EE/Phys5383 – Plasma Technology Class and Lab – Spring 2002

(XX5383 will be the new listing in the upcoming catalog. This is being taught under the following labels: EE4v95, EE7v82, Phys5v49)

Instructor: Prof. Matthew J. Goeckner
Office: EC 2.918
Phone: (972) 883-4293
Email: goeckner @ utdallas . edu

Office Hours:
Tuesday 1:30 to 3:30
Wednesday 1:30 to 3:30  (Really ~8:30 to 5 M-F)
Or by appointment

Prerequisites:
EE 4301 or equivalent

Class: Room: EC 2.120
Time: Monday, Wednesday 3:30-4:45
Final: 2:00 PM Friday, May 10th.

Texts:

Required:

Recommended:

NOTE YOU WILL BE EXPECTED TO LOOK AT OTHER BOOKS AS WELL AS THE TWO ASSIGNED

Grading: (dates subject to change)

Test 1 25% Wed. April 3rd.
Final or project 25% 2:00 PM Friday, May 10th.
Weekly notes 20% (Rewrite of the week’s reading/classnotes)
Homework 30%

*Homework and notes handed in after the due date will not be counted!
(They can be slid under my door anytime before 8 AM the next morning.)
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WHAT IS A PLASMA AND WHERE IS IT FOUND?

Often in grade school and high school students are told that there are three states of matter, solid, liquid and gas. These are in some sense differentiated by energy or temperature. Note that temperature has a very special meaning – that is temperature is a measure of random energy as opposed to directed energy. Random energy is where each individual particle is moving with a certain velocity but the average velocity of all particles is zero. Remember velocity is a vector and thus has both a magnitude and direction, while energy is a scalar and only has a magnitude. Directed energy is when the average velocity is not zero. We will discuss this in more detail later. Lets think about the chemical H₂O. When it is very cold, e.g. has low random energy we get ice or snow. (Note that one can through a snowball – giving it directed energy but not random energy.) If we put an ice cube on top of a stove and turn on the stove, we turn the H₂O in to water – a liquid. As we continue to heat the H₂O it boils and gives off stream – a gas. If we were able to continue to push energy into the H₂O

A fourth state of matter, plasma, occurs when we continue to heat a gas. Let us do a gedanken (thought) experiment to see what might happen. First the original gas might be composed molecules or free atoms or some combination of the two. As we heat the gas we are giving these particles more random energy. At some point some of this translational energy that the particles have get transferred into internal energy for the particles. This will usually occur through a collision type process. At this point a number of things might occur. 1) The molecules can breakup. (High energy usually does not allow the gas molecules to form larger molecules.) 2) An electron will be freed from the particle (atom or molecule). Having the molecules breakup is not interesting – we still have a gas, albeit slightly different. For example H₂O might become HO and H. This however is still a gas. On the other hand having an electron escape its orbit can provide some thing very different. As the electron carries a charge, ‘-e’, the left over part of the particle must also have a charge but of opposite sign, ‘e’, and it now known as an ‘ion’. If we have only a few of these charged particles in our gas, we do not see much charge in the properties of the system. However, if we continue to heat the gas and increase the number of charged particles eventually we will have enough of them that they interact in a ‘collective’ electromagnetic manner. At this point we have a plasma. (Note: A few years ago, ~1998, a fifth state of matter was observed in a high energy particle experiment. This state of mater is known as a “quark-gluon plasma”. In this case even the standard elementary particle, neutrons and protons, have been shattered. It is thought that this was the state of the very early universe.) Where the precise division is between gas and plasma is an open debate. Often one can see some collective behaviors when as little as 0.0001% – or less! – of the gas particles have been turned into ions. For example candle flames have been shown to be movable with electric fields. This fact was used to design (and patent) an improved fire sprinkler system. Think about this the next time you have a birthday. On the other hand some people claim that ‘true’ plasmas occur only when all of the particles have been ionized.

Plasmas exist over a huge range of particle densities and particle temperatures (energies). At one extreme in particle density we have the sun, which has a density similar to typical solids or liquids. At the other extreme we have interstellar space, which is almost a perfect vacuum. Ion temperatures may run from room temperature to many Mega °C. Electron temperatures are observed over similar ranges. Note: Different species are not always in thermal equilibrium and hence have different temperature. This is often true in the plasmas that we will consider here. Figure 1 shows just a few of the possible plasmas and where the fit in the density and energy range.
Figure 1: Where different plasmas exist in energy-density space. We will discuss mostly Glows as applied to plasma applications.

