

IN-DEPTH SURVEY REPORT:
CONTROL TECHNOLOGY FOR
MICROELECTRONICS INDUSTRY
AT
XEROX CORPORATION
MICROELECTRONICS CENTER
EL SEGUNDO, CALIFORNIA

Leslie J. Ungers, C.I.H.
PEDCo Environmental, Inc.
Cincinnati, Ohio 45246-0100

and

Gary J. Mihlan, C.I.H.
BATTELLE Columbus Laboratories
Columbus, Ohio 43701

and

James H. Jones, C.I.H.
National Institute for Occupational Safety and Health
Division of Physical Sciences and Engineering
Engineering Control Technology Branch
Cincinnati, Ohio 45226

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NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
Division of Physical Sciences and Engineering
Engineering Control Technology Branch
Cincinnati, Ohio 45226

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CONTENTS

	<u>Page</u>
Figures	111
Tables	1v
Introduction	1
Background for control technology studies	1
Background for the microelectronics industry study	2
Background for the Xerox microelectronics center survey	3
Plant Process Description	4
General description	4
Process description	11
Methodology	24
Workplace monitoring for chemical agents	24
Workplace monitoring for physical agents	28
Measurement of control parameters	30
Control Technology	31
Approaches to control	31
Description of programs	32
Photolithography	36
Wet chemical stations	46
Ion implantation	53
Chemical vapor deposition	60
Diffusion furnaces	62
Radio-frequency radiation sources	68
Gas handling system	73
Gas distribution system	74
Conclusions	78
Chemical handling	78
Process controls	79
References	86

FIGURES

<u>Number</u>		<u>Page</u>
1	Cassette- and Pallet-Type Ion Implanters	20
2	Aisle Layout of Photolithography Operation	38
3	Diagram of Work Activities and Location of Area and Personal Monitors During Photolithographic Operations	47
4	Cutaway View of Wet Chemical Station	49
5	Estimated Volumetric Flow Rates for Wet Chemical Wafer Etching and Solvent Cleaning Benches	50
6	Pictorial Diagram of Work Activities and Location of Personal and Area Monitors During Ion Implantation Operations at Implanters with Cassette-Type and Pallet-Type Loading Stations	61
7	Diffusion Furnace and Associated Work Stations	64
8	Gas Distribution System	76

TABLES

<u>Number</u>		<u>Page</u>
1	Summary of Results of Area and Personal Monitoring for Solvent Exposures from Photolithographic Operations	40
2	Survey of Ultraviolet Radiation Emissions from Mask Alignment-Exposure Units	41
3	Summary of Ventilation Measurements in Photolithography Aisle with an Automated Four-Lane Wafer Trak ^R	43
4	Summary of Ventilation Measurements in Photolithography Aisle with an Automated Two-Lane Wafer Trak ^R	44
5	Summary of Area Monitoring for Hydrogen Fluoride at Wet Chemical Wafer Etching Stations	52
6	Summary of Results of Area and Personal Monitoring for Arsine (AsH ₃) and Elemental Arsenic Exposures from Ion Implantation Operations	56
7	Summary of Results of Area and Personal Monitoring of Phosphine (PH ₃) Exposures from Ion Implantation Operations	57
8	Summary of Results of Area and Personal Monitoring of Boron Exposures from Ion Implantation Operations	58
9	Summary of G-M Survey and Dosimeter Measurements of X-Ray Emissions from Ion Implantation Operations	59
10	Summary of Area Monitoring for Hydrogen Chloride at Low-Pressure Chemical Vapor Deposition (LPCVD) Furnaces	63
11	Summary of Results of Area Monitoring for Phosphates at Diffusion Furnaces	65

TABLES (continued)

<u>Number</u>		<u>Page</u>
12	Results of Survey of Ultraviolet Radiation Emissions from Wafer Checking Operations	67
13	Summary of Results of Radio-Frequency Radiation Emissions from RF Sources	69
14	Summary of Air Flow Characteristics of Ventilated Gas Cylinder Storage Cabinets and Toxic Gas Storage Room	75

PLANT SURVEYED: Xerox Corporation
Microelectronics Center
Electronics Division
701 South Aviation Boulevard
El Segundo, California 90245

SIC CODE: 3674

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SURVEY CONDUCTED BY: Mr. Leslie J. Ungers, C.I.H.,
PEDCo Environmental, Inc.
Dr. Ralph I. Mitchell,
Battelle Columbus Laboratories
Mr. Robert D. Willson, C.I.H.,
PEDCo Environmental, Inc.
Mr. James H. Jones,
NIOSH
Mr. Paul J. Manna,
PEDCo Environmental, Inc.

EMPLOYER REPRESENTATIVES
CONTACTED: Mr. Chuck McHenry, Manager, Environmental
Health and Safety (213)536-5617

EMPLOYEE REPRESENTATIVES
CONTACTED: No employee representatives

ANALYTICAL WORK PERFORMED
BY: PEDCo Environmental, Inc.
11499 Chester Road
P.O. Box 46100
Cincinnati, Ohio 45246-0100

INTRODUCTION

BACKGROUND FOR CONTROL TECHNOLOGY STUDIES

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. As part of the Department of Health and Human Services (formerly the Department of Health, Education, and Welfare), it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct a number of research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering Control Technology Branch (ECTB) of the Division of Physical Sciences and Engineering has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, ECTB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial processes, or specific control techniques. Examples include studies of the foundry industry, various chemical manufacturing or processing operations, spray painting, and

the recirculation of exhaust air. The objective of each of these studies has been to evaluate and document effective techniques for the control of potential health hazards in the industry or process of interest and to create a more general awareness of the need for and availability of effective control measures.

Such studies are carried out in steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concepts or techniques. These are followed by in-depth surveys to determine the parameters of these controls and their effectiveness. The results of these in-depth surveys are used as a basis for preparing technical reports and journal articles on effective measures for controlling hazards. Ultimately, the information gathered from these research activities forms a publicly available data base for the use of health professionals responsible for preventing occupational illness and injury.

BACKGROUND FOR THE MICROELECTRONICS INDUSTRY STUDY

The electronic components manufacturing industry, in particular the semiconductor (SIC 3674) manufacturing or microelectronics industry, has grown tremendously in the last decade. Approximately 114,000 persons were employed in this industry in 1977. A number of hazardous materials are being used in the industry such as arsine, phosphine, and boron. Little information is available on exposures to these materials in the industry, but there are indications from a Cal/OSHA (1981) study that adequate controls for handling toxic gases like arsine and

phosphine exist in only a few plants. The Cal/OSHA study and a previous NIOSH study on the photovoltaic industry (NIOSH 1980) indicated that substances like arsine might pose an arsenic hazard to microelectronics workers.

BACKGROUND FOR THE XEROX MICROELECTRONICS CENTER SURVEY

This in-depth survey was performed as part of a larger data gathering effort to characterize basic exposures and to describe the processes and controls so that an assessment can be made of the technology applied for the control of hazards within the microelectronics industry. It is hoped that the firm visited during this survey and similar facilities throughout the industry will find the results presented herein useful in their attempts to control occupational hazards associated with production activities.

