

Chapter 8

Safety Considerations for Ion Implanters

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ABSTRACT

Ion implanters have several inherent hazards associated with their operation and maintenance. Although manufacturers of this equipment include numerous safety features into the design, the potential for serious injury or incident remains, particularly in situations where design safety features are overridden or recommended safe operating procedures are not followed. Although some incidences of equipment malfunction may, on their own, have the potential to result in a safety incident, these occurrences are much more likely to occur during maintenance or service operations where personal interaction with the hazards of the equipment can be much more direct.

Ion implanters have five main categories of hazard associated with them. These are hazardous materials, high voltage, radiation (ionizing and non-ionizing), mechanical systems, and ergonomic issues. In some instances, these categories can interact with each other to raise hazards that may not be readily recognizable to personnel. This paper will discuss specifics regarding each category and differentiate between operational and maintenance and service related issues. Suggested safe operating procedures are also discussed.

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8.1 INTRODUCTION

Ion implantation is now the most important doping technique for semiconductor devices. Ion implanters have changed from complicated experimental equipment to computer-controlled, automated machines. Semiconductor fabricators are increasingly expecting ion implanters to continually operate at high production efficiencies, with a minimum of initial set up and testing prior to entering a production regime. Implanter manufacturers understand this expectation and strive to continually improve on the safety features of their design. However, implanters still have inherent potential hazards which cannot be completely eliminated from their design. Ion implanter manufacturers and users must continue to work together to ensure that safety features are designed robustly in order to function as intended in the demanding semiconductor fabrication environment, and to ensure that operations and maintenance personnel understand and utilize these safety features as well as recommended work procedures to maintain a high level of safety in an increasingly time based environment.

The main hazards result from high voltages, radiation (most commonly x-rays), and from hazardous chemicals used to produce the desired ions. In general, with the increasing need for high-throughput implanters, currents have increased, as has the consumption of poisonous gases. Mechanical hazards such as those associated with rotary drives, gyro motors, batch disc doors, wafer handling carriages, and load lock windows are not so different from general mechanical hazards known for other semiconductor equipment or mechanical equipment such as lathes, drills, and milling machines. Of course, proper interlocking and safety measures are required to avoid danger from these mechanical components. Similarly, ergonomic hazards may arise, particularly during maintenance and service operations due to the size and weight of some implanter components as well as the work postures required to perform some of these tasks.

It should be noted that ion implanters have very good longevity and it is not uncommon to find tools still in service which are 20 or more years old. While modern accelerators are equipped with numerous interlocks to protect the operator from harm, older tools may not have such equipment and, in any case, an interlock may fail. In this paper, the potential hazards for typical implanters, including those not utilizing advanced design safety features, will be discussed.

8.2 HAZARDOUS MATERIALS

For silicon-based microelectronics, the n and p-type dopants are usually from the groups III- and V of the periodic table. The portion of the periodic table typically employed in ion implantation is illustrated in Fig. 8.1.

The most common dopants in ion implantation are arsenic, boron, and phosphorus, which account for roughly 95% of all ions implanted in silicon. For other semiconductors, however, other dopant ions are also used. Of importance are III-V compound semiconductors with the main dopants being beryllium, sulphur, selenium, and silicon. Use of hydrogen for the production of Silicon on Insulator (SOI) is increasing.

GROUP																																																																							
IA		IIA										IIIA										IVA										VA										VIA										VIIA										VIIIA									
1	H																			2	He																																																		
3	Li	4	Be																			10	Ne																																																
11	Na	12	Mg																			18	Ar																																																
19	K	20	Ca	21	Sc	22	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se	35	Br	36	Kr																																				
37	Rb	38	Sr	39	Y	40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd	47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te	53	I	54	Xe																																				
55	Cs	56	Ba	57	La	72	Hf	73	Ta	74	W	75	Re	76	Os	77	Ir	78	Pt	79	Au	80	Hg	81	Tl	82	Pb	83	Bi	84	Po	85	At	86	Rn																																				
87	Fr	88	Ra	89	Ac																			114	Fl	115	Mc	116	Lv	117	Ts	118	Og																																						

B	P-Type Dopant
Ge	Non-Dopant (Pre-Amorphization)
As	N-Type Dopant

Fig. 8.1: Chemical Periodic Table

In ion implantation, the dopant is first introduced to an ion source in the form of a vapor. The source of the vapor is usually a heated solid or a gas molecule containing the element of interest. For example, most boron implants are performed using the gas boron trifluoride. Many of the commonly used dopant species, their source, method of source introduction and some related comments are listed in Table 8.1.

In every country, laws exist which regulate production, transportation, handling, and disposal of toxic materials. Since October 1986, ordinances for toxic substances have been in effect in Europe and the USA (General Industry Standards), both of which regulate the use of toxic and carcinogenic substances. Industrial threshold limit values are always included in these regulations. For instance, in the USA these values are defined by the Occupational Safety & Health Administration (OSHA) [1], and in the Federal Republic of Germany by the Deutsche Forschungsgemeinschaft (DFG) [2].

In dealing with toxic substances, different abbreviations are used. The most important are given in Table 8.1. LC_{50} describes the concentration of a toxin (usually in ppm or mg/m^3) which leads to the death of 50% of the exposed persons or animals. PEL, TLV, TWA, and MAK all represent the concentration, averaged over an eight hour working day, for the full working life, which the average person can be exposed to without ill effects. The Immediately Dangerous to Life and Health (IDLH) value describes the concentration which is the maximum level that a person can be exposed to for up to 30 minutes without impeding escape or resulting in permanent health effects. Higher concentrations or longer exposure can result in permanent disability or death.

Table 8.1: Some abbreviations used in connection with toxic substances

LC₅₀	<u>L</u> ethal <u>C</u> oncentration 50%
PEL	<u>P</u> ermissible <u>E</u> xposure <u>L</u> imit (OSHA, Occupational Safety & Health Administration, USA)
TLV	<u>T</u> hreshold <u>L</u> imit <u>V</u> alue (ACGIH, American Conference of Governmental Industrial Hygienists, USA)
TWA	<u>T</u> ime <u>W</u> eighted <u>A</u> verage (Health & Safety Executive, England)
MAK	<u>M</u> aximale <u>A</u> rbeitsplatz <u>k</u> onzentration (Deutsche Forschungsgemeinschaft, Germany)
IDLH	<u>I</u> mmediately <u>D</u> angerous to <u>L</u> ife and <u>H</u> ealth

In Table 8. 2 [1-5], the toxic materials most commonly used in ion implanters are listed. Most of the doping elements can be classified in the groups

- 1) pure elements and oxides
- 2) hydrides
- 3) halides

The first group consists, for a large part, of solid, water soluble substances. These substances can, if incorporated over a long period of time, accumulate in the human body, and increase the risk of cancer. Arsenic may, for example, lead to the development of hyperkeratosis and melanoma, and in the event of accumulation of larger amounts, may lead to carcinomas of skin, respiratory tract, and liver. (For those not familiar with specific technical and medical terms, the most important ones are described in the appendix.) Materials such as solid phosphorus may also be flammable or pyrophoric. While some forms of phosphorus are pyrophoric and highly toxic (yellow, white), phosphorus used for ion implantation is typically red, or lump, phosphorus. This material is extremely flammable, though not pyrophoric, and only mildly toxic.

The hydrides are, in general, gaseous, and thus can reach the blood stream through the lungs, where they can block the nervous system by chemical reaction. Arsine possesses a strong hemolytic effect in concentrations of 1-10 ppm [6]. If inhaled over several hours at these concentrations, it can be dangerous to life (lethal). Worker exposure levels, currently set at 50 ppb (PEL) has been lowered to 5 parts per billion (ppb) by the ACGIH. This action was taken based on a number of animal studies indicating chronic effects at levels as low as 25 ppb[7, 37, 38] Diborane and phosphine have slightly lower toxicity, with TLV levels of 100 ppb and 300 ppb, and IDLH levels of 40 ppm and 200 ppm, respectively. Both diborane and phosphine can lead to pulmonary and nervous system effects with eventual death from cardiac arrest.

Decaborane (B₁₀H₁₄) and higher boranes such as octadecaborane (B₁₈H₂₂) are being researched for ultrashallow junction implantation [8, 39, 40]. Ionization of these dopant sources produce molecular or “cluster” ions that permit higher useful beam currents at lower energies than conventional sources. The obvious advantage of improving beam current for low energy implants has stimulated the development

development of unique ion sources and vapor delivery systems necessary to enable the technology.

Short term exposure cause irritation of the eyes, skin, and respiratory tract, as well as effects on the central nervous system, resulting in fatigue, hyperexcitability, loss of coordination, convulsions, and narcosis. These effects, though resulting from short term exposure may be delayed. [41]. Recovery from decaborane is less rapid than reported for diborane, and may take several days or more. [42] Chronic exposures can cause similar neurotoxic effects and liver effects. [43] Toxicological data for Octadecaborane is limited and much of the information is extrapolated for data concerning decaborane.

The third group, the halides, are less toxic than the substances of the previous groups. They should, however, also be handled with the necessary precautions. Halides can cause acid burns of the skin by hydrolysis and, if inhaled, also cause acid burns of the lungs and mucous membranes. After long term exposure, the development of pulmonary edema is frequent [8]. BF_3 and other fluorides also deserve additional attention due to the toxicity of the fluorine ion. Skin burns over a relatively small percentage of the body can be lethal due to fluoride binding of calcium, causing severe disruption of the body's electrolytic system [9].

From a process standpoint, gases are preferred over solid sources as they improve species switching times resulting in greater wafer throughput per implanter. For example, an implanter running solid As and P, requires up to 30-90 minutes to switch species (from As to P) whereas gas sources require 5-10 minutes [62]. The improvement in implanter uptime can be significant if the implanter cannot be run in a species dedicated mode and has to be switched many times per shift. The importance of fast species switching time has been demonstrated by recent attempts to reduce switching times by conducting chain implants. In this technique, species switching is accomplished by using the analyzer magnet to select the ion to be implanted from an "ion cocktail". The ion mixture is provided from a feed gas mixture containing the species of interest (e.g. AsH_3 and PH_3) [63]. In this case, the time to switch species is a function of the time it takes to retune the mass selection components. Chain implants may result in species switching times of less than 1 minute.

From a safety perspective, solids offer improvement in safety over gases as they are less likely to cause toxic exposure to personnel, as they cannot be released as readily to the workplace environment. Gases such as arsine, phosphine and boron trifluoride are highly toxic. Being packaged as compressed gases, they are potentially released to the work environment in the event of a gas panel leak. A compromise between solid sources and gas sources involves systems in which the gases are stored at, or can only be delivered at sub-atmospheric pressure (< 760 Torr).

Compressed gases used in ion implant are either diluted with hydrogen or supplied as pure gases, as described in Table 8.2. Usually the hydride gases (arsine and phosphine) are diluted with hydrogen as they are considered highly toxic and require dilution to reduce the hazard associated with a release. The dilution reduces the amount of gas contained in the cylinder resulting in relatively short cylinder

Table 8.2: Ion Implant Dopant Species and Chemical Source

Dopant Specie	Dopant Source	Chemical Name	Type	Method of Introduction	PEL / TLV (ppm or mg/m ³)	Comments
Antimony	Sb	Elemental Antimony	Solid	Vaporizer	0.5	High vaporization temperature limits use
	Sb ₂ O ₃	Antimony oxide	Solid	Vaporizer	0.1	Most common Sb source, vaporizes at 600 °C
	SbF ₃	Antimony trifluoride	Solid	Vaporizer		Corrosive, vaporizes at >160 °C
	SbH ₃	Stibine (antimony trihydride)	Gas	Gas Panel	0.1	Very unstable gas, no known commercial supply
Arsenic	As	Elemental Arsenic	Solid	Vaporizer	0.01	Vaporizes at >300 °C
	AsH ₃	Arsine	Gas	Gas Panel	0.05 / 0.005	Most common gas source
	AsF ₃	Arsenic Trifluoride	Liquid	Vaporizer	3.0	Rarely used in implant
	AsF ₅	Arsenic Pentafluoride	Gas	Gas Panel		Few applications
Beryllium	Be	Elemental Beryllium	Solid	Vaporizer	0.002	highly carcinogenic
Boron	BF ₃	Boron Trifluoride	Gas	Gas Panel	1.0	Most common source of boron
	¹¹ BF ₃	Boron Trifluoride (enriched)	Gas	Gas Panel	1.0	Used in beam current limited applications
	BCl ₃	Boron Trichloride	Gas	Gas Panel	5.0	Rarely used in implant
	B ₂ H ₆	Diborane	Gas	Gas Panel	0.1	Pure gas is unstable
	B ₁₀ H ₁₄	Decaborane	Solid	Vaporizer	0.05	For boron cluster ions
	B ₁₈ H ₂₂	Octadecaborane	Solid	Vaporizer		For boron cluster ions
Germanium	GeF ₄	Germanium Tetrafluoride	Gas	Gas Panel	0.8	Used as pre-amorphization species
	GeH ₄	Germane	Gas	Gas Panel	0.2	Rarely used, ion extraction poor
Indium	InCl	Indium Chloride	Solid	Vaporizer		Most common In source, corrosive and hydroscopic
	InCl ₃	Indium Trichloride	Solid	Vaporizer		Very corrosive
Phosphorous	P	Elemental Phosphorous	Solid	Vaporizer		Vaporizes ~360 °C
	PH ₃	Phosphine	Gas	Gas Panel	0.3	Most common gas source
	PF ₃	Phosphorous trifluoride	Gas	Gas Panel	1.0	Few Applications
	PF ₅	Phosphorous pentafluoride	Gas	Gas Panel	3.0	Rarely used in implant
Selenium	Se	Elemental Selenium	Solid	Vaporizer	0.1	Selenium has few implant applications
	H ₂ Se	Hydrogen Selenide	Gas	Gas Panel	0.1	Available pure or in mixtures
	SeO ₂	Selenium Oxide	Solid	Vaporizer	0.1	Lower vaporization temperature than Se metal
Silicon	SiF ₄	Silicon Tetrafluoride	Gas	Gas Panel		Used as pre-amorphization species
	SiH ₄	Silane	Gas	Gas Panel	5.0	Decomposes at elevated temperature

lifetime. The short cylinder lifetime is problematic as managing cylinder inventories becomes cumbersome and the high frequency of cylinder changes decreases implanter uptime and increases the risk of toxic gas exposure. The fluoride gases (BF_3 , GeF_4 , SiF_4 , PF_3 , AsF_3) are normally supplied in pure form as they are less toxic than the hydrides.

