PRELIMINARY CONTROL TECHNOLOGY SURVEY

on

MICRO POWER SYSTEMS, INC.
Santa Clara, California

to

U.S. Environmental Protection Agency
Industrial Environmental Research Laboratory
26 West St. Clair Avenue
Cincinnati, Ohio 45268

and

National Institute for Occupational Safety and Health
Division of Physical Sciences and Engineering
4676 Columbia Parkway
Cincinnati, Ohio 45226

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by

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BATTELLE
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PLANT SURVEYED:	Micro Power Systems, Inc. 3100 Alfred Street Santa Clara, California 95050
SIC CODE:	3674
SURVEY DATE:	January 15, 1982
SURVEY CONDUCTED BY:	Gary J. Mihlan Battelle Columbus Laboratories Robert D. Willson, CIH PEDCo Environmental, Inc. Paul E. Caplan, CIH NIOSH
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EMPLOYEE REPRESENTATIVES CONTACTED:	None (No Union)

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1.0 ABSTRACT

A preliminary control technology assessment survey was conducted by Battelle Columbus Laboratories at Micro Power Systems, Inc., Santa Clara, California, on January 15, 1982. The survey was conducted under a U. S. Environmental Protection Agency contract funded through an Interagency Agreement with the National Institute for Occupational Safety and Health. The facility manufactures complementary metal oxide semiconductor (CMOS) and bipolar integrated circuits.

The process operations performed at Micro Power Systems, Inc. include: 1) thermal oxidation of purchased silicon wafers; photolithography processes for defining circuit patterns, including photoresist application, substrate exposure, and photoresist development; 3) wet chemical etching and cleaning; 4) plasma etching; 5) doping, including diffusion and ion implantation; 6) epitaxial silicon deposition (for bipolar fabrication only); chemical vapor deposition of silicon nitride and silicon dioxide; and metalization by electron beam evaporation and direct current (DC) sputtering.

The process operations for integrated circuit fabrication are performed in a clean room environment. The supply air is passed through a neutron filter to a bag filter and then distributed to the fabrication area through ceiling diffusers. High efficiency particulate air (HEPA) filters are only used in laminar flow work stations for specific process operations.

Engineering controls used at the facility vary by process operation and process equipment. Several process operations are performed in sealed reaction chambers that isolate the processes from the workers. This isolation technique is used in plasma etching, ion implantation, chemical vapor deposition, epitaxial silicon deposition, and metalization. Shielding is used in ion implantation units to control X-ray radiation emissions, in plasma etching and epitaxial silicon deposition to control radio frequency radiation emissions, and in substrate exposure to control ultraviolet emissions. Local exhaust ventilation removes vapors, process gases and byproducts in wet chemical cleaning and etching, in photolithography processes, and in diffusion furnaces used for thermal oxidation and diffusion. Local exhaust ventilation is also used for gas storage cabinets. For some operations permanently installed inclined manometers monitor the ventilation system. Several process

operations are controlled automatically. These operations include electron beam evaporation, DC sputtering, plasma etching, ion implantation, chemical vapor deposition, and epitaxial silicon deposition.

No continuous area monitoring systems are present for evaluating emissions or operator exposures to chemical or physical agents. The plant plans to install a combustible-gas monitoring system. Previous monitoring activities include colorimetric, direct-reading tubes for dopants, and a survey meter for X-ray radiation. Film badges are also used to monitor operator exposures to X-ray radiation at the ion implantation unit.

Personal protective equipment is used by operators, maintenance and repair technicians, and chemical technicians to control worker exposures to chemical and physical agents. This equipment varies by the job title and task performed and includes safety glasses, face shield, acid-resistant coveralls, apron, gloves with gauntlets, unspecified dust respirators, and self-contained breathing apparatus (for emergencies). Operators are also required to wear product-protective equipment to control product quality. Micro Power Systems, Inc. has established a health and safety program that includes worker training in safety, materials handling, personal protective equipment, emergency response, and hazard reporting. The facility also employs consultants in industrial hygiene, safety, and health care.

Process operations that should be considered for detailed investigation whether by Battelle or Micro Power Systems, include plasma etching, ion implantation, and epitaxial silicon deposition. The effectiveness of the local exhaust ventilation system in controlling chromic acid, antimony trioxide, and phenol should be evaluated. Work practices that may affect emissions or operator exposures to chemical and physical agents could not be addressed for all operations during the preliminary survey. The facility has developed work practice policies such as special handling of antimony trioxide and the associated housekeeping practices that may be effective in controlling exposures. These work practices should be documented during a detailed survey.

2.0 INTRODUCTION

A preliminary survey was conducted at Micro Power Systems, Inc., Santa Clara, California, on January 15, 1982 as part of a control technology assessment of the semiconductor manufacturing industry. The study was performed under U. S. Environmental Protection Agency Contract No. 68-03-3026 through an Interagency Agreement with the National Institute for Occupational Safety and Health. The survey was conducted by Battelle Columbus Laboratories, Columbus, Ohio.

The following plant representatives supplied information at Micro Power Systems, Inc.:

1. Mark Bridley, Manager, Facilities Engineering,
2. Debbie Bush, Personnel Training,
3. James E. Byrne, Vice President, Wafer Fabrication Operations,
4. Bill Glaskell, Process Engineering Manager,
5. Jerry S. Olson, Senior Process Engineer,
6. Edward J. Sawicki, Consultant, and
7. David Steck, Personnel Training.

The study protocol was provided to Mr. Mark Bridley before the survey. During an opening conference, the study objectives and methods were described. Plant staff provided a detailed description of the facility's health and safety programs, including a review of the plant construction, workforce, health and safety programs, air supply and exhaust, chemical storage, and waste management practices.

Following the opening conference, the research team surveyed the wafer fabrication area and chemical and waste storage areas. A closing conference was held following the survey and all survey notes were reviewed with the plant staff. The facility later provided injury and illness reports for 1981.

3.0 PLANT DESCRIPTION

3.1 General

Micro Power Systems, Inc. has been in business since 1971. The facility consists of two buildings: 1) a 42,720 square feet building of concrete block construction used for administration, marketing and sales, and 2) a 11,340 square feet single story building of tilt up wall construction used for wafer fabrication. The wafer fabrication building was constructed in 1972 with a masking room added in 1973. The administration building was constructed in 1975 and has not undergone any major changes.

