Preface and Disclaimer

This is a special vacuum course made by Plasmetrex for The Northeast Advanced Technological Education Center (NEATEC). The majority of applications of vacuum technology here are for semiconductor manufacturing and related plasma processes. So semiconductor and plasma applications are an important outcome of the provided knowledge.

For additional and deeper knowledge refer to the Advanced Vacuum course.

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This project is sponsored in part by the National Science Foundation under ATE Grant #1555699. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation.
Units

The course uses primarily SI units. They are used in scientific and technical literature all over the world as well as by the NASA or the US National Institute of Standards and Technology (NIST), exclusively.

Why?

- They make calculations easy and consistent.
- From the 19th century U.S. customary units such as the foot and pound have been defined in relation to metric units.
- The use of two different unit systems was the cause of the loss of the Mars Climate Orbiter in 1998.
  - NASA specified metric units in the contract. NASA and other organizations applied metric units in their work, but one subcontractor, Lockheed Martin, provided thruster performance data to the team in pound force seconds instead of newton seconds. The spacecraft was intended to orbit Mars at about 150 kilometers (93 mi) altitude, but incorrect data probably caused it to descend instead to about 57 kilometers (35 mi), burning up in the Martian atmosphere.
- In US the so-called imperial units are still widely used in daily life and industry. So we provide also values in these units if reasonable.

http://www.nasa.gov/offices/oce/functions/standards/isu.html#VUtoQPYUBpg
http://en.wikipedia.org/wiki/Metrication_in_the_United_States

Explanation

- \([x] \) – Unit of physical value \(x\)
- \(\Delta x = x_2 - x_1\) – Difference between two values
- \(\langle x \rangle\) – Expectation value using distribution function, in most cases it is close to the mean.
- \(m^x n^{-y} = \frac{m^x}{n^y}\)
Overview

- Introduction
- Vacuum fundamentals
- Fundamentals of vacuum generation
- Components of vacuum tools
- Mass spectrometer and residual gas analysis RGA

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  - Work flow in a fab – Where is vacuum technology used?
    - CVD, implantation, dry etch, PE-CVD
  - Vacuum – The power of nothingness
  - Vacuum overview

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    - Ranges and measurement of pressure
  - Equation of ideal gas
  - Particle density and velocity
  - Particle flow in vacuum, mean free path, gas (particle) density
  - Vapor pressure and Virtual leaks

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  - Performance data of vacuum pumps
  - Rotary vane pumps
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- Standard flanges and ports
- Vacuum control
- Leaks
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  - Leak detection
- Principal vacuum tool set up
- Examples for etch tools in semiconductor manufacturing (AMAT, Lam)

Mass spectrometer and residual gas analysis RGA
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- Pressure and hot air
- Air pressure and water column
- Alarm clock in vacuum
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- Components of vacuum tools

- Mass spectrometer and residual gas analysis RGA

Process Flow in a Wafer Fab
Work Flow in a Fab – easy Bipolar Process

- The red colored processes are vacuum processes, mostly plasma processes.
- 22 of 39 processes are vacuum processes!
- The equipment for these processes is very expensive.
- Equipment used for vacuum is among the most costly equipment for IC manufacturing.

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Source: Plasma School Plasmetrex, © Plasmetrex

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Work Flow in a Fab - continued

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Source: Plasma School Plasmetrex, © Plasmetrex 2015
Work Flow in a Fab - continued

29. Metalization (Sputtering)
30. PE-CVD intermetallic dielectric
31. Resist mask Via
32. Oxide etch (RIE)
33. Resist removal
34. Metalization (Sputtering)
35. PE-CVD (Oxide/Nitride)
36. Resist mask bonding area
37. Oxide/Nitride etch (RIE)
38. Resist removal
39. Back side grinding

Plasma etch chamber
Novellus Concept 1

Plasma etch chamber with inductive RF-Power coupling LAM Kiyo

Source: Plasma School Plasmetrex, © Plasmetrex 2015

Vacuum Introduction

☞ What is vacuum?
   ➢ Definition: "Vacuum is the state of a gas in a vessel when the gas pressure is below the outside or atmospheric pressure."

☞ Linguistic origin:
   ➢ "Vacuum" comes from the Latin word "vacuus" and means "empty, free."

☞ In a vacuum, it is silent because sound needs a transmission medium (air/gas, fluid, solid state) as a carrier. Burning candles go out, due to the lack of oxygen from the air. Humans, animals or plants could not survive in a vacuum.
Vacuum – The Power of Nothingness

 Otto von Guericke (1602-1686) from Magdeburg, Germany, invented the air pump in 1649. Later, he managed to convert his invention so that he could suck air out of things - similar to a vacuum cleaner.

 He produced a vacuum between two iron half hemispheres (Magdeburg hemispheres). The edges of the two parts had been previously sealed by a layer of wax, oil and a leather strip.

 Then he hitched up the two sides of the ball to eight horses (four on each side), trying to separate the two halves at waist-height. The animals did not succeed, but only when they again took in air were the two pieces able to be pulled apart.

 Youtube: Magdeburger Halbkugeln

Vacuum Experiment with Magdeburg Hemispheres

 Removing air from the inner space by a vacuum pump.
Vacuum in Magdeburg Hemispheres

- The less gas is inside the sphere the higher the resulting pressure on the outer side.

![Diagram showing atmospheric pressure, low vacuum, and vacuum states](image)

Vacuum in Magdeburg Hemispheres

- The Magdeburg hemispheres had an diameter of around 50 cm (20 inches).
- If the inner pressure is much less than the outer pressure, the sphere is compressed by a force of 10 kN or the weight of 1 ton is needed for separation.

![Diagram showing forces of 10 kN](image)

Please note:
Area and force are comparable with that of many process chambers!
Overview of Vacuum

Operating ranges of major vacuum pumps and gauges

Applications in Semiconductor Manufacturing

Implantation: $p < 10^{-10}$ Pa

P3I: $p = 10^1 - 10^3$ Pa
Sputter Etch: $p = 2 - 10^2$ Pa
Plasma Nitridation: $p = 1 - 10$ Pa
Dry Etch: $p = 1 - 50$ Pa
PECVD: $p = 200 - 2000$ Pa
Diffusion: $\approx 10000$ Pa
Content Vacuum Fundamentals

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- Ranges and measurement of pressure
- Equation of ideal gas
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Fundamentals of vacuum generation

Components of vacuum tools

Mass spectrometer and residual gas analysis RGA

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Gas Properties

Gases consist of tiny particles called molecules or atoms.

Atoms/Molecules are so far apart that their volume is ignored.

Atoms/Molecules are so far apart that any attractive forces are ignored.

Four Qualities of a Gas:

- Volume $V$
- Temperature $T$
- Pressure $p$
- Number of Molecules $N$

$V = 1 \text{ l} = 0.001 \text{ m}^3$

$T = 20\degree \text{C} = 293 \text{ K}$

$p = 760 \text{ Torr} = 101.300 \text{ kPa}$

$n = 3 \times 10^{19} \text{ molecules/cm}^3 \rightarrow N = 3 \times 10^{22} \text{ molecules}$
Temperature

**Definition:** The Temperature is a measure of the average kinetic energy of the random microscopic motions of their constituent microscopic particles (atoms and/or molecules).

The coldest temperature possible is called absolute zero. It is denoted by 0 K on the Kelvin scale (−273.15 °C on the Celsius scale, and −459.67 °F on the Fahrenheit scale).

**Units:**

\[
\begin{align*}
\frac{\theta_C}{^\circ C} &= \frac{T}{K} - 273.15 \\
\frac{\theta_C}{^\circ C} &= 0.555 \left( \frac{\theta_F}{^\circ F} - 32 \right) \\
\frac{\theta_F}{^\circ F} &= 1.8 \left( \frac{\theta_C}{^\circ C} + 32 \right)
\end{align*}
\]

Pressure

**Definition:**

- Pressure is force per unit area applied in a direction perpendicular to the surface of an object.