The Xerox microelectronics facility at El Segundo was selected for study on the basis of a preliminary walk-through survey conducted on September 1, 1981. This facility (which is operated by the Xerox Corporation) allowed NIOSH representatives to observe the fabrication of integrated circuits that use a range of process and control technologies.

Of the many process operations common to the fabrication of integrated circuits, the following were studied in detail: photolithography, wet chemical stations (both acid-etching and the use of solvents), ion implantation, chemical vapor deposition, diffusion doping, operations using radio frequency radiation, and gas handling and distribution systems.

PLANT PROCESS DESCRIPTION

This section describes the physical plant, the entire circuit fabrication process, and various individual process operations at the Xerox microelectronics facility. The fabrication of integrated circuits is not easily described because the process steps represent a mixture of both job shop and line operations, which may be repeated many times during the complete fabrication process. Indeed, many of the individual steps could be considered distinct processes in themselves. For the most part, the process descriptions in this report address discrete operations and interrelate these operations only when necessary to improve the reader's understanding. Throughout the discussion the reader is referred to information sources that provide more detailed descriptions of the fabrication steps should such details be desired.

GENERAL DESCRIPTION

The laboratory is part of the Reprographic Business Group, Electronics Division of Xerox Corporation. The facility provides technical development, prototype engineering, and pilot pre-production of n-channel metal-oxide semiconductor (NMOS)-integrated circuits. The Microelectronics Center, where integrated circuits are manufactured, is contained within a building

of tilt-up slab construction. Integrated circuits are manufactured in a 13,000-ft² Class 100 clean room. Utility services are provided within the clean room penthouse and equipment chases. Constructed in 1975, the plant has since tripled in size. Just prior to the in-depth survey, the clean room area had been renovated. The renovations included consolidation of similar process operations into aisles, redesign of the ventilation system, and installation of a continuous TELOS[®] phosphine/arsine monitoring system. At the time of the in-depth survey, Xerox was constructing a penthouse toxic gas storage facility. The facility is designed to prevent serious destruction of the production area by placing toxic and hazardous (explosive and pyrophoric) gases above the main structure of the building.

The facility employs approximately 220 people, 150 in the production area and 70 in administration. The production staff includes 110 workers on the first shift, 25 on the second shift, and 15 on the third shift. The third shift performs maintenance and repair operations. Approximately 110 members of the production staff work within the clean room area.

Testing and packaging operations require approximately 50 workers. The HVAC (heating, ventilation, and air conditioning) system in the testing area has Class 100 air capability. The system for the packaging operation, which is located in a room adjacent to the clean room, is not currently designed to provide Class 100 air, but this system is expected to be upgraded in the near future.

Chemical Storage

Separate chemical storage rooms are used for gases and liquids. (Gas storage is described under Gas Handling System.) Most of the high-volume liquid chemicals are stored in a locked, unvented room. This liquid chemicals storage room is accessible only through a door in the rear of the diffusion furnace room. Chemicals are received in one-quarter pint, one-pint, and one-gallon bottles, which are then enclosed in plastic bags and stored on wooden shelves. Although the chemical storage room has a floor drain, it is not curbed or specifically designed to contain spills.

Acids, bases, and organic compounds are also stored in this room. Isopropanol and acetone used for general cleaning are stored in the equipment chases. Chemicals used in electron beam lithography processes are stored in the photolithography chase.

Gas Handling System

Process gases are stored in a locked, ventilated room adjacent to the liquid chemicals storage room. It is accessible only through a door in the rear of the diffusion furnace room. The room air is continuously monitored with a Matheson Model 8040[®] arsine/phosphine monitor. The gases stored in this room include phosphine, boron trifluoride, forming gas (95% nitrogen and 5% hydrogen), silane, Freon 12, Freon 13, Freon 14, Freon 115, silicon tetrafluoride, dichlorosilane, and silicon hexafluoride. Lecture-size gas bottles used in ion implantation are also stored in the room. Hydrogen chloride, ammonia, silicon tetrachloride, Freon, and carbon tetrachloride are stored in

ventilated cabinets near the process equipment in which they are used. The cabinet exhausts are monitored by magnehelic gauges. Nitrogen purge cylinders for dichlorosilane, silane, and ammonia are stored outside of the room in an adjacent storage area.

Gases stored in cylinders in the storage room are distributed to process equipment in welded stainless steel lines. Welds are radiographed and pressure-tested at the time of installation. Lecture bottles containing arsine, boron trifluoride, or phosphine are stored in ventilated gas cabinets that are an integral part of the process equipment.

Gas lines from the gas storage room and bulk storage are connected to solenoid valves that stop gas flow in the event of a power outage. Phosphine used in low-temperature oxide production and low-pressure chemical-vapor deposition (LPCVD) are stored at the furnace. A flow-limiting valve is used to stop excess gas flow (>20 cc/min.). A sampling port for phosphine/arsine is located at the jungle* cabinet of the LPCVD unit. The Matheson® arsine/phosphine monitoring unit continuously monitors the air. Process gas emergency shut-offs are located in the clean room change area and outside the clean room at the entrance to the change room.

Nitrogen, hydrogen, and oxygen are stored in bulk containers in the "pad" area outside of the fabrication building. Gases in large bulk storage containers are plumbed to the point

* Jungle is an industry term used to describe the complex network of gas lines servicing various pieces of process equipment.

of use. Individual gas cylinders are moved from the pad to an equipment chase. Hydrogen lines are of coaxial construction, with welded stainless steel lines inside a galvanized steel conduit tube.

Colorimetric indicator tubes are used to check for leaks in newly received gas cylinders. If a leak is detected in a phosphine cylinder that cannot be repaired by reseating the valve, the cylinder gas is purged in a 55-gallon drum containing activated charcoal. The effluent from the purging system is connected to the plant gas scrubbing system. For any other cylinder leakages that cannot be contained, the facility follows the treatment procedures recommended by the manufacturer.

Monitoring System

Xerox uses three separate systems to monitor the clean room area: (1) toxic gas monitoring, (2) combustible gas (hydrogen) monitoring, and (3) heat/smoke detection. Toxic gas monitoring is performed to detect the presence of arsine and phosphine. Air is continuously sampled from the gas storage rooms and from a duct exhausting the jungle cabinet of the LPCVD unit, and the air sampling streams are combined prior to analysis. Gas sampling is not sequenced between monitoring points. Analysis is provided by a Matheson[®] arsine/phosphine monitor. The basis of this analysis is that the arsine or phosphine reaction will darken a detector tape, which changes the output of a photocell. Monitoring results are not permanently recorded; instead, they are linked to an alarm system. One problem common with this unit is the risk that all of the detector tape can be used up

without any warning or indication. The Permissible Exposure Limit (PEL) of arsine as determined by OSHA (1978) is 50 ppb continuous exposure for an 8-hour day. The Matheson[®] Model 8040 signals this level after approximately 30 minutes. For phosphine the monitor responds to a PEL of 300 ppb after approximately 10 minutes. At the time of the in-depth survey, Xerox had just replaced the Matheson[®] system with a TELOS[®] arsine/phosphine monitoring system. The new system sequentially samples and monitors air from the eight sampling points for arsine and phosphine gas.