The facility manufactures bipolar and complementary metal oxide semiconductor (CMOS) integrated circuits. Operations performed at the facility include wafer fabrication and testing. The facility employs 313 people with approximately 89 individuals in wafer fabrication, 59 in wafer testing, 133 in administrative and technical services, and 32 individuals providing outside services. The wafer fabrication and testing staff includes 81 workers on the first shift, 48 on the second shift, and 19 on the third shift. Administrative, technical, and other staff primarily work the first shift (160 of 165). Workers in the test area may work overtime.

3.2 Chemical Storage

Liquid chemicals are segregated as acids or organics and stored in separate locked rooms in different buildings. The acids are supplied in 1-gallon glass containers that are stored in boxes. The boxes are placed on epoxy-coated metal shelves or on wooden shelves. The room is vented by an exhaust in the ceiling and has a sprinkler system for fire control. The room is not diked nor is a floor drain present. Workers handling acids are required to wear gloves with gauntlets, apron, leather shoes, and a face shield. Spill kits containing vermiculite are available in the room along with a fire extinguisher and a fire hose.

Organic solvents are supplied in 1-gallon glass containers that are stored in boxes and placed on wooden shelves. The room is vented by an exhaust take-off located at the floor level and has fire sprinklers and explosion-proof wiring. The room is not diked nor is a drain present. Spill clean-up materials or personal protective equipment were not observed in the room. The solvents are transported to the wafer fabrication area by a chemical technician. The technicians place the 1-gallon bottles into safety containers that are loaded onto a cart and transported into the fabrication area. Only the chemical technician or the area supervisor pour the chemicals.

3.3 Gas Handling System

Gases used in wafer fabrication are supplied from cylinders and from bulk tank (i.e., house) supplies. Liquid oxygen is stored in a tank located outside of the facility at the building used only for chemical storage and administrative services. Oxygen is distributed to the fabrication area in copper lines. Liquid nitrogen is stored in a bulk tank supplied by a pipeline from an area gas supply firm. The lines do not have earthquake valves or flow-limiting valves.

Gases supplied in cylinders are stored outside in a covered area. Full cylinders are not segregated by gas type. Cylinder gases piped from the outside include diborane, hydrogen, phosphine, and hydrogen chloride. The cylinders are stored in the enclosed area and under a canopy. The gas manifolds are mounted on an outside wall of the chemical storage building and the cylinders are chained to the wall. All toxic gases and hydrogen are distributed in stainless steel lines. The lines that run above the ceiling are welded and use compression (Swagelok®) fittings for connections below the ceiling. Solenoid valves are present in the epitaxial reactor systems to shut off hydrogen supply to the unit during power failures. All gas lines are labeled with arrows indicating the direction of flow.

All toxic, corrosive, or flammable gases in the wafer fabrication area are stored in ventilated gas cabinets. The gas cabinets are vented to the plant scrubber system described in Section 3.5. Gas cabinets containing silane cylinders have galvanized exhaust ducts that extend from the cabinet through the ceiling. The galvanized duct acts as a burn box to provide a controlled reaction of the spontaneously combustible gas should a leak occur. Special procedures for handling gas cylinders are described in Section 5.3.

3.4 Monitoring Systems

At the time of the survey there was no permanently installed continuous monitoring systems for evaluating toxic or combustible gases. Micro Power Systems, Inc. has now installed a combustible-gas monitoring system. Monitoring of combustible (hydrogen) gas is presently performed with a portable J and W TLV Sniffer®. The instrument is used to detect hydrogen leaks in the epitaxial reactor area. Direct-reading colorimetric detector tubes (Draeger®) are used to detect dopant gas (phosphine and diborane) leaks in the fabrication area.

Film badges monitor emissions and operator exposures to X-ray radiation in the ion implantation area. The badges are collected and sent to a laboratory for weekly readings. X-ray emissions are also monitored with a survey meter (unspecified).

3.5 Ventilation System

Specific details of the air circulation system at Micro Power Systems were not obtained during the preliminary survey. Wafer fabrication is performed in a clean room environment. Air is supplied to the area through two air handlers having a total flow rate of approximately 18,000 cfm. The air intake is located at roof level on the south end of the building.

The supply air is treated by passing it through an electrostatic filter and a bag filter to collect particulates. The air is distributed to the fabrication area through ceiling registers. High efficiency particulate air (HEPA) filtration units are located in the fabrication area above individual work stations. The air is supplied to the HEPA filtration units through a grille located on the front of the unit that draws in air from the area surrounding the work station. The photolithography area is maintained at a positive pressure with respect to the remainder of the fabrication area.

Air is removed from the fabrication area by local exhaust ventilation and by exfiltration. Exhaust from all wet chemical benches, photoresist application and developing stations, chemical vapor deposition systems, diffusion furnaces, ion implantation unit, and gas storage cabinets are vented to the house exhaust system and passed through a 13,000 cfm water scrubber. The scrubber exhaust is vented to the atmosphere through a 30-inch diameter, 14-ft. stack located approximately 30 ft. from the nearest air intake. The exhaust plenum for the wet chemical benches incorporates a demister to control acid mists. Exhaust from the epitaxial reactor is vented through a separate water scrubber of unspecified capacity.

Monitoring of local exhaust ventilation is performed monthly to ensure a minimum capture velocity of 150 fpm at wet chemical stations. Inclined manometers are installed at all wet chemical stations in the diffusion area, on the wet chemical station containing sulfuric and chromic acid, and on the chemical vapor deposition system used for silicon nitride deposition. The manometers are checked daily. A weekly review of the scrubber system is also performed to ensure proper fan performance (RPMs and belt tension). Ventilated gas cabinets are monitored weekly to determine if duct velocities are at least 300 fpm with access doors open. Diffusion furnace scavenger box exhaust is also monitored to ensure a velocity of at least 300 fpm in the exhaust duct.

3.6 Waste Management System

Liquid wastes are handled separately and may be categorized as organics (including HMDS, photoresist, and developer), acids containing fluorides, chromic acid, other acids without fluorides, and pump oils. Organic wastes are collected by chemical technicians and transferred to drums stored in a specified waste storage area. Chromic acid and acids containing fluorides are each drained from the point of use to separate manifolds and transferred into bottles by chemical technicians. The bottles are placed in wooden boxes and stored on wooden shelves in a separate secured acid waste room. The room is ventilated by a wall register and has a fire sprinkler system. The drums and bottles are collected by a waste hauler for off-site disposal.

