

# 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)

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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 10<sup>th</sup>.

Texts:

## **Required:**

*A User's Guide to Vacuum Technology*, John F. O'Hanlon, Wiley-Interscience, New York, 1989, ISBN 0-471-81242-0

*Plasma Etching: an Introduction* Edited by D.M Manos and D.L. Flamm, Academic Press, 1989, ISBN 0-12-469370-9

## **Recommended:**

*Introduction to Plasma Physics*, F.F. Chen, Plenum, New York, 1974, ISBN 0-306-41332-9

*Principles of Plasma Discharges and Materials Processing*, M.A. Lieberman and A.J.

Lichtenberg, Wiley-Interscience, New York, 1994, ISBN 0-471-00577-0

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 3<sup>rd</sup>.

Final or project 25% 2:00 PM Friday, May 10<sup>th</sup>.

**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.)*

# Approximate course syllabus: (Includes Lab!)

MF-1 = Manos and Flamm chapter 1, JO-3 = J. O'Hanlon chapter 3

Week Number	Lecture Period	Lab Period	Lecture Date	Lab Date	Topic	Reading	Lab Manual Author	Plasma Tool
1	1		14-Jan		Class Overview: What is plasma, where is it found etc. Overview of the subset of plasma technologies to be studied.	MF-1, JO-1,2		
		1		15-Jan	<b>No Lab</b>			
	2		16-Jan		Basic Gas Kinetics/Properties	JO-3		
2			21-Jan		<b>Holiday</b>			
		2		22-Jan	<b>System Overview I: Device ID-ing, Venting, Pump-down, Safety (Includes CR Gowning and procedures overview)</b>		JM/KB/MJG	Indy
	3		23-Jan		Gas Flow	JO-4,5		
3	4		28-Jan		Gas Release and Pressure Measurement	JO-5,6		
		3		29-Jan	<b>Gas Systems I: Using Pressure Measurement Devices</b>		JM	Holly and Maggie
	5		30-Jan		Pressure and Flow Measurements	JO-7		
4	6		4-Feb		Pumping I: Pump Speed	JO-10,11,13		
		4		5-Feb	<b>Gas Systems II: Using Flow Control: Pressure vs. Flow, Leak Rate and Outgassing</b>		GE	Maggie
	7		6-Feb		Pumping II: Pump Operation	JO-19,(1-2), 21		
5	8		11-Feb		High Vacuum and High Flow Systems	JO-16,17		
		5		12-Feb	<b>Gas Systems III: Pumping systems (Turbo-Cryo-Roots-Rotary Vane)</b>		AJC	Indy
	9		13-Feb		Vacuum chamber materials	JO-22		
6	10		18-Feb		Powered materials (Including Wafer Chucks) in plasma chambers	MF-3		
		6		19-Feb	<b>Gas Systems VI: Pressure vs. Conductance</b>		LJO	Cappy
	11		20-Feb		RF Matching I: Power Matching Networks			
7	12		25-Feb		RF Matching II:			
		7		26-Feb	<b>Gas System Diagnostics I: Leak Detection</b>		JM	Indy
	13		27-Feb		Plasma Physics I: Bulk Plasma Properties	TBD		
8	14		4-Mar		Plasma Physics II: Collisions/Distributions	MF-4		
		8		5-Mar	<b>Gas System Diagnostics II/Basic Plasma Properties I: Residual Gas Analyzers and Plasma Chemistry</b>		LJO	Cappy
	15		6-Mar		Plasma Physics III: Sheaths	TBD		
			11-Mar		Spring Break			
			12-Mar		Spring Break			
			13-Mar		Spring Break			
9	16		18-Mar		Plasma Physics IV: Plasma Sources	TBD		
		9		19-Mar	<b>Basic Plasma Properties II: I-V-P Response of Magnetron Plasmas</b>		MJG	Maggie
	17		20-Mar		Plasma Diagnostics I: Langmuir Probes	MF-2		
10	18		25-Mar		Plasma Diagnostics II: Mass, Optical Spectrums			
		10		26-Mar	<b>Basic Plasma Properties III: Optical Emissions</b>		AJC	Holly
	19		27-Mar		Plasma Diagnostics III: RF Probes			
11	20		1-Apr		<b>Catch-up/Review day</b>			
		11		2-Apr	<b>Plasma Generation, Use and Diagnostics I: RF1: Capacitive coupled systems for deposition (Includes Power/Impedance Diagnostics)</b>		LJO	Cappy
	21		3-Apr		<b>*** Exam I ***</b> (Through plasma diagnostics III)			

12	22		8-Apr		Plasma Chemistry I: Etching Mechanisms			
		12		9-Apr	<b>Plasma Generation, Use and Diagnostics II: RF2: Inductively coupled systems for etch (Includes Density and Power Diagnostics)</b>		GE	Indy
	23		10-Apr		Plasma Chemistry II: Silicon and Compounds			
13	24		15-Apr		Plasma Chemistry III: Metals and Oxides			
		13		16-Apr	<b>Plasma Generation, Use and Diagnostics III: DC1: Hollow Cathode systems for propulsion (Includes Langmuir probe Diagnostics)</b>		GE	Holly
	25		17-Apr		Plasma Chemistry III: Metals and Oxides	MF-7		
14	26		22-Apr		Plasma Chemistry IV: Deposition	TBD		
		14		23-Apr	<b>Plasma Generation, Use and Diagnostics IV: DC2: Magnetrons for Sputter Deposition (Includes Raman spectra Diagnostics of films and film thickness)</b>		MJG/AJC	Maggie and Raman
	27		24-Apr		Particulate Contamination	TBD		
15	28		29-Apr		<b>Catch-up/Review day</b>			
		15		30-Apr	<b>Lab Practical?</b>			
	29		1-May		Student Choice or Class Review			
				6-May	Final exam week			
			10-May		<b>Final Exam or Reports due</b>			

## **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. Let's think about the chemical  $H_2O$ . When it is very cold, e.g. has low random energy we get ice or snow. (Note that one can throw 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  $H_2O$  into water – a liquid. As we continue to heat the  $H_2O$  it boils and gives off steam – a gas. If we were able to continue to push energy into the  $H_2O$

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 of 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 gets 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 break up. (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 break up is not interesting – we still have a gas, albeit slightly different. For example  $H_2O$  might become  $HO$  and  $H$ . This however is still a gas. On the other hand having an electron escape its orbit can provide something 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 is 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 matter is known as a "quark-gluon plasma". In this case even the standard elementary particles, 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  $^{\circ}C$ . Electron temperatures are observed over similar ranges. Note: Different species are not always in thermal equilibrium and hence have different temperatures. This is often true in the plasmas that we will consider here. Figure 1 shows just a few of the possible plasmas and where they fit in the density and energy range.