In this text we are mostly interested in useful plasmas that we can control and manipulate, which for simplicity we will call ‘laboratory’ or in some cases ‘process’ plasmas. This eliminates all of the extremely high-energy plasmas and most of the non-earth based plasmas. Note that we are still interested in some space plasmas. This is because understanding these plasmas is critical space exploration and satellite communications. (In the accompanying lab one of our plasma systems serves to mimic – as best possible – interplanetary space or to mimic a ‘plasma rocket’.) We will also deal indirectly with plasma-based lighting. However, because of a lack of time, we will limit our studies to plasmas that typically operate at sub-atmospheric pressures. Atmospheric pressure plasmas – also known as thermal plasmas – have additional complexities that are best studied after one has a firm understanding of sub-atmospheric plasmas. While we are only considering a small fraction of all plasma systems, we still have a huge number of plasmas and accompanying processes to study. In addition, understanding these plasmas is critical to continued economic growth. For example, process plasmas are used in approximately 30% of all steps in the production of computer chip. Plasma based lighting greatly reduces energy needs and understanding space plasmas is critical to the telecommunication industry.

To study even this greatly reduced set of plasmas requires knowledge in many fields. ‘Process’ plasmas are studied in multiple engineering (electrical, chemical) and scientific (physics, chemistry, material) departments. Process plasmas, as used in the semiconductor industry, can be further divided into plasma-enhanced chemical-vapor deposition (PECVD) systems, plasma-based physical-vapor deposition (PVD) systems, plasma-ash systems, plasma-etch systems and plasma-based ion implantation (PBII) systems.

While there are great differences between the various plasmas we are going to study, they do have a large number of common facets. First, all of our plasmas operate at low pressures and hence we need to understand vacuum technologies. Second, many of the plasmas have reactive gas or
surface species and hence we need to develop a basic understanding of the chemistry involved. We also need to understand how to flow replacement particles into the system as reactive species are used up. Third, many of our plasmas are used to process a material or surface and thus we need to understand how to hold these surfaces in contact with the plasma. Fourth, we need to understand efficient methods for creating and sustaining the plasmas that are also not detrimental to the material being processed. Finally we need to understand safety and environmental issues that are critical to production process.

SAFETY AND ENVIRONMENTAL ISSUES

Because Laboratory plasmas use many chemistries that are very hazardous, one should learn to read Material Safety Data Sheets (MSDS). For example silane, a common feed gas for PECVD systems, is highly flammable and will easily explode in air if the density is to high. Likewise BF₃, which is used in PBII systems, creates gaseous HF when it is in contact with air. If the HF is breathed in, death can occur. An example of an MSDS from Air Liquide (on the gas Silane, SiH₄) is given in below. You can find MSDSs from vendors and they are by law kept on file where they are used. Note that you can also often find them on the web. Before working in a new lab make sure that care has been taken to properly deal with hazardous materials. In addition, because of the dangerous nature of many of these chemistries, ALL CHEMICAL (GAS, LIQUID OR SOLID) SPILLS SHOULD BE REPORTED IMMEDIATELY.

In addition to the hazardous chemistries, laboratory plasmas also have dangerous current and voltage sources. It used to be a good rule of thumb that if a power supply was big enough to hurt you if you picked it up, it could kill you with its electrical output. However, because power supply technology has greatly improved, even light weight power supplies can deliver enough energy to kill. In addition an electrical shock may not kill you instantaneously. Instead, the shock disrupts your electrolyte balances in your body and you might die 24 hours later. Before working in a new lab make sure that care has been taken to properly deal with electrical systems. Hence, ALL ELECTRICAL SHOCKS SHOULD BE REPORTED IMMEDIATELY.
3. HAZARD IDENTIFICATION

EMERGENCY OVERVIEW: Phosphoric Gase This product is a colorless, odorless gas, with a choking effect. This gas will rapidly ignite upon contact with air, releasing a dense white cloud of phosphoric acid. The primary health hazard associated with Silane is the potential for severe thermal burns from contact with flames resulting from the spontaneous ignition of this gas. Depending on the severity of the burns, such exposures can be fatal. Frame or high temperature engulfing on a localized area of the cylinder of this product can cause the cylinder to burst without activating the cylinder’s relief devices. If Silane is released at high pressure or high flow velocity, a delayed detonation may occur. Silane releases which have not spontaneously ignited must be considered extremely dangerous, and should not be approached. Emergency responders must have personal protective equipment and the protection appropriate for the situation to which they are responding.

