

Industrial Hygiene and Control Technology Assessment of Ion Implantation Operations

L.J. UNGERS^A and J.H. JONES^B

^APEI Associates, Inc. (formerly PEDCo Environmental, Inc.), 11499 Chester Road, Cincinnati, OH 45246; ^BNational Institute for Occupational Safety and Health, Robert A. Taft Laboratories, 4676 Columbia Parkway, Cincinnati, OH 45226

Ion implantation is a process used to create the functional units (pn junctions) of integrated circuits, photovoltaic (solar) cells and other semiconductor devices. During the process, ions of an impurity or a "dopant" material are created, accelerated and imbedded in wafers of silicon. Workers responsible for implantation equipment are believed to be at risk from exposure to both chemical (dopant compounds) and physical (ionizing radiation) agents. In an effort to characterize the chemical exposures, monitoring for chemical hazards was conducted near eleven ion implanters at three integrated circuit facilities, while ionizing radiation was monitored near four of these units at two of the facilities. The workplace monitoring suggests that ion implantation operators routinely are exposed to low-level concentrations of dopants. Although the exact nature of dopant compounds released to the work environment was not determined, area and personal samples taken during normal operating activities found concentrations of arsenic, boron and phosphorous below OSHA Permissible Exposure Limits (PELs) for related compounds; area samples collected during implanter maintenance activities suggest that a potential exists for more serious exposures. The results of badge dosimetry monitoring for ionizing radiation indicate that serious exposures are unlikely to occur while engineering controls remain intact. All emissions were detected at levels unlikely to result in exposures above the OSHA standard for the whole body (1.25 rems per calendar quarter). The success of existing controls in preventing worker exposures is discussed. Particular emphasis is given to the differential exposures likely to be experienced by operators and maintenance personnel. Recommendations are made regarding the additional personal protection and administrative controls needed to reduce the potential for worker exposures to dopant compounds and ionizing radiation. Future areas of research are identified.

Introduction

The emergence of new technologies presents workers with new and often unique sources of exposure to hazardous agents. As a result, industry is confronted with new challenges to control the workplace and protect the employee. To meet these challenges, companies must identify, develop and implement effective control techniques. In turn, knowledge regarding proven controls must be disseminated throughout the industry. Also, because control advances in one industry may be applicable to others, the experiences gained by one sector of the economy must be shared with other interested parties. Such information transfer enables the benefits of new technologies to be realized while avoiding any potentially adverse impacts. Solid-state electronics and the semiconductor industry are good examples of a technology and industry with unique sources of exposure. The fabrication of integrated circuits, photovoltaic (solar) cells and other semiconductor devices presents the industrial hygiene community with new challenges to control the work environment.

The National Institute for Occupational Safety and Health's (NIOSH's) Engineering Control Technology Branch of the Division of Physical Sciences and Engineering recently conducted a control technology assessment of the integrated circuit industry. The purpose of the investigation was to document and evaluate techniques for the control of health hazards associated with a number of the industry's process operations. The first phase of this two-phase investigation consisted of preliminary walk-through surveys of 21 semiconductor facilities. These facilities ranged from the largest

of multinational "Fortune 500" firms to relatively small, sometimes privately owned, operations. Their product lines included integrated circuits, photovoltaic cells and discrete semiconductor devices. During these walk-through surveys, attention was focused on those process operations that could be a source of workplace hazards. The second phase of the investigation consisted of in-depth surveys at four integrated circuit facilities. The objective of these in-depth surveys was to estimate the potential for worker exposure to various hazards and identify good control technology.

A key process associated with the fabrication of integrated circuits, photovoltaic cells and other semiconductor devices is ion implantation. During implantation small amounts of an impurity or "dopant" are introduced into the crystal lattice of a substrate material. These dopants dislodge and replace individual atoms within the larger crystal structure of the substrate. When properly introduced, the dopant alters the electrical characteristics of localized regions of the substrate. When a substrate of silicon is "doped" with Group IIIA elements of the periodic table (*e.g.*, boron), regions of positive (p) carriers are produced. In a similar fashion, silicon doped with Group VA elements (*e.g.*, arsenic) produces regions of negative (n) carriers. These localized areas of doped silicon are used electrically to define the basic functional units (called "pn junctions") of a semiconductor device. One or more pn junctions are defined in the substrate to form diodes, transistors and other active elements of an integrated circuit. Similar junctions also are used to define the active portions of photovoltaic cells.