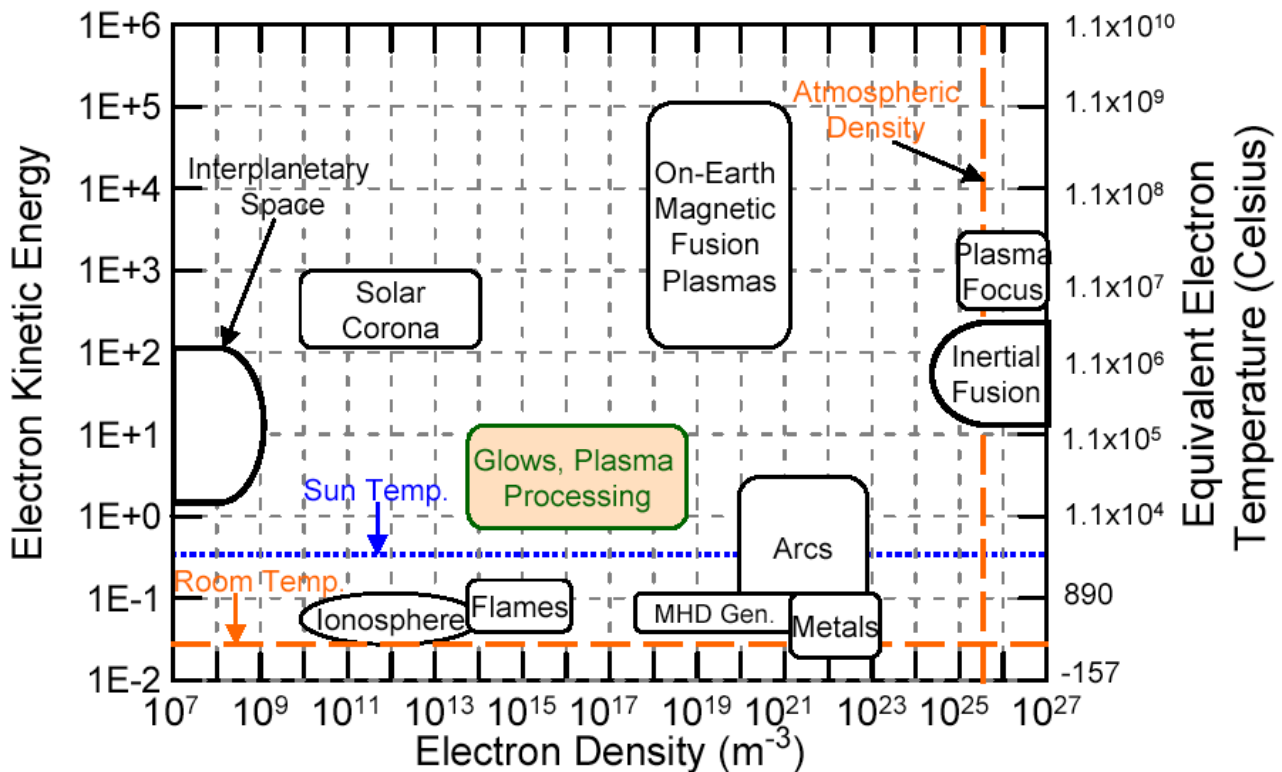


Figure 1: Where different plasmas exist in energy-density space. We will discuss mostly Glows as applied to plasma applications.

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 too high. Likewise  $\text{BF}_3$ , 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,  $\text{SiH}_4$ ) 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.**



# MATERIAL SAFETY DATA SHEET

Prepared to U.S. OSHA, CMA, ANSI and Canadian WHMIS Standards

## 1. PRODUCT IDENTIFICATION

**CHEMICAL NAME; CLASS:** SILANE

**SYNONYMS:** Silicon Tetrachloride; Monosilane; Silicane  
**CHEMICAL FAMILY NAME:** Hydride  
**FORMULA:** SiH<sub>4</sub>

**PRODUCT USE:** Document Number: 20148  
 Production of amorphous silicon and silicon substrates; other analytical/synthetic chemical uses.

**SUPPLIER/MANUFACTURER'S NAME:** AIR LIQUIDE AMERICA CORPORATION  
**ADDRESS:** 2700 Post Oak Drive  
 Houston, TX 77056-8229

**EMERGENCY PHONE:** CHEMTREC: 1-800-424-9300

**BUSINESS PHONE:** General MSDS Information 1-713/896-2896  
 Fax on Demand: 1-800/231-1366

## 2. COMPOSITION and INFORMATION ON INGREDIENTS

CHEMICAL NAME	CAS #	mole %	EXPOSURE LIMITS IN AIR						
			ACGIH			OSHA			OTHER
			TLV ppm	STEL ppm	PEL ppm	STEL ppm	IDLH ppm		
Silane	7803-62-5	> 99%	5	NE	5 (Vocated 1989 PEL)	NE	NE	NIOSH REL: 5 ppm	
Maximum Impurities		< 1%	None of the trace impurities in this product contribute significantly to the hazards associated with the product. All hazard information pertinent to this product has been provided in this Material Safety Data Sheet, per the requirements of the OSHA Hazard Communication Standard (29 CFR 1910.1200) and State equivalent standards.						

NE = Not Established C = Ceiling Limit See Section 16 for Definitions of Terms Used.  
 NOTE: All WHMIS required information is included. It is located in appropriate sections based on the ANSI Z400.1-1993 format.

## 3. HAZARD IDENTIFICATION

**EMERGENCY OVERVIEW: PYROPHORIC GAS!** This product is a colorless, air-reactive gas, with a choking effect. This gas usually ignites upon contact with air, releasing a dense white cloud of amorphous silicon dioxide. Silane can react with water to form corrosive silicic 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. Flame or high temperature impinging 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 fire protection appropriate for the situation to which they are responding.