**Base unit (SI):**

- \(1 \text{ Pa} = \frac{1 \text{ N}}{1 \text{ m}^2} = 1 \text{ kg} / (1 \text{ m} \cdot \text{s}^2)\)

\[
1 \text{ Pa} = 1 \text{ N} / \text{m}^2 \quad \text{SI}
= 10^{-5} \text{ bar} \quad \text{SI}
= 1.0197 \times 10^{-5} \text{ at} \quad 1 \text{ at} = 1 \text{ kp} / \text{cm}^2, \text{technical atmosphere}
= 0.98692 \times 10^{-5} \text{ atm} \quad 1 \text{ atm} = 101.3 \text{ kPa} = 760 \text{ Torr, standard atmosphere}
= 7.5006 \times 10^{-3} \text{ Torr} \quad 1 \text{ Torr} = 1 \text{ mm Hg, mercury column}
= 1.4504 \times 10^{-4} \text{ psi} \quad \text{pounds per square inch}
\]

Under standard conditions (101.3 kPa, 0 °C), air has a density of 1.293 kg / m³.
Torricelli's Experiment

- The mercury column will rise or fall until its weight per area is in equilibrium with the pressure difference between the two ends of the tube.

\[ p = \frac{m}{M} RT \]

\[ p = n k_B T \]

\[ n = \frac{N}{V} \]

\[ p \] – Pressure [Torr]  \[ m \] – Gas mass [kg]
\[ V \] – Volume [l]  \[ M \] – Molar mass [kg/mole]
\[ T \] – Temperature [K]  \[ R \] – Universal gas constant (8.314 J / (mol K))
\[ n \] – Amount of gas per volume  \[ k_B \] – Boltzmann constant (1.3806 ×10⁻²³ J / K)
\[ N \] – Amount of gas [atoms/molecules]

Source: Plasma School Plasmetrex
Why is Ideal Gas Law Important for Vacuum Processing?

Main messages of that law:

- The more particles (density) the higher the pressure
- The higher the gas temperature the higher the pressure.

Keeping pressure constant (as usually done) and varying the temperature results in a change of gas density.

Changes of the gas density are critical and lead to process drift – the main reason of the so-called first wafer effect.

What is the Pressure telling us?

The race driver

- The rolling friction of a car depends on the pressure in the tire.
- Flat tire

The process engineer

- In semiconductor manufacturing one doesn’t need to know the process chamber pressure!
- The really interesting parameter is the density of molecules, fragments, chemical active species, electrons and ions in the chamber.
Experiment: Pressure and Hot Air

- A burning candle stands in a bowl of water.

- A drinking glass is slowly slipped over a burning candle into the water until standing on ground.

- Describe and explain what happens!

Experiment: Air Pressure and Water Column

- Fill a glass with water completely.
- Push a piece of paperboard or a coaster on top.
- Turn the drinking cup, so that the opening faces downward.
- Take away your finger (pushing the coaster).

- Explain the result!
Vacuum Ranges I

Vacuum quality is subdivided into ranges according to the pressure required by the technology.

- **Low vacuum**, also called *rough vacuum* or coarse vacuum, is vacuum that can be achieved or measured with rudimentary equipment such as a vacuum cleaner and a liquid column manometer.

- **Medium vacuum** is vacuum that can be achieved with a single pump, but the pressure is too low to measure with a liquid or mechanical manometer. It can be measured with a McLeod gauge, thermal gauge or a capacitive gauge.

- **High vacuum** is vacuum where the mean free path exceeds the size of the chamber. The mean free path is the average distance a particle moves before between two subsequent collisions. High vacuum usually requires multi-stage pumping and ion gauge measurement.

- **Ultra high vacuum** requires baking the chamber to remove trace gases, and other special procedures. British and German standards define ultra high vacuum as pressures below $10^{-6}$ Pa ($10^{-8}$ Torr).
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  ➢ Ranges and measurement of pressure
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    • Hot Cathode Ion Gauges
    • Cold Cathode Ion Gauges

Fundamentals of vacuum generation

Fundamentals of vacuum generation

Components of vacuum tools

Mass spectrometer and residual gas analysis RGA

Absolute and Relative Pressure Measurement

Absolute pressure is zero-referenced against a perfect vacuum, using an absolute scale.
  ➢ Almost all vacuum measurements are on an absolute scale.

Differential or relative pressure is the difference in pressure between two points.
  ➢ Overpressure measurement in cleanroom.
  ➢ Underpressure measurement in labs dealing with biohazardous matter.
Vacuum Measurement Equipment

- Direct, gas-independent pressure measurement
  - Diaphragm vacuum gauges
    - Piezo-diaphragm vacuum gauges
    - Capacitive diaphragm vacuum gauges
    - So called Baratrons® are very often used in semiconductor industry for process control.

- Indirect, gas - and temperature dependent pressure measurement – absolute pressure measurement
  - Pirani – thermal transfer vacuum gauges
  - Penning – cold cathode ionization vacuum gauges
  - Hot cathode ionization vacuum gauges

Pressure Measurement in Vacuum System

- Depending on technology, etch, deposition, sputtering the different processes need various process pressure, mostly high vacuum.
- The high vacuum generation is done by two stages of vacuum pumps, a forepump stage and a high vacuum pump stage.
- The high vacuum pumps are controlled by pressure measurement because they need forevacuum for operation. Therefore a vacuum gauge is installed between the fore- and high vacuum pump-
Pressure Measurements, Principles and Ranges

Hydrostatic gauges (such as the mercury column manometer) consist of a vertical column of liquid in a tube whose ends are exposed to different pressures.

- The column will rise or fall until its weight is in equilibrium with the pressure differential between the two ends of the tube.
  - Measures pressures ranging from 100 Pa (1 Torr) to above atmospheric.
  - If $P_0 = 0$ then absolute pressure
  - If $P_0 > 0$ then differential pressure

Mechanical or Elastic Gauge

- Mechanical or elastic gauges depend on a Bourdon tube, diaphragm, or capsule, usually made of metal, which will change shape in response to the pressure of the region in question. A change in pressure leads to the flexure of the diaphragm, which results in mechanical movement of the indicator.

- Measurement range from 100 kPa ($10^3$ Torr) to $10^{-2}$ Pa ($10^{-4}$ Torr), and beyond.
Diaphragm Vacuum Gauges

- Diaphragm vacuum gauges are particularly suitable for gas type independent pressure measurements up to high vacuum. They measure the elastic deformation ($\Delta_s$) of a diaphragm, which is a result of different forces acting on different sides of the membrane (see figure).

- In the capacitance diaphragm vacuum gauge the pressure sensible membrane acts as one of the electrodes of a capacitor.
- The deformation ($\Delta_s$) as a function of the pressure $p_1$ difference causes a change in its capacitance, which can be directly and accurately measured.

---

Diaphragm Vacuum Gauges

- Diaphragm material
  - Stainless or steel with a small thermal expansion or
  - metal coated ceramics (less sensitive to temperature

- Limiting Effects:
  - Influence of temperature (therefore regulated sensor temperature)
  - Decreasing forces acting on the diaphragm at low pressures.

- The photo shows a well known type of a diaphragm vacuum gauge made by MKS. Baratron is MKS Trademark.
Heat flow in Vacuum and Material

- **Thermal conductivity**
  - The formula for the thermal conductivity is the same for solids, fluids and gases. The difference is:
  - There are big differences in the order of the coefficient of thermal conductivity.

- **Convection**
  - In fluids and gases exist an additional effect for heat flow, the convection fluid / gas.
  - For pressure higher 10 kPa in gases the convection is higher the conductivity.
  - The bad “thermal flow” in vacuum chambers is the result of the less convection!

- **Radiation**
  - Heat transfer without matter (mass: solid, fluid or gas)
  - Heat transfer by electromagnetic waves.
  - Strong dependence on temperature.

\[
\frac{\Delta Q}{\Delta t} = \sigma A (T_1^4 - T_0^4) \quad \sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}
\]

- Examples:
  - Light bulb, Sun, Gas radiation heater in open restaurants.

---

Thermal Conductivity Gauge – Fundamentals

- Following Fourier’s law, the thermal flow goes always from the hot end to the cold one. In case of a simple bar, the heat flow is

\[
\frac{\Delta Q}{\Delta t} = \frac{A}{l} \Delta T
\]

\[T_1 \quad \text{Thermal flow} \quad T_2 \]

\[\Delta T = T_1 - T_2 \quad T_1 > T_2\]

\(\kappa\) denotes the thermal conductance which depends of the material.

- This is analog to the relation of the electrical values voltage \(V\) the current \(I\)

\[I = \frac{A}{l} V\]

with the electric conductance \(\kappa_{\text{elec}}\).

---

Pirani – Thermal Conductivity Gauge

 Thermal conductivity gauge uses a wire filament which is heated by running current through it.

 The temperature of the filament is dependent on the rate at which the filament loses heat to the surrounding gas, and therefore on the thermal conductivity. A common variant is the Pirani gauge which uses a single platinum (preferred for chemically aggressive gases) or tungsten filament. The measured value is the wire resistance.

 Measurement range: 100 Pa (1 Torr) ... 0.1 Pa (1 mTorr).

1) The thermal conductivity is independent of the gas temperature, but the filament temperature depends on the ambient temperature of the tube.

Pirani – Constant Wire Temperature

 Principle: Constant wire temperature (resistance) and measurement of the heat power.