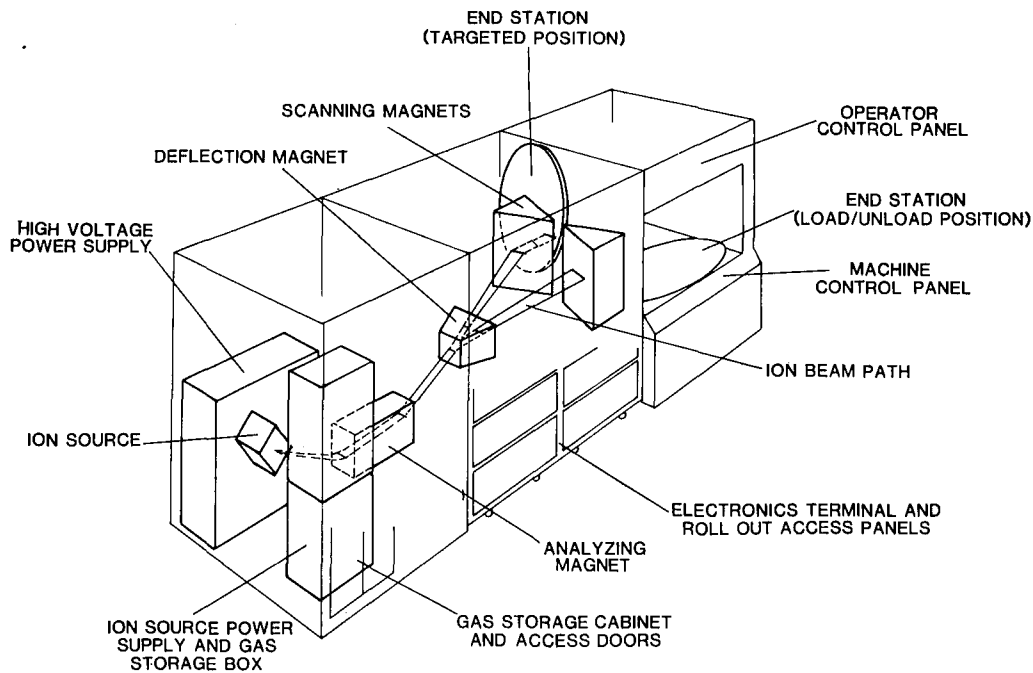


Figure 1 — High-throughput ion implanter.

Process Description

Several descriptions of ion implantation operations are available in the literature.⁽¹⁻³⁾ In brief, ion implantation is achieved by generating a beam of dopant ions, accelerating the ion beam toward a targeted substrate and bombarding selective areas of the substrate surface. Controlling the energy level (voltage) and the number of dopant ions (dosage) of the beam makes it possible to control both the depth to which the dopant is introduced and the eventual concentration of the ions in the substrate. A combination of beam targeting and masking of the substrate creates localized microscopic areas of doped silicon.

Figure 1 is a simplified diagram of a high-throughput ion implanter. In this example, a compressed gas cylinder located in the ventilated gas storage box supplies a gaseous compound to the ion source through stainless steel lines. The most common source materials used in ion implantation are gaseous compounds containing one of the Group IIIA or VA elements of the periodic table. Boron, phosphorous and arsenic, the most frequently used dopants, are commonly generated from arsine (AsH_3), boron trifluoride (BF_3) and phosphine (PH_3) gases. The dopant ions are produced by a confined electrical discharge in the arc chamber of the ion source. An ion beam then is drawn from the chamber by an extraction electrode and accelerated toward the analyzing magnet. Depending on the valence and species of the ion needed, the beam will be accelerated through an electrical potential ranging from 10 to 400 keV.^(4,5) Upon reaching the analyzing magnet, the beam is resolved, focused and analyzed for the desired ion species. Although a variety of ions are generated during the implantation process, the most commonly used species are the mono- and divalent cations of boron, phosphorous and arsenic.^(4,5) The selected ions are targeted through the deflection and scanning magnets.

These magnets ensure that a controlled and uniform dose of ions is presented to the wafer surface. The implantation of ions into the target wafer occurs at the end station of the ion implanter and represents the final process event. The ions bombard the silicon wafer and imbed themselves in the substrate.