Combustible gas (hydrogen) detectors are located in the ducts and ceilings and near equipment in the furnace area. They are located above the jungle cabinets and ventilation scavenger systems of the diffusion and chemical vapor deposition furnaces, and also in the penthouse above the furnace area and in the ceiling above the diffusion furnaces.

Smoke detectors are installed in the air supply systems. Heat/smoke detectors are located in the fabrication clean room and are interlocked to the gas handling system by solenoid valves that shut down the gas lines. Heat sensors are located in the equipment chase solvent cabinet, and additional smoke detectors are located in the electron beam lithography room.

Ventilation flow for gas storage cabinets is monitored by magnehelic gauges. The pressure drop through high-efficiency particulate absolute (HEPA) filters in the laminar flow benches is also monitored with magnehelic gauges. The gauges are not connected to an alarm. Face velocities on the laminar-flow

HEPA-filter hoods are designed for 150 feet per minute (fpm), and records are maintained for all systems.

Ventilation System

Air is supplied to the clean room fabrication area by five air handlers, which supply a total of 173,000 cfm. The supply air is filtered through an initial particulate filter and then through an activated carbon bed. The air is delivered to the clean room through HEPA filter units located in the ceiling or in laminar flow hoods over the work stations. The clean room area is maintained at positive pressure (approximately 0.2 inches H₂O) compared with the rest of the building.

Air is recirculated from the clean room through chases, which act as return air plenums. The air is drawn from the chases to a common ceiling plenum above the clean room. The air handlers located in a penthouse above the ceiling plenum draw air from the ceiling plenum, which is then combined with makeup air. Approximately 45,000 cfm (26 percent) makeup air is used.

All process exhausts, including local exhaust ventilation of wet chemical stations, photolithographic operations, and diffusion furnaces and pump exhausts from LPCVD, plasma etching, ion implantation, and metalization operations, are vented to two wet scrubber units. The units, which handle a total of 45,000 cfm, consist of a packed bed with water spray followed by a mist eliminator.

Waste Management System

Waste organic solvents are collected by a solvent drain system and stored in a holding tank. Photoresist and developer

wastes are also collected by the operators and added to the waste solvents. A waste management firm disposes of these wastes offsite. Hazardous wastes, both liquids or solids, are stored in a designated hazardous chemical storage area for pickup and disposal offsite by a waste management firm. Waste pump oils are collected and stored in 55-gallon drums for pickup and recycling by a waste management firm. Waste acids and caustics, including scrubber blowdown, are drained to holding tanks, where solids are allowed to settle, and pH is adjusted with aqueous ammonia. The neutralized waste is sent to a publicly operated treatment works.

PROCESS DESCRIPTION

Xerox manufactures NMOS-type integrated circuits. Because the processing sequence varies for each product being manufactured, a specific processing sequence is not described. Rather, a general overview of the process operations is provided. A general processing sequence for NMOS-type integrated circuits is provided by Colclaser (1980), if more information is desired.

Photolithography

Photolithography at Xerox included the following process operations: (1) photoresist application, (2) substrate exposure, (3) photoresist development, (4) photoresist removal, and (5) photomask preparation.

The application of photoresist to silicon wafers is performed by a Wafer Trak[®] system, a completely automated wafer-processing system controlled by microprocessor. The silicon

wafers are loaded into the processing system in cassettes. Individual wafers are automatically removed from the cassette and transported along one of two parallel tracks to in-line process substations, where they are mounted on a spinning platform enclosed within a clear plastic shield. The spinning wafers are sprayed with deionized water and then blown dry with nitrogen. After the wafers are further dried in an infrared prebake oven, they are transported to a second spin platform, where they are coated with hexamethyldisilazane (HMDS). Following the application of HMDS, the wafers remain at the station for the spin application of a positive photoresist consisting of methyl ethyl ketone, cellosolve acetate, xylene, n-butyl acetate, and diazo-ketone sensitizers (in a proprietary formulation). The coated wafers are then baked in an infrared oven, from which they are unloaded into a cassette.

Substrate exposure is performed by using a projection mask alignment system with ultraviolet (UV) light. Cassettes from the photoresist application process are placed in a staging area near the mask alignment equipment. A single cassette is loaded into the mask aligner, from which individual wafers are automatically removed from the cassettes by a vacuum chuck. The operator manually aligns the mask through a split-field binocular microscope. The substrate is exposed to UV light for a specified time period before the shutter closes, and the wafers are automatically moved to another cassette.

The photoresist developer is applied to the exposed wafers by use of a spin-on process similar to that used during the

application of photoresist. Cassettes containing exposed wafers are loaded into the developer system. Individual wafers are automatically removed from the cassette and mounted on vacuum chucks, which then spin the wafer while a developer solution of tetramethyl ammonium hydroxide is applied. The developer dissolves the exposed positive photoresist, leaving the unexposed pattern of the mask. Application of the developer is followed by a deionized water rinse and nitrogen blow-dry. The developed wafer is then transferred to a post- or hard-bake oven, where the remaining photoresist is cured. Finished wafers are loaded into cassettes and placed in a staging area for further processing.

Photomasks are either produced at the facility by use of electron-beam (e-beam) lithography or supplied by a photomask manufacturer. For masks produced at Xerox, the mask pattern is designed and translated to a digitized set of X-Y coordinates that is stored on computer tape. This set of X-Y coordinates controls the electron-beam exposure of the photomask. The mask consists of a precision glass plate with a hard surface coating of metallic chromium that is covered with a layer of photoresist. This plate is exposed to the electron beam as determined by the digitized information from the computer. After the exposed mask is developed and the remaining photoresist is checked for defects, the exposed underlying chromium layer is etched from the mask. Both these steps are performed in wet chemical work stations. Any mask defects are repaired by use of a helium-neon laser, which burns off defects in the chromium layer. The

photoresist layer is then stripped from the mask with an oxygen plasma stripper.

Wet Chemical Stations

Acid Etching/Cleaning--

Wafers are etched or cleaned by immersion in a bath of acid. The bath is recessed in a polypropylene bench and has a laminar-flow HEPA-filter unit overhead. Also in the bench, adjacent to the acid bath, are a deionized water bath and a spin dryer. The acid bath contains either hydrofluoric acid buffered with ammonium fluoride (for etching silicon dioxide) or sulfuric acid and hydrogen peroxide that has been heated to 70°C (for cleaning wafers). Benches containing the acid etching/cleaning solution are located in the etching aisle and diffusion furnace areas. Cassettes containing wafers are placed in the bath for a specific time period, and then removed and immersed in the deionized water bath. When the cassettes are removed from the water bath, they are placed in the spin dryer, dried, and returned to a cassette.

Solvent Cleaning--

Solvent cleaning removes organic contaminants from wafer-handling equipment. The solvents are contained in stainless steel tanks, which are enclosed in a fireproof case that is serviced by local exhaust ventilation. Ultrasonic sound is used to assist in the cleaning operation. Solvent compounds, such as acetone or isopropanol, are pumped to the individual baths from pressurized solvent containers. Waste solvent is removed by

aspiration to a solvent collection system, where the waste is stored in a holding tank.