Unlike many other semiconductor processes the gas cylinder and peripheral gas control equipment must be contained within the implanter due to the high voltage at which the implanter is operated. The high voltage precludes remote location of the gas box, as connecting plumbing cannot be run externally from the implanter. When using high pressure dopant gases, additional engineering controls such as the use of high pressure tubings and components, containment ventilation, toxic gas monitoring, and scrubbing are required to reduce danger to personnel from leaks in the gas system [11,15]. When the door of the gas cabinet is open, the air velocity should be about 1 meter / second (200 feet / minute) across the valves and fittings of the gas cylinder and lines.

Gas cylinder installation and removal involve the highest potentials for catastrophic chemical accident. Workers involved in these procedures must be trained in the hazards of the materials involved as well as in specific safe work practices. At a minimum, these persons must be trained in and use Personal Protective Equipment (PPE) including full body chemical protective coveralls, durable rubber gloves and positive pressure, supplied air breathing systems (these include air line respirators with portable escape pack, Self Contained Breathing Apparatus-SCBA, and portable, cart mounted air line cylinder systems). Other training required should include emergency response procedures, use of portable gas detector equipment, ventilation and detection system awareness, and procedures for establishing a safe perimeter around the gas cylinder change area. Gas cylinder changes should only be performed by a team of at least two individuals, both in full protective gear.

In the event of malfunction of the exhaust system, the implanter should automatically close the gas valves and stop operation. Employees should simultaneously be made aware of the defect by acoustic and optical alarms [12]. To assure timely detection of leaks in the gas system, the installation of a gas monitor is recommended. Such monitors are manufactured by different companies and can be sensitive enough (ppb to ppm range) to detect very small leaks [13].

It is recommended, however, to ensure that the specific technology to be selected is appropriate for the application. Some studies call into question the decomposition mechanism of BF_3 , suggesting that the decomposition to HF appears not to occur as quickly as previously believed. A reduction in the decomposition to HF may have a negative effect on the ability to detect small BF_3 leaks into large quantities of dilution exhaust typically present in gas cabinets [14]. Also, as previously mentioned, the ACGIH has lowered its 8 hour time weighted average exposure limit for arsine to 5 ppb. This lowered limit, may result in replacement or upgrade of much of the installed base of hydride detection equipment used today.

For normal operations, a multi point detection strategy is recommended. At a minimum, gas detection for those toxics with poor warning properties (gases which can be present at hazardous concentrations with little or no smell, irritation or visibility), should be configured to monitor the gas cabinet exhaust, the tool enclosure exhaust nearest to the source and the beamline roughing pumps (NOTE: these should be area exhausts, not the direct plumbed process exhausts from the pumps) to capture any breaches from the pump system or exhaust lines within the tool, and at the the operator station. It is also recommended that any facility using remote vacuum pumps, typically in the subfab, install containment enclosures, provide these enclosures with adequate ventilation, and monitor the exhaust of the enclosure

exhaust of the enclosure with the detection system.

Sub-Atmospheric Gas Delivery Systems (SAGS) have proven over the past ten years to be the preferred dopant delivery method for ion implantation. They offer the safety of a solid source, and the productivity of gases, and have essentially become the industrial standard as dopant sources for ion implantation. The principles, characteristics, and safety of these technologies are discussed in the following sections. SAGS include gas cylinders which under normal operation allows for gas flow from a cylinder only when the cylinder valve outlet is exposed to a pressure of less than one atmosphere pressure (760 torr). These systems may be configured either as adsorbent type: a seamless or welded cylinder containing a gas adsorbed on solid media at a storage pressure below 760 torr at 21 degrees Celsius, such as SDSTM, or mechanical type: a seamless cylinder containing a liquefied compressed gas or compressed gas, which is internally, mechanically regulated enabling delivery at pressure below 760 torr at 21 degrees Celsius, such as VACTM or UptimeTM.

The SDS gas source has been broadly accepted as the “adsorbed” sub-atmospheric standard technology for ion implantation [64]. It is based on the phenomenon of physisorption, where the gas molecules are adsorbed onto a substrate surface via van der Waal forces. This force is strong enough to convert gas phase molecules into a “liquid” like adsorbed phase. At the same time it is weak enough to release the adsorbed phase back to gas phase at reduced pressure. These two processes are collectively termed adsorption and desorption. The adsorption and desorption process is very similar to the vapor/liquid condensation process. It is a reversible process, and the equilibrium of the amount of adsorbed gas and the desorbed gas (i.e. free gas) is dependent on the adsorbent, adsorbate, and environmental conditions, such as temperature and pressure. During SDS manufacturing, high pressure gas is “condensed” onto the adsorbent in the cylinder. During use, the adsorbed phase is “vaporized” back to the gas phase by the pressure gradient generated by implanter vacuum.

One of the key features of SDS is its safety. Because of its sub-atmospheric pressure, in an event of inadvertent leak, the gases inside the SDS cylinder will not be “driven” out to the environment as in the case of high pressure cylinders. Instead, the gases will diffuse out at a very slow rate.[15] Gas release tests were conducted to simulate the release rate under static conditions where no ventilation was used. When a full arsine 2.2 liter cylinder was opened in a non-ventilated room, no arsine was detected (i.e. less than 6 ppbv) in a 4 feet radius circle around the cylinder valve outlet for a period of 60 minutes.

As a sub-atmospheric technology, SDS safety derives from the fact that gas is stored within the cylinder below atmospheric pressure. Since the cylinder pressure can be affected by cylinder temperature, appropriate cylinder storage and handling procedures should be followed in order to prevent temperature rise of the cylinder which can lead to increased pressures. All the SDS products follow a similar pressure-temperature relationship (Fig. 8.2), and cylinder pressure increases exponentially with cylinder temperature. For a fully loaded cylinder (i.e. initial pressure of 650 torr at 21°C), the pressure rises approximately 10- 15torr/°C below room temperature, 20-30 torr/°C near room temperature, and >30 torr/°C above room temperature. To ensure the cylinder pressure remains below ambient (e.g.760 torr), the full cylinders need to be stored and used at or below 76°F or 24°C. It should be pointed out that the pressure rise due to temperature increase is also dependent on the cylinder pressure. For the used cylinders (i.e. pressure less than 650 torr), the pressure rise rate is significantly lower than that of a full cylinder. At a pressure of 350 torr, the pressure rise is approximately 16 torr/°C.

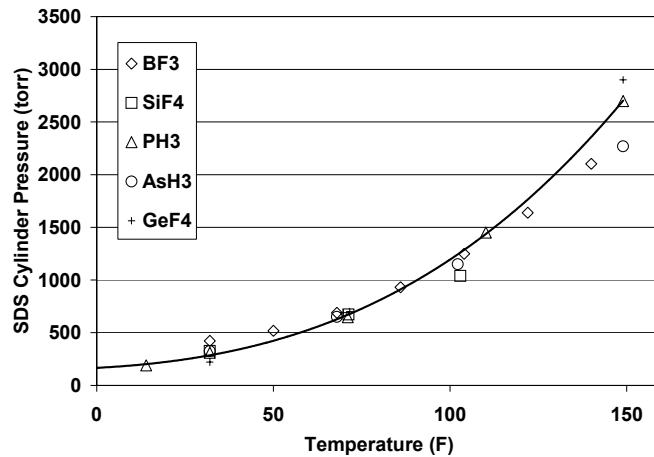


Fig. 8.2: SDS Pressure-Temperature Relationship

Mechanical devices inside the gas cylinder, designed to prevent flow of gas unless the cylinder outlet is at sub-atmospheric pressure are also being utilized for SAGS, and are designed to significantly reduce the risks associated with using high-pressure compressed gases[44]. The major difference between SDS and mechanical device equipped cylinders is that SDS stores and delivers gas both sub-atmospherically, while mechanical device equipped cylinders store gas at high pressure, and only delivers gas at sub-atmospheric pressure. These systems can provide substantial increases in delivery capacity over SDS for gases like BF₃, GeF₄ and SiF₄, and can also be used to deliver compatible mixtures, ideal for chain implantation. However, because the gas is stored at high pressure, mechanical SAGS do not provide the level of safety provided by SDS.

The key features of the technology are represented below using a product called Vacuum Actuated Cylinder (VAC™), although similar SAGS products such as Uptime™ are also available. The VAC SAGS consists of a dual ported valve, a set of set pressure regulators and a gas cylinder. The set pressure regulators (SPR) are located inside the gas cylinder upstream of the primary valve (Fig. 8.3). The gas is filled using the valve fill port, and discharged through the SPR and valve discharge port.

The key component of the SPR (Fig. 8.3) is an internal Pressure Sensing Assembly (PSA) used to both actuate and attenuate gas flow to control the discharge pressure. The PSA is a sealed welded bellows unit calibrated by filling with a helium/argon mixture to a pre-set pressure. When pressure below the PSA set-point (e.g. 500 torr) is applied to the downstream side of the SPR, the welded bellows assembly in the PSA expands, which unseats the poppet and allows gas flow through the regulator. After flow initiation commences, the bellows continues to expand or contract accordingly, depending on the discharge pressure downstream of the PSA. In this manner, downstream pressure is maintained at the setpoint of the PSA. Since the poppet is normally closed, the design is intrinsically safe. During use, the delivery pressure is regulated to within an accuracy of plus or minus ½ psig and the discharge rate is governed by the process mass flow controller located in the manifold in the tool gas box. The Mechanical SAGS delivers at a constant pressure independent of the tool operating pressure.

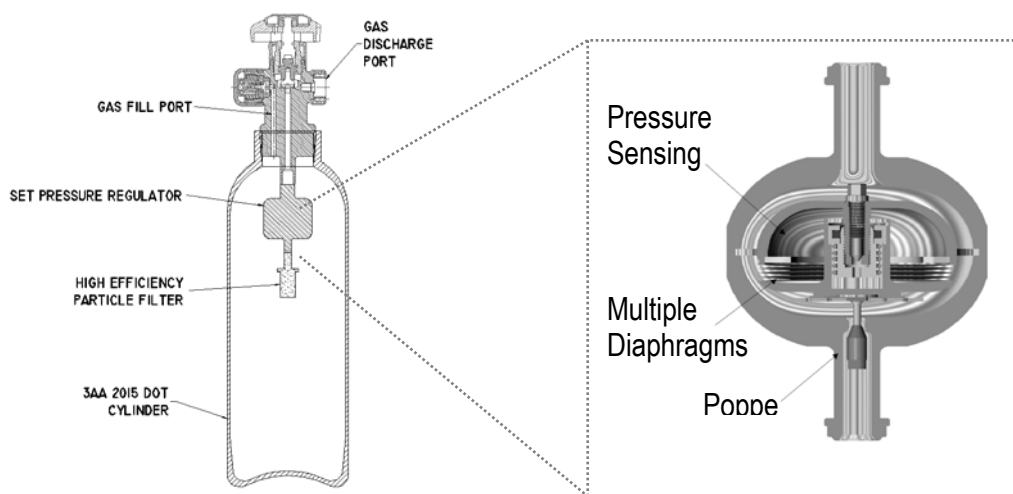


Fig. 8.3: VAC™ Gas Source Cut Away Showing Position of the Embedded Pressure Control Unit and Particle Filter. Drawing is not to scale.