The most common substrate material used in the industry is single-crystal silicon. The silicon substrate is presented to the ion implantation process in the form of high-purity wafers approximately 100 mm in diameter and 0.5 to 1.0 mm thick.⁽³⁾ During the implantation process the ion beam path is maintained under conditions of high vacuum (10^{-6} torr).⁽⁵⁾ This vacuum is achieved by use of a vacuum pumping system consisting of oil diffusion or cryo-pumps backed by chemical or direct-drive mechanical roughing pumps. High-throughput ion implanters such as the unit presented in Figure 1 are designed for routine processing of silicon wafers at dose levels of 5×10^{15} ions/cm² at rates of 200 to 300 wafers/hr.⁽⁵⁾

Work Practices

The preliminary walk-through surveys quickly indicated that activities requiring workers to come into close contact with the implanter could result in their exposure to one of two hazards: releases of dopant material or emissions of electromagnetic energy. The extent of worker interaction with the equipment is not easily discerned because much of the routine operation of an implanter is performed without the direct involvement of the process operator. The operator has been isolated from the process through remote electronic control of the implantation process. In the last few generations of equipment, electronic control has evolved to the point where process-related activities, which were previously the responsibility of operators, now are monitored and

TABLE I
Chemical Hazards
Associated With Ion Implantation Operations

Chemical Agent ^A	Formula	Source of Occupational Hazard
Arsenic (elemental)	As ^B	Ion source, beam path, pump oil
	As ^C	C
	As ⁻²	C
Arsenic pentafluoride	AsF ₅	Gas storage box
Arsenic trifluoride	AsF ₃	Gas storage box
Arsenic trihydride (arsine)	AsH ₃	Gas storage box
Arsenic trioxide	As ₂ O ₃	Ion source, beam path, general work area
Boron (elemental)	B ^C	C
	B ⁻²	C
Boron trichloride	BCl ₃	Gas storage box
Boron tribromide	BBr ₃	Gas storage box
Boron trifluoride	BF ₃	Gas storage box
Diborane	B ₂ H ₆	Gas storage box
Phosphorus (elemental)	P ^C	C
	P ⁻²	C
Phosphine	PH ₃	Gas storage box, general work area

^AThe chemical agents listed in this table represent those substances most commonly encountered during the investigation. Many other chemical substances also are used in ion implantation operations: argon (Ar), germane (GeH₄), germanium tetrachloride (GeCl₄), germanium tetrafluoride (GeF₄), phosphorus pentafluoride (PF₅), phosphorus tribromide (PBr₃), phosphorus trichloride (PCl₃), and phosphorus trifluoride (PF₃).⁽⁸⁾

^BElemental arsenic is used as a source of dopant ions in some implantation operations. Metallic arsenic (in the form of aluminum arsenide) has been reported to be present on internal components of the beam path when arsenic has been used as a dopant.⁽⁹⁾

^CCationic species of these dopants are generated during implantation; however, the existence and fate of these species in the workplace have not been reported.

adjusted automatically by preprogrammed, direct, digital-control systems. Despite these recent advances in equipment design, however, the worker still is required to interface with the equipment during wafer loading and unloading, changing of compressed gas cylinders and periodic preventive maintenance. It is during these activities that the greatest potential for worker exposure is believed to exist.

Wafer loading and unloading is a manual operation performed at the end station of the implanter. Workers transfer individual wafers or cassettes of wafers between the end station of the implanter and nearby wafer staging areas. During this task, they come into direct contact with newly implanted wafers. During the routine removal and replacement of compressed gas cylinders, workers are frequently exposed to incidental releases of dopant gas. Finally, periodic maintenance of the ion implanter, which includes changing and cleaning of the ion source, cleaning of the beam path, troubleshooting of the equipment and changing pump oils, is believed to place maintenance personnel at substantial risk. During each of these activities the maintenance worker is believed to be exposed directly to dopants or dopant compounds.

Although the design and operation of ion implanters suggest they may be a source of workplace exposures, early investigations did not provide a clear picture of these hazards. The first indications that implanters might be a source of workplace hazards were identified during a risk assessment of photovoltaic cell production processes.⁽⁶⁾ In what can be considered the first serious effort at quantifying health hazards in this industry, the California Department of Industrial Relations⁽⁷⁾ conducted air monitoring for inorganic arsenic around several implantation units that used arsine gas. The investigation did not find concentrations of inorganic arsenic above a detection limit of 1.0 µg/m³. Despite the lack of published data verifying perceived risks, the potential for workplace exposures near implanters remained a concern. Situations were believed to exist in which occupational exposures might result from direct interaction with the process equipment, the handling of process chemicals or contact with process wastes. Tables I and II summarize the potentially hazardous chemical and physical agents associated with ion implantation operations.