Chemical Vapor Deposition

Polycrystalline silicon, silicon nitride, and silicon dioxide are deposited by use of low-pressure chemical vapor deposition (LPCVD) furnaces. The LPCVD furnaces are operated in a pressure range of 0.4 to 3.0 torr (Baron and Zelez 1978). An oil-sealed mechanical pump is used to establish vacuum conditions in the chamber. Gas flow is carefully controlled to produce the desired film and to remove decomposition products of the CVD reaction. These decomposition products may include hydrogen chloride, hydrogen, oxygen, ammonia, ammonium chloride, chlorine, and nitrogen dioxide (Baron and Zelez 1978). Gases used in the LPCVD furnaces include (1) dichlorosilane, ammonia, and nitrogen for silicon nitride deposition; (2) silane, oxygen, and phosphine for doped silicon dioxide deposition; and (3) silane, phosphine, and nitrogen for polycrystalline silicon deposition. Gases used in CVD furnaces that operate at atmospheric pressure include (1) hydrogen and oxygen for oxidation, and (2) silane and phosphine for deposition of phosphorus-doped silicon dioxide.

The LPCVD furnaces are controlled by a microprocessor feedback control loops and preprogrammed "recipes." The system controls the furnace temperature profile, gas flow, and vacuum pumping and purging. The microprocessor can control the automatic cleaning of the furnace tube with hydrogen chloride, perform an automatic calibration cycle, and tailor the dynamic performance of the furnace to a given process step.

The wafers are loaded into fused quartz carriers that are inserted into the reaction chamber. The chamber temperature is stabilized, and the furnace tube is sealed and evacuated by use of an oil-sealed mechanical roughing pump. Process gases are then introduced, and their reaction at the wafer surface deposits the desired layer. Process gases are exhausted from the chamber through the pump exhaust to the facility scrubber system. When this deposition has been completed, the gas flow is stopped, the reactor is exhausted to approximately 10^{-3} torr, and the chamber is filled with nitrogen to atmospheric pressure.

Diffusion and Thermal Oxidation

Diffusion introduces impurities or dopants into the wafer surface by maintaining the wafers at a high temperature in an atmosphere containing the dopant gas. During the diffusion operation observed at Xerox, the wafers are first exposed to the phosphine dopant gas and followed by thermal oxidation. During thermal oxidation, only a silicon dioxide layer is produced on the wafer surface. This layer may be formed by oxidation of the silicon in a pyrophoric water (hydrogen/oxygen) atmosphere, by exposure to oxygen, or by exposure to water vapor. The thermal oxidation operation is performed at atmospheric pressure in a diffusion-type furnace.

Wafers to be doped with phosphorus are placed in carriers and loaded into the furnace tube. While the wafers are being heated, the tube is purged with an inert gas. Phosphine is then introduced into the tube for a specified time period to obtain the desired diffusion depth. This is followed by an oxidation

step involving the use of a pyrophoric water (hydrogen/oxygen) atmosphere or dry oxygen atmosphere. The tube is then purged, and the wafers are unloaded.

Xerox has both direct-digital-control and hybrid diffusion furnaces. The direct-digital-control furnaces have a micro-processor unit, which monitors gas flow, temperature, processing sequence, and time by use of feedback control loops that automatically adjust the diffusion furnace operating parameters. The older hybrid furnaces monitor similar furnace parameters, but the operator must intervene to make any necessary adjustments or corrections. Hydrogen chloride gas is used to clean the furnace tubes in both furnaces. The furnace tubes are heated by electrical resistance, and the temperature is monitored by thermocouples placed along the tubes.

Ion Implantation

Ion implantation is another means of introducing impurities or dopants into the wafer. The implant pattern is determined by the photolithographic processes. The Xerox laboratory has three ion implantation units. Two of them are cassette-loading units (a Varian DF-4 and an A-20) and the other is a pallet-type unit (Extrion 8010).

In ion implantation, a focused ion beam implants ions in or "dopes" the semiconductor material. The beam is generated at the ion source, which consists of a Freon-cooled arc chamber (anode) surrounding a tungsten filament source (cathode). An electrical arc discharge is maintained by passing a source gas (or vaporized liquid) through the chamber. The ion beam is

drawn from the arc chamber by an extraction electrode and directed to the analyzing magnet. The magnet analyzes, resolves, and focuses the beam and selects only the desired species of ions required for implantation. The selected ions are then targeted through the acceleration tube in the direction of the wafer target. The acceleration tube optimizes both the focusing and transmission of the selected ion beam. The selected beam enters the lens and scanner box, where it is further focused and deflected toward the wafer target. The scanner has the capacity to move the ion beam in a raster pattern, which enables the entire target area to be covered with the smaller ion beam diameter. The focused beam finally enters the target chamber, where a silicon wafer has been positioned for impact.

Four types of source gases are used: 15 percent arsine in hydrogen (AsH_3), 100 percent boron trifluoride, diborane, and 15 percent phosphine in hydrogen. The source gases are supplied from lecture bottles placed in a nitrogen-purged gas box inside the source cabinet.

The ion implanter maintains three independent vacuums: the source, the beam line, and the end station (or target). Typically, each vacuum is produced by a mechanical roughing pump and a diffusion pump. In cassette-type ion implanters, the input and output vacuum locks are serviced independently by two roughing pumps. Cryogenic pumps may be used in the source and end station regions. The beamline and end station are isolated from the beam regions of the instrument by use of liquid nitrogen

locks. Each pumping system is fully automatic and will shut down the implantation process in the event of a vacuum failure.

The source gas box in both types of implanters and the instrument panel area in the cassette-type equipment are vacuum vented using dry nitrogen. The target area is not exhaust-ventilated.

In the cassette-type implanters, individual wafers are automatically withdrawn from the cassette and transported into a vacuum lock. The chamber is evacuated, and the wafer is transferred to a platen, where it is mounted and positioned for exposure. Implantation of the wafer is regulated by the system microprocessor. Following the implantation of ions, the wafer is transferred first to the exit vacuum lock, where the chamber is purged to atmospheric pressure, and then to a cassette.

Pallet-type implanters receive wafers from an operator, who manually loads each of the two pallets. The operator performs the loading with a "wand" equipped with a vacuum chuck. Individual wafers are picked up from a cassette and transferred to the surface of a pallet. Each pallet can hold 25 wafers. Following the manual loading operation, the pallets are automatically raised and positioned in front of the ion beam line. After the pallet has been sealed against a vacuum lock, the implantation process begins. When the implantation sequence has been completed, the vacuum lock is repressurized, the pallet is lowered, and the finished wafers are manually removed with the vacuum chuck "wand." Figure 1 presents simplified diagrams of both the cassette- and pallet-type ion implanters.