Another possible source of hydrides is point of use generation of arsine, phosphine and stibine using electrolysis from a metal cathode [16]. Such a gas generator system consists of a replaceable electrochemical generator canister and a control system. Electrolysis produces gas only in its active state. When switched off, the system is purged and no toxic gas remains in the system.

Recently, in situ-cleaning processes have been introduced for ion implantation. Examples include the use of xenon difluoride in implanters utilizing traditional dopants and fluorine, generated using nitrogen trifluoride as a source material, in implanters using octadecaborane. Xenon difluoride is a solid loaded into a typical gas cylinder that is sublimated by the process vacuum and released into the source at flow rates typical of implant dopants in between implant recipe changes. The xenon difluoride reacts with deposits in the source area, releasing gaseous by-products that are removed by the vacuum system and exhausted as emissions. Increased source life, reduced downtime and reduced glitching are described as advantages of this process.

The use of fluorine cleaning in implanters utilizing octadecaborane (B18) is necessary for maintaining source life. Fluorine must be released into the source at regular intervals at flow rates in the range of liters per minute during the cleaning cycle. These gas flow rates are unprecedented in ion implanters. Selection of appropriate vacuum system components, exhaust ductwork material, and location of process exhaust scrubbers are critical to maintaining operation of these implanters.

During proper operation of an implanter, all toxic substances are confined to the vacuum system. Since only a fraction of the gas in the source is actually ionized and extracted as an ion beam, part of the source feed material is deposited or chemically bonded inside the system. A large amount, however, is also absorbed by pump oil (in systems typically 10 years old or more) or released to the environment through the pump exhaust.

Studies have shown that the concentrations within exhaust systems can be very high in relation to typical exposure limits. With hydrides, these exhaust concentrations can vary with beam conditions,

conditions, but given a stable beam, only about 6% of input gas can be accounted for in the exhaust stream. Acid gases, on the other hand, are consistently detected at levels of greater than 70% of the input [17]. Cryo pump regeneration can also release very high concentrations of toxic materials into the exhaust stream for short periods of time.

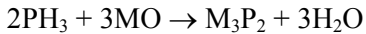
Ion implant processes present unique environmental and safety challenges. Each implant tool accommodates a number of pumps discharging different types and concentrations of hazardous and non-hazardous materials in a continuous (roughing pumps) or intermittent (cryo-pumps) mode. In-depth understanding of the types of materials, concentrations, and frequency of emissions from implanters is critical to evaluate the safety hazards and to develop optimized abatement systems. As an example, due to the high gas flow rates used during fluorine cleaning in implanters using B18, point of use scrubbing of the acid gas emissions of this process is essential to prevent build-up of acids which can liquefy and accumulate within facility exhaust ducts. These point of use scrubbers must also have the capacity to scrub high concentrations of material without excess pass through of emissions or a need for excessive scrubber maintenance.

Conventional point of use abatement devices used in the semiconductor industry are based on wet, thermal, dry, or plasma technologies or a combination thereof. Water scrubbers combined with injection of chemical enhancers can achieve the efficiency necessary to remove implant effluent materials. Cost of ownership, footprint, and issues related to the disposal of arsenic-containing liquids limit their practical use in this application. Thermal and plasma abatement methods simply dissociate materials into a solid form generating hazardous dust. In addition, electrical or fuel costs become prohibitive considering the relatively small volume of material removed. Of the four traditional abatement methods, dry scrubbers are best suited for the stringent requirements. Technology trends suggest moving required scrubbers as close to the implanter as possible (point of use). These point of use technologies typically consist of variations on the dry bed type of scrubbers [18, 19, 20]. These smaller devices were designed to remove hazardous materials immediately after each process tool in order to: (1) minimize particle generation reactions in the exhaust lines that could eventually plug the exhaust ducts; (2) prevent potential combination of incompatible gas streams that could result in excessive heat, fires, or explosions; (3) reduce the risks associated with transporting hazardous gas streams across the fab from the source (tool) to end-of-pipe scrubbers.

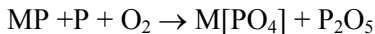
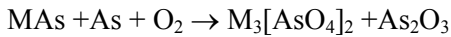
Dry scrubbers contain chemisorptive reagents that react with semiconductor effluents gases to form non-volatile substances. Dry scrubbers, for the most part, are unable to be regenerated and reused, and remain consumed after contact with the process gas. Unlike physisorptive processes, the materials cannot desorb or bleed-off any hazardous gases that entered the scrubber. The scrubbing media is packed in a canister providing a container for all toxic solid byproducts. An integrated toxic gas detector may be used to warn the user when the capacity of the scrubber canister is being depleted, and should be replaced. Considering the low volume of material exhausted during ion implant processes a typical dry scrubber can last years. Typical canisters containing the chemisorbing media are housed inside cabinets. Depending on the model and vendor, scrubber cabinets may include pressure control devices, temperature checks, miscellaneous valves and hardware, and monitors to ensure proper operation of the device.

The active ingredients of the dry scrubber may be distributed or coated on a high surface area substrate material. The bulk of the dry scrubber may also be composed of the active ingredient with a small amount of binder material for strength and retention of physical form. The active ingredient of the dry

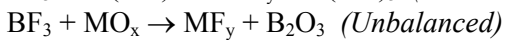
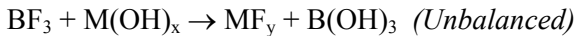
the dry scrubber is specifically designed for chemical reaction with the reactive species in the process gas. In ion implant applications, the reactive species released at the different pumps include acid and hydride gases. A common composition for hydride chemisorptions includes proprietary mixtures of metal oxides. Reaction of arsine and phosphine with these materials result in the reactions:



Where M represents the symbol of a metal element. Metal and elemental species are later oxidized with air to form the final compounds through the reactions:



Acid gas dopants such as boron trifluoride can be reacted using metal oxide and hydroxides to generate boric acid and boron oxide:



In addition to the metal oxide and hydroxide examples included above, copper sulfate (CuSO_4) and potassium permanganate (KMnO_4) reagents have been reported for these applications. The spent resin must be disposed as toxic waste in accordance with local, state, federal, and international regulations.

In ion implant processes, the exhaust from the different roughing and cryo pumps are combined and the collective effluent stream introduced into a single scrubber. During normal operation, the flow constraint created by the canister amounts to less than 1/10 of an inch of water pressure drop. However, flow rates in excess of 2000 slpm can occur for short amounts of time during the initial stages of chamber tool pumpdown. In these instances, the pressure drop across scrubber beds can exceed 100 inches of water depending on the canister design. Improved scrubber designs combined with the use of flow dampening devices installed at the pump can be used to reduce these pressure surges.

Fig. 8.4 shows the pressure performance during an implanter pumpdown before and after modifications were implemented. In that configuration, the pump exhausts of an implanter were combined and connected to the inlet of a Novapure[®] dry scrubber (ATMI). Without modifications, the absolute pressure (measured between the pump exhaust and scrubber inlet) exceeded 1 atmosphere during pumpdown of the source, beamline, and process chambers. System modifications were successful in preventing overpressure during the pumpdown of the entire implanter. It is important to ensure that overpressurization of exhaust lines leading to the scrubber is prevented. As discussed previously, the concentrations of toxic materials can be extremely high when compared to established exposure limits. Pressurization of the exhaust lines prior to abatement can lead to leaks into surrounding ambient air, if the exhaust lines are not properly sealed.

In the past several years, experimentation has been conducted towards incorporating scrubbing technology directly into implanters. This approach dedicates individual canisters to each ion implant pump. Compared to conventional dry scrubbers, these units reduce capital costs, eliminate the need for

for additional footprint, provide flexibility for tool expansions, and enable customization of the scrubbing material to the specific challenges of the pump location within the implanter.

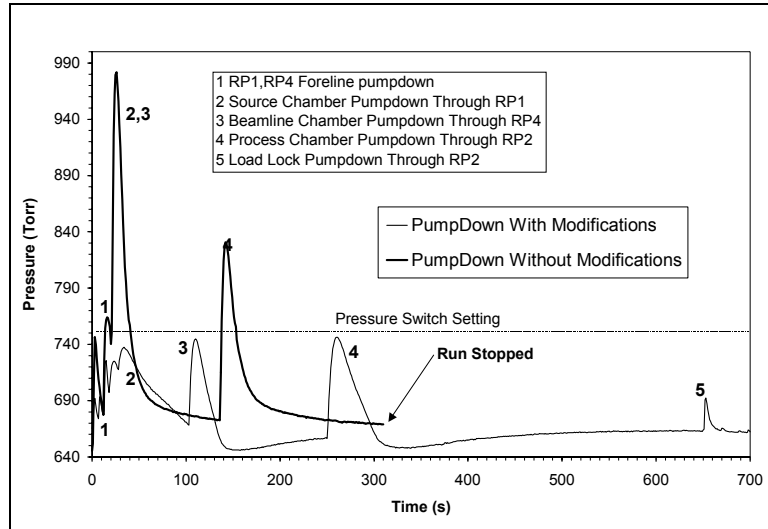


Fig. 8.4: Pumpdown of an Implanter Connected to a Dry Scrubber (Novapure[®]): Post-implanter Pressure Characterization before and after Improvements

An example of one such system is depicted in Fig. 8.5. The Novasafe canister is approximately 12 inches in height with a 10 inch diameter. The canister is designed for installation at the top or within the implanter housing. Roughing or a cryo pump effluents are plumbed directly to the canister. Flow through the canister is from bottom to top, with process gas effluent entering through the side of the canister. The Novasafe canister contains two separate beds of scrubbing material. The first layer is designed to remove acid species while the second one is responsible for removing hydrides in addition to reacting with any remaining fluorinated species. The clean gas stream exits the canister through the top and can easily be plumbed to the house exhaust. Based on typical ion implant process conditions, the volume of the canister is specifically designed for a lifetime of approximately one year. A hazardous gas monitor may be integrated in the system; its port is located at the 90% volume level to provide breakthrough indication that capacity is nearly completed. The only facilities required for the Novasafe scrubber are 50 to 150 sccm of clean dry air (CDA) and power necessary to run the sensor (optional).

In addition to releasing high concentrations of toxic gases during regeneration, cryo pumps also have the capacity to release substantial quantities of hydrogen into process exhaust ductwork during regeneration. This hydrogen can come from dilution gas mixed with hydrides, or also from off-gassing of photoresist during implantation. It is recommended that implanter manufacturers design nitrogen purge of sufficient quantity into the exhaust ductwork to act as a diluent for the hydrogen, maintaining it below its lower explosive limit of 4% [22]. It is also the responsibility of the user to ensure that this purge system is connected and maintained in an operational state with a sufficient emergency power backup to allow purging, both within the pump and in the exhaust, to commence and continue for approximately 1/2 hour in the event of power loss to the cryo compressor. This is important in order to

important in order to prevent uncontrolled regeneration of the pump, which may lead to ignition or explosion within the exhaust.

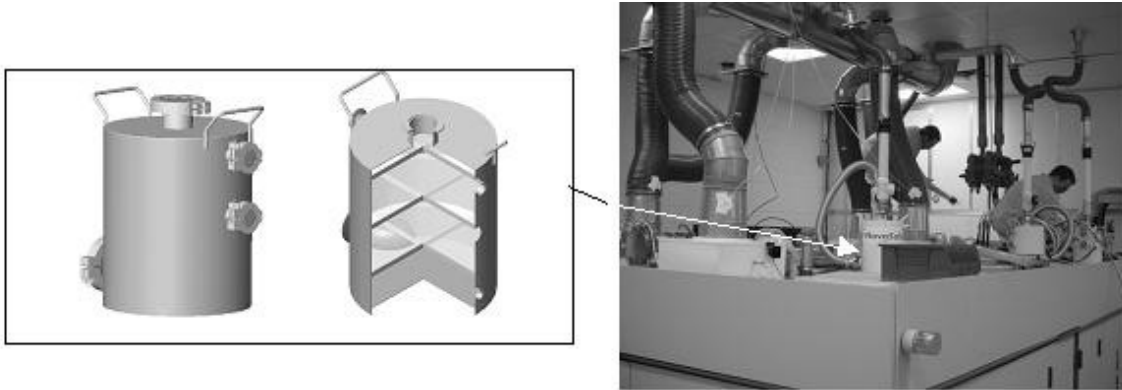


Fig. 8.5. External and Internal View of Novasafe System and Picture of the top of an Ion Implanter with Three Novasafe Scrubbers Installed

Cryo pumps may also fail in a manner which results in ignition or explosion within the pump body itself. Several mechanisms for this reaction have been identified. These are: power failure (with or without subsequent resumption of power after approximately 10 minutes), a "slow leak" in which the seal of the pump's isolation valve or other vacuum system leak allows air to be captured by an operating pump, resulting in eventual overwhelming of the pump, and a "fast leak" in which a vacuum accident or large scale leak results in a sudden uncontrolled regeneration. In the event of power failures, some implanters, not equipped with protective controls may lose power and begin an uncontrolled regeneration (warming and release of gases without nitrogen purge). In any regeneration, hydrogen is the first gas released from the arrays followed fairly quickly by oxygen. In these cases, without dilution nitrogen, an explosive mixture may develop. In some cases, there is enough residual energy in the system to cause ignition, resulting in an explosion within the pump. In other cases, a Hot Cathode Ion Gage (HCIG) is mounted within the contained pump body, and if power is returned, will "light up" in order to determine the vacuum state of the tool. If this occurs when the hydrogen oxygen mixture is correct, explosion occurs.