 Due to the measurement principle, the reading depends on gas temperature and gas composition.

 The measuring bridge (Figure) is adjusted so that the resistance of the filament wire is equal to that of the other bridge resistors (50 Ω). The measuring bridge current \( I \) for balancing is measured. The necessary power dissipated in the Pirani gauge is then equal to

\[
P_{\text{heat}} = \frac{1}{4} RI^2
\]
Pirani – Constant Heat Power

- Principle: Constant heat power and measurement of the wire temperature.

- The thermo-gauge sensor works on a similar principle as the Pirani gauge head shown already.

- Here, however, the temperature change of the heating wire is not measured across the resistor, but by means of a separate thermocouple. This is connected by a glass bead directly with the heated wire. The wire is heated by constant electric power.

Hot Cathode Ion Gauges – Bayard-Alpart

- In high vacuum gauges the ion current of a gas discharge is measured. This ion current is dependent on pressure.

- The required gas discharge is generated in a hot cathode system by using a filament emitting electrons due to the very high temperature above 1000°C.

- The resulting ions are collected at the negative electrode. The current depends on the number of ions, which depends on the pressure in the gauge.

Source: Plasma School Plasmetrex, © Plasmetrex
Penning – Cold Cathode Ion Gauge

- Ionization gauge calibration is very sensitive to construction geometry, chemical composition of gases being measured, corrosion and surface deposits.
- Typical sensitivity is 1 mA ion current per $10^{-2}$ Pa. Such currents are easily measured directly without any amplification. The response of the gauge is gas dependent and the discharge not quite stable. However, they are robust and reliable and provide an adequate measure of the status of a vacuum.

<table>
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<th>Operating Parameters:</th>
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<td>Voltage: 600 ... 1000 V</td>
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<tr>
<td>Magnetic flux density $B$: 1000 ... 2000 G (100 ... 200 mT)</td>
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<tr>
<td>Pressure range: $10^{-6}$ ... 1 Pa $10^{-7}$ ... $10^{-3}$ Torr</td>
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</table>

Penning – Measurement

- The filament is very sensitive to Oxygen and vibrations!

- Hot cathode gauges can be used from 0.1 Pa ($10^{-3}$ Torr) to $10^{-8}$ Pa ($10^{-10}$ Torr).

- Hot Cathode Ion gauges measure the process gas density by means of a gas ionization by electron collisions. The number of ions produced by an electron along a certain path is proportional to the process gas density and, in case of constant gas temperature, to the pressure.

- The hot cathode ion vacuum gauge is named by his inventor Bayard-Alpert.
Penning – Principle Design

In a cold cathode ion gauge the gas discharge is created by a high voltage (more than 1000 V) and a strong magnetic field. The electrons are accelerated in the external electric field and create ions.

- Cold cathode gauges are accurate from 1 Pa (10⁻² Torr) to 10⁻⁷ Pa (10⁻⁹ Torr).

![Diagram of cold cathode ionization gauge]

Pressure Measurement and Temperature Dependence

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<td>- Elastic Gauge</td>
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<td>- Diaphragm vacuum gauges (Baratron)</td>
<td>∝ nT</td>
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<th>Thermal conductivity Gauge (Pirani Gauge)</th>
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<th>Cold Cathode Ion Gauge (Penning)</th>
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<td>∝ \frac{p}{T} \quad \propto n</td>
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<th>Hot Cathode Ion Gauge (Bayard-Alpert)</th>
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Source: Plasma School Plasmetrex, © Plasmetrex
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    • Typical pumps used in semiconductor industry
- Components of vacuum tools
- Mass spectrometer and residual gas analysis RGA

Definition of Volume Flows

- The volume flow rate $S$ or pumping speed $S_{\text{eff}}$ is the quotient of the volume $V$ of gas flowing through a cross section in the time $t$. The volume flow rate at the inlet port of a pump is called pumping speed.

$$ S = \frac{\Delta V}{\Delta t} \quad \text{volume of the gas throughput} \quad \Delta t \quad \text{time} $$

$$ [S] = \frac{m^3}{s} = 10^3 \frac{l}{s} = 3600 \frac{m^3}{h} $$
Gas Flow / Gas Throughput – Definition and Units

ível the volumetric flow, one does not know the amount of gas flowing.

For vacuum processes, often product of volume flow and pressure is used to measure the quantity of gas:

\[ q_{pV} = S p = I k T \]

\[ [q_{pV}] = \frac{\text{Pa m}^3}{\text{s}} \]

Common unit for gas flow: sccm – standard cubic cm per minute at Standard Temperature and Pressure (STP), \( T = 0 \) °C and standard atmospheric pressure = 101.3 kPa = 1 atm = 760 Torr.

Please note: Usage of \( q_{pV} \) gets tricky if the gas temperature is changed, e.g., by compression in a forepump. Then \( q_{pV} \) can vary and does not reflect the conservation of mass any longer.

Definition of Gas Particle Flow

The gas particle flow is always well defined and reflects the conservation of mass.

The gas particle flow \( I_p \) or particle current flux is equal to the quotient of the number of gas particles (atoms and molecules) flowing through the considered cross section per time (\( n \) denotes the gas density).

\[ I_p = \frac{\Delta N}{\Delta t} = n S , \quad [I_p] = \frac{1}{\text{s}} \]

So the (macroscopically) measurable gas particle flow with the pressure \( p \) is:

\[ I_p = \frac{p}{k_B T} S \]
Content Vacuum Generation

- Introduction
- Vacuum fundamentals
- Fundamentals of vacuum generation
  - Gas flow
  - Performance data of vacuum pumps
  - Pumping principle
    - Vacuum pumps and their applications
    - Piston vacuum pump
    - Diaphragm pump
    - Rotary vane pumps
    - Roots vacuum pump
    - Turbo-molecular pumps
    - Entrapment pumps (cryopumps, getters, and ion pumps)
  - Typical pumps used in semiconductor industry
- Components of vacuum tools
- Mass spectrometer and residual gas analysis RGA

Basic Parameters in Typical Pump Specification

- Pumping Speed for N₂ [l/s]
- Attainable ultimate pressure range [Pa]
- Run-up time for turbomolecular pump [min.]
- Ultimate pressure [Pa]
- Total partial pressure without gas ballast [Pa]
- Total pressure with gas ballast [Pa]
- Max. working temperature [°C]
- Main Voltages [V] and Frequency [Hz]
- Power consumption [W]
- Main fuses [A]
- Weight [kg]
- Connections
  - Suction side
  - Air side
Vacuum Pump Performance – Ultimate Pressure

- Ultimate pressure $p_e$ is the lowest pressure that can be asymptotically reached by blank-flanged vacuum pump. This value can only be observed under special test conditions.

- A pump operating at ultimate pressure has a pumping speed of zero.

- In this case throughput (gas particle flow) and vapor recovery flow are equal.

---

Vacuum Pump Performance – Gas Ballast

- Additional air or non-condensing gas is admitted into the vacuum pump. It is used to dilute:
  - Aggressive gases, e.g. etch or plasma clean gases using Cl or F chemistry.
  - Condensing gases. Here it enables the outlet valve to open before vapor condenses.

- The gas ballast reduces the attainable base pressure. Therefore the base pressure is specified with and without gas ballast.
Pump Principles: Positive Displacement Pumps

Gas particles must be removed from a gas filled volume to reduce the gas pressure. This is the reason we use vacuum pumps.

Positive displacement pumps use one or more compression stages to move the gas particles of the pumped out volume to the atmosphere (compression pumps). The transport of the gas particles is carried out by displacement. The basic principle is the cyclic evacuation of a defined pump volume.

- E. g. rotary vane pump, diaphragm pump, piston pump, scroll pump, ...

Pump Principles: Momentum Transfer Pump

A momentum transfer pump accelerates gas particles from the vacuum side towards the exhaust side. This requires a sufficiently low pressure to avoid collision of the accelerated gas particles moving to the gas outlet of the pump.

So momentum transfer pumping does not work at pressure higher than 10 Pa (100 mTorr) at pump outlet. It always requires a forepump.