Acids that do not contain fluoride are collected along with scrubber blowdown by a central drain system and transferred to a neutralizing tank where the pH is adjusted with ammonia. The neutralized acid is then piped to the city sewer system. Pump oil from oil-sealed mechanical pumps used in process equipment is drained by line maintenance workers. The waste is transferred to drums and disposed by a waste hauler.

4.0 PROCESS DESCRIPTION

The fabrication sequence used for metal oxide semiconductor (MOS) and bipolar integrated circuits varies according to the specific type of device manufactured. Process operations observed at the facility are discussed below. The specific sequence in which the process operations are performed is not presented. A general processing sequence for MOS and bipolar integrated circuit manufacturing is provided by Colclaser (1980) and should be consulted for a more detailed review of the fabrication process. Several process operations are employed more than once in the fabrication sequence and some process equipment is used for more than one process operation. The silicon wafers used as a substrate for device fabrication are purchased.

In the thermal oxidation process, wafers are oxidized at a high temperature (approximately 900 to 1200°C) in a diffusion furnace assembly with water vapor present in the furnace tube atmosphere. Hydrogen chloride gas is added to the furnace tube to clean ("gettering") the growing oxide and furnace tube of sodium ion contamination (Colclaser, 1980). The wafers are loaded into carriers that are inserted into the diffusion furnace. The furnace tube is heated by electrical resistance to the operating temperature while the tube is purged with nitrogen. The oxidation may also be performed with oxygen. Gas flow into the furnace tube is controlled by a manual analog system that requires the operator to monitor and adjust the gas flow.

Following thermal oxidation, the wafers are ready for photolithography including: 1) wafer cleaning, 2) primer and photoresist coating, 3) pre- or soft-bake, 4) mask alignment and exposure, 5) development, 6) post- or hard-bake, 7) etching, and 8) photoresist stripping. The wafer is cleaned by spin-on application of xylene. Hexamethyldisilizane (HMDS) and photoresist are then applied to the wafer by spin application. The photoresist consists of a proprietary mixture of photosensitive organic polymers in a xylene carrier solution. The coated wafer is soft-baked in a resistance-heated oven. The spin operation is controlled automatically, requiring manual operation only to load and unload the spin platforms with wafers.

The mask pattern is transferred to the coated wafer by ultraviolet light (unspecified wavelength) using either proximity or contact printing. The operator aligns the wafer with the mask by viewing through a split-field binocular microscope. With both systems the wafer and mask are exposed to ultraviolet light from a mercury lamp located behind the mask. Photomasks are produced to plant specifications by an outside vendor.

The exposed wafers are developed by spin-on application of the developer. A mixture of n-butyl acetate and xylene develops the negative photoresist and an alkaline solution develops the positive photoresist. The developed wafers are hard-baked in a resistance-heated oven.

The exposed underlying layer may be etched using either wet chemical or plasma etching techniques. Wet chemical etching is performed by immersing the wafers in an etching solution. The etching methods include: 1) hydrofluoric acid and ammonium fluoride (i.e., buffered oxide etch) for etching silicon dioxide and cleaning wafers, 2) phosphoric/nitric/acetic acid or ammonium hydroxide for etching metal, 3) phenol, sulfonic acid, chlorobenzene and unspecified aromatic solvents for cleaning photoresist from wafers, 4) sulfuric and chromic acid for cleaning photoresist from metalized wafers, 5) hydrochloric acid and hydrogen peroxide for equipment cleaning, 6) sulfuric acid/hydrogen peroxide for cleaning wafers and for stripping photoresist, and 7) phosphoric or sulfuric acid for cleaning wafers. The etching operations are performed in tanks recessed in polypropylene benches.

Plasma etching is performed by placing wafers in a plasma gas formed by a radio frequency power source operating at 13.56 MHz. The plasma gas contains ions, free radicals, and free electrons that react with the layer to be etched. The gas used for creating the plasma is selected based upon the individual layer and is either 1) carbon tetrafluoride and oxygen for etching silicon nitride, or 2) oxygen for stripping photoresist. The plasma is formed in a sealed reaction chamber at a vacuum of 0.1 to 20 torr created by an oil-sealed mechanical pump.

Doping introduces impurities into the wafer, altering the electrical properties of the doped area. Wafers are doped at various stages of the processing sequence either by diffusion or ion implantation. Diffusion is accomplished by exposing the wafer to a high temperature atmosphere containing the dopant. The operation is performed in a diffusion furnace assembly using a solid (antimony trioxide) or liquid (boron tribromide or phosphorus oxychloride) dopant source. Hybrid control diffusion furnaces similar to those used for thermal oxidation are employed for diffusion. The diffusion process may also include oxidizing the wafer during the process.

Wafers are also doped via ion implantation. A source material is ionized and passed through an analyzing magnet where the desired ions are collected, accelerated, and implanted into an individual wafer held in a vacuum chamber. The ion source, the analyzing and accelerating chamber, and the wafer exposure chamber are operated at vacuum conditions of approximately 10^{-6} torr. This vacuum is maintained by two sets of pumps; each set consists of an oil-sealed mechanical pump and an oil diffusion pump. The dopant source is either phosphorus pentafluoride or boron trifluoride. The process operation requires the operator to load a cassette into the load station of the ion implantation unit. Individual wafers are automatically removed from the cassette to a load lock chamber which is pumped to vacuum by an oil-sealed mechanical pump. The wafer is transferred to the exposure chamber where the dopant ions are implanted. The dosage received by the wafer is controlled automatically. The implanted wafer is transferred through a second load lock chamber and then into a cassette.

A single crystal silicon layer is deposited on the wafer surface by epitaxial growth in an enclosed chamber. Epitaxial silicon deposition is only performed for bipolar integrated circuit fabrication. The single crystal silicon layer is deposited by the reaction of silicon tetrachloride and hydrogen. A doped silicon layer is deposited by introducing phosphine. Epitaxial silicon is deposited at high temperature (approximately 950 to 1250°C) in a reaction chamber at atmospheric pressure and heated by radio frequency radiation operating at a frequency of 450 to 550 kHz and a power of 50 kilowatts. The operation sequence is automatically controlled and requires the operator to load wafers onto a platen that is then sealed in a bell jar reaction chamber. A description of epitaxial silicon deposition is provided by Atherton (1981) and Hammond (1978) and should be consulted for more detailed information.