Survey Design

The objective of the in-depth survey was to describe the controls associated with ion implantation operations and to monitor the workplace for hazardous agents. The intent was for the descriptions to document the range of controls used in the industry, while the monitoring results would define the level of exposure to hazardous agents and provide a measure of the efficacy of various control alternatives. The control descriptions focused on the engineering features, administrative programs and personal protection programs designed to protect the worker during both normal operations and maintenance activities. Monitoring for airborne concentrations of arsenic, boron and phosphorus was conducted to detect the presence of dopant substances in the work environment. Monitoring also was performed for emissions of ionizing radiation, and when access to ventilation systems was possible, the airflow characteristics of the implanter exhaust system were determined.

Sampling and Analysis of Chemical Hazards

Concentrations of inorganic arsenic in the workplace were determined by the NIOSH Method for Arsine (S229).⁽¹⁰⁾ Air samples were collected by drawing a measured volume of air through a standard 100/50 mg charcoal tube with a low-flow

TABLE II
Physical Hazards
Associated With Ion Implantation Operations

Physical Agent	Source of Occupational Hazard
Ionizing radiation (X-ray)	Analyzing magnet and ion source
Nonionizing radiation (radio-frequency)	Radio-frequency power source
Electrical energy	High-voltage power supply and ion source power supply

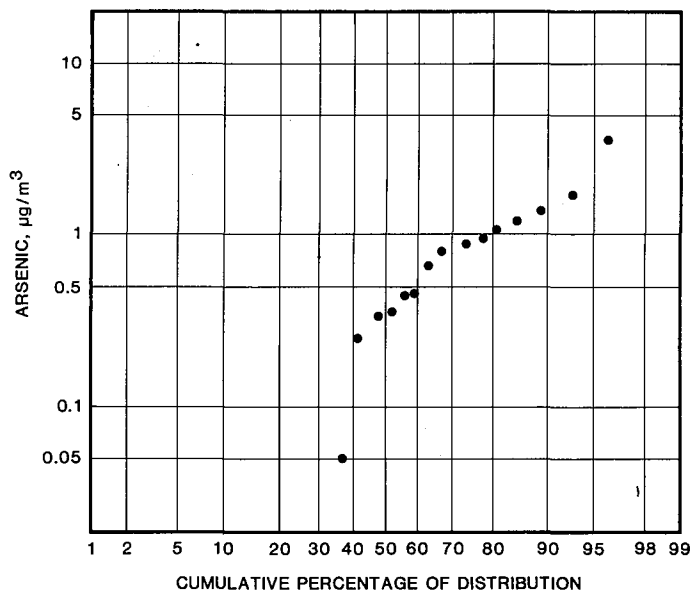


Figure 2 — Log-normal probability plot of arsenic concentrations.

(50 to 200 mL/min) stroke pump (SKC Model Number 222-3) for time periods ranging between 2 and 4 hr. The analyte was desorbed with nitric acid and analyzed by flameless atomic absorption. A detection limit of 6 ng/sample was achieved with this analytical method. The analytical results were corrected for reagent and charcoal blanks. The analytical results were corrected for a collection/desorption efficiency of 0.90.⁽¹⁰⁾ The sampling results are reported in micrograms of inorganic arsenic per cubic meter of air ($\mu\text{g}/\text{m}^3$) at standard conditions of 25°C and 760 mm Hg.