**SYMPTOMS OF OVER-EXPOSURE BY ROUTE OF EXPOSURE:** The gas is pyrophoric; over-exposures to the unignited gas would be unlikely under normal circumstances of use. The following symptoms may develop in the event 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 silicic acid, which can be irritating to the mucous membranes and the respiratory system. Severe Silane over-exposures via inhalation may result in pulmonary edema. Decomposition of Silane will result in the production of amorphous silicon dioxide. Though inhalation of amorphous silicon dioxide can be irritating to the nose and throat, such exposure does not present the potential for adverse health effects as inhalation of crystalline silicon dioxide.

**SKIN and EYE CONTACT:** Silane reacts with water to form silicic acid, which can be irritating to the skin and eyes. Decomposition of Silane will result in the production of amorphous silicon dioxide. Skin or eye contact with particulates of amorphous silicon dioxide 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. Though 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 air or moisture can produce silicic acid and amorphous silicon dioxide; both decomposition products can irritate the eyes, mucous membranes and respiratory tract.

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

**TARGET ORGANS:** Respiratory system, skin, eyes.

HAZARDOUS MATERIAL INFORMATION SYSTEM			
HEALTH	(BLUE)		1
FLAMMABILITY	(RED)		4
REACTIVITY	(YELLOW)		3
PROTECTIVE EQUIPMENT		X	
EYES	RESPIRATORY	HANDS	BODY
See Section 8			
For routine industrial applications			

## 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)

Remove victim(s) to fresh air, as quickly as possible. Only trained personnel should administer supplemental oxygen and/or cardio-pulmonary resuscitation, if necessary.

**THERMAL BURNS:** In the event personnel are burned as a result of a Silane release, trained personnel should provide first aid treatment. Get medical attention immediately.

**SKIN EXPOSURE:** If silicic acid (from the reaction of Silane and water) contaminates the skin, immediately begin decontamination with running water. Minimum flushing is for 15 minutes. If amorphous silicon dioxide (from the reaction of Silane with oxygen) contaminates the skin, flush area with copious amounts of water. Remove exposed or contaminated clothing, taking care not to contaminate eyes. Victim must seek medical attention if irritation persists, or if there are other adverse health effects.

**EYE EXPOSURE:** If the decomposition products (silicic acid, amorphous silicon dioxide) contaminate the eyes, immediately begin decontamination with running water, open victim's eyes while under gently running water. Use sufficient force to open eyelids. Have victim "roll" eyes. Minimum flushing is for 15 minutes. Victim must seek medical attention.

Victim(s) must be taken for medical attention. Rescuers should be taken for medical attention, if necessary. Take copy of label and MSDS to physician or other health professional with victim(s).

#### 5. FIRE-FIGHTING MEASURES

**FLASH POINT:** Not applicable. Pyrophoric gas.

**AUTOIGNITION TEMPERATURE:** Not applicable. Pyrophoric gas.

**FLAMMABLE LIMITS (in air by volume, %):**

Lower (LEL): 1.4%  
Upper (UEL): 96%

**FIRE EXTINGUISHING MATERIALS:** Extinguish Silane fires by shutting-off the source of the gas. Use a fine water spray or fog to reduce combustion products formed in air. Do not use halocarbon-type fire extinguishing agents. Cool fire-exposed cylinders with water spray, from the maximum distance possible.

**UNUSUAL FIRE AND EXPLOSION HAZARDS: PYROPHORIC GAS!** This product is a colorless, air-reactive gas. This gas usually ignites upon contact with air, releasing a dense white cloud of amorphous silicon dioxide. The products of thermal decomposition of this material include amorphous silicon dioxide and hydrogen. Silane can react with water to form corrosive silicic acid. The decomposition products of Silane can be irritating to exposed tissue. **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.**

**DANGER!** Fires impinging (direct flame) on the outside surface of unprotected cylinders of this product can be very dangerous. Exposure to fire could cause a catastrophic failure of the cylinder releasing the contents into a fireball and explosion of released gas. The resulting fire and explosion can result in severe equipment damage and personnel injury or death over a large area around the cylinder. For fires in large areas, use unmanned hose holder or monitor nozzles; if this is not possible, withdraw from area and allow fire to burn.

**Explosion Sensitivity to Mechanical Impact:** Not sensitive.

**Explosion Sensitivity to Static Discharge:** Static discharge may cause this product to ignite explosively.

**SPECIAL FIRE-FIGHTING PROCEDURES:** Structural fire-fighters must wear Self-Contained Breathing Apparatus and full protective equipment. If water is not available for cooling or protection of cylinder exposures, evacuate the area. Follow the evacuation guidelines of the North American Emergency Response Guidebook (Guide #116).

#### 6. ACCIDENTAL RELEASE MEASURES

**LEAK RESPONSE:** Evacuate immediate area. Silane is a pyrophoric gas and can ignite spontaneously upon contact with air. Uncontrolled releases should be responded to by trained personnel using pre-planned procedures. Normally, an accidental release of Silane will result in a fire. 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. This gas usually ignites upon contact with air, releasing a dense white cloud of amorphous silicon dioxide.

SILANE - SiH<sub>4</sub> MSDS

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#### 7. HANDLING AND USE (Continued)

- Use an alternate vacuum and inert gas purge cycles of the system to purge all air out of the system after it has been leak-tested or opened for any reason.
- Before disconnecting any system that has Silane in it, thoroughly purge the system of Silane with an inert gas. Any portion of a system that is dead-ended or allows "pocketing" of Silane should be treated with considerable vacuum-purge cycles.
- Vent Silane or Silane mixtures through small-diameter pipe or tubing ending under a shallow seal to prevent back diffusion of air. Venting should be to an area designed for Silane disposal, preferably by burning. Concentrations, even in the low percentage range, are dangerous and should not be exposed to air. Silane can also be vented by diluting with an inert gas to prevent ignition upon discharge to the atmosphere.

**SPECIAL PRECAUTIONS FOR HANDLING GAS CYLINDERS:** Compressed gases can present significant safety hazards. The following rules are applicable to work situations in which cylinders are being used.

**Before Use:** Move cylinders with a suitable hand-truck. Do not drag, slide or roll cylinders. Do not drop cylinders or permit them to strike each other. Secure cylinders firmly. Leave the valve protection cap (where provided) in-place until cylinder is ready for use.