Another process operation performed during the fabrication sequence is the deposition of a thin film on the wafer surface by chemical vapor deposition, i.e., where the solid products of a vapor phase chemical reaction are deposited on the substrate. Atmospheric pressure chemical vapor deposition (CVD) is used to deposit silicon nitride by the reaction of silane with ammonia or nitrous oxide. The operation is performed in a sealed reaction chamber. The process operation requires the operator to place wafers onto a flat plate susceptor that is loaded onto a loading platform. The operator initiates the process sequence by push-button control and the susceptor is automatically loaded into the reaction chamber where it is heated by electrical resistance.

Silicon dioxide is deposited by the reaction of silane with oxygen in either of two horizontal reactor systems. The wafers are placed onto platens and either loaded into a reaction tube or placed on a conveyor where they are transported into the deposition zone. Both operations require the operator to load and unload cassettes and to monitor the process equipment during operation.

A metal or metal alloy layer is deposited onto the wafer surface by direct current (DC) sputtering or by electron beam evaporation. The metal is deposited on the wafer surface in a sealed reaction chamber or bell jar that is maintained at a vacuum of approximately 10^{-6} torr by a set of pumps consisting of an oil-sealed mechanical pump and an oil diffusion pump or an oil-sealed mechanical pump and a cryogenic pump. Aluminum is deposited by electron beam evaporation and a proprietary metal alloy is deposited by DC sputtering. The process operation sequence requires the operator to place the wafers in a planetary structure or metal platen that is loaded into the reaction chamber. The process operation is then controlled automatically.

Process operations such as photolithography, doping, metalization, and chemical vapor deposition may be repeated several times during wafer fabrication. Between these processing steps, wafers may be cleaned with sulfuric acid/hydrogen peroxide, hydrofluoric acid, sulfuric acid, or phosphoric acid. These wet chemical cleaning operations are performed in enclosed benches as previously described.

The final step in wafer fabrication is backside metalization. This operation is not performed at the plant. Following metalization, the wafers are then electrically tested and sent to an assembly plant for die separation, assembly, and packaging. The plant does perform a limited amount of the assembly and packaging operation for products that require a quick turnaround. These operations include diamond scribing and cutting of the wafer, assembly of the die in plastic, ceramic, or cerdip (ceramic dual in-line package), and marking and packing. These operations were not observed at the plant during the preliminary survey.

5.0 DESCRIPTION OF PROGRAMS

5.1 Industrial Hygiene

Micro Power Systems, Inc. does not employ a full- or part-time industrial hygienist or safety engineer. The facility engineering manager coordinates all health and safety matters. The facility employs two consultants in safety and industrial hygiene.

Monitoring of emissions or operator exposures to chemical agents has been limited to the use of a portable combustible-gas meter and direct-reading, colorimetric detector tubes to check for leaks of process gases. Personal sampling of workers has previously been performed but the facility has contracted with a consulting firm to conduct personal sampling in the future. The facility also has plans to install a combustible-gas detection system as described in Section 3.4, and to conduct area monitoring of the diffusion and photolithography (masking) areas. Film badges monitor emissions and operator exposures to X-ray radiation at the ion implantation unit. The badges are collected weekly and sent to a contract laboratory for analysis. A survey meter (unspecified) is used to monitor X-ray radiation from the ion implantation unit following maintenance of the unit. Measurements of the ventilation sytem are described in Section 3.5.

5.2 Education and Training

Training programs have been developed in the areas of safety, materials handling, personal protective equipment, emergency procedures, and hazard reporting. New employees undergo a safety orientation which reviews personal protective equipment requirements, electrical safety, gas cylinder and chemical safety, response procedures during earthquakes and fires, and evacuation procedures. A manual has been developed that addresses each of these areas in detail. Newly hired employees are reviewed for a period to ensure safe work practices. The supervisor is responsible for training new employees.

Wafer fabrication area employees are trained on the job by senior line technicians. The training requires 2 to 4 weeks and covers the use of personal protective equipment and spill cleanup. Operators are required to be able to perform any other operator's job functions. A safety committee, consisting of employee representatives, direct-line supervisors, and management meets weekly.

5.3 Respirators and Other Personal Protective Equipment

All workers in the wafer fabrication area are required to wear safety glasses, chemically resistant aprons, and safety shoes. Sandals or cloth type shoes are prohibited in the fabrication area. Chemical technicians, responsible for mixing and transferring liquid chemicals and wastes, are required to wear acid-resistant coveralls, boots, gloves with gauntlets, face shields, and aprons. Heat-protective aluminized asbestos gloves (Nomex® or Zytel®) are used by operators handling hot equipment in the diffusion furnace area. Operators use a respirator (unspecified type) when handling antimony trioxide during the diffusion operation.

Emergency equipment available at the facility includes self-contained breathing apparatus. Emergency showers, eye wash stations, and emergency breathing oxygen are also available in the fabrication area. The emergency showers do not have drains.

Operators responsible for changing gas cylinders are required to wear safety glasses. Cylinders are checked by a qualified person using a Snoop® bubble test of welded seams and valves. A self-contained breathing apparatus is readily accessible in the gas storage area.

5.4 Medical

The facility does not employ a full- or part-time nurse or physician. Medical services provided at the plant are limited to first aid and cardiopulmonary resuscitation (CRR) provided by trained employees present on all three shifts. An off-site industrial medical clinic provides emergency care. Micro Power Systems does not require preplacement or periodic medical examinations of any employees. No routine biological monitoring is performed. OSHA injury and illness statistics for 1981 show only four reported injuries: 1) a cut on the thumb from a hand saw, 2) a broken right thumb from a fall,

3) a muscle strain from lifting materials, and 4) a hematoma on the forearm following blood donation.

5.5 Housekeeping and Maintenance

Housekeeping and maintenance activities are necessary parts of maintaining product quality and equipment operations. General housekeeping procedures include prompt cleanup of spills and placing all trash and scrap into waste containers. Hazardous conditions that housekeeping can correct are immediately reported to the supervisor when observed by employees.

Specific housekeeping procedures which were identified by the plant to prevent worker exposures to chemical agents include a portable vacuum in the diffusion area for cleaning antimony trioxide spills and for removing any antimony that has condensed around the scavenger box exhaust.

Planned maintenance activities could not be identified for each process operation at the facility due to time constraints. General maintenance activities include periodic draining and replacement of pump oils from the oil-sealed mechanical pumps used for ion implantation, plasma etching systems, and metalization systems.