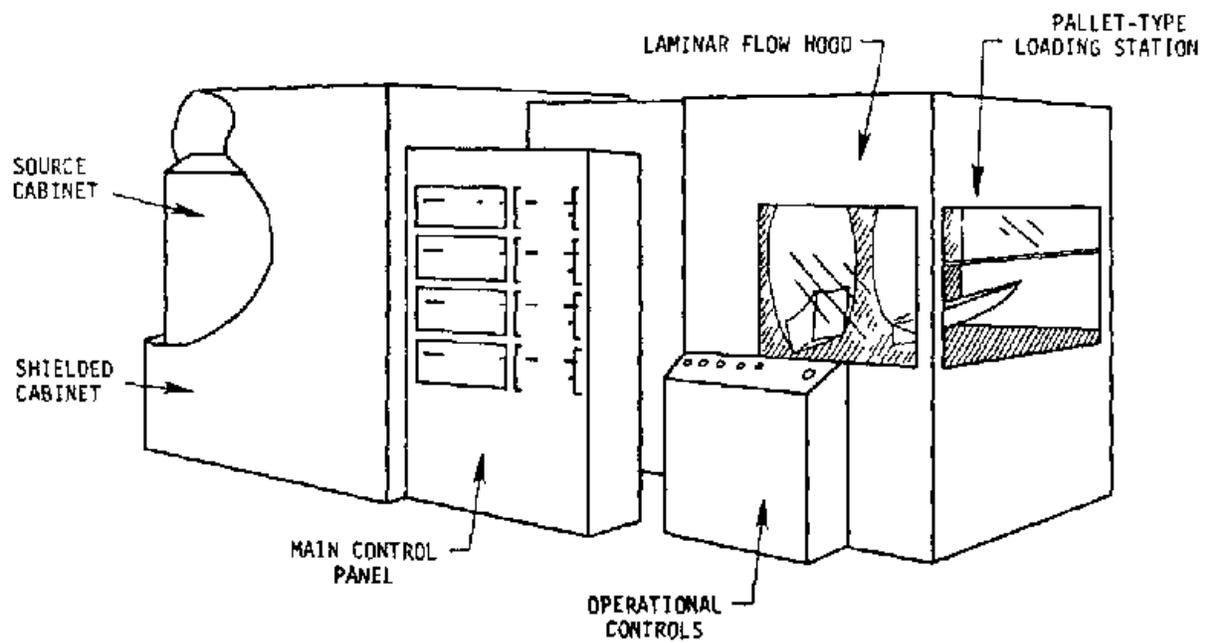
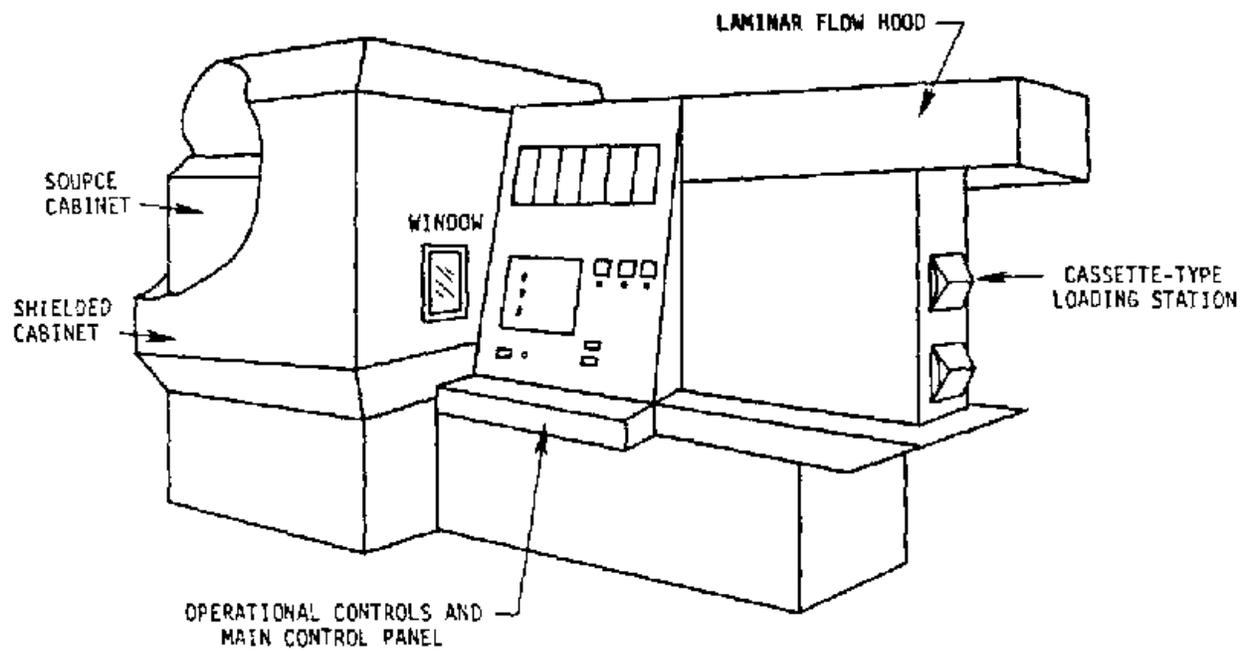


Figure 1 Cassette- and pallet-type ion implanters.

Radio-Frequency Radiation Sources

Plasma Etching--

Plasma etching systems are used to strip photoresist and to etch silicon nitride, polycrystalline silicon, and aluminum. As previously discussed the laboratory uses three plasma etching systems, including two in-line planar plasma etching units and one barrel or tunnel reactor plasma etching unit.

Stripping of photoresist is performed in the barrel or tunnel reactor plasma etching system. Wafers are loaded into carriers and manually placed in the reaction chamber. The chamber is sealed and pumped to vacuum (approximately 1 torr) by an oil-sealed mechanical pump. Oxygen is introduced into the chamber, a radio frequency field is applied to the electrodes in the chamber, and an oxygen plasma is formed. When the plasma reacts with the photoresist, volatile species are created, which are pumped from the reaction chamber. A viewing port on the front of the unit is constructed of quartz glass with a smoked Lucite[®] cover and metal mesh screen. The lucite cover is designed to control ultraviolet radiation emissions, and the metal mesh screen is designed to control radio frequency emissions.

Polycrystalline silicon and silicon nitride are etched in one of the continuous in-line planar plasma etching systems. Wafers are placed in a carrier and set in the load station. The wafers are automatically removed from the carrier and transported to the reaction chamber through a load-lock station. From there, they are transported into the reaction chamber,

where a radio-frequency field is established between the anode (the conveyor that is transporting the wafers through the chamber) and the cathode. Freon 14 is used for etching polycrystalline silicon and silicon tetrafluoride is used for etching silicon nitride. The in-line plasma etching unit operates at a frequency of 13.56 MHz.

Aluminum is etched in another continuous in-line planar plasma etching system. The wafers are placed in cassettes and loaded into the reaction chamber as described above. They are transported through the chamber on a conveyor that acts as the anode of the radio-frequency power source. Carbon tetrachloride is introduced to the chamber, and a radio-frequency field is established between the anode containing the wafers and a cathode located opposite the wafers. A plasma is created in the radio-frequency field that reacts with the aluminum. The metal volatilizes and is removed from the chamber by the vacuum pumping system. At a station integrated into the exit unloading lock, photoresist is stripped by using an oxygen plasma. The etched wafer is then transported to a cassette. The process is automatically controlled through a microprocessor system, which continuously monitors process parameters and controls wafer motion/location and system logic. The operating radio frequency of the unit is 13.56 MHz.