**During Use:** Use designated CGA fittings and other support equipment. Do not use adapters. Use piping and equipment adequately designed to withstand pressures to be encountered. Do not heat cylinder by any means to increase the discharge rate of the product from the cylinder. Do not use oils or grease on gas-handling fittings or equipment. Do not "crack" valve open before connecting it. Since self-ignition may occur. Leak check system with leak detection solution or other leak detection instruments suitable for Silane, never with flame. Immediately contact the supplier if there are any difficulties associated with operating cylinder valve. Never insert an object (e.g. wrench, screwdriver, pry bar, etc.) into valve cap openings. Doing so may damage valve, causing a leak to occur. Use an adjustable strap wrench to remove over-tight or rusted caps. Never strike an arc on a compressed gas cylinder or make a cylinder part of an electric circuit.

**After Use:** Close main cylinder valve. Valves should be closed tightly. Replace valve protection cap. Mark empty cylinders "EMPTY".

**NOTE:** Use only DOT or ASME code containers designed for flammable gas storage. Earth-ground and bond all lines and equipment associated with this product. Close valve after each use and when empty.

**STANDARD VALVE CONNECTIONS FOR U.S. AND CANADA:** Use the proper connections, **DO NOT USE ADAPTERS.**

**THREADED:** Up to 500 psig - CGA 510  
Up to 3000 psig - CGA 350  
**PIN-INDEXED YOKES:** Not Applicable  
**ULTRA HIGH INTEGRITY:** Up to 3000 psig - CGA 632

**PROTECTIVE PRACTICES DURING MAINTENANCE OF CONTAMINATED EQUIPMENT:** Follow practices indicated in Section 6 (Accidental Release Measures). Make certain application equipment is locked and tagged-out safely. Purge gas handling equipment with inert gas (i.e. nitrogen) before attempting repairs. Always use product in areas where adequate ventilation is provided.

#### 8. EXPOSURE CONTROLS - PERSONAL PROTECTION

**VENTILATION AND ENGINEERING CONTROLS:** Silane detectors should be installed in or near areas where this product is being used or stored. If appropriate, install automatic monitoring equipment to detect the level of oxygen and the presence of potentially explosive air-gas mixtures. Use with adequate ventilation. Provide natural or explosion-proof ventilation adequate to ensure Silane does reach its lower flammability limit of 1.4%. Local exhaust ventilation is preferred, because it prevents gas dispersion into the work place by eliminating it at its source.

**RESPIRATORY PROTECTION:** Maintain oxygen levels above 19.5% in the workplace. Use supplied air respiratory protection if oxygen levels are below 19.5% or during emergency response to a release of this product. If respiratory protection is required, follow the requirements of the Federal OSHA Respiratory Protection Standard (29 CFR 1910.134), or equivalent State standards.

**EYE PROTECTION:** Safety glasses.

**HAND PROTECTION:** Wear leather gloves when handling cylinders of this product.

**BODY PROTECTION:** Use body protection appropriate for task. Cotton clothing is recommended for use to prevent static electric build-up. Safety shoes are recommended when handling cylinders. Fire retardant clothing may be appropriate under some circumstances of use.

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#### 6. ACCIDENTAL RELEASE MEASURES

Proper protective equipment should be used. In case of a gas release, clear the affected area, protect people, and respond with trained personnel. Eliminate any possible sources of ignition, and provide maximum explosion-proof ventilation. If the gas is leaking from cylinder or valve, contact the supplier. Adequate fire protection must be provided. Use only non-sparking tools and equipment during the response.

Minimum Personal Protective Equipment should be **Level B: fire-retardant protective clothing, gloves and Self-Contained Breathing Apparatus.** Use only non-sparking tools and equipment. Locate and seal the source of the leaking gas. Protect personnel attempting the shut-off with water-spray. Allow the gas to dissipate.

Monitor the surrounding area for combustible gas levels. The level of Silane must be at acceptable levels (see Section 2, Composition on Information on Ingredients) before personnel can be allowed in the area without Self-Contained Breathing Apparatus. Combustible gas concentration must be below 10% of the LEL (1.4%) prior to entry. Attempt to close the main source valve prior to entering the area. If this does not stop the release (or if it is not possible to reach the valve), allow the gas to release in-place or remove it to a safe area and allow the gas to be released there.

**THIS IS A PYROPHORIC GAS.** Protection of all personnel and the area must be maintained.

#### 7. HANDLING and USE

**WORK PRACTICES AND HYGIENE PRACTICES:** Non-sparking tools should be used. Do not attempt to repair, adjust, or in any other way modify the cylinders containing Silane. If there is a malfunction, or another type of operational problem, contact nearest distributor immediately. Working alone with Silane should be avoided when possible. All work operations should be monitored in such a way that emergency personnel can be immediately contacted in the event of a release.

**STORAGE AND HANDLING PRACTICES:** Cylinders should be stored upright (with valve-protection cap in place) and firmly secured to prevent falling or being knocked over. Cylinders can be stored in the open, but in such cases, should be protected against extremes of weather and from the dampness of the ground to prevent rusting. Cylinders should be stored in dry, well-ventilated areas away from sources of heat, ignition and direct sunlight.

Keep storage area clear of materials which can burn. Do not allow area where cylinders are stored to exceed 52°C (125°F). Store containers away from heavily trafficked areas and emergency exits. Store away from process and production areas, away from elevators, building and room exits or main aisles leading to exits. Protect cylinders against physical damage. Because of the potential for delayed ignition of Silane, storage and use areas should be designed and constructed to protect workers from possible explosive detonation.

Cylinders should be separated from oxygen cylinders, or other oxidizers, by a minimum distance of 20 ft., or by a barrier of non-combustible material at least 5 ft. high, having a fire-resistance rating of at least 0.5 hours. Isolate from other incompatible chemicals, such as strong oxidizers, metals, and metal oxides (refer to Section 10, Stability and Reactivity, for more information).

Storage areas must meet national electrical codes for Class 1 Hazardous Areas. Post "No Smoking or Open Flames" signs in storage or use areas. Consider installation of leak detection and alarm for storage and use areas. Have appropriate extinguishing equipment in the storage area (i.e. sprinkler system, portable fire extinguishers).

Full and empty cylinders should be segregated. Use a first-in, first-out inventory system to prevent full containers from being stored for long periods of time.