Concentrations of boron compounds in the workplace air were determined by the NIOSH Method for Diborane

(P&CAM 341).⁽¹⁰⁾ Air samples were collected by drawing a measured volume of air through a three-stage sampler consisting of a Teflon® filter cassette (millipore PTFE or equivalent), an oxidizer-impregnated charcoal tube SKC 226-67 or equivalent) and a personal high-flow pump (Dupont P2500, MSA Model G, or Bendix BDX 55-HD) at a rate of 1.0 L/min for periods ranging between 2 and 4 hr. The analyte was desorbed with 3% hydrogen peroxide and analyzed for total boron by plasma emission spectroscopy. This analytical method achieved a detection limit of 0.25 $\mu\text{g}/\text{sample}$. The analytical results were adjusted by a desorption efficiency factor of 0.90 determined at PEI Associates' analytical laboratory. The desorption efficiency factor was calculated by the procedure described by NIOSH.⁽¹⁰⁾ The results also were corrected for charcoal tube and reagent blanks. The sample flow rates of the rotameter-controlled pumps were corrected for changes in temperature and pressure. The sampling results were reported in micrograms of boron per cubic meter of air ($\mu\text{g}/\text{m}^3$).

Concentrations of phosphorous compounds in the workplace were determined by the NIOSH Method for Phosphine (S332).⁽¹⁰⁾ Air samples were collected by drawing a measured volume of air through a treated silica-gel tube (SKC 226-10-05 or equivalent) with a low-flow (50 to 200 mL/min) stroke pump (SKC Model Number 222-3) at a rate of 0.2 L/min for periods ranging between 2 and 4 hr. The analyte was extracted with a hot acidic permanganate solution, and after it had formed a phosphomolybdate complex, it was analyzed for phosphate. The complex was extracted with a mixture of isobutanol and toluene and then reduced with stannous chloride. The absorbance of the reduced phosphomolybdate complex was measured at 625 nm. A detection limit of 2 μg was achieved with this analytical

TABLE III
Summary of Area and Personal Samples Taken During
Ion Implantation Operations

Dopant	Sampling Approach	Sample Location	Number of Samples	Concentration, $\mu\text{g}/\text{m}^3$			
				Geometric Mean	Geometric Std. Dev.	Minimum Measurement ^B	Maximum Measurement
Arsenic ^A	Area	Machine control panel	11	0.5	3.7	<0.1 ^B	3.6
		End station	15	0.3	2.6	<0.1 ^B	1.2
		Manipulator (during beam path maintenance)	1	13 643.0	-	-	-
		Ion source (during maintenance)	7	2.6	14.1	<0.1 ^B	83.0
		Ion source (under cleaning hood)	2	<0.1 ^B	-	-	-
	Personal	Operator	5	0.3	4.7	<0.1 ^B	1.7
Boron ^C	Area	Maintenance personnel	3	0.2	2.0	<0.1 ^B	0.4
		Machine control panel	6	1.6	6.1	<0.5 ^B	26.8
	End station	7	0.6	1.7	<0.5 ^B	2.8	
Phosphorus ^D	Area	Machine control panel	1	<6.5 ^B	-	-	-
		End station	3	<6.5 ^B	-	-	-
	Personal	Operator	1	25.6	-	-	-

^AConcentrations were determined by the NIOSH method for arsine.⁽¹⁰⁾ The results are reported as total arsenic.

^BMinimum measurement represents the lowest detection limit achieved for this substance by the appropriate NIOSH sampling and analytical method.

^CConcentrations were determined by the NIOSH method for diborane.⁽¹⁰⁾ The results are reported as total boron.

^DConcentrations were determined by the NIOSH method for phosphine.⁽¹⁰⁾ The results are reported as total phosphorus.

TABLE IV
Summary of Ionizing Radiation
Measurements Taken During Ion Implantation Operations^A

Physical Agent	Monitoring Approach	Sample Location	Number of Samples	Total emissions, mrems			Average Weekly Dose, mrems
				Geo-metric Mean	Geo-metric Std. Dev.	Range Min. Max.	
Ionizing radiation (X-ray)	Area	Machine control panel	3	<10	-	<10 -	<1 ^B
		End station	3	<10	-	<10 -	<1 ^B
		Ion source	4	236	21	<10 14 850	1768 ^C
	Personal	° Inside cabinet	4	16	3	<10 70	2 ^C
		° Outside cabinet	4	<10	-	<10 -	<1 ^B
		Operator	2	<10	-	<10 -	<1 ^B
	Maintenance personnel	4	<10	-	<10 -	<1 ^B	

^ASurvey for sources of emission was performed with Nuclear Chicago Model 2650 and Vicotreen Model 4040 RFC Geiger-Muller counters. Total emissions were determined by Landauer Type P-1 dosimetry badges.

^BThe average weekly dose was determined by multiplying the mean total emission by a ratio of 40/888. This ratio represents an estimated exposure period of 40 hr (one shift) per week divided by the 880-hr (three shifts, 37 days) badge exposure.

