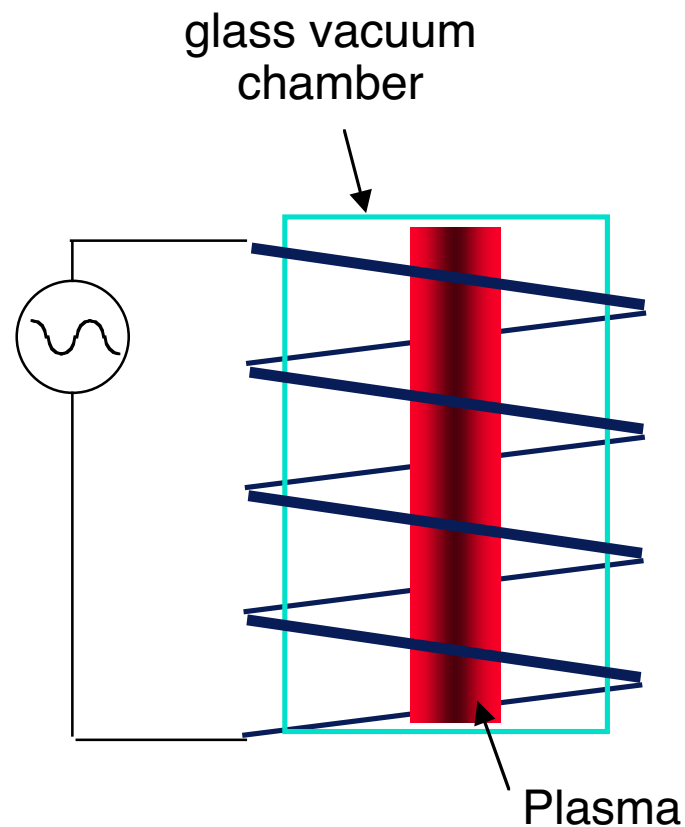


Other Names: Radio frequency inductive (RFI) & Transformer coupled plasmas (TCP)

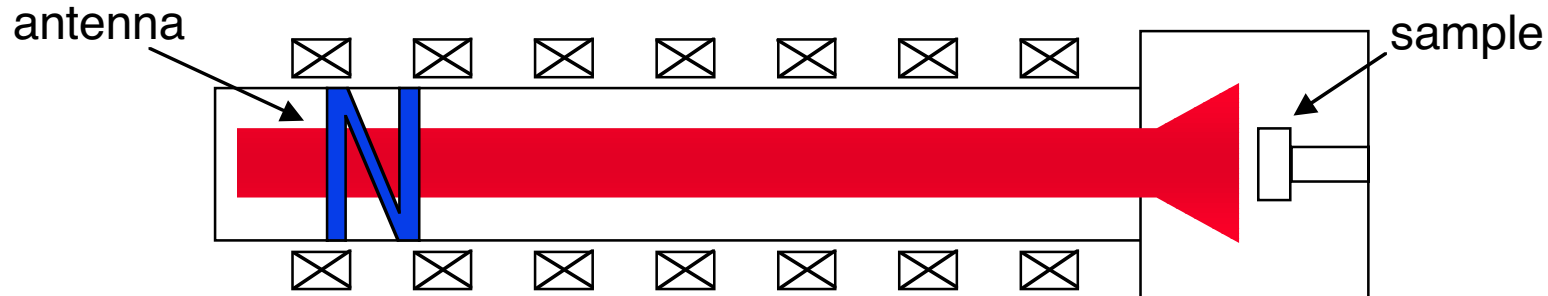
# Example antenna configurations for ICP discharges



13.56 MHz



# Helicon Discharges



The antenna is used to launch Helicon waves.