Use non-sparking ventilation systems, approved explosion-proof equipment, and appropriate electrical systems. Electrical equipment used in gas-handling operations, or located in storage areas, should be non-sparking or explosion proof. Use a check valve in the discharge line to prevent hazardous backflow. Never tamper with pressure relief devices in valves and cylinders.

**SPECIAL HANDLING PROCEDURES FOR HANDLING SILANE:**

- Do not condense Silane by avoiding temperatures of -148°F (-100°C) or less. Condensation of Silane runs the risk of leaks developing and forming explosive mixtures (due to sucking-back of air into the system).
- Do not use Silane in conjunction with heavy-metal halides or free halogens, with which Silane will react violently. Care should be taken that all handling systems are purged free of halogens that might exist from degreasing agents, or chlorinated hydrocarbons.
- Evacuate and thoroughly pressure-check all systems, preferably with helium, for leaks at pressures two to three times the anticipated working pressure. In addition, regular leak-testing should be instituted and performed.

SILANE - SiH<sub>4</sub> MSDS

PAGE 4 OF 8

EFFECTIVE DATE: JUNE 1, 1998

#### PHYSICAL and CHEMICAL PROPERTIES

**GAS DENSITY @ 0°C (32°F):** 0.0899 lbm/ft<sup>3</sup> (1.44 kg/m<sup>3</sup>)

**BOILING POINT @ 1 atm:** -112°C (-169°F)

**FREEZING/MELTING POINT @ 1 atm:** -184.7°C (-300.5°F)

**SPECIFIC GRAVITY @ 21.1°C (70°F) and 14.7 psia (air = 1):** 1.2

**pH:** Not applicable.

**SOLUBILITY IN WATER @ 20°C (68°F):** Negligible.

**MOLECULAR WEIGHT:** 32.112

**EVAPORATION RATE (nBuAc = 1):** Not applicable.

**EXPANSION RATIO:** Not applicable.

**ODOR THRESHOLD:** Not determined.

**SPECIFIC VOLUME (ft<sup>3</sup>/lb):** 12.0

**VAPOR PRESSURE @ -122.2°C (-188°F) psig:** 7.73

**COEFFICIENT WATER/OIL DISTRIBUTION:** Not applicable.

**APPEARANCE AND COLOR:** Colorless gas, with a choking effect.

**HOW TO DETECT THIS SUBSTANCE (warning properties):** The odor cannot be considered a good warning property, because the odor threshold is above the level necessary for the ignition of Silane. This gas usually ignites upon contact with air, releasing a dense white cloud of amorphous silicon dioxide.

#### 10. STABILITY and REACTIVITY

**STABILITY:** Pyrophoric. Ignites spontaneously on exposure to air.

**DECOMPOSITION PRODUCTS:** Amorphous silicon dioxide and hydrogen.

**MATERIALS WITH WHICH SUBSTANCE IS INCOMPATIBLE:** Silane will react violently with heavy-metal halides and free halogens (i.e. bromine, chlorine, carbonyl chloride, antimony pentachloride, tin(IV) chloride). Silane ignites in oxygen and can react with other oxidizers. Silane is also incompatible with bases.

**HAZARDOUS POLYMERIZATION:** Will not occur.

**CONDITIONS TO AVOID:** Contact with air. Contact with incompatible materials and exposure to heat, sparks and other sources of ignition. If the cylinders are exposed to extremely high temperatures, these cylinders can rupture.

#### 11. TOXICOLOGICAL INFORMATION

**TOXICITY DATA:** The following toxicity data are available for Silane.

Inhalation - Rat: LC<sub>50</sub>: 9600 ppm/4 hours

Inhalation - Mouse: LC<sub>50</sub>: 9600 ppm/4 hours

**SUSPECTED CANCER AGENT:** Silane is not found on the following lists: FEDERAL OSHA Z LIST, NTP, CAL/OSHA, IARC and therefore is not considered to be, nor suspected to be a cancer-causing agent by these agencies.

**IRRITANCY OF PRODUCT:** This decomposition products of Silane are irritating to the eyes, skin, and tissues of the respiratory system.

**SENSITIZATION TO THE PRODUCT:** Silane is not known to be a sensitizer.

**REPRODUCTIVE TOXICITY INFORMATION:** Listed below is information concerning the effects of this product on the human reproductive system.

**Mutagenicity:** No mutagenicity effects have been described for Silane.

**Embryotoxicity:** No embryotoxic effects have been described for Silane.

**Teratogenicity:** No teratogenicity effects have been described for Silane.

**Reproductive Toxicity:** No reproductive toxicity effects have been described for Silane.

A **mutagen** is a chemical which causes permanent changes to genetic material (DNA) such that the changes will propagate through generation lines. An **embryotoxin** is a chemical which causes damage to a developing embryo (i.e. within the first eight weeks of pregnancy in humans), but the damage does not propagate across generational lines. A **teratogen** is a chemical which causes damage to a developing fetus, but the damage does not propagate across generational lines. A **reproductive toxin** is any substance which interferes in any way with the reproductive process.

**MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE:** Skin conditions and respiratory disorders may be aggravated by exposures to Silane and its decomposition products.

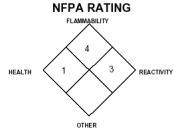
**RECOMMENDATIONS TO PHYSICIANS:** Administer oxygen, if necessary; treat symptoms; eliminate exposure. Be observant for initial signs of pulmonary edema.

**BIOLOGICAL EXPOSURE INDICES (BEIs):** Currently, Biological Exposure Indices (BEIs) are not applicable for Silane.

SILANE - SiH<sub>4</sub> MSDS

PAGE 6 OF 8

EFFECTIVE DATE: JUNE 1, 1998





**12. ECOLOGICAL INFORMATION**

**ENVIRONMENTAL STABILITY:** Silane ignites spontaneously upon contact with air, generating amorphous silicon dioxide and hydrogen. Silane, upon contact with water or moisture, will generate silicic acid. All work practices must be directed at eliminating environmental contamination.

**EFFECT OF MATERIAL ON PLANTS or ANIMALS:** The primary health hazard associated with Silane is the potential for severe thermal burns to plants and animals from contact with flames which result from the spontaneous ignition of this gas. Depending on the severity of the burns, such exposures can be fatal.

**EFFECT OF CHEMICAL ON AQUATIC LIFE:** Silane, upon contact with water or moisture, will generate silicic acid. Silicic acid can lower the pH of water; subsequently, releases of Silane can have an adverse effect on aquatic life in contaminated bodies of water.