Components of the ion implantation unit are disassembled and cleaned by bead blasting in a glove box using a silicon abrasive. Diffusion furnace tubes may be cleaned by an *in situ* process using hydrogen chloride gas. The bell jar chamber from the epitaxial reactor system is removed and cleaned two times per month with hydrofluoric acid. The bell jar chambers from the metalization systems are removed and cleaned with hydrochloric acid and hydrogen peroxide three to four times per year. Quartzware from the silicon nitride CVD operation is cleaned every 3 weeks with hydrofluoric acid.

6.0 DESCRIPTION OF CONTROL STRATEGY FOR PROCESS OPERATIONS OF INTEREST

A variety of control strategies are used at Micro Power Systems to control emissions and worker exposures. These control strategies include local and general exhaust ventilation, process isolation, process and environmental monitoring, and personal protective equipment. Devices or work stations that contain toxic materials considered of potential danger to life and health are controlled by local exhaust ventilation, whereas less potentially hazardous areas are controlled by general exhaust ventilation. Specific engineering control strategies for individual process operations are described below. Monitoring systems are described in Section 3.4 and briefly described below for each specific process operation. General personal protective equipment requirements are described in Section 5.3; specific requirements for some process operations are summarized below.

Process automation has influenced many work practices and, therefore, operator exposures to chemical and physical agents. Automated process controls limit the time that operators are working with the equipment and only require that the operator load and unload wafers, initiate the processing sequence (with push-button controls), and perform routine cleaning operations. The operator is then free to perform other tasks such as wet chemical cleaning and etching or to operate other automated units as he or she is not required to be at a specific unit for an entire work shift. Hence, any exposures to chemical or physical agents would be limited to relatively short time periods throughout the shift.

Specific descriptions are given below for control strategies employed for thermal oxidation, photolithography, wet chemical etching and cleaning, plasma etching, diffusion, ion implantation, epitaxial silicon deposition, chemical vapor deposition (CVD), and metalization. Although wafer testing and some scribing and assembly operations are performed at the plant, these were not observed during the preliminary survey.

6.1 Thermal Oxidation

A diffusion furnace assembly is used to oxidize purchased silicon wafers. The wafers are exposed to water vapor in a high temperature environment in the furnace tube. The water vapor is supplied by boiling water in a flask that is connected to the furnace tube. Oxidation is also performed as part of the diffusion operation using oxygen.

The diffusion furnace assembly consists of: 1) a load station where carriers containing wafers are loaded and unloaded in the furnace tube; 2) a furnace cabinet containing the furnace tubes and electrical resistance heat source; and 3) a source cabinet that encloses the furnace tube end. Process gases enter the furnace tube through tubing which connects at the source cabinet end. The furnace cabinet acts as a protective barrier against the hot contact surfaces of the furnace tube. Processing gases include nitrogen, oxygen, and hydrogen chloride. The hydrogen chloride gas is used to clean or getter both the growing oxide and the furnace tube of sodium ion contamination (Colclaser, 1980).

The diffusion furnace assembly is ventilated at the furnace tube opening by a scavenger box that encloses the opening. The air velocity at the scavenger box is maintained at 300 fpm.

Nitrogen and oxygen are provided from house supplies described in Section 3.3. Hydrogen chloride gas is supplied in cylinders stored in a covered and secured area outside of the building.

The operation is performed by placing wafers in carriers that are loaded into the furnace. The tube temperature is increased (the specific temperature depends on the operation performed) and purged with nitrogen followed by introduction of the water vapor. The oxide film is then cleaned by the addition of two to six percent of HCl gas. After completion of the process sequence, the operator removes the carriers. The furnace operating parameters use a manual analog control that is preset but requires operator observation and adjustment as needed.

No permanently installed, continuous monitoring systems are present in the area for evaluating combustible or toxic gases. General personal protective equipment requirements include safety glasses and heat-protective, aluminized asbestos gloves.

6.2 Photolithography

The photolithography process may be repeated several times during the processing sequence. The photolithography process consists of four basic steps; 1) substrate preparation, 2) substrate exposure, 3) substrate developing, and 4) photoresist stripping. Following wafer developing, the exposed underlying layer may be etched using either a wet chemical etching or plasma etching operation described in Sections 6.3 and 6.4 respectively. The photoresist stripping operation is also performed either by wet chemical etching or plasma etching. Photomasks used for substrate exposure are produced to plant specifications by an outside vendor.

6.2.1 Substrate Penetration. The operations performed in substrate preparation include: 1) cleaning of the wafer by spin application of xylene, 2) spin-on application of hexamethyldisilizane and a photoresist, and 3) softbake of the coated wafer in a resistance-heated oven.

The operator places the wafers on a loading jig and places the jig over a set of four spin platforms. The process is initiated by pushbutton and the spin platform rises to lift the wafers above the jig. The loading jig is removed by the operator, and the wafers are spun. Xylene is automatically applied to the wafer followed by HMDS and either a negative or positive photoresist. The wafers are then removed from the platform with the loading jig. Coated wafers are placed in a resistance-heated oven that is purged with nitrogen. The oven is vented to the room air.

The photoresist is a mixture of proprietary photosensitive organic polymers in a xylene carrier. Xylene, HMDS and the photoresist are supplied in separate 5-gallon pressurized metal containers that are stored in a cabinet beneath the spin platforms. The containers are electrically grounded.

The spin platforms are ventilated from below through the waste drain into a collection tank that has an in-line blower to boost the exhaust into the main duct. The exhaust is directed to the plant scrubber system as described in Section 3.5.

No monitoring systems are present for evaluating emissions or exposures to chemical or physical agents. Personal protective equipment used by operators includes the normal fabrication area requirements described in Section 5.3.

6.2.2 Substrate Exposure. A mask pattern is transferred to the photoresist-coated wafers by a mask image with ultraviolet (UV) light using either proximity or contact printing. The two methods differ in that the mask is either in contact with the wafer (contact printing) or the mask is separated from the wafer (proximity printing). The ultraviolet light source for both systems is a mercury lamp producing UV light of unspecified wavelength. The mercury lamp is enclosed to prevent direct viewing of UV light. The lamp enclosures are not vented. The exposure systems are located beneath vertical laminar flow HEPA filtration units to control wafer contamination by particulates.

The process is performed by an operator seated at the unit. A cassette, containing photoresist-coated wafers, is loaded into the exposure unit. An individual wafer is automatically removed from the cassette and rotated into position. The operator aligns the mask and wafer with a split-field binocular microscope, then exposes the wafer to UV light. The wafer is automatically removed and the process is repeated.