In the case of slow leaks and fast leaks, essentially the same scenario occurs. A leak develops in the isolation valve or a vacuum accident occurs during processing of wafers and the pump is overwhelmed (this will occur easier if manufacturers' recommendations for frequent regeneration are not followed), heating to a point where incoming gases are no longer effectively captured. Once this occurs, the pumps insulating capacity is lost and the pump quickly warms, driving the hydrogen, followed by oxygen off the arrays, potentially resulting in ignition and explosion.

It is important to note that "slow leaks" can be more dangerous since an operating pump can be isolated and the chamber surrounding it vented to atmosphere and disassembled for maintenance. The pump may continue to operate for several hours before the potentially explosive reaction occurs. These reactions are powerful and capable of severely damaging isolation valves and other structures within the beam line, and even, in some cases, to momentarily "pop open" process chambers. A worker in close

worker in close proximity to an isolation valve of a cryo during maintenance can be severely injured in the event an explosion occurs.

With high volume and 300 mm processing becoming more important, cryo pumps are being added to process chambers of many commercial implanters. This raises the potential that workers may enter the process chamber to aid a robotic wafer handler or recover a dropped wafer and encounter a leak scenario explosion. A fast leak can lead to severe hazard, since process chambers can typically be vented and opened within several minutes. Implanters available commercially are equipped with protections against these events, however it is up to the operator to ensure that they are active and are not defeated by personnel wishing to "save some time" by avoiding regeneration prior to accessing the beamline or process chamber side of cryo isolation valves.

Preventive Maintenance (PM) offers the greatest number of opportunities for workers to be exposed to hazardous chemicals when working with implanters. In PM, the worker is disassembling parts, scrubbing contaminated surfaces, or performing other tasks involving parts of the vacuum system (e.g., scrubbing source housings, resolving housings, changing pump oils, etc.). Hazardous material residues collect on the interior surface of the vacuum system and in the process exhaust lines. These residues can take the form of particulates, liquids, or semi-solids,

Arsenic, antimony, and beryllium (in the case of gallium arsenide processes) are often found in the form of fine particles. Exposure usually occurs through inhalation, but may also occur through skin contact or ingestion. Short term exposure to these materials does not typically result in an immediate symptoms, however, chronic toxicity (e.g: poisoning, cancers) is high.

Phosphorus accumulations can take the form of dust, flakes or semi-solid material and is extremely flammable. Friction of simply disassembling components may result in ignition and fire. Of particular concern are sources, source housings, isolation valves, vacuum pump forelines and exhaust lines. It is important to inspect vacuum pump lines and isolation valves, at least on a quarterly basis, to ensure that serious buildup does not occur. This can not only be a direct fire hazard within the implanter during maintenance, but can contribute and lead to operational fires from arcing within the exhaust line's transition zone from high voltage to ground potential. In these cases, the phosphorus or other dopant contamination causes the non conductive portion of the exhaust pipe to become conductive, promoting arcing. Arcing can perforate the exhaust line causing entrainment of air and potential for fire.

HF residues can collect as liquids or semi-solids in any areas where moisture may be present. This includes pump oils, cryo pumps, mist eliminators, and exhaust lines.

For implanters using B18, deposits of octadecaborane occur throughout the beamline from source through the process chamber and also in the vacuum forelines and pump exhausts. These deposits are reactive on contact with air to produce a hydride gas and distinctive odor. Air monitoring indicates that the level of hydride production drops over time (typically within ½ hour), however it is possible to continue to detect the distinctive odor even in cases where hydride detection is no longer occurring (the limit of detection in these cases is 30 ppb as diborane).

B18 deposits in the vacuum pumping system can be quite heavy including deposition in turbomolecular pumps, forelines and roughing pumps. Vacuum system designs must take into account these deposits and provide mitigations to predictably control the deposition such that it can be safely removed from the

safely removed from the system either by regular maintenance or exhaust. A current method to limit the deposits in unwanted areas is selective heating using pump heaters and heated jackets for the forelines. In concert with the heating, the location of the deposits can be selected through the use of cold plates or traps. Other strategies may also be effective such as purging to reduce the partial pressures or the introduction of a reactive agent which allows the B18 to move through to the abatement system.

It has been shown that arsine and phosphine can off-gas from implanter components that become contaminated from running arsenic and phosphorus. This may occur from either solid or gas sources. Arsenic and phosphorus react with aluminum beam line components to form aluminum arsenide and aluminum phosphide deposits. These by-products are not stable in air, and react with moisture in the air and break down into arsine and phosphine [23]. When the vacuum chamber is opened, the reaction causes arsine and phosphine to slowly off-gas.

Hydrides can build up in an enclosed area such as a sealed bag, a lidded trash can, or inside the beam line. In such confined spaces, arsine and phosphine that off-gases may accumulate to high levels. While maintenance personnel must be made aware of the potential for generation of hydrides from exposed implanter components, Industrial Hygiene (IH) testing concerning PM activities indicates that hydride exposure is typically within accepted exposure limits. PM workers should be taught specifically to avoid exposure to unventilated areas, keep their faces away from beam-line components, minimize the time the beam strike guide is open for vacuuming operations, and to blank off cryo pumps quickly.

Personnel performing PM activities must be trained in safe work procedures and be supplied with and trained in the use of PPE including disposable or launderable coveralls, durable chemical resistant gloves, and, at a minimum, a 1/2 face High Efficiency Particulate Air (HEPA, N100 or P100 style) respirator. Some operations, in particular the use of B18, require use of supplied air systems for increased protection against particulates, or if it is determined that hydride gases or other vapors are present at a level of concern. In the cases of B18 and decaborane, particulate respirators are considered ineffective for protection against particulates since particulates captured by the respirator can then vaporize and be inhaled by the user. On all modern implant systems, integrated local exhaust ventilation for implanter chambers is highly desirable for controlling potential employee exposures. Use of local exhaust ventilation can reduce or eliminate the need for respiratory protection by maintenance personnel.

Whenever work is done on an implanter, in the terminal or any of the mechanical areas, PPE should include coveralls, gloves, safety glasses and safety shoes. Protective clothing is required to prevent contamination with hazardous dusts or oils which may be deposited on equipment surfaces.

In the absence of integrated local exhaust ventilation, it is essential that the respirator be worn at all times when the vacuum chamber is open to atmosphere. Even when no dust is visible, arsenic, which is a potential carcinogen, may still be present in quantities sufficient to cause long term health effects. Small amounts of arsenic (or other toxic dusts) may be released from the vacuum chamber simply by opening it due to the turbulence created when venting to atmospheric pressure with nitrogen. This turbulence may cause arsenic dust to be suspended inside the chamber and released when opened.

Reports of exposure monitoring conducted on PM workers indicate that, approximately 25% of the time, exposures to arsenic could exceed exposure limits, resulting in over exposures if respiratory

protection is not worn. These potential exposures can result from a variety of activities including source housing and resolving housing scrubbing, as well as cryo and diffusion pump maintenance, or other PM activities. These potential exposures are not necessarily predictable based on frequency of maintenance or on the specific activities performed. The highest potential exposure measured was approximately eight times (8X) the OSHA PEL for arsenic [24].

These monitoring results are the basis for a minimum recommendation for the use of a ½ face, disposable HEPA, N100 or P100 style filter equipped respirator whenever the vacuum chamber of the implanter is opened. When scrubbing contaminated components within the machine, this recommendation is increased to a full face HEPA, N100 or P100 style filter equipped model.

Half face respirators cover just the nose and mouth and can be prone to leaks when not carefully fitted. This type of respirator offers a 10 times (10X) level of protection which is adequate when using wet scrub cleaning procedures, however a full-face respirator offers a better sealing surface and a 50X level of protection. Positive pressure, supplied air systems such as SCBA or air line systems offer 1000X against contaminants and should be used where available, and especially in cases where potential for significant exposure to hydride off-gassing exists. See Fig. 8.6.

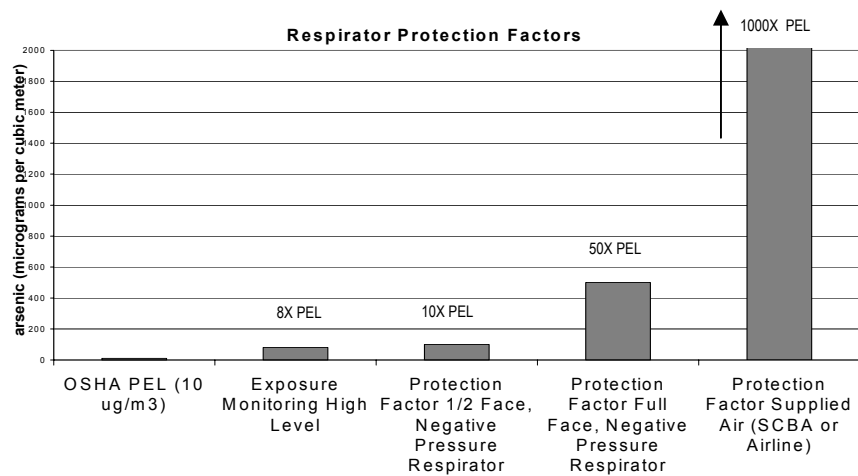


Fig. 8.6: Respiratory Protection Selection Factors

Clean room gloves must be replaced and upgraded to heavier latex or nitrile gloves during scrubbing procedures. The stronger gloves are less prone to ripping, and are recommended for scrubbing to ensure that skin is not exposed to chemicals.

PM facilities should be equipped with the following safety equipment: an exhausted fume hood, portable HEPA vacuum, wet slurry blaster, and flexible or portable local exhaust ventilation for scrubbing components which cannot be removed from the tool.

The exhausted fume hood should have a minimum 100 feet per minute (30 meters per minute) face velocity. At 100 feet per minute face velocity, any particles that are generated will be captured before they enter the breathing zone. The face velocity should be measured by a qualified safety professional and the maximum allowable opening posted at the face of the hood. If the sash covering the fume hood is raised higher than this maximum rated opening, the face velocity will decrease and particles may

may escape. In addition, personnel should be instructed not to lean inside the hood while scrubbing, as this will greatly increase the level of exposure. Some fume hood designs have an angled slope to the sash window so that the worker can lean over the work and look inside without being in danger of exposure. All hoods should be equipped with a static pressure monitoring device such as a manahelic or photohelic gauge to ensure adequate flow at all times.

A portable HEPA filter-equipped vacuum cleaner should be used for all cleaning operations. Do not use "shop" or regular vacuum cleaner as they do not have an acceptable filtration system; arsenic dust can pass through the vacuum and back into the room. Furthermore, do not use a "house" or central vacuum systems. Phosphorus fires can be started as a result of friction within the ductwork, possibly resulting in a facility fire. Workers using the portable HEPA vacuum should be trained to "wet wipe" the nozzle exterior following each use. Failure to do this may result in release of toxic particulates into the ambient air.

Whenever possible, contaminated components should be removed from the implanter and cleaned using a wet (water and bead) slurry blaster. A wet slurry blaster will keep airborne dust and arsenic levels within the blaster down during the blasting operation. This type of blaster also encloses the hazardous materials, maintaining a barrier between the materials and the PM worker. If only a dry blaster is available, PM workers should be instructed to wear a respirator with HEPA, N100, or P100 style cartridges to prevent inhalation of any dust that may leak from the blaster.