SYMPTOMS OF OVER-EXPOSURE BY ROUTE OF EXPOSURE: The gas is phosratic: over-exposure to the unhaled gas will be unlikely under normal circumstances of sudden release. The result of over-exposure to Silane and its decomposition products.

INHALATION: Inhalation of high concentrations of this gas can result in headache, nausea, dizziness, and irritation of the upper respiratory tract. Silane reacts with water to form phosphoric acid, which can be irritating to the mucous membranes and the skin. Inhaling the gas can result in pulmonary edema. Decomposition of Silane will result in the production of phosphoric acid. Though the inhalation of phosphoric acid can be irritating to the nose and throat, such exposure does not present the potential for adverse health effects associated with exposure to phosphoric acid.

SKIN and EYE CONTACT: Silane reacts with water to form phosphoric acid, which can be irritating to the skin and eyes. Decomposition of Silane will result in the production of phosphorus acid. Silane or water contact with phosphorus acid may be irritating.

OTHER POTENTIAL HEALTH EFFECTS: The chief health hazard presented by Silane is that it ignites so rapidly, personnel in the area of a release can receive severe thermal burns. Depending on the severity of the burns, such exposures can be fatal.

HEALTH EFFECTS OR RISKS FROM EXPOSURE: An Explanation in Lay Terms. Over-exposure to Silane may cause the following health effects:

ACUTE: The primary health hazard associated with Silane is the potential for severe thermal burns from contact with flames which result from the spontaneous ignition of this gas. Through unlikely to occur under normal circumstances, inhalation of high concentrations of Silane can cause headache, nausea, and irritation of the upper respiratory tract. Reaction of Silane with water or moisture can produce phosphorus acid and phosphonic acid. Both decomposition products can inflame the eye, skin, and respiratory tract.

CHRONIC: No chronic health effect is currently associated with exposure to Silane.

TARGET ORGANS: Respiratory system, skin, eyes.

4. FIRST-AID MEASURES

RESCUERS SHOULD NOT ATTEMPT TO RETRIEVE VICTIMS OF EXPOSURE TO THIS PRODUCT WITHOUT ADEQUATE PERSONAL PROTECTIVE EQUIPMENT. At a minimum, Self- Contained Breathing Apparatus and Fire-Retardant equipment should be worn. Adequate fire protection must be provided during rescue situations.

NOTE: Silane releases which have not spontaneously ignited must be considered extremely dangerous, and should not be approached.
4. FIRST-AID MEASURES (Continued)

PROPER first-aid and immediate medical care should be provided. The person exposed may require monitoring and treatment as an outpatient because some of the effects caused by this chemical may not become apparent for several hours or days following exposure.

5. FIRE-FIGHTING MEASURES

Flash Point: Not applicable. Pyrophoric gas.
Autoignition Temperature: Not applicable. Pyrophoric gas.
Flammability Limits (Upper or by volume, %): Lower: 0.01, Upper: 0.01
Extinguishing Media: Water mist, dry chemical, foam, CO2. Do not use hand-held extinguishers capable of generating flames or sparks.
Fire Fighting: In the event of a fire, wear self-contained breathing apparatus and use water to control the spread of the material. Follow standard fire fighting practice.
Flash Point: Not applicable. Pyrophoric gas.
Autoignition Temperature: Not applicable. Pyrophoric gas.
Flash Point: Not applicable. Pyrophoric gas.
Extinguishing Media: Water mist, dry chemical, foam, CO2. Do not use hand-held extinguishers capable of generating flames or sparks.

6. ACCIDENTAL RELEASE MEASURES

leck Response: Extinguish fire by means of a pyrophoric gas if it can ignite spontaneously upon contact with air. Uncontrolled releases should be reported immediately. Do not use water if the spill involves any release into drain systems or harbors. If spilled or in contact with water, it will produce hydrogen fluoride, which is toxic and can cause severe burns.