- e. g. diffusion pump, turbomolecular pump, ..
Pump Principles: Entrapment Pump

Cooling (cryo) trap:
Condensation of gas molecules to a solid or adsorbed state. Chemical pumps which react with gas to create a solid residue.
- Examples: cryopump, sorption pump,
- Pressure range: 0.1 Pa ...\(10^{-7}\) Pa (\(10^{-3}\) Torr ...\(10^{-9}\) Torr)

Electrical trap:
Ion pump where strong electrical field is used to ionize gases and propel the ions into a solid substrate (typical voltage 3 ... 7 kV).
- Examples: ion pump, getter pump,...
- Pressure range: Up to \(10^{-9}\) Pa (lower \(10^{-11}\) Torr)
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Vacuum Pumps and their Applications

- Forepumps
  - Piston vacuum pump
  - Diaphragm pump
  - Rotary vane vacuum pump
- Roots vacuum pump
- Turbomolecular pump
- Entrapment pumps (cryopumps, getter, and ion pumps)
Forepumps

- Forepumps are required if pumps should be used which are not able to pump against atmospheric pressure.
- They provide the operating pressure for high vacuum pumps or for pumps to enhance the gas throughput.
- Rotary vane pumps are designed as single stage or two stage version.
- Two or multi-stage pumps achieve a lower ultimate pressure than single stage pumps.

![Diagram of a single stage forepump](source)

![Diagram of a two stage forepump](source)

Source: Plasma School Plasmetrex, © Plasmetrex

Piston Pump

- A piston pump is a type of positive displacement pump where the pressure sealed piston is moved back and forth. The valves are controlled by over and under pressure, respectively. Piston pumps can be used to move liquids or to compress gases.
- In short, the inlet valve is opened by reduced pressure, and the discharge valve is opened by increased pressure.

![Diagram of a piston pump](source)
Diaphragm Pump

Diaphragm vacuum pumps are single or multistage dry compressing vacuum pumps with up to four stages. Here the circumference of a diaphragm is tensioned between a pump head and the casing wall.

It is moved in an oscillating way by means of a connecting rod and an eccentric. The pumping or compression chamber, the volume of which increases and decreases periodically, effects the pumping action. The valves are arranged in such a way that during the phase where the volume of the pumping chamber increases it is open to the intake line.

Diaphragm Pump – Stages of Pumping Cycle

The pictures show one pump cycle of a diaphragm pump. Due to the compact design they are well suited to pump dangerous gases.

The eccentric shaft moves the piston-diaphragm so as to draw gas in through the left-hand inlet valve, and a half-stroke later expel the gas through the right hand exit valve.
**Diaphragm Pump: Parameters and Application**

- **Typical pumping speed:** 1 m³/h - 10 m³/h

- **Base pressure depending on number of stages:**
  - Single stage: 8 kPa (60 Torr),
  - Double stage: 1 kPa (7.5 Torr),
  - Four stages: 50 - 100 Pa (375 - 750 mTorr)

- **Application**
  - Suited as fore pumps for turbomolecular pump systems (Compound or wide range turbomolecular pumps)
  - Generation of absolutely oil free vacuum for measurement equipment like mass spectrometer systems and leak detectors

- **Issue:** Wear of diaphragm, in particular in aggressive environment.
Rotary Vane Pump

- The rotary vane pump is a oil-sealed rotary displacement pump.

- The pumping system consists of:
  - a housing (1), the off-center rotor (2),
  - the spring force radially moving sliders - vane (3)
  - and the input and outlet (4).
  The exhaust valve is oil overlaid.

- The oil in the pump is the operating fluid and, fulfills in a rotary pump different tasks:
  - it lubricates the moving parts and
  - fills the space below the exhaust valve, and the narrow gap between the inlet and outlet.
  - It seals the gaps between the slides and the work space and makes out through heat transport over for optimum temperature balance.

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Rotary Vane Pump: Parameters and Application

- Pumping speed depending on size: 15 m³/h – 150 m³/h
  - Typical pumping speed for 300 mm etch chamber 80 m³/h

- Ultimate pressure mainly depending on number of stages:
  - 10 Pa – 0.3 Pa (75 mTorr – 2 mTorr)

- Application
  - Pressure about 10 Pa (75 mTorr) → (single stage)
    - Electron beam welding
    - Light bulb manufacturing
    - Surface coating
    - Vacuum drying
    - Leak detection, metallurgy
    - Load lock application
  - Pressure about 0.3 Pa (2 mTorr) → (two stage)
    - Industrial applications such as transformer drying, coating, chemistry
    - Suitable for turbopump pumping systems
    - Vacuum tools (etching and deposition) in semiconductor manufacturing
    - Diffusion and implantation tools
    - Analysis, research and development

Source: Plasma School Plasmetrex, © Plasmetrex
Pumping Speed of Forepumps

- The pumping speed of forepumps is roughly constant over a wide range of pressure but it drops sharply at the lower pressure end.
- Gas and so the pump heats up by compression. This limits the pumping speed.
- Pumping speed curve (pumping speed vs pressure) found in the pump manufacturer’s references.

![Graph showing pumping speed vs pressure](image)

The ultimate pressure is limited by the compression ratio. This is mainly given by the ratio of volumes inside the pump, at suction side and air side.

Mechanical Pumps in Vacuum Systems

- The pumping speed of a vacuum pump is influenced by connection parts like flanges, tubes, and other vacuum system elements.
- The ultimate pressure is limited by the compression ratio.
- So the reachable vacuum is only in the range of about 10 Pa (75 mTorr).
Roots Pump

Roots pumps are used in pump combinations together with forepumps (rotary vane- and rotary piston pumps) and extend their operating range well into the medium vacuum range. With two stage Roots pumps this extends into the high vacuum range.

A Roots vacuum pump is a rotary positive-displacement type of pump where two symmetrically-shaped helical rotors rotate inside the pump casing past each other in close proximity. Two rotors are synchronized.

Pumping Speed of Roots Pumps

The pumping speed of roots pumps drops sharply at the lower pressure end and high pressure end. The highest pumping speed is in the range of $10 \ldots 10^4$ Pa ($0.1 \ldots 10^2$ Torr).

Pumping speed curve (pumping speed vs pressure) found in the pump manufacturer’s literature.

The typical compression ratio of roots pumps with forepump is usually in the range of $10 \ldots 75$.

The pumping speed is here given with forepump. Due to the gap between the helical rotors, a roots pump is not able to pump against atmosphere.
Roots Pump: Parameters and Application

- Pumping speed depending on size: 30 - 1000 m³/h
- Start pressure: < 10⁴ Pa (75 Torr)
- Ultimate pressure of one stage: 1 Pa (7.5 mTorr)
  Maximum of pressure difference is 5 kPa ... 8 kPa (50 Torr ... 80 Torr)
- Pressure is limited by backflow (about 0.1 mm gap between the rotors) and pump chamber-residual volume. They operate in combination with a forepump – pumping against atmosphere is not possible.

Application
- Production of medium vacuum at high gas throughput.

Peculiarities:
- Propellant freedom (except for lubricants from warehouse).
- Two-wave system (opposite rotation of the rotors).
- Forepump is necessary.


Roots Pumps in Vacuum Systems

- Roots pumps are used for vacuum processes with high gas throughput and large vacuum chambers to reduce pump down time.
- The compression ratio is small compared to other pumps but provides a significant increase of the whole system in particulate at high gas throughput.
Turbomolecular Pump

The turbomolecular pump uses the interaction of gas molecules with high-speed propeller to move them towards an outlet.

The rotors turn at speeds sufficiently high to give their outer parts velocities comparable with molecular velocities. As seen at the picture each rotor is paired with stator.

The rotor turns up to 76 000 1/min (rpm).

Turbomolecular Pump

The momentum transfer of the rotating rotor blades to the gas molecules overcomes their non-directional thermal motion imparting directed motion.

At pressures below 0.1 Pa (0.75 mTorr), the mean free path of gas molecules exceeds the distance between the rotor blades and the stator vanes, which is typically a few tenths of a millimeter.
Turbomolecular Pump – Parameters and Application

- In the range above 10 Pa the operation of the rotor is disturbed by frequent collisions between the particles. Therefore, a turbo-molecular pump is not capable to pump gases against higher outlet pressure.
- An increasing particle density leads to a higher power consumption and a subsequent heating of the pump. This result also a a upper pressure limit.

- A significant pumping speed only can be achieved if the peripheral speed (the outer edge) of the rotor blades in the order of the mean thermal velocity of the Gas molecules.
- Gas theory gives for different gases the thermal velocity (see Advanced Course).

\[ p \text{ [Pa]} \]

Turbomolecular Pumps in Vacuum Systems

- The classical Turbo-molecular stage must be supported by a properly sized forepump.
- In most of cases the forepump pumps through the turbo pump. Below 10 Pa (75 mTorr), the turbo pump is started.
- Some tools use a special bypass (dashed line) for soft pump down.

\[ p \text{ [Pa]} \]

Source: Plasma School Plasmetrex, © Plasmetrex 2014
Cryopump

Cryopumps are gas entrapment pumps where gaseous substances are bound to the cold surfaces within the pump by means of cryocondensation, cryosorption or cryotrapping. For that purpose the cold surfaces (cryopanels) must be cooled to a sufficiently low temperature.