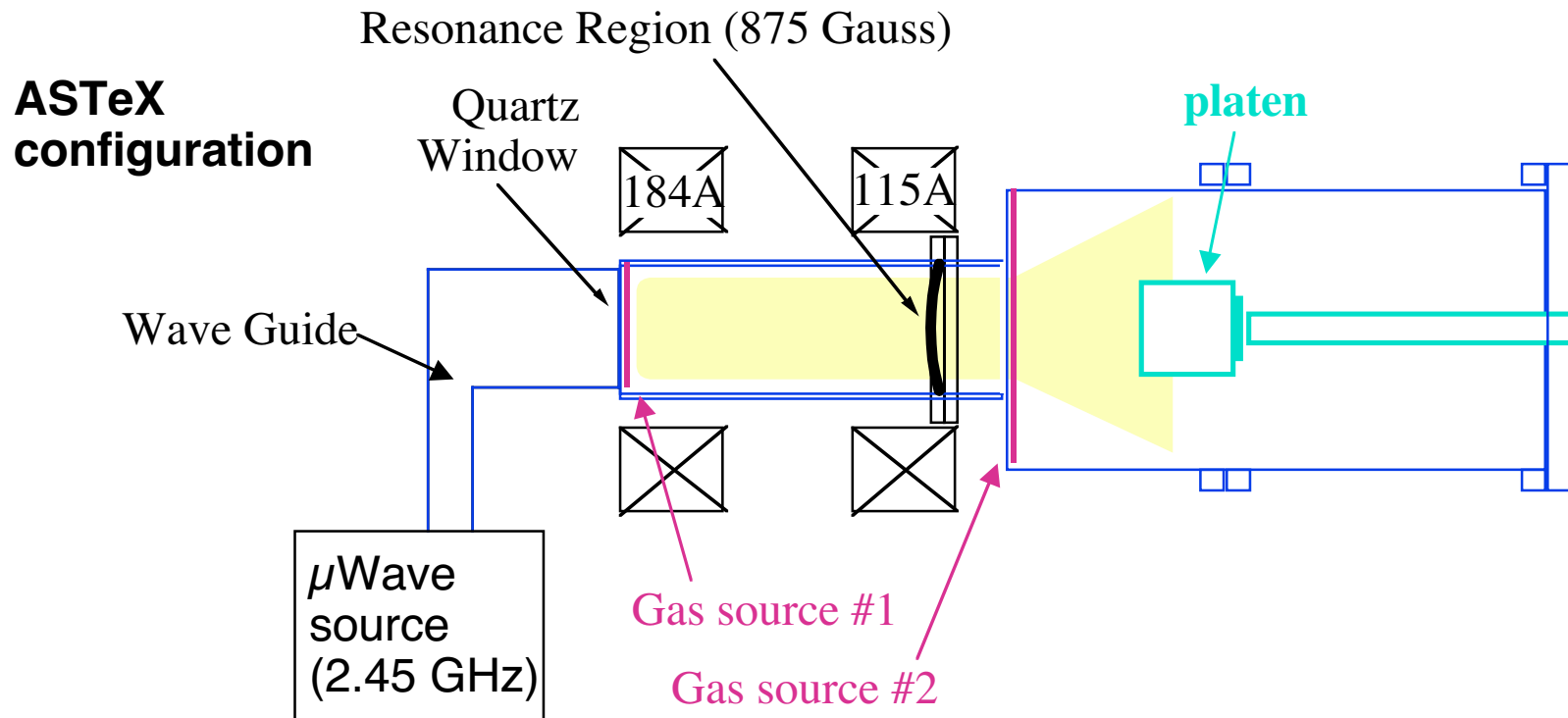
Helicon waves can be excited over a range of frequencies  $f$

$$f_{ci} \ll f_l \ll f \ll f_{ce} \ll f_{pe}$$

Typically  $f \approx 7$  to  $10$  MHz

Currently Helicon discharges are being evaluated in basic physics experiments (This will change soon?)

# Electron Cyclotron Resonance (ECR) discharges



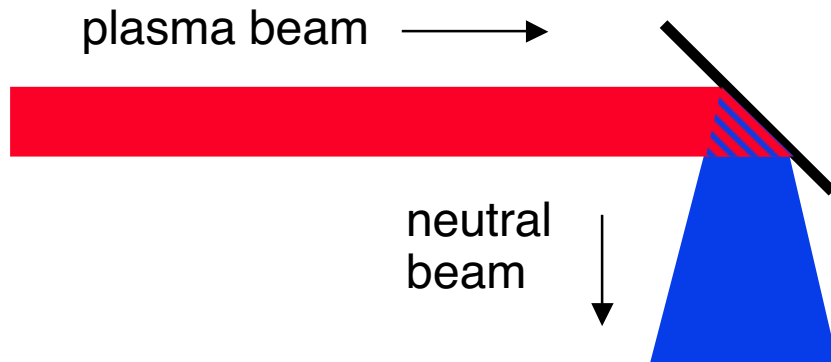
In a magnetic field the electrons resonate at the cyclotron frequency