**13. DISPOSAL CONSIDERATIONS**

**PREPARING WASTES FOR DISPOSAL:** Waste disposal must be in accordance with appropriate Federal, State, and local regulations. Return cylinders with any residual product to Air Liquide. Do not dispose of locally.

**14. TRANSPORTATION INFORMATION**

**THIS MATERIAL IS HAZARDOUS AS DEFINED BY 49 CFR 172.101 BY THE U.S. DEPARTMENT OF TRANSPORTATION.**

**PROPER SHIPPING NAME:** Silane  
**HAZARD CLASS NUMBER and DESCRIPTION:** 2.1  
**UN IDENTIFICATION NUMBER:** UN 2203  
**PACKING GROUP:** Not applicable.  
**DOT LABEL(S) REQUIRED:** Flammable Gas  
**NORTH AMERICAN EMERGENCY RESPONSE GUIDEBOOK NUMBER (1996):** 116

**MARINE POLLUTANT:** Silane is not classified by the DOT as a Marine Pollutant (as defined by 49 CFR 172.101, Appendix B).

**SPECIAL SHIPPING INFORMATION:** Cylinders should be transported in a secure position, in a well-ventilated vehicle. The transportation of compressed gas cylinders in automobiles or in closed-body vehicles present serious safety hazards and should be discouraged.

**NOTE:** Shipment of compressed gas cylinders which have not been filled with the owners consent is a violation of Federal law (49 CFR, Part 173.301 (b)).

**TRANSPORT CANADA TRANSPORTATION OF DANGEROUS GOODS REGULATIONS:** THIS MATERIAL IS CONSIDERED AS DANGEROUS GOODS. Use the above information for the preparation of Canadian Shipments.

**15. REGULATORY INFORMATION**

**SARA REPORTING REQUIREMENTS:** Silane is not subject to the reporting requirements of Sections 302, 304 and 313 of Title III of the Superfund Amendments and Reauthorization Act.

**SARA THRESHOLD PLANNING QUANTITY:** Not applicable.

**TSCA INVENTORY STATUS:** Silane is listed on the TSCA Inventory.

**CERCLA REPORTABLE QUANTITY (RQ):** Not applicable.

- OTHER U.S. FEDERAL REGULATIONS:**
- Silane is not subject to the reporting requirements of CFR 29 1910.1000.
  - Depending on specific operations involving the use of Silane, the regulations of the Process Safety Management of Highly Hazardous Chemicals may be applicable (29 CFR 1910.119). Silane is not listed in Appendix A of this regulation, however, any process that involves a flammable gas on-site, in one location, in quantities of 10,000 lbs (4,553 kg) or greater is covered under this regulation unless it is used as a fuel.
  - Silane does not contain any Class I or Class II ozone depleting chemicals (40 CFR part 82).
  - Silane is listed under Table 3 as a Regulated Substance, per 40 CFR, Part 68, of the Risk Management for Chemical Release Prevention, as a flammable substance. The threshold quantity for Silane under this regulation is 10,000 lbs.
  - Silane is listed under Section 112(r) of the Clean Air Act. The threshold quantity for Silane under this regulation is 10,000 lbs.

**15. REGULATORY INFORMATION (Continued)**

**OTHER CANADIAN REGULATIONS:** Silane is categorized as a Controlled Product, Hazard Classes A, B1, B6, and F as per the Controlled Product Regulations.

**STATE REGULATORY INFORMATION:** Silane covered under specific State regulations, as denoted below:

Alaska - Designated Toxic and Hazardous Substances: Silane.  
California - Permissible Exposure Limits for Chemical Contaminants: Silane.  
Florida - Substance List: Silane.  
Illinois - Toxic Substance List: Silane.  
Kansas - Section 3820313 List: None.  
Massachusetts - Substance List: Silane.  
Minnesota - List of Hazardous Substances: Silane.  
Missouri - Employer Information/Toxic Substance List: Silane.  
New Jersey - Right to Know Hazardous Substance List: Silane.  
North Dakota - List of Hazardous Chemicals, Reportable Quantities: None.  
Pennsylvania - Hazardous Substance List: Silane.  
Rhode Island - Hazardous Substance List: None.  
Texas - Hazardous Substance List: Silane.  
West Virginia - Hazardous Substance List: None.  
Wisconsin - Toxic and Hazardous Substances: None.

**CALIFORNIA PROPOSITION 65:** Silane is not on the California Proposition 65 lists.

**16. OTHER INFORMATION**

**MIXTURES:** When two or more gases or liquefied gases are mixed, their hazardous properties may combine to create additional, unexpected hazards. Obtain and evaluate the safety information for each component before you produce the mixture. Consult an Industrial Hygienist or other trained person when you make your safety evaluation of the end product. Remember, gases and liquids have properties which can cause serious injury or death.

Further information can be Silane found in the following pamphlets published by: Compressed Gas Association Inc. (CGA), 1725 Jefferson Davis Highway, Suite 1004, Arlington, VA 22202-4102. Telephone: (703) 412-0900.

P-1 "Safe Handling of Compressed Gases in Containers"  
AV-1 "Safe Handling and Storage of Compressed Gases"  
"Handbook of Compressed Gases"

**PREPARED BY:** CHEMICAL SAFETY ASSOCIATES, Inc.  
9163 Chesapeake Drive, San Diego, CA 92123-1002  
619/565-0302  
Fax on Demand: 1-800/231-1366



This Material Safety Data Sheet is offered pursuant to OSHA's Hazard Communication Standard, 29 CFR, 1910.1200. Other government regulations must be reviewed for applicability to this product. To the best of Air Liquide America Corporation's knowledge, the information contained herein is reliable and accurate as of this date; however, accuracy, suitability or completeness are not guaranteed and no warranties of any type, either express or implied, are provided. The information contained herein relates only to this specific product. If this product is combined with other materials, all component properties must be considered. Data may be changed from time to time. Be sure to consult the latest edition.