Contaminated parts should always be scrubbed wet, preferably in an exhausted fume hood, using only DI water. Use of either isopropyl alcohol or hydrogen peroxide instead of water when scrubbing, may result in severe hazards. Hydrogen peroxide may ignite any phosphorus present, resulting in a fire. The oxidation reaction taking place when hydrogen peroxide is used for cleaning appears to be easier and faster, however, the "smoke" that is created when hydrogen peroxide reacts with arsenic or phosphorus contains toxic oxides of arsenic or phosphorus. Use of isopropyl alcohol when cleaning contaminated components can increase the risk of fire from sparks generated while cleaning or will increase the severity of fire if phosphorus contamination ignites during the cleaning operation. Isopropyl alcohol may be used following cleaning to aid in component drying and recovery of machine vacuum. An exception exists for implanters using B18. For B18 deposits, a wiper wetted with a 50% solution of isopropyl alcohol is the desired cleaning agent.

A portable or flexible exhaust can be used near the source, or in areas where scrubbing is being performed. This allows particles to be captured at the source rather than released into the air.

Parts removed from the implanter should immediately be placed into a sealed container, such as a bag or "source bucket". There may be a slow release of hydrides such as arsine phosphine, or diborane from these contaminated parts. Containing and sealing the parts will prevent a worker from being exposed to the gas or the dust that may be released. Contaminated parts should only be removed from their containers with a exhausted fume hood.

Any contaminated wipers, scrub pads, or other contaminated materials generated by cleaning operations should be put directly into a hazardous waste bag. Do not throw contaminated materials on the floor to be cleaned up at a later time. This will contaminate the floor and require the hazardous materials to be handled twice.

Source liners are available for most ion implanters and can be removed for cleaning in a wet slurry

blaster or exhausted fume hood. This greatly reduces both the PM time involved in scrubbing and the need for scrubbing the housing. A source liner will also greatly reduce potential exposure from scrubbing at the machine.

Machine surfaces should be protected with a plastic sheet or dampened wipers during scrubbing. Lay the plastic or damp wipers on the floor so that any particles that fall can be easily collected and deposited in the hazardous waste bag. This procedure will prevent contamination of the machine surfaces, especially those with which a worker may come into contact during non vacuum related component maintenance. When scrubbing procedures are complete, wet wipe all exposed machine surfaces. Workers should also be instructed to wet wipe all tools before replacing them in their toolbox. If tools are replaced without being cleaned, the whole toolbox can become contaminated with toxic materials such as arsenic. This contamination could be spread to the next user of the tools.

Workers should also be instructed in basic personal hygiene. This includes removing gloves whenever leaving the work area. This is a basic rule that is often ignored or forgotten. If gloves are not removed, any tools, telephones, or doorknobs that are touched with the gloves will become contaminated and pose a hazard to other workers. Reusable clean room suits that have been worn and potentially contaminated should be placed directly into the laundry bin. Many clean room laundry services are equipped with means to treat wash water contaminated with hazardous materials deposited on the garments. Fab operators should check to ensure that this is the case, or use disposable protective garments. Never use these suits for more than one day. Immediately after work has been completed, workers should wash their hands and faces. This may help limit harmful effects from accidental or unnoticed exposure to materials.

At the end of each day, workers should also clean and inspect reusable respirators, and dispose of disposable respirators or cartridges. Respirators should be disassembled and washed thoroughly. After cleaning and drying, the respirator should be placed into a clean bag. Never place a cleaned respirator into a used bag. Materials contaminating the external surfaces of a dirty mask are likely to contaminate the bag. Reuse of this bag is likely to spread contaminated material to the interior surfaces of a previously cleaned respirator, potentially resulting in avoidable exposures to personnel.

Contaminated materials resulting from maintenance and cleaning, as well as used vacuum oil, must be handled as hazardous waste and be disposed of in accordance with the laws of the respective country.

8.3 HIGH VOLTAGE

High voltages, necessary for the operation of ion implanters, present a number of serious hazards. These voltages include not only the acceleration voltage, which is in the range of several kV to several hundred kV, but also many auxiliary voltages used for beam extraction, scanning, electron suppression, etc.. In Table 8.3, a list of these is shown in detail.

Table 8.3: Power supplies used for typical medium-current and high-current implanters. The maximum ratings do not necessarily occur simultaneously

Purpose	Medium Current		High Current	
	Max. Voltage (V)	Max. Current (mA)	Max. Voltage (V)	Max. Current (mA)
Acceleration	200,000	10	200,000	100
Extraction	70,000	10	80,000	140
Arc	140	2,000	200	2,000
Quadrupole	25,000	5	-	-
Suppression	1,000	5	40,000	20
Scanner	50,000	5	-	-

The electrical resistance of the human body is rather low. Moreover, it decreases with increasing voltage, since the skin at the contact points may immediately be destroyed at higher voltages, thus reducing the total resistance. In this case, as a good approximation for the resistance between the two hands of a person, a value of approx. 1200 Ω can be assumed.

Besides the dangers of skin burns or electrolytic decomposition, the most serious danger of high voltages arises from the blocking of nerve conductance. Since the electrochemical potential of nerve membranes is in the order of 60 mV over the distance of one nerve cell, even low voltages interfere with this potential, thus disabling the individual from disconnecting the electrical power or pushing an "emergency off" button.

Usually, one can sense a DC current above 2 mA and an AC current above 0.5 mA. For an AC current at frequencies of 50 or 60 Hz, a current as low as 15 mA in the arm may result in a spasm which usually disables the person from removing his hand from the current source. Below 300 mA for DC currents in contrast to AC no cramps occur. Even more serious is the influence of electrical currents on the heart. Whenever the electrical field at the heart exceeds 50 mV/cm², the cardiac nerve signals are suppressed and ventricular fibrillation results which may be lethal within 3 to 5 minutes due to circulatory failure. It should be mentioned that in European countries with a voltage of 230 V and a frequency of 50 Hz, almost 3 % of all contacts with a power line are lethal. According to experience, for DC currents, lethal accidents only occur if the current passes completely through the torso. If the feet are on negative potential, the dangerous level of DC for ventricular fibrillation increases from 300 mA to 600 mA, for time periods above 750 msec (one heart period). In this case, the level is about a factor of 3 to 4 higher than for AC [25]. The different hazard regimes for DC are shown in Fig. 8.7.

Many techniques are employed by designers of electrical equipment to safeguard the operators as well as the equipment itself. Among the safety devices used are electronic fuses and circuit breakers for the power-supply output, current-limiting resistors, and bleeding resistors which discharge the filter capacitors on the DC power supply output. Switched high-voltage power supplies can be used to reduce the filter capacitance as well as the size of the transformer. With such power supplies, transient over-current spikes can be monitored, leading to a very rapid switching-off of the equipment when required.

Despite these controls, high voltage arcing can cause equipment damage and fires. This arcing may occur, both in vacuum and in air, between components at varying potentials. Fire can occur from within power supplies which are overly stressed as a result of repeated arcing as well as direct arc contacts with combustible components of implanters. Numerous structures, particularly those crossing high voltage gaps within implanters are constructed of plastic materials primarily selected for their non-

for their non-conductivity. In some cases, particularly on older model implanters, fire resistance has not been adequately considered in this selection process. Another contributing factor often discovered following arcing fires, is the operator's reports of continuing resets of the high voltage power supplies, immediately prior to discovery of a fire. Operators should be trained to consider repeated trips of high voltage power supplies to be an indicator of trouble and to inspect the equipment for signs of arcing after no more than three resets of the power supplies.

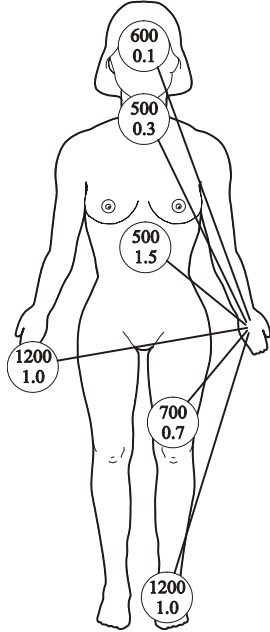


Figure 8.6b Heart factor (lower values) and electrical resistance (upper value) of a typical implanter operator for DC or low frequency AC between one hand and several points of the body. (Picture included as an excuse to show a naked German lady.)

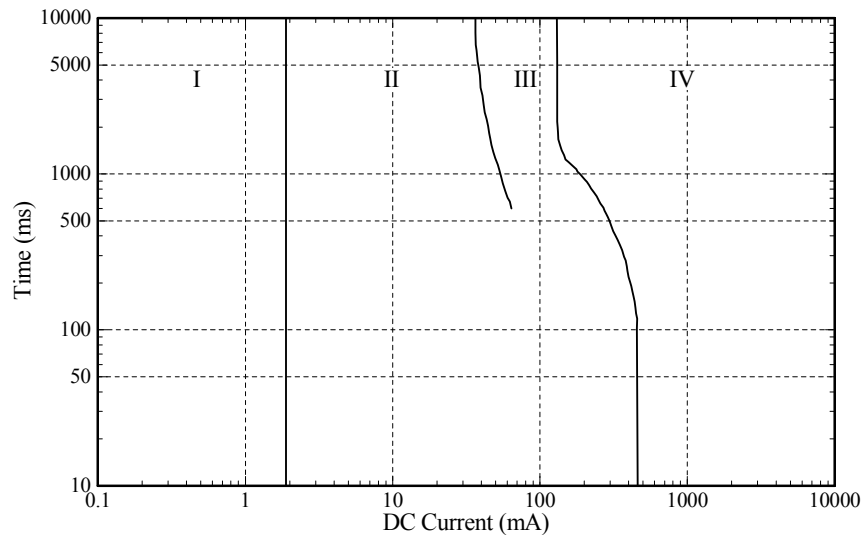


Fig. 8.7. Effect of DC cross-torso current on humans: I. No reaction, II. Usually no pathophysiologically dangerous effect, III. In general no organic damage, with increasing current and time, reversible irritation of cardiac nerve signals IV. Ventricular fibrillation probable, with increasing current and time further pathophysiologic effects such as burns. Border between II and III below 500 ms unknown. Curve between III and IV holds for vertical current (feet on positive potential).

Particular care should be taken to inspect roughing pump exhausts for deposits as discussed in the previous segment, terminal components and enclosures for cleanliness, DI water distribution systems for cleanliness, tubing integrity and DI water quality, and to ensure that all cabling and other terminal apparatus between high voltage and ground structures are returned to the manufacturer's recommended configuration following maintenance. Damaged or worn materials should be replaced immediately.

It is the system designer's and the operator's responsibility to ensure that components which are at high potential are properly shielded from human contact under normal operating conditions. The most effective protection against high voltages is to enclose the affected parts completely in a Faraday cage (grounded shielding). Occasionally, such shieldings must be opened to allow access to the machinery and circuitry. Electrical interlocks should be used to switch off the high voltage if an access door is opened. Additionally, simple but effective mechanical interlocks such as the drop bar can ensure that the terminal is connected to ground when opening a door. Besides this, key operated switches and door locks should be provided to prevent access by unauthorized personnel.

In ion implanters, almost all high-voltage power supplies are capable of providing currents high enough to cause severe injury. High voltage may be sensed by the feeling of a static discharge before a dangerous contact occurs. However, the spark length for high DC voltage equals 1 mm per 1 kV or about 1 inch per 20 kV which means that a distance of this order corresponds to a direct contact.

Still, high voltage is not well understood by much of the ion implanter user community. While many of these workers are qualified electrical or electronic personnel, some assumptions concerning the behavior of high voltage are erroneously made. Most common among these is that since the equipment does not arc to the doors while under normal operation, it is safe to be just outside the plane of opened doors during testing or troubleshooting with equipment interlocks bypassed. These personnel are not accounting for the fact that the electrical field from high voltage to ground will stretch out from the plane of the open doors to a distance approximately equal to that of the door opening. For instance, if the door is open 2 feet wide, the electrical field will extend approximately 2 feet out from the plane of the door. This concept is illustrated in Fig. 8.8.

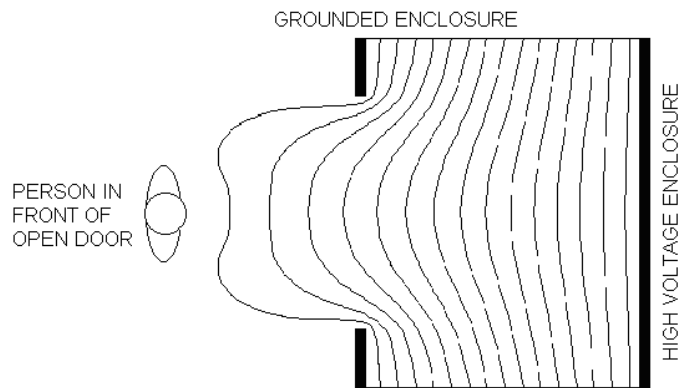


Fig. 8.8: Electrical field extending from door openings in ion implanters.