$$f = eB / 2\pi m_e c = 2.80 \times 10^6 B \text{ Hz}$$

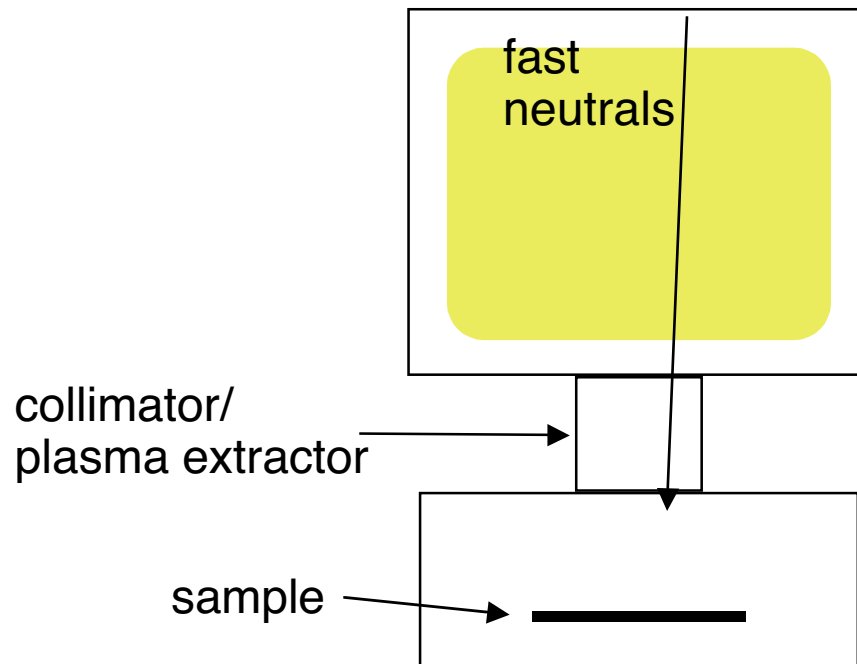
When in resonance with the  $\mu$ Waves, the electrons absorb energy

These energized electrons ionize the local neutral gas

# Neutral beam sources



Currently being used here to study D-T recycling

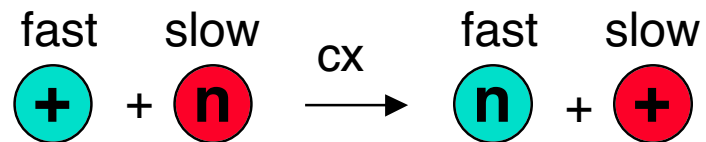
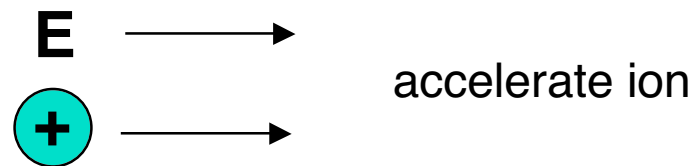


Currently being built here to study fast O impact on spacecraft parts

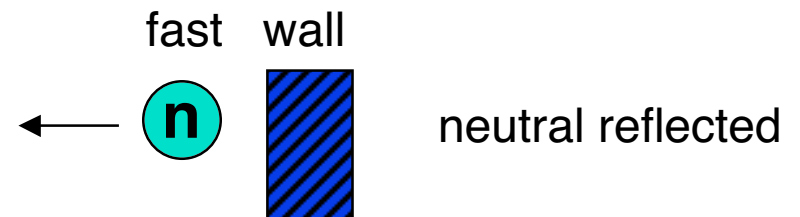
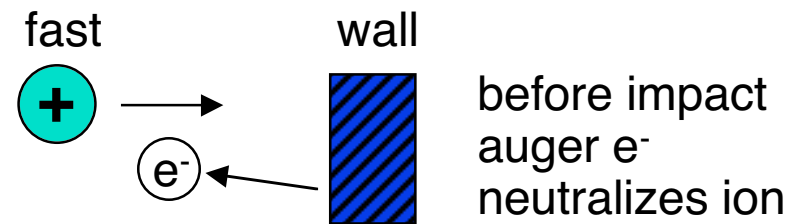
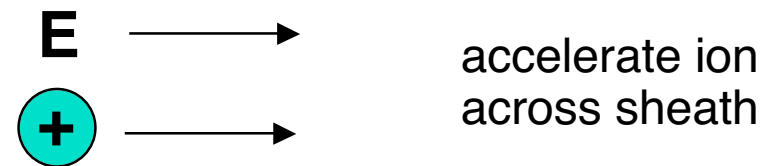
# Neutral beams