The most efficient cryopumps used two-stage cold heads. Cryopumps use the Gifford/McMahon principle and produce a hydrocarbon free ultra high vacuum.

Cryopumps are applied in vacuum pressure range $10^{-1}$ Pa – $10^{-9}$ Pa $(10^{-3}$ Torr – $10^{-11}$ Torr).

Typical applications
- PVD / metalization technology
- Sputter tools
- Ion implantation
- Optical deposition tools

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Cryopump Design

1. High vacuum flange
2. Pump housing
3. Fore-vacuum flange
4. Baffle
5. Cold head 2$^{nd}$ stage $\approx 10$ K
6. Thermal radiation shield
7. Safety valve
8. Cryopanels
9. Cold head 1$^{st}$ stage $\approx 50$ - $80$ K
10. Gauge for the Hydrogen vapor pressure
11. Helium gas connections
12. Motor of cold head with housing and electric connections
Cryopumps Advantages

- As opposed to high vacuum pumps with mechanical bearing such as turbomolecular pumps, cryopumps have no mechanically moving oil or grease lubricated parts.
- Cryopumps are insensitive to mechanical interference such as process particles or external vibrations.
- More compact than other pumping systems with pumping speed > 1500 l/s.
- Fore-vacuum pump is only needed at the start phase and for the regeneration.
- Outstanding cost/performance ratio and high efficiency, in particular at higher pumping speed.
  - High pumping speed for Ar and H₂
  - Easy handling
  - Simple integration into complex high vacuum systems
  - Automatic regeneration
Determination of a Suitable Forepump

The gas quantity transported through a high vacuum pump and the tube connecting the chamber to the pump must also pass the forepump. Moreover, in the operation of the high vacuum pump (diffusion pump, turbomolecular pump), the maximum permissible backing pressure must never be exceeded.

- Effective pumping speed $S_{\text{eff}}$ at the pumping port of the chamber (high-vacuum inlet) pressure $p_{HV}$.
- Pumping speed of forepump $S_f$ at the fore pressure $p_f$.

If the temperature can be assumed to be constant, the gas throughput $q$ is constant from the outlet of the chamber to final outlet. So the required pumping speed of the forepump $S_f$ can be determined by

$$S_f = \frac{p_{HV}}{p_f} S_{\text{eff}}$$
Exercise: Determination of a suitable Forepump

Given:

- Turbomolecular pump with a nominal pumping speed of 400 l/s
- The effective pumping speed is 50% of the value stated in the catalog when using a longer tube.
- Max. permissible fore vacuum $p_f$ is 20 Pa. The pumping speed required as a minimum for the forepump depends on the intake pressure $p_{HV}$.
- At an intake pressure of $p_{HV} = 1$ Pa the pumping speed for the high vacuum pump as stated in the catalog is about 100 l/s, subsequently 50% of this is 50 l/s.

Needed: Pumping speed $S_f$ of forepump.

Exercise continued

Given:

- Intake pressure $p_{HV} = 0.1$ Pa
- The pump has already reached its nominal pumping speed of 400 l/s.

Needed:

- The effective pumping speed $S_{eff}$ by using a baffle.
- Pumping speed for the forepump $S_f$. 

Comparison of Pump Types

The pumping speed of high vacuum pumps is also roughly constant over a wide pressure range below 1 Pa (10 mTorr) but it drops sharply at higher pressures.

- There is no pump which can be used for the whole pressure range.
- Forepumps are able to pump against atmosphere, but the ultimate vacuum is limited to a few Pa (a few tens of mTorr).
- High vacuum pumps reach very low pressure, but require a forepump to work.

A real Vacuum System

- Due to the possibility of large temperature differences inside a modern vacuum (e.g., plasma) chamber, we must use the gas particle flux \( I \) instead of the commonly used gas throughput \( q_{PV} = I k T \).
- Permeation through and from chamber wall
- Leaks in flanges
- Adsorption and desorption of water and byproducts
- Gas from substrate, solvents and byproducts
- Process gas providing reactants
- Byproduct removal through pump

Source: Plasma School Plasmetrex, © Plasmetrex
Real Vacuum Chambers

Ceramic chamber wall
Etch chamber SPTS®

View port
Etch chamber
AMAT® HART®

Chamber Body
Etch chamber AMAT® HART®

Source: Plasma School Plasmetrex, © Plasmetrex 2014

Simple Pumping System

...consists of

- **Chamber for processing**, can be large up to 1 m³.
- **Pump**, usually heavy and so usually not connected directly to the chamber.
- **Connecting tube**, reducing the pumping speed → should be as short as possible.
Base Pressure

For real vacuum systems, a base pressure must be reached for the sake of process purity and stability. This pressure must be reached in a determined period of time and is always higher than the ultimate pressure.

The base pressure of a process chamber is a technological key parameter indicating that the leakage rate is in regular range.

Base pressure methods are often used in semiconductor manufacturing to check process chambers against leaks periodically.
  ➢ Example for base pressure procedure in production line is shown in advanced vacuum course.

Experiment: Base Pressure

Determine the ultimate pressure of the demo vacuum system (max. 5 min) and decide if the leakage rate is in the regular range.

Work out an instruction for a base pressure test of the demo vacuum chamber.
Evacuation in the rough vacuum region

- In this case the required effective pumping speed $S_{\text{eff}}$ of a vacuum pump assembly is dependent only on the required pressure $p$, the volume $V$ of the recipient, and the pump-down time $t$.

- With constant pumping speed $S$ and assuming that the ultimate pressure $p_{\text{ult}}$ attainable with the pump arrangement is such that $p_{\text{ult}} \ll p$, the decrease with time of the pressure $p(t)$ in a chamber is given by the equation:

$$\frac{\Delta p}{\Delta t} = \frac{S_{\text{eff}}}{V} \cdot p$$

- Beginning at 101.3 kPa (atmosphere) at time $t_0 = 0$, the effective pumping speed is calculated depending on the pump-down time $t_{pd}$ as follows:

$$\ln \frac{p}{101.3 \text{ kPa}} = - \frac{S_{\text{eff}}}{V} \cdot t_{pd} \quad S_{\text{eff}} = \frac{V}{t_{pd}} \ln \frac{101.3 \text{ kPa}}{p}$$

Origin of the Variables

- Many boundary condition of the vacuum system are given by technological and economical requirements.

- Substrate size

$$S_{\text{eff}} = \frac{V}{t_{pd}} \ln \frac{101.3 \text{ kPa}}{p}$$

- Atmospheric pressure

- Throughput

- Process / Technology
Exercise: Determine the effective Pumping Speed

Given:
- Vacuum chamber volume $V = 600 \text{ l}$ shall be pumped down to $p = 100 \text{ Pa}$ within $t_{pd} = 15 \text{ min}$.

Wanted:
- Effective pumping speed

\[ S_{eff} = \frac{V}{t_{pd}} \ln \frac{101300}{p} \quad \text{or} \quad S_{eff} = \frac{0.6}{0.25} \ln \frac{101300}{100} \]

\[ S_{eff} = 2.4 \cdot 6.92 = 16.6 \text{ m}^3/\text{h} \]

Exercise: Chamber Pump down Characteristic:

- Explain the pumping down procedure.
- Show in a diagram the pump down curve only with forepump.
- Show in a second diagram the pump down curve with forepump and high vacuum pump (turbomolecular pump).
- After check by the lecturer, perform the experiment using the demo tool.
Experiment: Chamber Pump Down Characteristic

Pumping Speed of Forepump

1. Switch the turbopump off and make sure that the rotation speed is zero.
2. Switch off the foreline pump and vent the chamber using the needle-valve.
3. Switch the foreline pump on and start taking measurements of pressure with a reasonable temporal interval.
4. Plot the data using a spread sheet software. The general formula for the curve is:

\[ p(t) = p_0 e^{-\frac{t}{V S_{eff}}} \]

5. Determine the time \( t_{1/e} \) when the pressure decrease by 1/e = 1 / 2.718 = 37 %.
6. Calculate the effective pumping speed.

\[ S_{eff} = \frac{V}{t_{1/e}} \]
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    - Leak detection
  - Materials in Vacuum and Components
    - Sealing, electrical contact, grounded
    - Standard flanges and ports
  - Vacuum control
- Mass spectrometer and residual gas analysis RGA

Mass Flow Control

- As semiconductor devices get faster and levels of integration increase, higher precision is required in device construction, and new materials are being introduced into the wafer production process to increase production efficiency.
- The gas composition in a vacuum chamber is important for etch or deposition results. The requirements of accuracy of gas flow management increase with reduced structure size and larger wafer diameter.
- Mass flow controller (MFC) are available for different applications:
  - High flow for flat screen and solar cell manufacturing
  - Low flow for low pressure technologies and thin layer modification.
- Note:
  - MFCs are only accurate down to 10% of their maximum rated flow. Do not use a 1000 sccm MFC to control 5 sccm → bad accuracy!
  - The measurement of the gas flow in the MGC is gas type dependent. So it must be corrected or calibrated to the gas type used.
Gas Flow controlled by MFCs

- The gas cabinet shows the complexity of gas composition for semiconductor processing.
- In semiconductor production the vacuum chambers must be leak tested to ensure that air leakages are below specified limits.