Metalization--

Metal deposition systems at the facility include sputtering (DC and RF) and filament evaporation. Sputtering is used to

apply an aluminum alloy film to the wafer surface. Using tweezers, the operator manually mounts the wafers in a rotating structure called a "planetary." This operation is performed at a staging area in a laminar-flow HEPA-filter work station adjacent to the unit, and the planetary is then placed in the chamber. The operator initiates the processing cycle through a push-button control. The operation sequence, which is controlled by microprocessor, includes the following steps: (1) pumping down to low vacuum; (2) energizing the substrate; rotating the planetary, and starting the substrate heaters; (3) controlling temperature and pressure of the chamber for a specific time interval; (4) energizing the source; (5) resetting the deposit control and starting deposition; (6) turning off the source and substrate heat of the chamber; (7) cooling down of the chamber; (8) turning off the substrate rotation; and (9) venting the chamber.

Filament evaporation is used to deposit gold. The wafers are mounted in a planetary device (as described above), which is placed in a bell jar. The operator activates the push button to initiate the microprocessor-controlled process, which lowers the bell jar over the planetary and filament source. The bell jar is sealed, and the chamber is evacuated to a low vacuum (typically 10^{-6} torr). Worker interaction with the process is limited to loading and unloading wafers and push-button control of the process operation.

METHODOLOGY

The in-depth survey at Xerox's El Segundo facility included sampling for chemical agents, monitoring for physical agents, and measuring control parameters. The sampling apparatus, instrumentation, and analytical methods used during this survey are described in this section.

WORKPLACE MONITORING FOR CHEMICAL AGENTS

Several chemical agents were sampled. The sampling strategies used to characterize the workplace levels of these chemical agents depended on the agent in question, the nature of the process operation, and the nature of the job being performed by the exposed worker. The sampling apparatus and analytical methods used to quantify each chemical agent were taken from NIOSH's Manual of Analytical Methods (NIOSH 1983).

Arsenic (Collected as Arsenic Trioxide)

Arsenic concentrations in the workplace air were determined by using the NIOSH Reference Method for Trace Metals (P&CAM 173). Arsenic compounds were collected by drawing a measured volume of air through a 0.8- μ m mixed-cellulose ester-membrane filter (Millipore MCE or equivalent) with a personal high-flow pump (Dupont P2500, MSA Model G, or Bendix BDX 55-HD). The analyte and filter were digested with nitric acid and analyzed by flame atomic

absorption spectrophotometry. A detection limit of 0.035 μg was achieved during these analyses. The analytical results were corrected for reagent and filter blanks. The sample flow rates of the rotometer-controlled pumps were corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Arsenic (Collected as Arsine Gas)

Arsine concentrations in the workplace were determined by using the NIOSH Reference Method for Arsine (S229). The arsine was collected by drawing a measured volume of air through a charcoal tube with a low-flow (50 to 200 ml/min) stroke pump (SKC model number 222-3). The analyte was desorbed with nitric acid and analyzed by flameless atomic absorption. A detection limit of 0.06 μg was achieved during these analyses. The analytical results were corrected for reagent and charcoal blanks. The sampling results were reported in micrograms per cubic meter of air.

Diborane (Measured as Boron)

Diborane concentrations in the workplace air were determined by using the NIOSH Reference Method for Diborane (P&CAM 341). Diborane was absorbed on an oxidizer-impregnated charcoal tube (SKC 226-67 or equivalent) by drawing a measured volume of air through a three-stage sampler consisting of a Teflon[®] filter cassette (Millipore PTFE or equivalent), the treated charcoal tube, and a personal high-flow pump (Dupont P2500, MSA Model G, or Bendix BDx 55-HD). The analyte was desorbed with 3 percent

hydrogen peroxide and analyzed for total boron by plasma emission spectroscopy. A detection of 0.25 μg was achieved during these analyses. The analytical results were adjusted by using an empirically derived desorption efficient factor and corrected for charcoal tube and reagent blanks. The sample flow rates of the rotometer-controlled pumps were corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Hydrogen Chloride

Hydrogen chloride concentrations in the workplace air were determined by using the NIOSH Reference Method for Hydrogen Chloride (S246). Hydrogen chloride (as hydrochloric acid aerosol) was collected in 0.5 M sodium acetate by drawing a measured volume of air through a semipermeable membrane impinger (Industrial Hygiene Specialties Model 100500-2 or equivalent) with a personal high-flow pump (Dupont P2500, MSA Model G, or Bendix BDX 55-HD) at approximately 1.0 liter/min. The analyte solution was diluted with 25 ml of distilled water and analyzed by using a chloride ion specific electrode. The analytical results were corrected for sample and reagent blanks. The sample flow rates of the rotometer-controlled pumps were corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Hydrogen Fluoride

Hydrogen fluoride concentrations in the workplace air were determined by using the NIOSH Reference Method for Hydrogen Fluoride (S176). Hydrogen fluoride (as hydrofluoric acid aerosol)

was collected in 0.1N sodium hydroxide by drawing a measured volume of air through a semipermeable membrane impinger (Industrial Hygiene Specialties Model 100500-2 or equivalent) with a personal high-flow pump (Dupont P2500, MSA Model G, or Bendix BDx 55-HD). The analyte solution was diluted with an ionic-strength activity buffer (TISAB) and analyzed by ion-specific electrode, resulting in a 60- μ g detection limit. The analytical results were corrected for sample and reagent blanks. The sample flow rates of the rotometer-controlled pumps were corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Organic Compounds In Air

The concentration of various organic compounds in the workplace air were determined by absorption or charcoal, desorption with CS₂, and analysis by mass spectroscopy. Organic compounds were collected by drawing a measured volume of air through a charcoal tube with a low-flow (50 to 200 ml/min) stroke pump (SKC Model No. 222-3). The analyte was desorbed with 1 ml of CS₂ and analyzed by mass spectroscopy with single ion monitoring. The following information describes the equipment, column, and operating conditions used during the analysis:

Gas chromatograph:	Hewlett-Packard 5992 GC-MS
Column:	10% TCEP (tris cyano ethoxy propane), 80 in x 0.125 in. o.d. nickel
Detector:	Single ion monitoring MS, ions: 43, 45, 106, 146, 58, and 59
Initial column temperature:	50°C
Hold time:	5 min.
Final column temperature:	150°C
Hold time:	7 min.
Program rate:	10°C/min.
Carrier gas:	Helium at 0.45 torr
Injection temperature:	180°C

The analytical results were corrected for charcoal tube and reagent blanks. The sampling results were corrected for temperature and pressure and reported in parts per million.