Personnel should be trained to recognize this situation and to minimize its effects by opening doors to the minimum degree possible for completing such tasks. This is also sensible from a radiation

protection perspective since implanter doors contain shielding required for protection purposes. In addition to minimizing door opening size, personnel should be trained to place barriers to access at a distance equal to the door opening width plus one meter. In this manner, personnel can ensure that they remain at least the distance of the electrical field, plus arm's length as a protection against inadvertent pointing or other bodily intrusion into the field. See Fig. 8.9 for illustration.

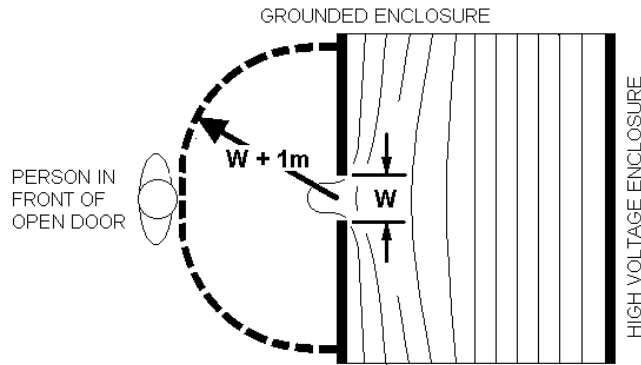


Fig. 8.9: Placement of barriers to avoid high voltage field contact.

Isolated parts such as coaxial cables may store some electrical charge; even if disconnected and discharged, they can cause severe electrical shocks. Static charges on insulated surfaces can also result in a noticeable shock (e.g. insulating paint on gas boxes or even high voltage bushings). It is, therefore, recommended to short circuit or ground these parts carefully before starting maintenance. Care should always be taken to inspect the grounding apparatus to ensure that the cable braiding and attachments are in good condition and, in fact, connected to ground. Besides these maintenance precautions, all assemblies or enclosures containing high voltages should have "Danger High Voltage" labels on their outer surfaces.

Cases where interlocks must be bypassed for specific calibration or troubleshooting procedures present the highest danger to personnel. These workers must be trained and specifically qualified to understand the behavior of high voltage fields and safe work practices. Specific procedures for bypassing interlocks should include the following steps. First, attempt to identify an alternate method to accomplish the task which enables the interlocks to remain enabled and the doors closed. Interlock bypass should be viewed as a last resort for accomplishing a required task rather than as a convenience.

Next, if interlock bypass must be undertaken, workers should establish and follow a written checklist of safety precautions and required task steps. The checklist will help ensure that all steps and precautions are taken, despite the workers' concentration on trying to determine the cause of a particular problem. Specific interlock bypass devices (preferably supplied by the manufacturer) should always be used. These devices should have a highly visible warning tag component and be constructed in a way that it is impossible to close the implanter door with the bypass in place. Minimize exposures by reducing the door opening size and by re-enabling interlocks as soon as the task allows.

Barriers with signs such as "Danger High Voltage" should be erected at least the width of the door opening plus one meter as discussed above. This barrier should be considered a protective device for

the workers involved, and not only as a barrier to passers by. In semiconductor fabs, implanters are often installed with only one meter between machines. In these cases, the barrier should be placed at the entry to the aisle created by the tools and remote viewing methods such as video cameras or mirrors should be used.

Workers should use lockout tagout procedures to disable any electrical systems which are not needed for the particular task at hand. In this way, the hazards can be minimized to only those absolutely necessary. Workers should be trained to use the grounding apparatus each time they open implanter doors, even if they are sure the machine has been off and discharged previously. Establishing habitual use of the grounding hook under any condition will aid in ensuring that it is used when necessary.

Workers must always work with at least one other person any time work with live electrical conductors is involved, even in cases where high voltage is not an issue. It is important to have the second person observing the task and in close proximity to an emergency off button, so that he or she may use it quickly to rescue a worker in distress.

In cases where test fixturing or high voltage probes are to be used, workers should be trained to never consider themselves part of the test fixture. This means that hand held equipment should not be used. Probes should have some type of attaching mechanism that can be placed on the conductor when it is off, allowing the worker to retreat to a safe distance, turn on the power, observe the reading from a safe distance, turn off the power, and using a grounding apparatus, return to the tool to remove the probe or replace it for a new measurement.

In semiconductor fabs, floors are either antistatic (10^7 to $10^8 \Omega$) or conducting (10^6 to $10^7 \Omega$) in order to avoid the build-up of electrostatic charge which could destroy semiconductor devices. In both cases, sufficient insulation between ground and a human body is not guaranteed. A non-conducting floor and insulating shoes (which are available for voltages up to 1000 V) should be considered.

8.4 RADIATION

Ionizing Radiation

Units and Biological Effects

Corpuscular radiation and electromagnetic radiation, as well as all types of charged or neutral particles, are detected and measured by their interaction with matter. There are two classes of units. One of them counts the photons or particles, such as the flux (e.g., photons/sec) and the Becquerel (in radioactive decays/sec). The other group of units, Roentgen, rad, Gray, or Sievert, measures the deposited energy. Since, in commercially used implanters, mainly x-ray radiation is released, the second type of unit is more convenient.

The Roentgen (R) is the most commonly used unit, by far, to measure the radiation dose. As defined by the International Commission on Radiological Units and Measurements, one Roentgen is the quantity of x-ray radiation which creates ions carrying 1 esu of electrical charge of either sign in one cubic centimeter of dry air under standard conditions (0°C , 760 torr). Thus, 1 R creates $1.61 \cdot 10^{12}$ ion pairs in 1 g of dry air. The SI unit for the absorbed dose D is the Gray measured in Joules (J) per kg.

kg. An older but still used unit is the rad. The rad (rd) defines the amount of radiation which deposits 100 ergs per gram in an arbitrary material (see Table 8.5).

Different types of radiation show quite different path lengths in the absorbing medium, due to the different stopping cross sections, which results in different relative biological effectiveness. For this reason, each type of radiation was assigned values of a quality factor q and another radiation unit, the dose equivalent H measured in Sievert (Sv) or the rem (Roentgen Equivalent Man) was devised. It holds:

$$H = q \cdot D \tag{8.1}$$

Table 8.5: Radiation units

Name	Unit	Conversion
Ion Dose J	C/kg	1 R = $2.58 \cdot 10^{-4}$ C/kg
Absorbed Dose D	Gray = J/kg	1 rd = 0.01 Gy
Dose Equivalent H	Sievert = J/kg	1 rem = 0.01 Sv

The q factors for all important types of radiation are given in Table 8.6. For x-rays, the value of q is unity, by definition. Thus, a rad of x-rays equals one rem or one Gray equals one Sievert. Moreover, the quantity of radiation defined by the Roentgen in air or in tissue and by the rad are all approximately the same within ten to fifteen percent.

Table 8.6: Quality factors q for different types of radiation

Radiation	q
x-ray, γ	1
β	1
α	20
protons	10
neutrons	5..15

Table 8.7 summarizes the physiological effects upon humans of whole-body exposure received within a few hours. In Table 8.8, the radiation-safety standards of several countries are given. The standards are given as Absorbed Dose per Time (D/t) assuming an exposure for a 8 hour working day for the full working life. These safety standards are calculated on the assumption that the risk of lethal radiation damage is equal to the risk of all other types of accidents through one's life.

Table 8.7: Effects of whole-body exposure received within a few hours

0.01 Sv	(1 rem)	No detectable change
0.1 Sv	(10 rem)	Blood changes detectable
1.5 Sv	(100 rem)	Some injury; no disability
2.5 Sv	(250 rem)	Injury and disability
5 Sv	(500 rem)	50 % deaths occur within 30 days

Table 8.8: Radiation-safety standards in several countries

USA	2.5 $\mu\text{Sv/h}$	(0.25 mrem/h)
Germany	2.5 $\mu\text{Sv/h}$	(0.25 mrem/h)
Japan	0.6 $\mu\text{Sv/h}$	(0.06 mrem/h)
England	7.5 $\mu\text{Sv/h}$	(0.75 mrem/h)

The absorption of ionizing radiation by a tissue produces excited atoms, molecules, ions and radicals, resulting in chemical processes which influence the biological reactions inside the cells.

One process is the oxidation of enzymes which contain a SH (sulfhydryl) group by a diffusing OH⁻ radical. The chemically active SH groups are destroyed and, as a consequence, the enzyme is blocked. The biological consequences of high-dose radiation exposure are, therefore, similar to the damage caused by certain poisons, e.g. nitrogen mustard gas ((ClCH₂-CH₂)₂-NCH₂CH₂). Another major process leading to damage of the cell is the production of hydrogen peroxide. The ionization of water molecules under the presence of oxygen induces the formation of H₂O₂ which is highly toxic for the cell.

International recommendations assume strict proportionality between dose and stochastic biological effects, i.e., no threshold dose is assumed for genetic mutation and cancer induction. Therefore, small doses are to be avoided; the likelihood of any effect, however, is correspondingly small.

If N persons are exposed to a dose equivalent D (in Sv) the number n of persons who fall sick is:

$$n = NfD \quad (8.2)$$

where f is the risk factor given for some diseases in Table 8.9

Table 8.9: Risk factors for malignant tumors

Disease	Risk factor f (Sv^{-1})	Remarks
leukemia	$2.3 - 6.3 \cdot 10^{-4}$	Not statistically proven
bone cancer	$5 \cdot 10^{-4}$	Absorbed inside the bones
thyroid cancer	$5 \cdot 10^{-4}$	--
lung cancer	$2 \cdot 10^{-3}$	Higher under chemical irritation
breast cancer	$2.5 \cdot 10^{-3}$	-
all other tissue	$5 \cdot 10^{-3}$	Equally-distributed irradiation
total	$\leq 2 \cdot 10^{-2}$	--

Especially important for monitoring the effects of radiation damage are blood tests, since blood is continuously produced within the bones. Through a radiation dose of the order of 10 rem, a dose-dependent blood change (increase in the number of leucocytes, followed by an increase in erythrocytes) is induced.

Electron Induced X-Rays

Implanters accelerate ions in an electrostatic field. The largest potential difference is usually equal to the desired ion energy. Energetic particles may ionize electrons from the inner shell of the atoms, thus producing characteristic x-rays corresponding to the transition energies of the electrons. Moreover, during the retardation of charged particles, bremsstrahlung is emitted as a broad band of x-rays. According to the principles of classical electrodynamics, the emitted energy E is given by:

$$\frac{dE}{dt} = \frac{2}{3} \frac{q^2}{c^3} \left| \frac{d^2 x}{dt^2} \right|^2 \quad (8.3)$$

with q being the charge of the particle and c the velocity of light. The most abrupt velocity change takes place if charged particles strike a target. Equation (8.3) is only valid for a statistical average of many charged particles.

An abrupt change of the particle velocity takes place for ions at the target, as well as for electrons which are accelerated in a direction opposite to the ions and strike parts of the system. Electrons in an accelerator are mainly produced through collisions between ions and residual gas atoms or the walls of the systems.

The emission of photons during bremsstrahlung represents a statistical process of electrons retarded in the electrical field of an atomic nucleus. The x-ray intensity of photons of energy E within an energy interval dE depends on the photon energy E , with a maximum energy E_0 which corresponds to the energy of the electrons $q(V_0)$ [V_0 : acceleration voltage]. The spectral intensity $P_e dE$ for thick targets with atomic number Z , where an electron current I is completely slowed down, is given by [26]:

$$P_e dE = \text{const.} \cdot I \cdot Z \cdot (E_0 - E) dE \quad (8.4)$$

Using $E_0 = q \cdot V_0$, the total emitted radiative power is given by:

$$P(w) = \int_0^{E_0} P_e dE = A_o \cdot Z \cdot I \cdot V_o^2 \quad (8.5)$$

The efficiency for converting electrical (electron) power to radiative power for electron energies up to about 500 keV is given by [27]:

$$\varepsilon = A_o \cdot Z \cdot V_o \quad (8.6)$$

With $A_o \approx 10^{-9} \text{ V}^{-1}$. The yield of bremsstrahlung increases with electron energy and atomic number of the target material. The angular distribution of the emitted x-rays changes from spherical shape to increased forward emission at higher energies.

The bremsstrahlung spectra are superimposed by characteristic x-rays which depend on the atomic number of the target. Accelerated electrons also ionize atoms. When an inner-shell electron, e.g. from

from the K-shell is removed by electron impact, the K-shell may be refilled by electrons from outer shells accompanied by emission of characteristic x-rays with distinctive energies. The most intense x-ray line is emitted when the strongly-bound electrons of the K-shell are refilled. Characteristic energies of K- and L-shell x-ray radiation are given in Table 8.10.