Source: Plasma School Plasmetrex, © Plasmetrex 2014
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Leak Detection

- Introduction
  - Leak definition
  - Leak testing methods
  - Leakage rate
- Most applied leak detection in semiconductor industries
  - Ultimate and base pressure
  - Helium leak detection
  - Example for leak detection in production
Introduction

In Semiconductor manufacturing, the vacuum chambers must be leak tested in order to ensure that air leakages are below specified limits.

The three basic functions of leak testing are:
- Determining if there is leakage or not (detection)
- Measurement of leak rate and
- Leakage location.

There are a lot of methods and types of test equipment used for solving these problems, but unfortunately there is no technique that fits every situation. Each test method is suitable only for one range of leak rate.

Leak – Definition

A leak is an unintended crack, hole, or porosity in an enveloping wall or joint.

Critical leak spots in closed systems are usually connections, gaskets, welded and brazed joints, defects in material, etc.

A leak test is usually a quality procedure to assure device integrity, and should preferably be a one-time non-destructive test, without impact on the environment and operators.

The most commonly used leak test methods are
- underwater bubble test,
- bubble soap paint,
- pressure and vacuum decay, and
- tracer gas detectors (halogen, helium and hydrogen).
Leak Sources

- We can distinguish different types of leak sources.
  - Leaks caused by defects in the containing envelope.
  - Leaks in newly manufactured products are most commonly imperfect joints or seals by which various parts are assembled to form the final article. There are known demountable and fixed joints. Between them the most often used are welds, brazed and soldered joints glass-to-metal and ceramic-to-metal seals, O-rings and other gaskets, etc.
  - Materials permitting gas diffusion and permeation through the wall.
  - Virtual leak, a special type of leak in vacuum technique, which is not really a leak but is the internal source of gas or vapor. These are cavities in a chamber wall with thin connections to the inner vessel space such as improper welds, closed threads and holes etc.

Leakage Rate

- **Definition:**
  - \( q_l \) is the leakage rate, i.e. a gas flow that enters the vacuum chamber through leaks at a volume of \( V \). The leakage rate is determined by the pressure rise \( \Delta p \) over time \( \Delta t \):

  \[
  q_l = \frac{\Delta p \cdot V}{\Delta t}
  \]

- **Unit of leakage rate \( T = 0^\circ \text{C} \):**

  \[
  1 \frac{\text{Pa} \cdot \text{m}^3}{\text{s}} = 10 \frac{\text{mbar} \cdot \text{l}}{\text{s}} = 7.5 \frac{\text{Torr} \cdot \text{l}}{\text{s}} = 600 \text{ sccm}
  \]

  or more realistic leakage rates

  \[
  1 \frac{\text{Pa} \cdot \text{m}^3}{\text{min}} = 10 \frac{\text{mbar} \cdot \text{l}}{\text{min}} = 7.5 \frac{\text{Torr} \cdot \text{l}}{\text{min}} = 10 \text{ sccm}
  \]
Leakage Rate – Example

Let us assume a bicycle tube with a volume of \( V = 5 \text{ l} \) and has been inflated to 300 kPa = 3 bar = 43.5 psi. After 25 days a maximum pressure loss of \( \Delta p = 200 \text{ kPa} = 2 \text{ bar} = 29 \text{ psi} \) was observed.

\[
q_l = \frac{200000 \text{[Pa]} \cdot 0.005 \text{[m}^3\text{]} }{25 \cdot 24 \cdot 3600 \text{[s]}} = 4.63 \cdot 10^{-4} \frac{\text{Pa} \cdot \text{m}^3}{\text{s}}
\]

Days \cdot hours \cdot seconds

Measurement of Leakage Rate – Pressure Rise Method

The pressure rise method is used to show:
- The theoretical pressure rise if there is only a leak
- The pressure rise caused by outgassing from the surface of a test object. Outgassing declines when the majority of adsorbate (process gas or byproducts) removed from the inner surface of the chamber.

The leakage rate \( q_l \) can be determined by multiplying \( \Delta p/\Delta t \) with chamber volume \( V \).

\[
q_l = \frac{\Delta p \cdot V}{\Delta t}
\]
Experiment: Pressure rise method and leakage rate

- Determine the leakage rate of the demo vacuum tool using the pressure rise method
  - Close all valves and measure the pressure rise after outgassing.
  - Please use the formula:

\[
q_t = \frac{\Delta p \cdot V}{\Delta t}
\]

Leakage Rates in Real Chambers

- High vacuum chamber:
  - Very close: \( q_{\text{leak}} < 10^{-7} \text{ Pa m}^3 / \text{s} \)
  - Sufficiently close: \( q_{\text{leak}} < 10^{-6} \text{ Pa m}^3 / \text{s} \)
  - Leaky: \( q_{\text{leak}} > 10^{-5} \text{ Pa m}^3 / \text{s} \)

- Not penetrable by
  - Bacterium (diameter of bacterium about 0.5 mm) if \( q_{\text{leak}} < 10^{-5} \text{ Pa m}^3 / \text{s} \)
  - Virus (diameter of virus about 10 nm) if \( q_{\text{leak}} < 10^{-9} \text{ Pa m}^3 / \text{s} \)

- Modern Helium leak detection equipment detects leakage rates down to \( q_{\text{leak}} = 5 \times 10^{-13} \text{ Pa m}^3 / \text{s} \)!
Tracer Gas Leak Detection

- Test gases used for leak detection, so-called tracer gases, have to satisfy the following requirements:
  - Nontoxic to environment, humans and animals
  - Should not displace air to avoid hazardous situations like suffocation.
  - Should be inert and should neither react chemically nor be flammable.

- Leak detection is a measure of quality assurance for production.

- There are two different test methods
  - Integral leak detection
  - Local leak detection

Why Leak Detection with Helium?

- Helium atoms move faster through the air due to the low atomic mass and small cross section. Therefore the measurement is very fast.

- Only a tiny percentage of Helium is contained in the atmosphere. Adding Helium to the atmosphere close to a potential leak, enables even small leaks to be detected.

- Advantages
  - Highest sensitivity in detection of smallest leaks
  - Quantitative measurement of leaks rate
  - Excellent reproducibility of the measurement results
  - Helium is non-toxic and not flammable
  - Can not be used with cryopumps.
Local Leak Detection Procedures

- Chamber or part of a vacuum system is pumped down.
- Helium is sprayed onto a critical or suspicious area with a spray gun.
- Moving from bottom to top!

Vacuum leak detection
- Vacuum test vessel
- Spraying with He
- Detection limit
  \(< 5 \times 10^{-13} \text{ Pa m}^3/\text{s}\)

Different Leak Detection Procedures

Integral leak detection
Leak yes or no

Evacuated chamber
Sniffer
Test gas
Vacuum
Leak tester Basic unit with pump system

Local leak detection
Where is the leak?

Evacuated chamber
Sniffer
Test gas
Leak tester Basic unit with pump system

Vacuum leak detection
- Workpiece is in vacuum
- Test chamber is also under vacuum
- Detection limit about
  \(< 5 \times 10^{-13} \text{ Pa m}^3/\text{s}\)

Sniffer leak detection
- Overpressure Test vessel
- Detection with sniffer probe
- Detection limit about
  \(< 5 \times 10^{-13} \text{ Pa m}^3/\text{s}\)

Vacuum leak detection
- Vacuum test vessel
- Spraying with He
- Detection limit
  \(< 5 \times 10^{-13} \text{ Pa m}^3/\text{s}\)
Example Leakage Tester PHOENIXL 300 (Oerlikon)

a) Workpiece mounted on flange
b) Pump down leakage rate estimated from increase of ultimate pressure
   \( \approx 10^{-10} \text{ mbar l/s} \)
c) Give He on the workpiece
d) Cover it the object under test.
   Leakage test starts.
   He passes leak, leakage rate increases.
e) Leakage rate is stable.

Source: Plasmetrex, © Plasmetrex 2015

Out-gassing influences Processing

- Adsorbed layers at the wall or trapped gas pockets can cause the same effect as real leaks (virtual leak).