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 gloving, 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**

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Plasma Laboratories

Matthew J. Goeckner

**Outline**

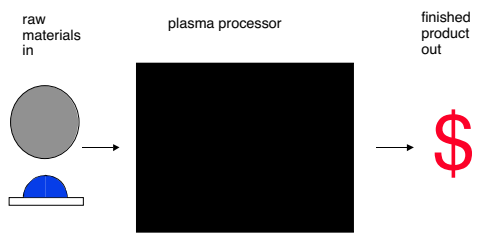
- 1) Why study plasma processing?
- 2) Diagnostic tools used to study processes
- 3) Overview of some plasma processes
- 4) Overview of some processing discharges
- 5) Opportunities in plasma processing

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**How some view plasma processing**

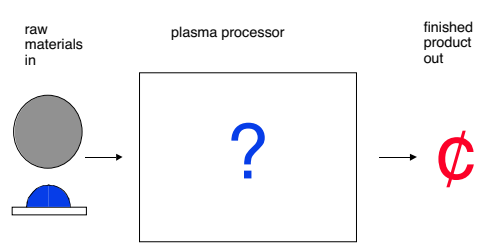


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**How plasma processing really works**



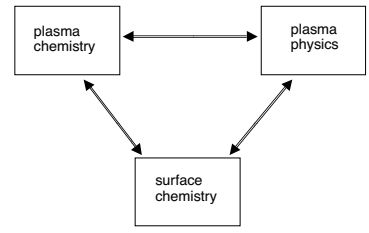
One desires to understand the process so as to improve the value of finished product

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**Plasma processing**



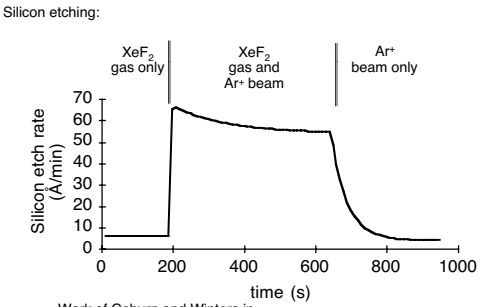
Every process is a complex interaction between  
 • gas phase chemistry  
 • plasma conditions  
 • surface phase chemistry/conditions

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**Classic example**



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

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**Plasma Physics**

The basic plasma physics can be examined using probes

Langmuir probes give:  
 •  $n_e$ ,  $T_e$ ,  $V_{pi}$  &  $V_{ti}$

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

Certain details can only be obtained with more exotic diagnostic techniques

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

**These other techniques are more difficult**

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## Gas and Surface phase chemistry

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

The chemistry can be examined with the following

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

Each has advantages and disadvantages

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## Outline

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## General Types of Plasma Processes

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

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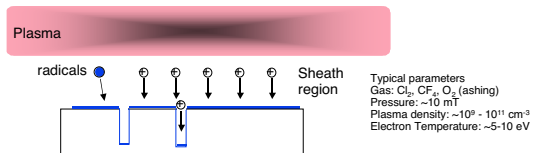
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## Plasma Assisted Etching

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

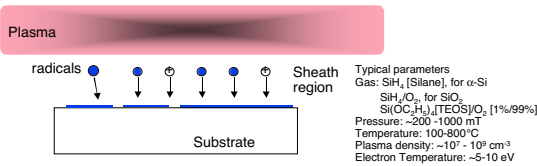
The resulting molecules leave in gaseous form

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## 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

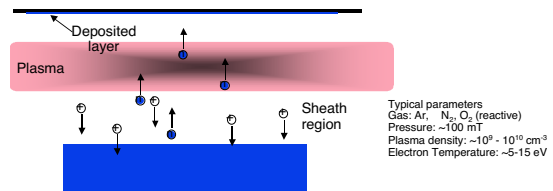
Growth pattern is very complex

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## Sputtering



Ions are accelerated into target

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

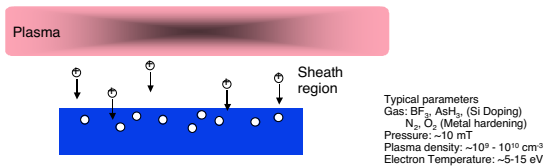
These sputtered atoms "flow" across the chamber to where they are deposited

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## 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)

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## Outline

- 1) Why study plasma processing?
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- 4) Overview of some processing discharges
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### General types of processing discharges

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

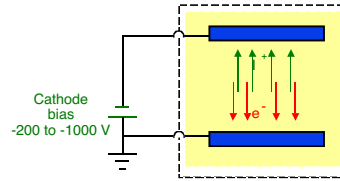
The choice of source depends on the desired process.  
We will look at some of the major sources for Si Processing (and a few others).

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### Cold Cathode (DC/ Pulsed DC discharge)



Ions are accelerated to the cathode

~10% of the impacts produce a secondary electron

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

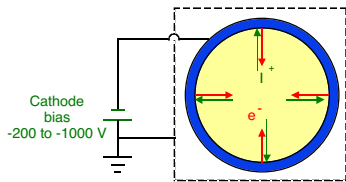
Pulsed version used for Plasma based ion implantation

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### 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

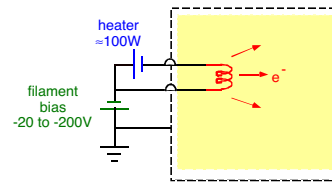
Pulsed version used for Plasma based ion implantation  
Patent pending (Goeckner et al.)

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### 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

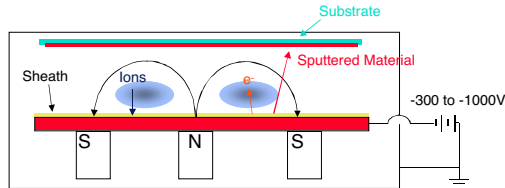
Used for standard ion implantation and Plasma based ion implantation

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### Sputtering Magnetrons (Magnetized cold cathodes)



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

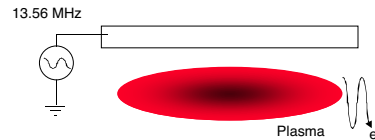
The plasma source  
Secondary, created by ion bombardment of the cathode  
are trapped between the sheath and B field and produce more ions

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### 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

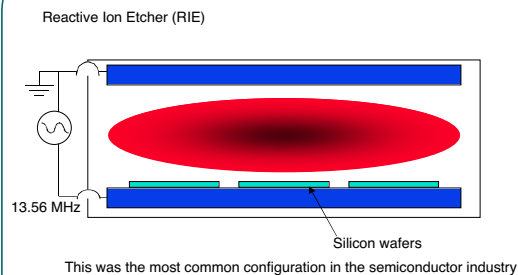
The electrons gain energy and ionize the local gas