Table 8.10: Characteristic x-ray energies of some elements [28]

Element	Atomic Number	K-Energy (keV)	L-Energy (keV)
Be	4	0.111	
C	6	0.284	
Al	13	1.560	0.118
Si	14	1.834	0.149
Fe	26	7.112	0.846
Mo	42	20.000	2.865
W	74	69.530	12.100

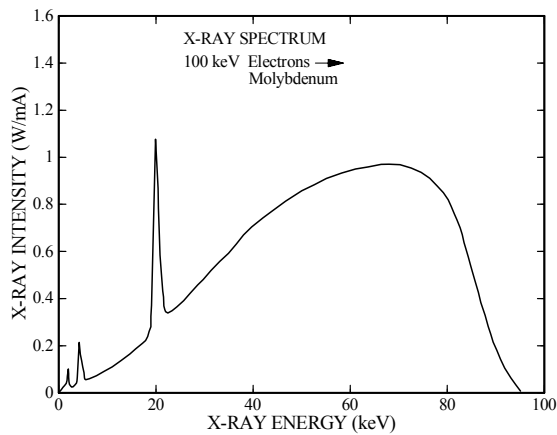


Fig. 8.10: Typical x-ray intensity spectrum vs electron energy for a medium-Z target.

In Fig. 8.11, the critical points for x-ray production are shown. These are typically the extraction electrodes in all implanter types and, in addition, the beam-defining apertures in medium-current and post-acceleration implanters. A reduction in x-ray generation is possible by preventing the electrons from entering the electric field regions. This is accomplished by using negatively-biased electrodes in front of the field regions, as shown schematically in Fig.11. Use of suppression electrodes is also necessary to avoid extraction of electrons from the beam plasma, thus destroying the space-charge neutrality of the beam. This would lead to a beam blow-up (depending on the current density) and additional x-ray production by electrons generated when the ion beam strikes the walls of the system. Therefore, an interlock on this voltage is recommended and is provided in all commercial accelerators.

The electron current across the extraction gap in a well-designed and well-operated implanter may be as high as 10 % of the extraction current.

Since the x-ray production is proportional to the square of the acceleration voltage, the x-ray emission is especially strong in the case of a post-analysis implanter. The electron current in the acceleration

acceleration tube of a two-stage implanter is also usually a few percent of the ion current. However, in case of a poor vacuum, misaligned electrodes, or lack of (or improper) suppression, it can be much higher. It is generally limited only by the power supply.

Some ion sources make use of electrostatic lenses in the source region with voltages up to 50 kV. The high electron density available in this region and the resulting current lead to extensive bremsstrahlung production.

The material of the electrodes which are struck by the electrons is of great importance for x-ray production. To reduce such production in two-stage accelerators, the beam-defining aperture is made of carbon ($Z = 6$) or aluminum ($Z = 13$). The latter, however, is only suitable for low-current implanters. Sometimes a coating of beryllium ($Z = 4$) is also used. The extraction electrode is often made of molybdenum ($Z = 42$) or, preferably, carbon ($Z = 6$).

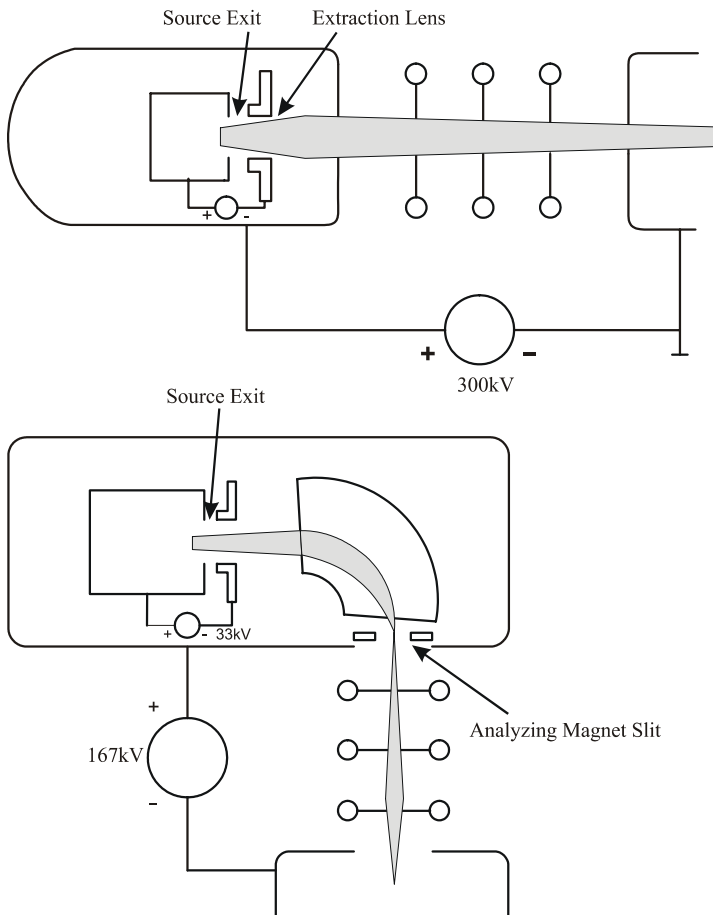


Fig. 8.11. Critical points of x-ray generation of single-gap and two-gap implanters and electron suppression electrodes

Ion Induced Nuclear Reactions

The x-ray production caused by ions is much lower than that due to electrons (approx. by 6 orders of magnitude), since ions have a much lower velocity than electrons accelerated with the same voltage. Ions can, however, produce characteristic x-rays by inner shell ionization. Energies of characteristic x-

characteristic x-rays are rather low which leads to high absorption. Together with their low generation rate, characteristic x-rays are normally a minor contribution to the total x-ray budget of an implanter.

Nuclear reactions resulting from acceleration of ions can also occur. For most ion species of interest in ion implantation, the threshold energies for nuclear reactions are too high (several MeV) in order to be of practical relevance, however, acceleration of deuterium, hydrogen and ^3He in commercially available ion implanters can produce significant nuclear reactions, producing neutrons and/or high energy gamma rays. Deuterium and hydrogen in particular have been a topic of increasing interest for semiconductor processing. These materials appear to have process advantages in damage engineering and interface state control processes [29]. Hydrogen is also commonly used as a dopant in gallium arsenide wafer processes.

In the case of deuterium, acceleration at any energy can produce neutrons. Acceleration of deuterium at energies as low as 20 keV can produce dose rates likely to exceed occupational health limits (5 rem/year) [1]. As energies increase, neutron generation increases significantly. Figure 8.8 illustrates experimental results of deuterium acceleration at varying energies in a commercial ion implanter.

This reaction is occurring as a result of deuteron:deuteron, $\text{D(d,n)}^3\text{He}$, collisions within beam strike plates, faradays, etc.. The accelerated deuterons are quickly implanted and/or adsorbed within the carbon matrices of these structures to a sufficient degree to become an effective deuterium target for subsequent accelerated deuterons. Calculations indicate that only a 0.05% concentration of deuterium within the surface carbon is necessary to produce the results indicated in Fig. 8.12 [30].

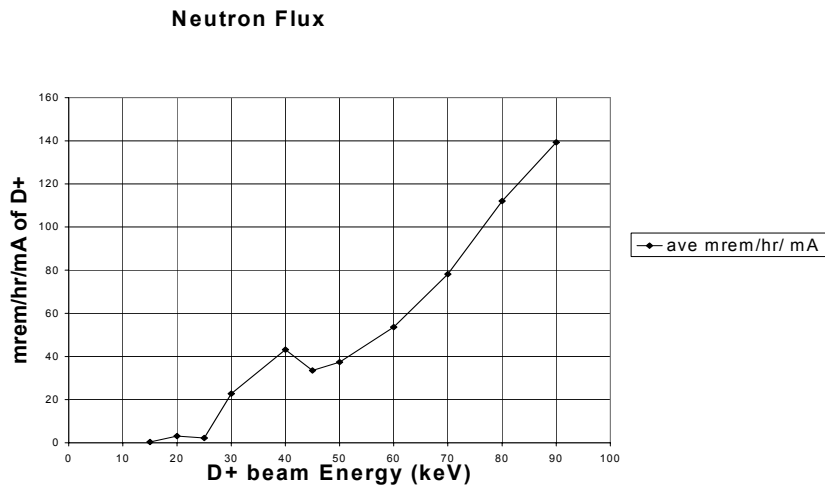
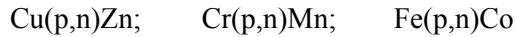


Fig. 8.12: Neutron dose per mA D+ at varying energies.

Neutron generation reactions can also take place while accelerating H_2^+ at energies in excess of 300 keV. It is believed that the mechanism of neutron production in this case is a deuteron:carbon reaction, $^{12}\text{C(d,n)}^{13}\text{N}$. This reaction has a threshold energy of 328 keV and results from the natural 1/6000 fraction of deuterium in hydrogen [31].

Reactions triggered by MeV-protons can also generate neutrons during ion implantation. Lifetime

engineering of devices using proton implantation may require proton energies of several MeV. These energies enable nuclear reactions, such as:



Continued generation of neutrons can not only result in dangerous exposures to personnel, but can also activate various implanter components, resulting in long term, radioactive material disposal issues for the equipment. Deuterium should not be accelerated in commercially available semiconductor processing ion implanters. All major manufacturers of these tools have issued product safety notices in this regard.

Acceleration of protons can result in production of high energy gamma rays. Two main gamma radiation producing reactions can occur at the faraday cup. These are $^{11}\text{B(p,}\gamma)^{12}\text{C}$ produced by the impact of a proton into boron 11 which is a common dopant and, therefore, a significant contaminant of the faraday carbon, and $^{12}\text{C(p,}\gamma)^{13}\text{N}$ produced by the impact of a proton into carbon.

The $^{11}\text{B(p,}\gamma)^{12}\text{C}$ reaction has a resonance at 163 keV, producing characteristic peaks of gamma radiation at 4.4 MeV, 11.7MeV and 16.1MeV [32].

The $^{12}\text{C(p,}\gamma)^{13}\text{N}$ reaction has a resonance at 457 keV, however literature reports that this reaction becomes significant at about 400 keV [33,34]. This reaction produces 2.36 MeV gamma rays. It also activates the carbon within the target, forming nitrogen 13 which then undergoes a positron decay to carbon 13. This positron decay results in production of a 0.51 MeV gamma ray. ^{13}N has approximately a 10 minute half life.

Other possible target materials that undergo reactions with proton beams include:

- $^{19}\text{F(p,}\alpha\gamma)^{16}\text{O}$ with a resonance at 224 keV
- $^{24}\text{Mg(p,}\gamma)^{25}\text{Al}(\beta^+)^{25}\text{Mg}$ with a resonance at 226 keV
- $^{27}\text{Al(p,}\gamma)^{28}\text{Si}$ with a resonance at 226 keV
- $^9\text{Be(p,}\gamma)^{10}\text{B}$ with a resonance at 330 keV
- $^{15}\text{N(p,}\gamma)^{16}\text{O}$ with a resonance at 360 keV
- $^{15}\text{N(p,}\alpha\gamma)^{16}\text{O}$ with a resonance at 360 keV [32].

Commercially available semiconductor processing ion implanters are not designed with shielding capable of controlling high energy gamma rays produced by the types of reactions discussed above. Do not accelerate protons in commercial semiconductor processing ion implanters without first consulting with qualified radiation safety professionals and the tool manufacturer.

Attenuation of Radiation

For a point-like source, the radiation flux density decreases with the square of the distance. High voltage protection already demands distances of the order of one meter between high voltage biased components and the implanter housing. This leads to a reduction in radiation density at accessible areas of the order of 100 compared to the radiation flux directly outside the beam line at the "hot spots".

X-ray radiation from a point source can be attenuated by absorption or scattering. In scattering, the radiation is spread over a wide volume, whereas in absorption, the radiation is transformed into heat. There are four interaction mechanisms, each showing characteristic dependence on the density and binding strengths of the electrons of the shielding material and by the x-ray energy. In most of these interactions, the energy spectrum of the radiation is shifted towards a lower energy, which is finally absorbed as heat.

By Rayleigh scattering, i.e. elastic scattering of photons by electrons which dominates at low energies, the radiation is distributed isotropically without absorption.

In the photo effect regime, a x-ray photon transfers its energy to an electron, exciting it to a higher energy level or actually ejecting the electron from its bound state in the target atom. Consequently, absorption edges are observed exactly for those energies at which, in the inverse process of x-ray production, characteristic x-rays are generated. The photo effect is the dominant process for low-energy photon absorption.