## Methods of producing fast neutrals

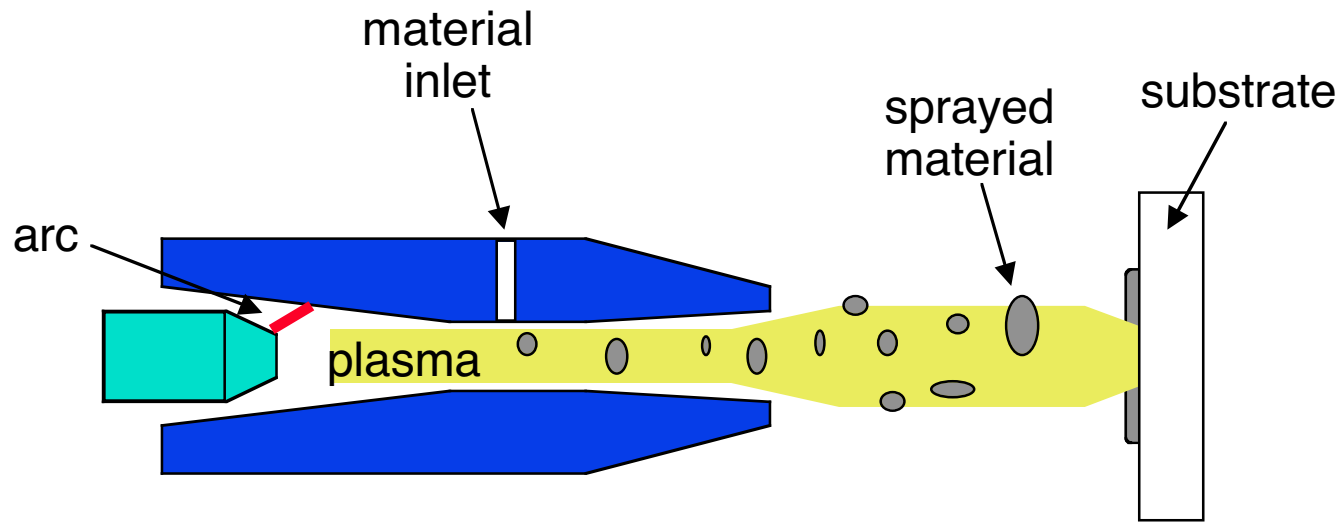
### Charge exchange



### Wall neutralization



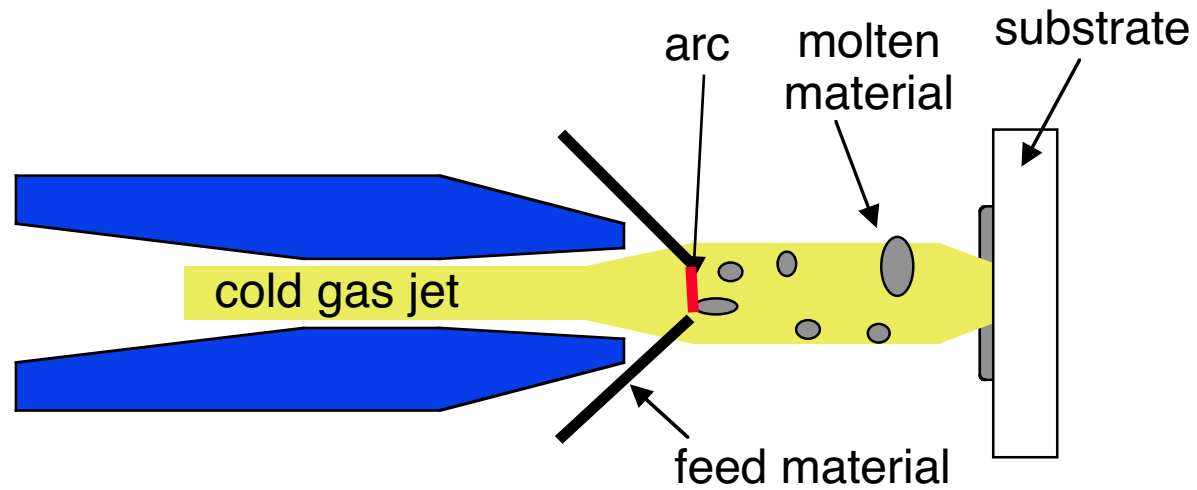
# Thermal plasma sprays



Sprayed material is “melted” by plasma

Thermals

# Thermal arc sprays



# Is Plasma Science Physics, Engineering or Chemistry?

The simple answer is: A lot of physics, engineering and chemistry.

The typical process plasma is not well understood.

Until recently the typical process plasma was “tweaked” to make it work.

Because of increasing demands on industry there is a push to understand why a process works, e.g. physics and chemistry.

This knowledge is then used to see how the process can be improved, e.g. engineering

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# Opportunities in Plasma Processing

Are there opportunities in plasma processing?

Yes. While not limitless there are opportunities.

Academic: There appears to be a shift toward more applied physics.

National Labs have built strong plasma processing groups  
Leaders are: Sandia & Los Alamos

Research Universities are hiring 3 to 6 Profs/Year (Phys. & Eng.)

Small Universities like Plasma Processing  
Relatively low \$ to run and easy to involve students

Industrial: Over the last few years hiring has increased dramatically  
Some “fresh” PhDs are getting ~10 interviews and 3-4 job offers.

(Note the market place does change!)