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

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How plasma processing really works

One desires to understand the process so as to improve the value of finished product
Every process is a complex interaction between
- gas phase chemistry
- plasma conditions
- surface phase chemistry/conditions
Classic example

Silicon etching:

- XeF₂ gas only
- XeF₂ gas and Ar⁺ beam
- Ar⁺ beam only

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.

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.

Typical parameters:
- Gas: Cl₂, CF₄, O₂ (ashing)
- Pressure: ~10 mT
- Plasma density: ~10⁹ - 10¹¹ cm⁻³
- Electron Temperature: ~5-10 eV
Plasma Assisted Chemical Vapor Deposition (PCVD)

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.

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

Typical parameters:
- Gas: Ar, N₂, O₂ (reactive)
- Pressure: ~100 mT
- Plasma density: ~10⁹ - 10¹⁰ cm⁻³
- Electron Temperature: ~5-15 eV
Implantation

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)

Typical parameters
Gas: BF$_3$, AsH$_3$, (Si Doping)
N$_2$, O$_2$ (Metal hardening)
Pressure: $\sim$10 mT
Plasma density: $\sim$10$^9$ - 10$^{10}$ cm$^{-3}$
Electron Temperature: $\sim$5-15 eV
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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 are a variant of the planar cold cathode. The major advantage is that the electrons are better confined. The result is a denser plasma. The pulsed version is used for plasma-based ion implantation. Patent pending (Goeckner et al.)
A heating current is drawn through a filament (Typically Thoriated Tungsten - Looks like a light bulb)

At about 1800°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
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)

13.56 MHz

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)

Silicon wafers

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

“pancake”

13.56 MHz
glass vacuum chamber

Plasma
The antenna is used to launch Helicon waves.

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

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

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

\[ f = \frac{eB}{2\pi m_e c} = 2.80 \times 10^6 \text{ B Hz} \]

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

\[ \text{accelerate ion} \quad \text{E} \quad \begin{array}{c} + \end{array} \quad \begin{array}{c} + \end{array} \quad \text{fast} \quad \text{slow} \quad \text{cx} \quad \text{fast} \quad \text{slow} \]

Wall neutralization

\[ \text{accelerate ion across sheath} \quad \text{E} \quad \begin{array}{c} + \end{array} \quad \begin{array}{c} + \end{array} \quad \text{fast} \quad \text{wall} \quad \text{e}^- \quad \text{neutralizes ion} \quad \text{neutral reflected} \]
Sprayed material is “melted” by plasma

Thermals
Thermal arc sprays

cold gas jet

arc

molten material

substrate

feed material
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!)