Phosphine

Concentrations of phosphine (measured as airborne phosphate) in the workplace were determined by using the NIOSH Reference Method for Phosphine (S332). The phosphine was 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). The analyte was extracted by using hot acidic permanganate solution, and then analyzed for phosphate following the formation of phosphomolybdate complex, the extraction into a mixture of isobutanol and toluene, and the reduction by the use of stannous chloride. The absorbance of the reduced phosphomolybdate complex was measured at 625 nm. The analytical results were corrected for silica gel tube and reagent blanks. The sampling results were corrected for temperature and pressure and reported in micrograms per cubic meter.

WORKPLACE MONITORING FOR PHYSICAL AGENTS

Three physical agents were monitored during the in-depth survey: radio-frequency radiation, X-radiation, and ultraviolet light. The monitoring strategies used to characterize these workplace exposures varied according to the agent being studied, the nature of the process operation to be characterized, and the

nature of the job being performed. The monitoring instruments and survey methods used during this survey are described.

Radio-Frequency (RF) Radiation

Radio-frequency emissions were monitored with a Holaday[®] (Model HI 3002) meter by using an electric field probe having a frequency response of 500 kHz to 6 GHz and a magnetic field probe with a frequency response of 5 to 300 MHz. Readings were taken during normal process equipment operating cycles. Normal operating frequencies, power outputs, and cycle times were recorded. The results were reported for near-field measurements as maximum electric field strength (V^2/M^2) and maximum magnetic field strength (A^2/M^2).

X-Radiation (X-Ray)

Exposure levels at various work stations were surveyed with a Vicotreen Model 4040 RFC Geiger-Muller counter. The magnitude of potential exposure at "hot" survey locations was characterized by using Landauer Type P-1 dosimetry badges (with a minimal detection limit of 10 millirems). The Geiger-Muller survey results were reported in milliroentgens per hour (mR/h), and the dosimeter readings were reported in millirems (mrem) for the specific time period monitored.

Ultraviolet (UV) Light

Exposures to ultraviolet light were surveyed with an International Light Model IL440 light meter. The photoelectric cell response to energy is in the near ultraviolet spectral region only. The photoelectric cell supplied with this instrument has a

frequency response of 290 to 430 nm with a peak response at 366 nm. The exposure estimates were determined as the highest average reading in milliwatts per square centimeter as measured during a 2- to 3-minute monitoring period.

MEASUREMENT OF CONTROL PARAMETERS

Face velocities, duct traverses, and general air flow observations were made during the in-depth survey. The velocity measurements were performed with a Kurz^R Model 441 air velocity meter. The measurement results were reported in feet per minute (fpm). A multipoint traverse method of data collection was used during the in-depth survey to collect the air velocity measurements necessary to construct representative averages. The physical dimensions of exhaust ducts and takeoffs were also measured whenever possible.

CONTROL TECHNOLOGY

APPROACHES TO CONTROL

Occupational exposures can be controlled by the application of a number of well-known measures, including engineering measures, work practices, personal protection, and monitoring. These measures may be applied at or near the hazard source, to the general workplace environment, or at the point of occupational exposure to individuals. Controls applied at the source of the hazard, including engineering measures (material substitution, process/equipment modification, isolation or automation, local ventilation) and work practices, are generally the preferred and most effective means of control in terms of both occupational and environmental concerns. Controls that may be applied to hazards that have escaped into the workplace environment include dilution ventilation, dust suppression, and housekeeping. Control measures that apply to individual workers include the use of remote control rooms, isolation booths, supplied-air cabs, personal protective equipment, and safe work practices.

In general, a system that includes these control measures provides worker protection under normal operating conditions as well as during process upsets, equipment failures, or maintenance activities. Process and workplace monitoring, personal exposure monitoring, and medical monitoring are important mechanisms for

providing feedback concerning the effectiveness of the controls in use. Ongoing monitoring and maintenance of controls to ensure their proper use, monitoring of operating conditions, and the education and commitment of both workers and management to occupational health are also important ingredients of a complete, effective, and durable control system.

These control measures apply to all situations, but their optimum application varies from case to case. The following subsections describe the application of these measures during the production of NMOS integrated circuits at the Xerox Microelectronics Center.

DESCRIPTION OF PROGRAMS

Industrial Hygiene

The laboratory employs two full-time industrial hygienists, who have primary responsibility for both safety and industrial hygiene. Xerox has also hired consultants, as needed, in the areas of health physics, fire safety, emergency medical care, and explosion control.

Limited monitoring has been conducted of worker exposures to acid mists, arsenic, and organic solvents. Worker exposures to ionizing radiation and radio-frequency radiation have also been monitored. More extensive monitoring of worker exposure is planned for the future. Air flow of the laminar-flow HEPA filtration units is measured to assure a face velocity of 150 fpm.

The laboratory has established a review program for all new and existing process equipment. The review includes the following:

(1) electrical grounding, (2) electrical interlocks of equipment, (3) emergency shutdown, (4) fires, (5) gas installations, (6) inherent equipment engineering controls that offer protection during normal operations and emergency conditions, (7) potential for X-ray release, and (8) review of operating and maintenance procedures.

Education and Training

Training programs that Xerox conducts for plant personnel cover worker safety, materials handling, and use of personal protective equipment. A training session consists of three 1-hour lectures. Priority has been given to developing emergency response capabilities. A training program is being developed on toxic hazards, which will be used to train staff emergency medical technicians and local hospital personnel.

Personal Protective Equipment

Workers in the clean room area are required to wear equipment consisting of hoods, lab coats, booties, and latex gloves to protect the product. All production area workers are also required to wear safety glasses or goggles for personal protection. Goggles and face shields are required when handling chemical solutions. Workers use full-face, air-line respirators when changing gas cylinders in the gas storage room. A self-contained breathing apparatus is required for workers changing arsine, phosphine, and boron trifluoride lecture bottles in the ion implantation units and LPCVD furnace. Emergency showers, eye-wash stations, and self-contained breathing apparatus are

available in the fabrication area. Long rubber gloves with gauntlets are required for workers who pour or handle chemicals. Workers are trained in the use of personal protective equipment at a monthly or quarterly training session.

Medical Program

The facility employs two full-time nurses during the first (primary) workshift. Emergency care is available at the plant during the first shift, and a nearby medical center is on call 24 hours a day. All employees who work more than 4 hours per day must have a periodic medical examination. A periodic medical examination is also required for all workers in the fabrication area regardless of the duration of their workshift. This examination includes a chest X-ray, lung function test, hematology, and urinalysis (including creatinine and arsenic determinations).

Housekeeping and Maintenance

The production quality control requirements limit the particulate levels in the laboratory. The fabrication area is designed as a Class 100 clean room. Dust levels in the production area are controlled by laminar-flow HEPA-filter hoods placed above the production equipment and ceiling HEPA-filter units. Air is directed downward from the hoods and the ceiling units and across the equipment work stations. Additional controls have been included in the design of the production area. These include acid waste lines with aspirators for etching solution disposal and the automated dispensing of photolithography chemicals directly from containers. When pump oils from oil-sealed mechanical

roughing pumps are replaced, the used oil is drained into containers, which are then transferred to a central waste-oil collection container located adjacent to the gas storage room.