- The removal of air and water vapor from the surface can be accelerated by increased chamber wall temperature.
  - Heating with hot water
  - Heating lamps
  - Heating by ion bombardment (RF plasma)

- In semiconductor manufacturing, so-called warm up procedures are used after chamber opening to remove water vapor and air.

- High out-gassing time increases the effective process time and reduces throughput and productivity!

- In case of product mix out-gassing can impact the process results when the product was changed.
Content Component of Vacuum Tools

- **Introduction**
- **Vacuum fundamentals**
- **Fundamentals of vacuum generation**
- **Components of vacuum tools**
  - Mass flow control
  - Leaks
    - Leak detection
  - Materials in Vacuum and Components
    - Sealing, electrical contact, grounded
    - Standard flanges and ports
  - Vacuum control
- **Mass spectrometer and residual gas analysis RGA**

Materials used in Vacuum

- **Requirements:**
  - 1. Vacuum
    - Gas tightness (pores, structure, diffusion channels)
    - Low vapor pressure (also melting temperature sensitive)
    - Low foreign gas content (inclusions, pores, manufacturing processes)
    - Clean surfaces (smallest possible specific surface area, little Adsorbate, fats, etc.)
  - 2. Processes (technology)
    - Chemical resistance
    - Thermal expansion behavior
    - Thermal shock resistance
    - Mechanical strength
  - 3. General
    - Dimensional stability
    - Compressive strength

- **The better the vacuum the tighter the material requirements and the smaller the choice of materials!**
  Most important is the question of materials for UHV technology!
Materials in Vacuum

- **Pure metals:**
  - Iron
  - Titanium
  - Aluminum
  - Copper
  - Gold, Silver
  - Indium

- **Alloys:**
  - Stainless steel (Cr, Ni, Ti-steel)
  - Iron-Nickel-alloys
  - Al-Alloys
    - AlMgSi1Cu (6061) mostly used for vacuum chambers
  - Fe-Ni-Co-alloys
  - Molybdenum disulphide
  - Copper-alloy (Bronze)

- **Non-metals:**
  - **Solids:**
    - Silicates (glass, quartz)
    - Ceramic (Al₂O₃, Zeolite)
    - Elastomers (Viton, PTFE, ..)
    - Fats and resins
  - **Liquids:**
    - Mineral oils
    - Silicone oils
    - LN₂, LHe
  - **Gas:**
    - Argon, Helium
    - Nitrogen (dry)
    - Hydrogen
    - Freon

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Sealant Means

- Sealants are made from elastomers or metal. Sealant choice and flange connection are dependent on the vacuum range and temperature load.

- Mostly elastomer O-rings are used. For special applications in IC manufacturing Karlrez® and/or Chemraz® O-rings are utilized. For UHV (ultra high vacuum) processing metal seals are necessary.

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Source: Plasma School Plasmetrex, © Plasmetrex 2014
Elastomer Seal Forms

- **rectangular groove**
- **dovetail groove**
- **confined gasket**

- **double gasket**
- **L-gasket**

Source: Plasma School Plasmetrex, © Plasmetrex 2014

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Most used Metal for Vacuum Chambers

- **AlMg1SiCu - Al alloy 6061 T6**
  - High strength, low density
  - Vacuum components (pipes, flanges, etc.)
  - AlSi alloys with high hardness, metallic seals (300°C)
  - Low vapor pressure ($10^{-4}$ Pa at melting point 660°C)
  - Very good thermal and electrical conductivity
  - Surface of etch tools is mostly
    - anodized about 50 μm or
    - deposited with Y₂O₃ 50 μm – 200 μm

- **Copper or Tantalum chamber lid as Target for special applications like hollow cathode magnetron.**

Source: Plasma School Plasmetrex, © Plasmetrex 2014
Flanges and Valves

- Flanges and their sealing
  - Small flange KF
  - Clamp flange
  - Fixed flange
  - CF flange

- View port and electrical feed through

- Venting and needle valves

Flanges and Fitting

- ISO KF or QF vacuum systems use components with metric dimensions, defined by the International Standard Organisation ISO. So a high degree of compatibility between components from different suppliers is reached. KF stands for Klein Flange and QF for Quick Flange.
  - KF size: DN (diameter nominal) 10, 16, 25, 40, 50

- CF flange system is fully compatible with Varian Conflat® types and similar flanges manufactured by Balzers and others.
  - CF metric size in mm: DN 16, 25, 40, 63, 100, 160, 200, 250
  - Imperial (US) size in inch: 2¼, 2¾, 3¾, 4½, 4¾, 6, 6¼, 8, 10, 12, 13¼, 14, 16½

- ISO LF (large) flange system is used for tube sizes from 63.5 mm to 500 mm diameter
**KF Flanges**

**KF flanges:**
- Mostly sealed with Viton or Buna-N®

Source: Plasma School Plasmetrex, © Plasmetrex 2014

**CF Flanges**

**CF flanges:**
- Mostly sealed with Viton or Buna-N® in HV range
- For UHV application copper-made seals.

Source: Plasma School Plasmetrex, © Plasmetrex 2014
View port and electrical feed through

Chamber view ports are used to check the process during processing. These ports enable the connection of endpoint systems and/or optical emission spectrometer for process control.

DN40KF view port with different window diameter      Original view port of AMAT MxP
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- Mass spectrometer and residual gas analysis RGA

Vacuum Components for Process Control

- Needle valve
  - Laboratory equipment,
  - Training and Education
  - Manual vacuum control
- Throttle valve
  - Plasma etch and PECVD tools
  - Automatic vacuum control –
  - by reduction of pumping speed
- MFC (Mass Flow Controller)
  - Sputter etch tools
  - Automatic vacuum control –
  - by gas flow
- Temperature control
  - Temperature
    (e.g. DTCU at AMAT DPS)
    - Chamber wall
    - Wafer carrier (ESC)

Source: Plasma School Plasmetrex, © Plasmetrex 2014
Vacuum System Components

Valves:
- Inline valves
- Needle and venting valves

Gas Feed Line Connectors

SwageLok® connectors:
- VCO® → O-Ring Face Seal
- VCR® → Metal Gasket Face Seal
Mass Spectrometer and Residual Gas Analysis RGA

- Sector field mass spectrometer (magnetic field for mass separation)
- Quadrupole mass spectrometer (QMS)
Operating principle

- Mass spectrometry is a very popular analysis method used world-wide. It analyzes the gas composition by measurement of the partial pressure of different gases.
- The sum of all partial pressures in a given volume is called total pressure. With measurement of the partial pressures separately the gas composition can be determined.

Mass Spectrometer Components

- The gas to be investigated comes from an inlet system with a capillary or needle valve in the vacuum system, which is separately pumped down to the working pressure.
- In the vacuum system are
  - the ion source ionizing neutral gas particles,
  - the mass filter where the ionized particle are sorted on the basis of their mass-to-charge ratio,
  - a Faraday detector or a secondary electron multiplier measuring the ion current after passing the separating system (mass filter).
- The analysis system is a special software which presents these currents in various forms.
Mass Spectrometer Types

- The main differences in mass spectrometers is the separating system. The most widely used types of mass filters are:
  - Sector field systems use the deflection effects of moving charge carriers in a magnetic filed.
  - Time-of-flight mass (TOF) systems utilize the different velocity of ionized molecules of equal energy for separation.
  - The influence of high frequency fields on the trajectories of ions is used in ion traps.
  - Resonance effects on moved ions in a high frequency field (comparable to ion traps) is used in quadrupole mass spectrometers.

- This course focuses on sector field spectrometers as well as quadrupole mass spectrometers because these two types are most used in vacuum technologies.