^CThe average weekly dose was determined by multiplying the mean total emission by a ratio of 40/336. This ratio represents an estimated exposure period of 40 hr (one shift) per week divided by the 336-hr (three shifts, 14 days) badge exposure.

method. The analytical results were corrected for silica gel and reagent blanks. The sampling results were corrected to standard temperature and pressure and reported in micrograms of phosphorus per cubic meter of air ($\mu\text{g}/\text{m}^3$).

Monitoring of Physical Hazards

Potential exposures to ionizing radiation were determined through the use of both survey meters and badge dosimetry. Nuclear Chicago Model 2650 and Vicotreen Model 4040 RFC Geiger-Muller counters were used to detect radioactivity near the implanter. The magnitude of radiation emissions at these survey locations was characterized by Landauer Type P-1 dosimetry badges with a minimum detection limit of 10 millirems (mrems). The dosimetry readings were reported as total and weekly millirems of exposure.

Face velocities and general airflow characteristics were measured with a Kurtz[®] Model 441 air velocity meter. The measurement results are reported in linear feet per minute (fpm). When feasible, a multi-point traverse method of data collection was used to determine average air velocity of exhaust ducts.

Results

Sampling was conducted for airborne concentrations of arsenic, boron and phosphorus near eleven ion implantation units at three integrated circuit facilities. Monitoring of ionizing radiation was conducted near four implanters at two of the facilities. Some ventilation measurements were collected during the in-depth survey. During all monitoring efforts, the control technology associated with each implanter operation was observed and documented.

Chemical Hazards

Area and personal samples were collected during both normal process operations and maintenance activities. Because probability plots of the data suggest that the workplace concentrations might be log-normally distributed, the air monitoring results in Table III are presented as geometric means. In addition to this measure of central tendency, Table III also presents the geometric standard deviation and range of results for both area and personal samples. The minimum measurements presented in Table III represent the lowest detection limit achieved through use of the combined sampling and analytical methods. The maximum measurement represents the highest concentration detected during the survey.

Figure 2 presents a log-normal probability plot of all the area arsenic concentrations found near ion implanters. "Less-than-detectable" results were plotted as the mid-point between the lowest detection limit for arsenic ($0.1 \mu\text{g}/\text{m}^3$) and zero. The area sampling results for workplace concentrations of arsenic were plotted because of the importance of inorganic arsenic as a human carcinogen. Breathing zone concentrations of arsenic, and breathing zone and workplace concentrations of boron and phosphorus (presented in Table III) were not plotted because the paucity of data prevented the construction of useful probability plots.

Control of chemical exposures at ion implanters is achieved through a combination of enclosure, exhaust ventilation and personal protection. Although the configuration of the exhaust system varies for different types and models of equipment, ventilation generally is supplied to the enclosed gas storage cabinet, the enclosed ion source and the vacuum pumping systems. The manufacturers' suggested exhaust flow rates range between 600 and 1000 cfm.^(4,5) Although it

was not possible to construct a complete picture of the exhaust flow characteristics of the equipment surveyed, spot checks during the in-depth survey indicated that rates of 420 to 468 cfm were being provided to the ion source. Personal protection was provided to workers during gas cylinder changing at each of the 21 integrated circuit facilities visited during the preliminary walk-through surveys; however, only a few firms required such protection during maintenance activities. Preventive maintenance on the ion source, beam path and vacuum pumping system can lead workers to defeat completely the protection provided by equipment enclosures and exhaust systems. These engineering controls, although an integral part of the implanter, must be supplemented by personal protective equipment during maintenance activities. Only a few of the firms visited required personal protection during ion source and beam path maintenance; however, most required such protection during changing of gas cylinders. The use of full-face, air-supply-line respirators during maintenance activities was cited by a number of companies as being necessary to avoid the exposure of maintenance workers to both the dopant gases and related chemical compounds generated during implanter operations.