7. HANDLING AND USE (Continued)

Use appropriate equipment for the type of work being done. Use respiratory protection if the level of contaminants is above the permissible exposure limit. Wear appropriate protective clothing and equipment to protect against skin contact. Use appropriate personal protective equipment to protect against eye contact. Keep away from clothing and other materials that could ignite spontaneously. Use proper ventilation systems and controls to reduce exposure to the gas.

8. EXPOSURE CONTROLS - PERSONAL PROTECTION

VENTILATION AND ENGINEERING CONTROLS: Use a self-contained breathing apparatus in an area where the gas may be present. If the gas is detected, use self-contained breathing apparatus. If there is a leak, use air-monitoring equipment to detect the presence of the gas. Do not enter the area if the gas is detected.

HAND PROTECTION: None known. Wear appropriate protective clothing and equipment to protect against skin contact.

5. PHYSICAL AND CHEMICAL PROPERTIES

GAS DENSITY @ 20°C (68°F): 0.00996 g/L (1.43 kg/m³)
BOILING POINT @ 1 atm: -112°C (-170°F)
SPECIFIC HEAT (1 atm, 25°C (77°F)) MOLAR:
Evaporating Heat (in kcal/mol): 23.14
EXPANSION RATIO: Not applicable.
SOLUBILITY IN WATER @ 25°C (77°F): 1.1 g/mL
DENSITY: 0.12
COEFFICIENT OF WATER/DISTRIBUTION: Not applicable.
ACIDITY AND ALKALINITY: pH values are not available.
HOW TO DETECT THIS SUBSTANCE (warning properties): The odor is not consistently detectable. It is not readily detected by its chemical, physical, or biological properties. The substance may be detected by its chemical, physical, or biological properties.
10. STABILITY AND REACTIVITY

STABILITY: Pyrophoric. Ignites spontaneously on exposure to air.
INCOMPATIBILITY PRODUCTIONS: Amorphous silicon dioxide and carbon.
MATERIALS WITH WHICH SUBSTANCE IS INCOMPATIBLE: Silicones will react violently with water and other moisture-containing substances.
REACTIVITY OF SUBSTANCE: Decomposition of the substance may be accompanied by violent combustion. It is not known to be compatible with water or other reactive materials.
11. TOXICOLOGICAL INFORMATION

Toxicity: The toxicity data for this substance are not available. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials.
Acute Toxicity: The acute toxicity data are not available. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials.
OTHER TOXIC EFFECTS: The other toxic effects data are not available. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials.
PHYSICAL DATA: The physical data for this substance are not available. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials.
INTERACTIONS WITH OTHER CHEMICALS: Decomposition of the substance may be accompanied by violent combustion. It is not known to be compatible with water or other reactive materials.
SUGGESTIONS FOR SPECIAL USES: It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials.
NATIONAL REGULATIONS: It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials. It is not known to be compatible with water or other reactive materials.
Figure 2: A typical MSDS as prescribed by US law. Note other countries have different forms.

The final issue in this area is related to ‘safety’ for the item being produced. Often these items are microscopic in nature and thus small particulate can damage or destroy the item. Because of this plasma systems are often found in ‘cleanrooms.’ The cleanliness of the cleanroom is given in "class 'some number'" or particulate per cubic meter. (UTD’s cleanroom typically operates from class one in the lithography areas to class 1000 in the teaching lab areas.) These cleanrooms are rooms with special air filtration (Hepa-filters) systems. In addition special clothing and glowing, known as gowning, is often required to maintain this cleanliness around a person working in the cleanroom. (The human body and most clothing shed dust.) Before entering any cleanroom first learn and then practice the required gowning techniques. The gowning level is determined by the product, the number of filters, the air-flow speed and the number of workers and systems in the cleanroom. Add figure of how a cleanroom runs.

CREATING PLASMAS
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
raw materials in
plasma processor
finished product out

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

Plasma processing
plasma chemistry
plasma physics
surface chemistry

Every process is a complex interaction between:
- gas phase chemistry
- plasma conditions
- surface phase chemistry/conditions

Classic example
Silicon etching:

<table>
<thead>
<tr>
<th>XeF₂ gas only</th>
<th>XeF₂ gas and Ar⁺ beam</th>
<th>Ar⁺ beam only</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (s)</td>
<td>0 200 400 600 800 1000</td>
<td></td>
</tr>
<tr>
<td>Silicon etch rate (Å/min)</td>
<td>0 10 20 30 40 50 60 70</td>
<td></td>
</tr>
</tbody>
</table>

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

Outline
1) Why study plasma processing?
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Plasma Physics
The basic plasma physics can be examined using probes

- Langmuir probes give:
  - \( n_e, T_e, V_e, \) & \( V_i \)
- 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
- microwave 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.