Sector Field Mass Spectrometer

- Due to the robust and simple design, sector field mass spectrometers are used for Helium leak detectors, when the requirements on resolution are not so high.
### Appendix

#### Symbols I

<table>
<thead>
<tr>
<th></th>
<th>Vacuum pumps</th>
<th>Vacuum accessories</th>
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<tr>
<td>![icon]</td>
<td>Rotary vane pump</td>
<td>![icon] Roots pump</td>
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<tr>
<td>![icon]</td>
<td>Adsorption pump</td>
<td>![icon] Diaphragm pump</td>
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<td>![icon]</td>
<td>Diffusion pump</td>
<td>![icon] Piston pump</td>
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<tr>
<td>![icon]</td>
<td>Turbomolecular pump</td>
<td>![icon] Cooling (kryo) trap</td>
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<tr>
<td>![icon]</td>
<td>Ion getter pump</td>
<td>![icon] Burette</td>
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<tr>
<td>![icon]</td>
<td>Kryopump</td>
<td>![icon] Filter</td>
</tr>
</tbody>
</table>
### Symbols II

- **Vacuum accessories**
  - Gate valve
  - Angle valve
  - Dosing valve
  - Straight-way tap
  - Right-angle stop cock

- **Vacuum line general**
- **Flexible vacuum line**
- **Vacuum vessel**
- **Baffle**
- **Sorption trap**

### Symbols III

- **Measurement devices**
  - Vacuum meter (VM) general
  - Diapragm VM
  - Modulation VM
  - U-tube VM
  - Compression VM

- **Friction VM**
- **Thermal conductivity Vacuum gauge**
- **Cold-cathode ionization gauge**
- **Hot-cathode ionization gauge**
- **Mass spectrometer**
## SI Units - Fundamentals Units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Abbreviation</th>
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</thead>
<tbody>
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<tr>
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<tr>
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<tr>
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## Units - Selected Derived Units

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<tr>
<td>Force</td>
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</tr>
<tr>
<td>Energy</td>
<td>Joule</td>
<td>J = Ws = Nm</td>
</tr>
<tr>
<td>Power</td>
<td>Watt</td>
<td>W</td>
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<tr>
<td>Electrical charge</td>
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<tr>
<td>Electric potential</td>
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<td>V</td>
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<td>Ω</td>
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<tr>
<td>Capacitance</td>
<td>Farad</td>
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<tr>
<td>Inductance</td>
<td>Henry</td>
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<tr>
<td>Magnetic flux density</td>
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<td>T = 10000 G</td>
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## Physical Constants

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<td>A</td>
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<td>G</td>
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</tr>
<tr>
<td>C</td>
<td>F</td>
<td>Capacitance</td>
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<td>C_E</td>
<td>F</td>
<td>Capacitance of electrode sheath</td>
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</tr>
<tr>
<td>C_(W, gap, s, ...)</td>
<td>F</td>
<td>Capacitance (of wall, gap, sheath, ...)</td>
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<td>D</td>
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<tr>
<td>\lambda_i</td>
<td>mm</td>
<td>Mean free path of ions</td>
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<td>\lambda_e</td>
<td>mm</td>
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<td>Power</td>
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<td>Etch rate for layer</td>
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<td>atom / ion</td>
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<td>K ($^\circ$C)</td>
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<td>V</td>
<td>Voltage</td>
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<tr>
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<td>V</td>
<td>Voltage of bulk</td>
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</tr>
<tr>
<td>$U_{(\text{gap,bulk,s,bias,\ldots})}$</td>
<td>V</td>
<td>Voltage (gap, bulk, sheath, bias, ...)</td>
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<tr>
<td>$U_{\text{electrode}}$</td>
<td>V</td>
<td>Voltage of electrode sheath</td>
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</tr>
<tr>
<td>$U_f$</td>
<td>V</td>
<td>Floating potential</td>
<td></td>
</tr>
<tr>
<td>$U_{if}$</td>
<td>V</td>
<td>Voltage of generator</td>
<td></td>
</tr>
<tr>
<td>$U_P = \hat{U}$</td>
<td>V</td>
<td>Peak voltage</td>
<td></td>
</tr>
<tr>
<td>$U_{\text{sheath}}$</td>
<td>V</td>
<td>Voltage of sheath</td>
<td></td>
</tr>
<tr>
<td>$U_T$</td>
<td>V</td>
<td>Electron temperature</td>
<td></td>
</tr>
<tr>
<td>$U_{\text{wall}}$</td>
<td>V</td>
<td>Voltage of wall sheath</td>
<td></td>
</tr>
<tr>
<td>$U_o$</td>
<td>eV</td>
<td>Binding energy</td>
<td></td>
</tr>
<tr>
<td>$U$</td>
<td>s$^{-1}$</td>
<td>Collision rate</td>
<td></td>
</tr>
<tr>
<td>$u_{eff}$</td>
<td>s$^{-1}$</td>
<td>Effective collision rate</td>
<td></td>
</tr>
<tr>
<td>$v$</td>
<td>m / s</td>
<td>Mean velocity of reactants</td>
<td></td>
</tr>
<tr>
<td>$v_e$</td>
<td>m / s</td>
<td>Velocity of electrons</td>
<td></td>
</tr>
<tr>
<td>$\omega = 2pf$</td>
<td>s$^{-1}$</td>
<td>Circular frequency</td>
<td></td>
</tr>
<tr>
<td>$\omega_{ce}$</td>
<td>s$^{-1}$</td>
<td>Electron cyclotron frequency</td>
<td></td>
</tr>
<tr>
<td>$\omega_{p+}$</td>
<td>s$^{-1}$</td>
<td>Ion plasma frequency</td>
<td></td>
</tr>
<tr>
<td>$\omega_{pe}$</td>
<td>s$^{-1}$</td>
<td>Electron plasma frequency</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{chamber}}$</td>
<td>cm$^3$</td>
<td>Chamber volume</td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>-</td>
<td>Degree of ionization</td>
<td></td>
</tr>
</tbody>
</table>

Proportional to: $\propto$
In order of: $\sim$
Approximate: $\approx$
## SI Units

### Fundamentals units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>kilogram</td>
<td>kg</td>
</tr>
<tr>
<td>Length</td>
<td>meter</td>
<td>m</td>
</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>s</td>
</tr>
<tr>
<td>Temperature</td>
<td>Kelvin</td>
<td>K</td>
</tr>
<tr>
<td>Electrical current</td>
<td>ampere</td>
<td>A</td>
</tr>
<tr>
<td>Amount of substance</td>
<td>mole</td>
<td>mol</td>
</tr>
</tbody>
</table>

### Selected derived units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Hertz</td>
<td>Hz</td>
</tr>
<tr>
<td>Force</td>
<td>Newton</td>
<td>N</td>
</tr>
<tr>
<td>Energy</td>
<td>Joule</td>
<td>J = Ws = Nm</td>
</tr>
<tr>
<td>Power</td>
<td>Watt</td>
<td>W</td>
</tr>
<tr>
<td>Electrical charge</td>
<td>Coulomb</td>
<td>C = As</td>
</tr>
<tr>
<td>Electric potential</td>
<td>Volt</td>
<td>V</td>
</tr>
<tr>
<td>Electrical resistance</td>
<td>Ohm</td>
<td>Ω</td>
</tr>
<tr>
<td>Capacitance</td>
<td>Farad</td>
<td>F = As/V</td>
</tr>
<tr>
<td>Inductance</td>
<td>Henry</td>
<td>H = Vs/A</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>Tesla</td>
<td>T = 10000 G</td>
</tr>
</tbody>
</table>
Range of parameter for RF discharge

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure ( P )</td>
<td>1 - 1000 Pa (10 – 10000 mTorr)</td>
</tr>
<tr>
<td>Power ( P )</td>
<td>50 - 2000 W</td>
</tr>
<tr>
<td>Frequency ( F )</td>
<td>50 kHz - 100 MHz</td>
</tr>
<tr>
<td>Volume ( V )</td>
<td>1 - 200 l</td>
</tr>
<tr>
<td>Electrode area ( A )</td>
<td>300 - 60000 cm²</td>
</tr>
<tr>
<td>Magnetic field ( B )</td>
<td>0 - 100 G</td>
</tr>
<tr>
<td>Plasma density ( N )</td>
<td>( 10^9 - 10^{11} ) cm⁻³</td>
</tr>
<tr>
<td>Electron temperature ( T_e )</td>
<td>1 - 6 V</td>
</tr>
<tr>
<td>Ion energy ( e_i )</td>
<td>20 - 2000 V</td>
</tr>
<tr>
<td>Fractional ionization ( x_{iz} )</td>
<td>( 10^{-6} - 10^{-3} )</td>
</tr>
</tbody>
</table>

Physical constants

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of light (in vacuum)</td>
<td>( c )</td>
<td>299 792 458</td>
<td>m / s</td>
</tr>
<tr>
<td>Vacuum permeability</td>
<td>( \mu_0 )</td>
<td>( 1.26 \times 10^{-6} )</td>
<td>H / m</td>
</tr>
<tr>
<td>Vacuum permittivity</td>
<td>( e_0 )</td>
<td>( 8.85 \times 10^{-12} )</td>
<td>As / Vm</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>( k_B )</td>
<td>( 1.38 \times 10^{-23} )</td>
<td>Ws / K</td>
</tr>
<tr>
<td>Elementary charge</td>
<td>( e )</td>
<td>( 1.60 \times 10^{-19} )</td>
<td>As</td>
</tr>
<tr>
<td>Electron mass</td>
<td>( m_e )</td>
<td>( 9.11 \times 10^{-31} )</td>
<td>kg</td>
</tr>
<tr>
<td>Atomic mass unit</td>
<td>( u )</td>
<td>( 1.67 \times 10^{-27} )</td>
<td>kg</td>
</tr>
</tbody>
</table>