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### Example configuration of an RF discharge



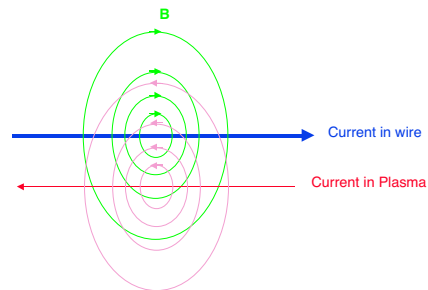
This was the most common configuration in the semiconductor industry

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### Inductively coupled plasmas (ICP)



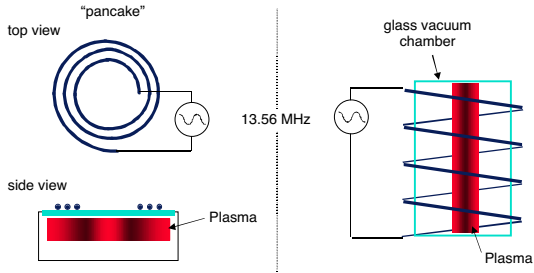
Other Names: Radio frequency inductive (RFI) &  
Transformer coupled plasmas (TCP)

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### Example antenna configurations for ICP discharges



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### Helicon Discharges



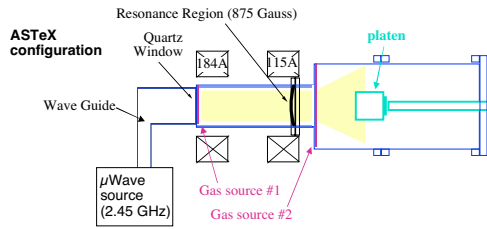
The antenna is used to launch Helicon waves.  
 Helicon waves can be excited over a range of frequencies  $f$   
 $f_{ci} \ll f_1 \ll f \ll f_{ce} \ll f_{pe}$   
 Typically  $f \approx 7$  to  $10$  MHz  
 Currently Helicon discharges are being evaluated in basic physics experiments (This will change soon?)

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### Electron Cyclotron Resonance (ECR) discharges



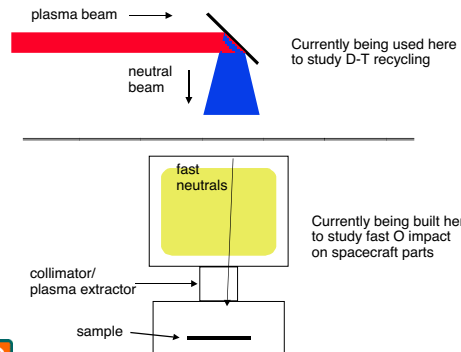
In a magnetic field the electrons resonate at the cyclotron frequency  
 $f = eB / 2\pi m_e c = 2.80 \times 10^6 B$  Hz  
 When in resonance with the  $\mu$ Waves, the electrons absorb energy  
 These energized electrons ionize the local neutral gas

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### Neutral beam sources



Currently being used here to study D-T recycling

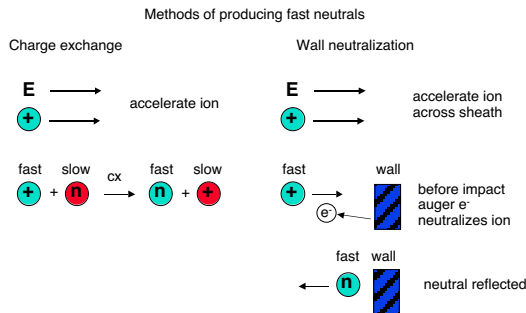
Currently being built here to study fast O impact on spacecraft parts

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### Neutral beams

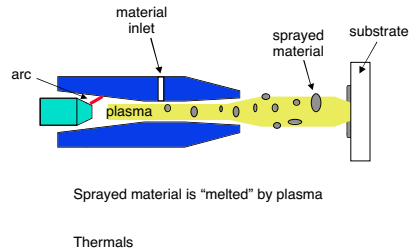


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### Thermal plasma sprays



Sprayed material is "melted" by plasma

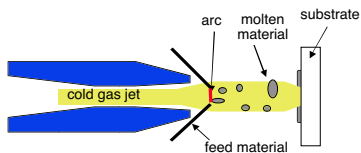
Thermals

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### Thermal arc sprays



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### 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

UTD

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Outline	Opportunities in Plasma Processing
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	Are there opportunities in plasma processing? Yes. While not limitless there are opportunities. Academic: There appears to be a shift toward more applied physics. National Labs have built strong plasma processing groups Leaders are: Sandia & Los Alamos Research Universities are hiring 3 to 6 Profs/Year (Phys. & Eng.) Small Universities like Plasma Processing Relatively low \$ to run and easy to involve students Industrial: Over the last few years hiring has increased dramatically Some "fresh" PhDs are getting ~10 interviews and 3-4 job offers. (Note the market place does change!)

## 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

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## 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 to atmospheric pressure while ultra high is the closest to perfect 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.

	Torr	Pascals	Particle Density (#/cm <sup>3</sup> )
Low vacuum	760-23	10 <sup>5</sup> -3×10 <sup>3</sup>	2.5×10 <sup>19</sup> -7.5×10 <sup>17</sup>
Medium	23-10 <sup>-3</sup>	3×10 <sup>3</sup> -10 <sup>-1</sup>	7.5×10 <sup>17</sup> -2.5×10 <sup>13</sup>
High	10 <sup>-3</sup> -10 <sup>-6</sup>	10 <sup>-1</sup> -10 <sup>-4</sup>	2.5×10 <sup>13</sup> -2.5×10 <sup>10</sup>
Very high	10 <sup>-6</sup> -10 <sup>-9</sup>	10 <sup>-4</sup> -10 <sup>-7</sup>	2.5×10 <sup>10</sup> -2.5×10 <sup>7</sup>
Ultra high	10 <sup>-9</sup> -10 <sup>-12</sup>	10 <sup>-7</sup> -10 <sup>-10</sup>	2.5×10 <sup>7</sup> -2.5×10 <sup>4</sup>

1 atmosphere = 760 Torr (mm Hg) = 101323 Pa = 2.5×10<sup>19</sup> 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 collisions 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.