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.

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.

Sputtering

Ions are accelerated into the 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

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

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
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
4) Neutral Beams
5) Thermal Plasmas
   - Arcs
   - Torches
   - 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 sustain 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°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)
- 13.56 MHz
  - 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

The antenna is used to launch Helicon waves.
Helicon waves can be excited over a range of frequencies $f$
$f_{ci} < f < f_e < f_{pe}$
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

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

When in resonance with the µWaves, 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

$$E \to \text{accelerate ion}$$

$$E \to \text{accelerate ion across sheath}$$

Thermal plasma sprays

Sprayed material is “melted” by plasma
Thermals

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
CREATING AND SUSTAINING PLASMA

In each of the plasma sources discussed above, the plasma is sustained by heating electrons which in turn collide with neutrals to produce new ions and electrons.

In general electrons have larger velocities and are more energetic than ions. We can determine this from simple freshman physics. Let us first assume that the electron energy is the same as the neutrals and the ions. Thus

\[ E \]

VACUUM TECHNOLOGY OVERVIEW.

The plasmas that we are studying operate under a variety of pressures ranging from ‘low’ vacuum to ‘ultra high.’ Note that low is closest or atmospheric pressure while ultra high is the closest to prefect vacuum that can be reached. This is, for some people, backwards to what they might originally guess. The typical definitions are given in the table below.

<table>
<thead>
<tr>
<th>Pressure Level</th>
<th>Torr</th>
<th>Pascals</th>
<th>Particle Density (#/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low vacuum</td>
<td>760-23</td>
<td>10^5-3\times10^3</td>
<td>2.5\times10^{19}-7.5\times10^{17}</td>
</tr>
<tr>
<td>Medium</td>
<td>23-10^-3</td>
<td>3\times10^{3}-10^{1}</td>
<td>7.5\times10^{17}-2.5\times10^{13}</td>
</tr>
<tr>
<td>High</td>
<td>10^{-3}-10^{-6}</td>
<td>10^{-1}-10^{-4}</td>
<td>2.5\times10^{13}-2.5\times10^{10}</td>
</tr>
<tr>
<td>Very high</td>
<td>10^{-6}-10^{-9}</td>
<td>10^{-4}-10^{-7}</td>
<td>2.5\times10^{10}-2.5\times10^{7}</td>
</tr>
<tr>
<td>Ultra high</td>
<td>10^{-9}-10^{-12}</td>
<td>10^{-7}-10^{-10}</td>
<td>2.5\times10^{7}-2.5\times10^{4}</td>
</tr>
</tbody>
</table>

1 atmosphere = 760 Torr (mm Hg) = 101323 Pa = 2.5\times10^{19} at STP (Loshmidt’s Number)

These numbers provide an effective method for describing two important issues in process plasmas, 1) how often a given particle collides with another and 2) how often a given particle collides with a surface or wall. This last item can be turned around to look at 3) how often a given spot on a surface gets hit by a particle (or how often the wall ‘collides’ with an atom). These three issues are important for the following reasons. 1) gives how often a particle interacts with other particles and can be used to determine how far it travels between collisions, the ‘mean free path’. In a similar manner 2) gives how often a particle interacts with the wall. For the more massive particles (ions and molecules) these collision cause energy transfer and hence help set the temperature of the particles. Thus comparing 1) and 2) will allow us to understand some of the energy transfer that occurs in plasmas. Typically particles in a low vacuum system will interact with
other particles much more than with the wall, while in a ultra high vacuum system, particles will interact mostly with the walls. Finally 3) gives how fast a monolayer might form on a surface.

We can achieve these various pressure regimes using an assortment of pumping and vacuum sealant systems.

Pump types:
1) Rotary vane and piston pumps
2) Roots blowers
3) Ion pumps
4) Sorption pumps and cryo-pumps
5) Diffusion pumps
6) Turbomolecular pumps (‘TMP’ or ‘turbo’)

Sealant types:
1) O-ring
   a) ISO
   b) KF (Kwik flange)
   c) Custom o-ring
2) Metal
   d) Conflat (copper)
   e) Gold

Gas flow is also important.