The intensity of the ultraviolet light is monitored for quality control. The lamp is replaced when the intensity decreases below a predetermined limit. Bettes (1982) provides a detailed review of controlling ultraviolet exposure systems and should be consulted for additional information.

Operators are required to wear safety glasses which may be effective in protecting workers from UV exposure. However, removal of the glasses during alignment of the wafers may result in ocular exposure should UV light emissions occur. Monitoring systems for evaluating emissions or operator exposures to physical or chemical agents were not present in the area.

6.2.3 Substrate Developing. Photoresist-coated wafers that have been exposed to the mask pattern are developed by spin-application of the developer solution onto the wafer surface. Negative photoresist is developed with xylene, and n-butyl acetate. Positive photoresist is developed with an alkaline solution. The developers are applied to the wafer in a spin-on operation similar to that used for photoresist application described in Section 6.2.1. The spin system used for developing differs by the presence of a hinged plastic enclosure that is placed over the spin platforms.

Following application of the developer solution, the wafers are inspected visually. The wafers are then hard-baked in a resistance-heated oven that is purged with nitrogen and vented to the room atmosphere.

Engineering controls for the developer operation are similar to those described in Section 6.2.1. No monitoring systems are present for evaluating emissions or operator exposures to chemical or physical agents. Personal protective equipment requirements include safety glasses and safety shoes.

6.3 Wet Chemical Cleaning and Etching

Wet chemical operations are used to clean wafers, to etch deposited layers, and to clean process equipment. Polypropylene benches are used for acid cleaning and etching operations. Chemicals used in wet benches include: 1) hydrofluoric acid and ammonium fluoride (buffered oxide etch) for etching silicon dioxide; 2) sulfuric acid/hydrogen peroxide, sulfuric acid, hydrofluoric acid, buffered oxide etch, or phosphoric acid for cleaning wafers before specific process operations; 3) phosphoric acid/nitric acid/acetic acid or ammonium hydroxide for etching metal; 4) phenol, sulfonic acid, chlorobenzene, and unspecified aromatic solvents for cleaning photoresist from wafers; 5) sulfuric acid and chromic acid for cleaning photoresist from metalized wafers; 6) hydrochloric acid and hydrogen peroxide for cleaning the metalization system bell jar; and 7) sulfuric acid/hydrogen peroxide for photoresist stripping. Cleaning and etching operations are performed by placing carriers containing wafers into the appropriate etching bath. The tank contents and concentrations are labeled for all tanks.

Engineering controls used on wet chemical benches are similar for all operations, although some variations in the use of local exhaust ventilation do exist. The tanks containing the etching or cleaning solutions are recessed in the benches. For some benches the work surface is perforated with a ventilated spill plenum located below the perforated deck. A slot across the rear panel of the bench provides additional ventilation of the tank. In tanks without a perforated deck, ventilation is provided by slots located around the tank perimater and by a slot across the rear panel of the bench.

In addition to the perforated deck and rear panel slot exhaust, a slot across the top of the hood enclosure provides additional control in the bench containing chromic acid. The spill plenum and slot exhausts enter a demister plenum located at the rear of the bench. The tanks containing the etching or cleaning solutions are located across the rear of the bench in front of the slot exhaust. Additional tanks containing deionized water are located in each bench to rinse wafers before further processing. A recirculating, water-cooled lid is placed over the phosphoric acid tank to control vapors. The lid is removed to immerse the wafers. The exhausts from all wet chemical benches are vented to the plant scrubber system described in Section 3.5.

Permanently installed inclined pitot-static manometers monitor the performance of the local exhaust ventilation for the majority of benches. The manometers display a duct velocity (fpm) and are checked daily by plant engineering. Hinged, clear-plastic splash shields are mounted across the front of each bench.

Wastes are either drained to a central system for pH neutralization or they are drained into containers below the benches and collected by chemical technicians for disposal by a waste contractor. A detailed description of the waste management practices is provided in Section 3.6.

Operators are required to wear safety glasses, aprons, and chemical-resistant gloves. Chemical technicians who are responsible for mixing, transporting, and pouring chemicals and for removing wastes wear safety glasses, face shields, acid-resistant coveralls, aprons, safety shoes or boots, and gloves with gauntlets. No routine monitoring is performed to evaluate emissions or operator exposures to chemical agents.

All acids are transported in polypropylene carts. Written procedures for using the carts are posted and require that the bottom shelf of the cart should be filled before the top shelf to prevent the cart from tipping. Emergency showers and eyewash stations are available throughout the fabrication area. Spill kits containing vermiculite are also available in the area.

6.4 Plasma Etching

Plasma etching is a chemical etching method using a plasma gas containing ions, free electrons, and free radicals to remove a specific material or layer from the wafer surface. The plasma is created by ionizing a gas in a radio frequency field at 13.56 MHz. The gases and types of reactors (barrel and planar) vary according to the layer to be etched. A barrel reaction chamber is used to strip photoresist from the wafer with an oxygen plasma. A planar reaction chamber, operating at 100 watts, is used to etch silicon nitride with a carbon tetrafluoride and oxygen plasma. A detailed description of plasma etching technologies is provided by O'Neill (1981) and Bersin (1976) and should be consulted for additional information.

Plasma etching is performed with the reaction chamber pressure negative to the room pressure. The vacuum is approximately 0.1 to 20 torr and is maintained by an oil-sealed mechanical pump. The plasma gases, containing the volatile species formed by the plasma ions reacting with the substrate, are exhausted from the unit by the pump and go to a scrubber. Carbon tetrafluoride/oxygen is supplied from a cylinder stored adjacent to the unit. Oxygen is provided from house supplies.

Tasks performed by the operator depend on the system used. Silicon nitride etching is performed in an automated cassette-to-cassette unit that processes individual wafers. Operators load and unload cassettes containing wafers into the unit and initiate the process by pushbutton. Photoresist stripping is performed as a batch operation in an automated unit. The operator places carriers containing wafers into the reaction chamber. The chamber door is closed and the process sequence is initiated by pushbutton.

Personal protective equipment requirements consist of safety glasses.

Periodic maintenance includes draining and replacement of pump oil by line maintenance technicians. The oil is considered a hazardous waste and the disposal practices are described in Section 3.6.

The plasma etching systems were not observed in operation during the preliminary survey.