Physical Hazards

The results of monitoring for ionizing radiation are presented in Table IV as geometric means, based on the assumption that the exposures are log-normally distributed. Table IV also presents the geometric standard deviation and range of values. The monitoring results are given in total millirems of ionizing radiation emissions as detected using badge dosimetry. The mean total emission value then was used to calculate an average weekly dose (millirems/week). Estimated doses for area monitors located at the machine control panel and end station and for personal monitors carried by operators and maintenance personnel were determined by use of a ratio of 40 hr (a one-shift workweek) to 888 hr (three shifts, 37 days) of badge exposure. The estimated doses for area monitors located on either side of the ion source cabinet were determined by use of a ratio of 40 hr and 336 hr (three shifts, 14 days) of badge exposure.

The control of exposures to physical agents is achieved through the use of shielded enclosures and administrative control of employee access. Only the shielding provided by the equipment manufacturers was evident during the in-depth surveys. None of the facilities visited believed it was necessary to supplement the manufacturer's design with additional engineering controls. Two of the facilities did restrict access to implantation work areas, however.

Discussion

The results of the workplace monitoring clearly establish the fact that workers at ion implantation operations are routinely exposed to low-level concentrations of dopants; however, they do not indicate a similar problem with ionizing radiation. Exhaust ventilation, enclosure and shielding of the implanter equipment appear to prevent any noteworthy exposure to dopant compounds or ionizing radiation during

normal process operations; however, maintenance personnel appear to be at risk of exposure because the performance of these activities frequently requires workers to bypass or defeat the engineering controls.

Chemical Hazards

Concentrations of arsenic, boron and phosphorus were all found in the workplace air near implantation equipment. Although the identity of the specific dopant compounds released to the work environment was not ascertained, the amounts of each elemental dopant present indicate that no OSHA Permissible Exposure Limits (PEL)⁽¹¹⁾ or ACGIH Threshold Limit Values (TLV)⁽¹²⁾ for any suspect dopant compounds would be exceeded. For example, the highest workplace concentration of boron was 26.8 $\mu\text{g}/\text{m}^3$; if converted into an equivalent concentration of boron tribromide, boron trifluoride, diborane or boron oxide, no exposure limits would be exceeded.

Because inorganic arsenic is considered a human carcinogen, special attention was paid to workplace concentrations of this dopant. The probability plot of arsenic concentrations in samples taken near ion implanters (see Figure 2) indicates that no workplace concentrations were found above the OSHA action level of 5 $\mu\text{g}/\text{m}^3$ for inorganic arsenic. During the in-depth survey few area concentrations of arsenic were found to exceed a maximum value of 3.6 $\mu\text{g}/\text{m}^3$ (see Table III). A limited number of personal samples taken during the in-depth survey indicates that operator exposures to arsenic are lower than one might infer from the area monitoring results. Personal samples collected on maintenance personnel also failed to exceed the OSHA PEL. One important finding was that area samples collected at key maintenance points on the implanters were high enough to indicate a potential for very serious exposures well in excess of the OSHA PEL (see Table III). The difference between area and personal samples is attributed to maintenance personnel spending part of their time away from the implanter during performance of their "maintenance" tasks.

Usually, controlling exposure to chemical agents at ion implanters is achieved by a combination of exhaust ventilation and personal protection. The engineering controls associated with the implanters are judged to be adequate for normal process operations; however, the enclosures and ventilation that are an integral part of the equipment provide little if any protection during maintenance activities. Contrary to normal process operations, preventive maintenance requires workers to perform several tasks directly on components of the ion source, beam path, and vacuum pumping system. During these activities respirators, gloves and protective clothing should be used. Personal protection programs are needed to ensure proper use of the protective equipment.

Company industrial hygienists at a number of facilities visited frequently referred to "odor" problems associated with ion source and beam path maintenance activities. The general consensus was that a dopant or chemical compound of the dopant was being released from the equipment com-

ponents. Area samples taken at specific maintenance points on the implanters (see Table III) confirmed the presence of arsenic in large concentrations ($83 \mu\text{g}/\text{m}^3$ to $13\,643 \mu\text{g}/\text{m}^3$). These data, along with the recent discovery of an "out-gassing" phenomenon associated with newly implanted silicon wafers,⁽¹³⁾ suggest that dopant materials indeed may be responsible for the "odor" problem. Facilities that had identified the release of dopant as a potential health problem were the first to institute respirator programs. Maintenance workers at these facilities are required to wear air-line, pressure demand type, full-facepiece respirators during preventive maintenance.