When the photon energy increases beyond the K-shell for a given absorber, the photo effect loses significance because then the binding energy of the electrons is small compared to the incident photon energy. In this energy range, Compton scattering becomes dominant. In the Compton process, a photon collides with an electron; part of the energy is transferred to the electron, and a scattered photon is emitted with a lower energy. Compton scattering shows relatively little variation with energy in the range between 10 and 500 keV.

At energies above 1.02 MeV, the photon energy is high enough for the formation of electron-positron pairs. All these mechanisms show different cross sections as a function of the incoming photon energy E and the absorber atomic number Z . The E and Z dependencies are listed in Table 8.11.

Table 8.11: E and Z dependence in various attenuation processes

Process	Absorption	E dependence	Z dependence
Elastic scattering	no	$\cdot E^{-2}$	Z^2
Photo effect	yes	$\cdot E^{-3 \dots 3.5}$	$Z^4 \dots Z^5$
Compton effect	yes	$\cdot E^{-1/2}$	Z
Pair formation	yes	$\cdot \log E$	$Z \dots Z^2$

Fig. 8.13 and 8.14 show the relative importance of the attenuation mechanisms and the total mass attenuation coefficient μ/ρ , as well as the mass attenuation for a light element, Al, and a heavy element, Pb. Materials chosen for shielding are generally high- Z elements with high density. As shown in these figures, the attenuation coefficients for the four attenuation mechanisms may be added to the total coefficient μ_o :

$$\mu_o = \mu_R + \mu_P + \mu_C + \mu_{pair} \quad (8.7)$$

where μ_R , μ_P , μ_C , and μ_{pair} are the coefficients for elastic scattering, photo effect, Compton effect, and pair formation, respectively.

For a monochromatic x-ray beam, the intensity of the beam after passing through an absorber of thickness x is given by:

$$I = I_0 \exp(-\mu_0 x) \tag{8.8}$$

with I_0 the incident intensity and μ_0 the total attenuation coefficient.

The bremsstrahlung radiation from an implanter will, however, have a continuous energy spectrum extending up to the acceleration energy. Since the total absorption coefficient μ_0 decreases steadily with photon energy, the selective absorption of the softer x-rays in the low energy region renders the spectrum towards the high-energy part of the spectrum. This approximation is almost exact in shielding situations where the incident radiation is reduced by many orders of magnitude.

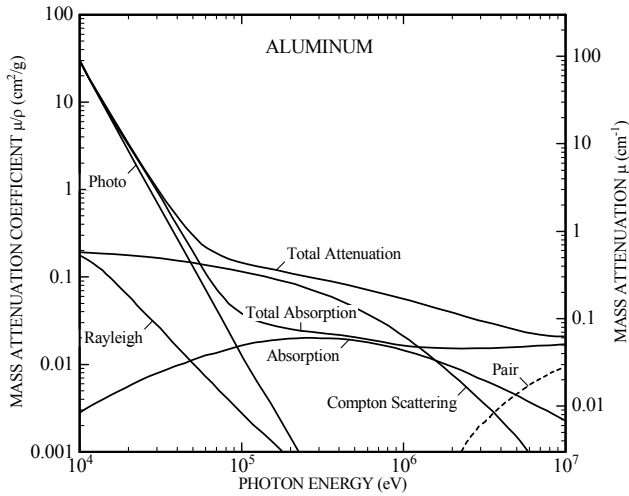


Fig. 8.13: Mass attenuation and absorption coefficient for Al, showing the relative contributions of the different attenuation mechanisms.

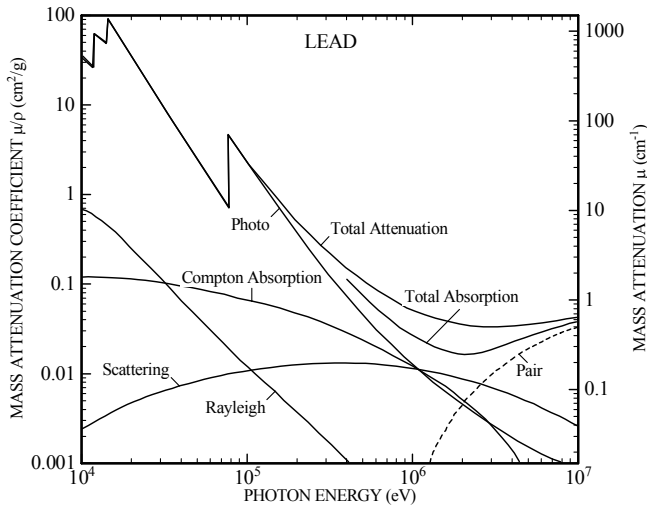


Fig. 8.14: Mass attenuation and scattering coefficient for Pb, showing the relative contributions of the different attenuation mechanisms

Examples of Shielding Calculations

The x-ray intensity in an energy interval dE at energy E is given by

$$P_e dE = \text{const.} \cdot I \cdot Z \cdot (E_0 - E) dE \quad (8.9)$$

For practical calculation, the spectral distribution is divided into small energy intervals ΔE where the mass absorption coefficient $\mu(E)$ is approximated by a constant value [25].

The intensity after transmission through a radiation shield of thickness x is given by

$$\begin{aligned} P'_e \Delta E &= P_e \Delta E \cdot \exp(-\mu(E) \cdot x) = \\ &= \frac{2}{q^2} \cdot A_0 \cdot Z \cdot I \cdot (E_0 - E) \Delta E \cdot \exp(-\mu(E) \cdot x) \end{aligned} \quad (8.10)$$

or the total radiation intensity:

$$P = \sum P_e \Delta E \quad (8.11)$$

The intensity per area at a distance r of the radiation source scales like

$$P(r) = \frac{P}{4\pi r^2} \quad (8.12)$$

In order to calculate the resulting Absorbed Dose per Time (D/t), the energy dependence of the mass-energy conversion coefficient (η/ρ) has to be taken into account

$$\frac{D}{t} = \frac{2A_0}{4\pi r^2 q^2} \cdot Z \cdot I \cdot \sum_i (E_0 - E_i) \Delta E \cdot \exp(-\mu(E) \cdot x) \cdot \left(\frac{\eta}{\rho} \right) \quad (8.13)$$

The factor (η/ρ) is in the order of $10^{-2} \text{ m}^2/\text{kg}$ for photon energies between 20 keV to 1 MeV [25, 35].

For a medium-current implanter with an ion current up to 1 mA, extraction currents up to 5 mA are used. In this case, the reverse electron current is approx. 2 mA, which is stopped in a molybdenum aperture ($Z=42$). At an accelerator voltage of 120 keV and a lead shielding of 5 mm thickness, the x-ray dose will be about 1 $\mu\text{S/h}$ at a distance of 10 cm of the hot spot. At the normally accessible area for operators at a distance of 1m, the dose is only about 10 nS/h. With a carbon aperture instead of a molybdenum one, one would lower the dose by another factor of 7. But decreasing the lead thickness to 2.5 mm would increase the dose to 60 $\mu\text{S/h}$. Shielding requirements will further increase for higher currents and especially higher energies. For a 100 mA, 200 kV implanter the lead shielding has to be 1 cm in order to reduce the dose to 2.5 $\mu\text{S/h}$ for the conditions mentioned above.

Although shielding is partly done by the vacuum tube, as a rule of thumb, the lead shielding for energies higher than 100 keV should be at least 5 mm thick. With Van de Graaff accelerators having energies higher than 2 MeV, the lead shielding should be in the order of several cm in thickness,

although the electron currents are low. Another method applied to lower radiation levels is to keep electron energies low, thus reducing shielding requirements. One approach is to use small magnets to deflect electrons towards apertures on the wall of the beamline. With these accelerators, special shielding precautions may also be taken due to nuclear reactions with some type of ion beams.

Work Practices

Commercially available semiconductor processing ion implanters do not typically exhibit significant ionizing radiation hazards to operators and maintenance personnel. Electron suppression systems, attenuation, and shielding designs reduce the emissions to levels typically equal to or lower than than consumer television sets. However, troubleshooting procedures which require interlocks to be disabled and doors opened, high voltage calibrations or maintenance procedures requiring removal of shielding can increase the risk to maintenance personnel. Maintenance workers should be included in a radiation badge dosimetry program to assess and maintain records of their cumulative exposure. Shielding should always be replaced and a radiation emissions assessment be completed following maintenance which requires disturbance of shielding or work on electron suppression systems.

Non Ionizing Radiation

Non ionizing radiation in implanters consists of Radio Frequency (RF) radiation, magnetic fields and lasers. While none of these present a very large danger to operation and maintenance personnel, workers should be made aware of their existence. Rf radiation is sometimes used for acceleration of dopant materials. Numerous electromagnets are incorporated into the design of implanter beamlines. Lasers are typically present in wafer handling stations and used occasionally for alignment purposes by maintenance personnel.

Shielding inherent in the high voltage, beamline, and enclosure structures controls all of these emissions to safe levels for most personnel. Persons wearing pacemakers, however, may be exposed to magnetic and Rf radiation fields in excess of recommended limits. This is particularly true in the case of maintenance activities in close proximity to the magnet components within the beamline. Operators and maintenance personnel should be medically screened for pacemaker usage and restricted accordingly.

8.5 MECHANICAL SYSTEMS

Mechanical systems, particularly in the wafer processing area can exert large forces. Some examples include scanning motors, gyro motors, spinning disks, belt drives, load lock doors, wafer handlers etc.. Work on these systems should be conducted in accordance with normal safe work practices utilized on other types of equipment. This principally includes using Lockout Tagout when performing maintenance. Lockout Tagout is a system which requires each individual maintenance person to deenergize all sources of hazardous energy (electrical, pneumatic, hydraulic, chemical, mechanical, etc.), lock the energy cut off point in the off position (using an individually keyed padlock), and tag it with information regarding the maintenance task and the worker's identity. In this way each maintenance person is solely responsible for his or her own safety.

8.6 ERGONOMICS

Ergonomics is increasingly gaining importance in the semiconductor fab. As tools and wafers grow in

in size, tool maintenance and wafer handling issues become more critical. Older implanters were not necessarily designed with maintenance activities in mind, and many potential ergonomic stressors can exist within maintenance tasks. These include lifting heavy, bulky assemblies, and using awkward postures due to cramped spaces. With semiconductor fabs placing a premium on square footage, tool manufacturers have been making efforts at compacting the tool. This puts a heavier burden on maintenance personnel due to even more cramped spaces, and, in some cases, raising the height of assemblies, in order to reduce the footprint while maintaining the same cubic dimensions [36]. As wafer sizes increase to 300 mm, handling and loading of cassettes places a larger ergonomic burden on operators, particularly if the cassettes must be rotated 90° for loading.

Many tool manufacturers are now incorporating ergonomics into their designs. These features include wafer handling and loading stations, lifting fixtures which can be used for a variety of component removal tasks, and improved controls and operating procedures. Workers should be made aware of, and provided with manual lifting aids, fixtures and other tools and procedures which can reduce the ergonomic stress of ion implanter related operations.

8.7 CONCLUSIONS

Although ion implanters inherently involve numerous hazards, design of commercially available semiconductor processing equipment successfully controls these hazards to a remarkable degree. Nevertheless, hazardous materials can still pose extensive hazards related to personnel exposure and fire, especially during gas handling, and preventative maintenance. Fires can also result due to phosphorus contamination and hydrogen contained in cryo pumps. Electrical hazards are usually encountered during maintenance or with experimental implanters. Radiation (ionizing and non ionizing) is not a significant problem with proper shielding and for commercial equipment, but it can be quite dangerous for experimental implanters not properly designed. Mechanical systems and ergonomics are becoming more important to implanter safety design as the semiconductor industry continues to seek faster, smaller equipment and larger wafer sizes.

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8.10 APPENDIX: Technical and Medical Terms:

Carcinoma:	Malignant and invasive tumor that spreads by metastasis
Cardiac:	Pertaining to the heart
Cornea:	The transparent anterior part of the external coat of the eye covering the iris and the pupil
Hemolysis:	The breaking down of erythrocytes (red cells of the blood) with liberation of hemoglobine
Hyperkeratosis:	Proliferation of the cells of the cornea
Leucocytes:	White cells of the blood
Melanoma:	Darkly pigmented tumor especially of the skin
Mucous membrane:	Lubricating membrane lining an internal surface such as the alimentary, respiratory, and genitourinary canals
Pathophysiologic effect:	Disturbances of bodily function resulting from disease
Percutaneous incorporation:	Introduced and effective through the skin
Pulmonary edema:	Abnormal accumulation of watery fluid in the lungs
Pyrophoric:	Capable of igniting spontaneously in air
Venticular fibrillation:	Uncontrolled twitching or quivering of the muscular fibrillis of the lower chambers of the heart