6.5 Diffusion

Diffusion of dopants into the wafer is performed in a diffusion furnace assembly similar to that described in Section 7.1 for thermal oxidation. The wafers are heated to a high temperature (approximately 600 to 1200°C depending on the source used) and a dopant is introduced that diffuses into the wafer. The dopant is supplied as either a solid (antimony trioxide) or a liquid (boron tribromide or phosphorus oxychloride).

Antimony trioxide is supplied in a powdered form. The dopant is placed into a quartz spoon that is loaded into a source furnace. The source furnace is located in the source cabinet and attached to the furnace tube. The antimony trioxide is stored in a sealed, nitrogen-purged cabinet at the back of the diffusion furnace assembly.

The liquid dopants are supplied in bubblers that are placed in cooling flasks located in the source cabinet. The flasks use ethylene glycol to maintain a stable temperature. The bubbler is attached to the furnace tube. Nitrogen or oxygen is introduced into the bubbler and becomes saturated. The saturated gas is vented into the furnace tube.

Engineering controls present in the diffusion operation are outlined in Section 6.1 for diffusion furnace assemblies. These controls include local exhaust ventilation of the furnace tube opening by a scavenger box. The source cabinet containing the liquid bubblers or source furnace is not ventilated or enclosed. A vacuum cleaning system (a portable shop vacuum cleaner) is used to clean the scavenger box and the vacuum nozzle is located next to the furnace tubes. The vacuum cleaning system is also used to clean up powder that may be spilled during transfer.

Operators wear a respirator (unspecified) when transferring antimony trioxide into the furnace tube. Aluminized asbestos gloves are used for handling hot quartzware.

Detailed written procedures for handling liquid bubblers have been developed. These procedures include: 1) the use of acid resistant gloves and a chemical apron with sleevelets when handling the bubblers, 2) instructions for unpacking the bubblers, and 3) instructions for attaching the bubblers to the diffusion furnace. Workers replacing bubblers are required to wear safety glasses, face shield, gloves with gauntlets, and an apron. A self-contained breathing apparatus is available for cleaning up the liquid dopant if a spill should occur. Written spill cleanup procedures have been developed.

6.6 Ion Implantation

Ion implantation introduces impurities or dopants into the wafer surface. The impurities are p- or n-type ions created by a confined electric discharge sustained by a dopant gas. The ion beam is drawn from the arc chamber by an extraction electrode and directed toward the analyzing magnet. The magnet resolves and focuses the ion beam and selects only the desired ion species for wafer implantation. The selected ions are targeted through an acceleration chamber and focused to produce a uniform dose to the substrate. The ion implantation is performed in a sealed chamber at vacuum conditions of approximately 10^{-6} torr. The ion implantation unit operates at a power of 200 keV.

Phosphorus pentafluoride and boron trifluoride, both at 100 percent concentrations, are used as the dopant source gases. The gases are stored in a ventilated cabinet located within a lead shield enclosure at the source end of the unit.

The power source and ion source are contained in a lead-shielded cabinet to control X-ray radiation emissions. The cabinet is electrically interlocked to the power source to shut down if the cabinet access door is opened. The beam exits the cabinet and is directed to a deflection magnet which directs the beam to one of two implant chambers located in the room. Controls for the unit are located near the implantation chambers.

Two sets of pumps maintain vacuum conditions in the unit. The pump sets consist of an oil-sealed mechanical (roughing) pump and an oil diffusion pump. One set evacuates the ion source and the second set evacuates the ion beamline. A separate oil-sealed mechanical pump evacuates the implantation chamber where wafers are processed. The pump exhausts are vented to the house scrubber system described in Section 3.5.

The operation is a batch process where wafers are loaded by the operator onto one of two carousels. Each carousel is contained in a separate implantation chamber. After loading the wafers, the chambers are sealed and the operator initiates the process sequence by push-button control. The control panel is located between the two implantation chambers.

Scheduled maintenance of the unit includes draining and replacement of pump oils for the mechanical pumps with a silicon-based oil. Every 2 years parts of the implantation unit are disassembled and cleaned by blasting with silica beads in a glove box. The maintenance operation is performed by an engineer or maintenance technician.

Radiation film badges are used for monitoring worker exposure to X-ray radiation. The badges are analyzed weekly by an outside laboratory. A portable survey meter (unspecified type) is used by the facility engineer to monitor X-ray radiation emissions. Previous surveys have indicated detectable X-ray emissions at the deflection magnet. The magnet is not shielded and is in an area near the operator that is also accessible to other workers in the area.

Personal protective equipment requirements include safety glasses. Personal protective equipment requirements for handling compressed gas cylinders are described in Section 5.3. The ion implantation unit was not in use at the time of the survey. Therefore, work practices for controlling emissions or operator exposures were not observed.

6.7 Epitaxial Silicon Deposition

A single crystal silicon layer is deposited on the silicon wafer in an epitaxial reactor system consisting of a reactor assembly cabinet and system control console. The process sequence is controlled automatically but specific operating parameters, such as gas flow, are controlled by the operator. The components of the reactor assembly cabinet include a gas distribution system, radio frequency power supply, reactor chamber, and system exhaust.

The reactor chambers consist of two quartz bell jars that are contained within separate enclosures in the assembly cabinet. Access to the bell jars is through a sliding panel on the front of the unit. The control console is also located in the cabinet next to the bell jars.

The first step in epitaxial silicon deposition is the etching of wafers with hydrofluoric acid. The operation is identical to that described in Section 6.3. The quartz bell jar is mechanically raised to expose a flat plate graphite susceptor. The operator places wafers onto the susceptor and the bell jar is lowered into place. The enclosure containing the bell jar is closed with a sliding panel and the process sequence is initiated. The chamber is heated to operating temperature by a 450 to 550 KHz radio frequency power source operating at 50 kilowatts. The wafers are cleaned in the chamber with hydrogen chloride followed by deposition of the epitaxial silicon layer through the introduction of silicon tetrachloride into the chamber. The chamber is cooled, purged, and the wafers are unloaded by the operator for inspection. The wafers are inspected with laser ellipsometry using an ultraviolet laser at 273 nm wavelength. The power level and operating mode were not specified.

Process gases include 1) hydrogen chloride for wafer cleaning, 2) silicon tetrachloride and phosphine (300 ppm in hydrogen) for deposition of a phosphorus-doped epitaxial layer, and 3) hydrogen and nitrogen for purging the reactor chamber. The process gases are supplied in cylinders stored outside of the building in a covered area described in Section 3.3. The epitaxial reactor is located in a room with an outside wall contiguous with the gas storage area. Gases are distributed in stainless steel lines that are labeled with the direction of flow and gas content.