Cleaning the ion source components and changing the vacuum pump oils also were considered problem maintenance tasks at a number of facilities. The ion source must be cleaned to remove deposits of dopants that build up during use. Bead-blasting or other forms of abrasive cleaning often are used, and various control measures have been developed to prevent worker exposures during this task. A typically good control program would have workers wear air-line, pressure demand type, full-facepiece respirators during removal and transfer of the ion source to an enclosed glove box equipped with exhaust ventilation. At several facilities, workers changing vacuum pump oils were required to wear chemical goggles, protective gloves and chemical splash aprons to avoid contact with the spent pump oil. The spent pump oil is suspected to contain organo-arsenicals and phosphates.

Physical Hazards

Although fairly limited, the monitoring results for ionizing radiation indicate that the enclosures and shielding that are an integral part of the implantation equipment afford adequate worker protection (see Table IV). Personal monitors worn by both operators and maintenance personnel did not record exposures above a minimum detection limit of 10 mrem. Area monitors located at operators' work stations (*i.e.*, machine control panel and end stations) also failed to record radiation levels above 10 mrem for the time periods sampled. These emissions are well below the existing OSHA standard for whole body exposure to ionizing radiation (1.25 rems per calendar quarter).⁽¹⁴⁾ Dosimetry badges mounted inside and outside the shielded ion source cabinets provided a good indication of the magnitude of the radiation hazard present (1768 mrem/wk) and the protection afforded by the equipment shielding (attenuation to 2 mrem/wk).

The source of ionizing radiation is attributed to spurious electrical currents forming near the ion source and analyzing magnet during operation of the equipment. Control of this hazard is achieved through lead-shielded cabinets and a system of interlocks that automatically shut down the implanter when the cabinet doors are unlocked and opened. The process workers' defeat of these engineering controls was an administrative and work-practice problem frequently encountered during the investigation. Shielding provided by the equipment cabinet was circumvented when operators or process engineers partially disassembled shielding or "short-circuited" interlocks to observe equipment operations dur-

ing processing. The importance of these interlocks is critical to the safe operation of ion implanters because they also provide protection against electrical shock.

Recommendations

Based on the results of this investigation, several recommendations can be made for the reduction of worker exposures to dopant compounds and emissions of ionizing radiation:

Engineering Controls

In general, exhaust ventilation, enclosures and radiation shielding afford adequate protection to operators during normal process activities; however, this protection may not extend to maintenance personnel, who may reduce or defeat the effectiveness of these engineering controls during the performance of preventive maintenance or equipment repairs. The nature of these maintenance activities is such that additional engineering controls may be difficult to implement. Supplemental controls for such activities currently are believed to be achieved best by personal protection and administrative controls.

Personal Protection

Although personal protection is not required during normal process operations on properly maintained implanters, personal protective equipment is needed during maintenance activities conducted on the ion source and beam path and during the changing of gas cylinders and vacuum pump oils. Maintenance personnel involved in these "problem" activities should wear air-line, pressure demand type, full-facepiece respirators. The potential for exposure to chemical hazards from waste pump oils has been identified (see Table I); however, no effort was made to quantify these potential exposures. In the absence of actual data it appears prudent to recommend the use of protective aprons and gloves when workers handle waste pump oils. Although no test data was available on the permeability of various glove materials to pump oil, neoprene and nitril gloves were being used at a few of the operations. Disposable gloves and aprons also are recommended when handling the ion source and components of the beam path.

Administrative Controls

Exposure monitoring, worker awareness and entry restrictions should be considered important parts of an industrial hygiene program addressing the hazards at ion implanters. Monitoring should be performed during maintenance activities to ensure that adequate personal protection is being provided to maintenance personnel. The monitoring also will serve to identify poor work practices and reduced efficiency of engineering controls. Training programs should be designed to make workers aware of the existence of dopants in the work environment. The purpose and need for radiation shielding and cabinet interlocks also should be stressed.

Future investigations of industrial hygiene and safety problems associated with ion implanters should attempt to characterize the nature and magnitude of dopant or dopant compounds being released from equipment components

during maintenance activities. Specifically, arsenic emissions should be analyzed to determine the arsenic compounds present in the work environment during preventive maintenance. It is believed that this research will have an important impact on monitoring and personal protection programs in the industry. Similar attention also should be given to releases of other commonly used dopants. Finally, investigations should be conducted to identify the occurrence, nature and magnitude of nonionizing radiation leakage from ion implantation equipment using radio-frequency power sources.

Acknowledgments

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