The reactor chamber bell jars are contained in separate enclosures in the cabinet. Cooling coils are mounted on the walls of each enclosure for heat control. The walls of the enclosure also act as exhaust plenums with air entering through slots located at the base of the walls, level with the susceptors. The exhaust plenums provide heat control to the enclosure and removes process gases that may escape from the bell jar chamber. The sliding panel that provides access to the bell jars is interlocked with the radio frequency power source and will shut off power if the panel is opened. The bell jars are ventilated by a separate exhaust system through stainless steel tubing to a wafer scrubber separate from the plant scrubber system.

Routine monitoring is performed with a TLV Sniffer® to check for hydrogen leaks. Direct reading colorimetric tubes are used to check for phosphine leaks. At the time of the survey the installation of a combustible-gas (hydrogen) monitoring system was planned within 45 to 60 days. The system is now in operation. Personal protective equipment requirements include safety glasses and heat-protective, aluminized asbestos gloves for handling hot materials.

6.8 Chemical Vapor Deposition

Chemical vapor depositon (CVD) is the process of depositing a film on the wafer surface by a chemical reaction or pyrolytic decomposition in the gas phase. Silicon nitride and silicon dioxide are deposited using two different CVD systems described below.

Silicon nitride is deposited by the reaction of silane with ammonia or nitrous oxide. The system consists of a cabinet containing the reaction chamber, a loading station, and a control console. The operation is performed at atmospheric pressure with the reaction chamber vented to the plant scrubber system. The reaction chamber is heated by an infrared heat source. Ammonia and silane are supplied in cylinders stored in a ventilated cabinet located in the room. A galvanized metal duct is used to exhaust the storage cabinet. A cylinder containing nitrous oxide is chained to a wall adjacent to the unit. A small canopy hood encloses the gas regulator attached to the cylinder to provide ventilation in case of a leak.

The wafers are placed on a flat plate susceptor and automatically loaded into the horizontal reaction chamber. The process sequence is initiated by push-button control. The chamber is sealed, purged, and the wafers are heated by electrical resistance. The process gases are introduced and react to deposit a silicon nitride layer. The chamber is cooled and the susceptor is automatically unloaded from the reaction chamber. The operator removes the wafers from the susceptor.

Additional engineering controls include thermal shielding of the reaction chamber provided by the cabinet to prevent worker contact with hot surfaces. The reaction chamber access door is interlocked to the gas flow control to prevent opening before the 3 minute purge cycle is completed.

Routine maintenance of the unit includes an in situ cleaning with hydrogen chloride once every shift. Once every 3 weeks the chamber components are cleaned with hydrofluoric acid at a wet chemical station similar to those described in Section 6.3.

Silicon dioxide is deposited by the reaction of silane with oxygen in either of two horizontal reactor systems. The first system consists of a sealed reaction chamber operating at atmospheric pressure. The wafers are placed on a susceptor and loaded into the chamber tube. The operation sequence is initiated by push-button control and the tube is automatically closed. The reaction chamber is vented to the plant scrubber system. The second system uses a gas distribution/deposition head mounted above a conveyor. The wafers are loaded onto platens and placed on the conveyor. The wafers are heated on the conveyor and transported to the deposition head. The deposition head consists of parallel metal plates that are mounted vertically and perpendicular to the conveyor path. The plates provide uniform distribution of the process gases across the wafer surface. The deposition head is ventilated at both ends where the wafers enter and exit. The exhaust is vented to the plant scrubber system.

Process gases for both silicon dioxide deposition systems are supplied in cylinders stored in a ventilated cabinet located in the room. The gas cabinet is vented to the plant scrubber system.

6.9 Metalization

A metal or metal alloy is deposited onto the wafer surface as an electrical contact with the circuit components. Metals are deposited by: 1) direct current (DC) sputtering of a proprietary metal alloy, and 2) electron beam evaporation of aluminum. The metalization process is performed in a sealed reaction chamber under low pressure (approximately 10^{-6} torr) maintained by a set of pumps including an oil-sealed mechanical pump and oil diffusion pump or an oil-sealed mechanical pump and a cryogenic pump. The pump exhausts are vented to the plant scrubber system.

Both metalization systems are automatically controlled. Operators are required to mount the wafers onto a planetary structure or a platen that is then placed inside the reaction chamber. The process sequence is initiated by push-button control, the chamber is sealed and evacuated by the pumping system. The power is applied to the metal source and the metal is evaporated or sputtered onto the wafer. Following metal deposition the chamber is cooled, vented, and the wafers are unloaded.

There appeared to be little potential for operator exposure to chemical or physical agents during normal process operation. Personal protective equipment requirements include safety glasses.

Routine maintenance operations include draining and replacement of the pump oil as described in Section 5.5. The reaction chamber bell jar from the electron beam evaporation unit is removed from the unit and cleaned with hydrochloric acid and hydrogen peroxide at a wet chemical station similar to that described in Section 6.3. The cleaning operation is performed three to four times per year. The reaction chambers are also cleaned in place by vacuum cleaning.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Components of the integrated circuit fabrication process at Micro Power Systems, Inc. are representative of the present state-of-the art in wafer processing. Process operations observed that may also be indicative of future processing trends include the use of plasma etching. The plant has included a variety of engineering controls to limit emissions or operator exposures to chemical and physical agents. These controls consist of local exhaust ventilation of all operations involving potentially hazardous agents, monitoring of some exhaust systems with permanently installed inclined manometers, and special housekeeping and work practices that control emissions or operator exposures. The facility staff recognizes the potential hazards that exist at the facility and has developed training programs, engineering controls, work practices, personal protective equipment, and monitoring systems to control the hazards. The engineering controls are frequently included in the original design of the purchased equipment or are an integral part of the process operation. Specific recommendations are outlined below.

1. Preplacement and periodic medical examinations should be established, especially for those individuals potentially exposed to toxic agents such as antimony trioxide and chromic acid.
2. The deflection magnet of the ion implantation unit should be shielded to control X-ray radiation emissions.

A detailed survey should evaluate radio frequency emissions from plasma etching and epitaxial silicon deposition and X-ray radiation from ion implantation. The effectiveness of the local exhaust ventilation system to control emissions of chemical agents such as chromic acid, phenol, and antimony trioxide should also be evaluated.

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