Maintenance is performed by an operator-technician and by a third-shift maintenance crew. Maintenance operations observed during the survey involved the addition of pump oil to a diffusion pump for the LPCVD system. Oil is manually changed every 3 to 5 days. The laboratory utilizes a central oil-dispensing system in which a 55-gallon drum of pump oil is connected to a distribution system. The oil is pumped from the drum to the pump, and the used oil is removed by a similar central collection system. This system is needed to facilitate the required daily oil replacement.

Maintenance procedures for additional process equipment include the following. Metal deposits inside the metalization chambers are removed by bead-blasting the interior shields and the exposed parts with a glass-type abrasive. The bead blasting is performed in a glove box. The chamber is also wiped with isopropanol. Bead blasting is also used to clean the ion source of the ion implanter. Routine maintenance of plasma etching units includes wiping down the chamber with isopropanol. Pump oil for the plasma etching pumps is replenished every two weeks, as described earlier. Maintenance of the gas handling system is performed (as required) by three technicians, who are responsible for changing gas bottles in the gas storage room and ion implanters.

PHOTOLITHOGRAPHY

Photolithographic operations are built around two automated Wafer Trak[®] systems. Associated with these photolithographic operations is the production of photomasks using electron beam (e-beam) lithography. The two photolithographic Wafer Trak[®] systems and an exposure-mask alignment process will be discussed first.

The deionized water cleaning operation and the application of HMDS and photoresist to the wafers are automated spin-on processes, which are enclosed under plastic covers. The enclosures are ventilated at the base of each platform to produce a down-draft around the spinning platform. This ventilation system is designed to prevent redeposition of aerosols onto the wafer surface. The wafer-processing system is located beneath laminar-flow HEPA-filter hoods.

The ventilation system servicing the Wafer Trak[®] units appears to have been installed and modified by the addition of more ducts as process changes were introduced. The main ducts are located in the equipment chase, and flexible process ducts penetrate the clean room to connect to the process equipment. The ventilation system appeared to have been modified in a manner inconsistent with guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH 1980). For example, the ACGIH does not recommend the use of a four-way tee connection, which was being used in the photolithography aisle. The tee appeared to have three process exhausts entering at 90 degrees, and the exit duct was the same as the duct entering the tee.

The HMDS and photoresist are supplied in one-gallon glass bottles, which are stored in the Wafer Trai[®] unit. The liquids are automatically dispensed by suction probes placed in the bottles.

The mask pattern is transferred to the wafer by exposure to ultraviolet light transmitted through the photomask. The projection mask aligner is located under a laminar flow HEPA-filter hood. The wafer and mask are aligned by use of a blue light source (wavelength unknown) that is filtered to prevent ultraviolet light release. Once the wafer is aligned, the microscope is rotated from the alignment stage, and the wafer is then exposed to ultraviolet light.

The photoresist is developed in a spin-on operation performed under a plastic cover. Wafers are automatically transferred from the cassette to the spin platform. The developer solution is supplied in one-gallon glass containers, which are stored in the equipment, and the solution is siphoned directly from the containers to the spin operation. The developer operation is located under a laminar-flow HEPA-filter hood and local exhaust ventilation provided at the base of the spin platform. Figure 2 presents the layout of a photolithography aisle at Xerox.

The e-beam lithography process is located in an aisle separate from other clean room operations. The computer and mask exposure are contained within two separate rooms adjacent to the clean room aisle. The e-beam power shutoff is located in the e-beam computer room. Equipment chases are located on both sides

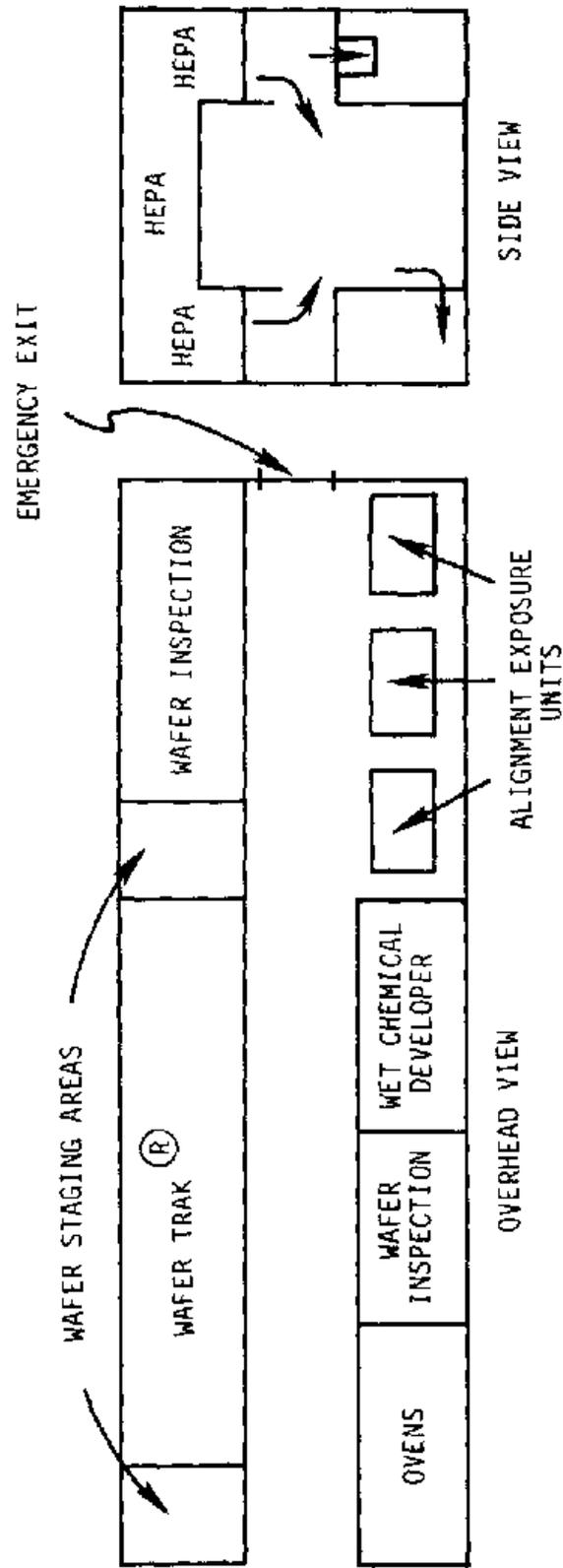


Figure 2 Aisle layout of photolithography operation.

of the aisle. A cabinet for flammable liquids and a solvent storage cabinet are located in the chase.

Monitoring Results

The photolithographic operations at Xerox were monitored for emissions of six organic solvents, including the surfactant hexamethyldisilazane (HMDS), acetone, n-butyl acetate, xylene, Cellosolve acetate, and methyl Cellosolve. Ultraviolet radiation was also monitored. Measurement of the chemical substances was conducted with both area and personal monitors, and the results are presented in Table 1.

A survey of ultraviolet radiation emissions was performed on two mask alignment-exposure units. A Perkin Elmer 120 instrument was surveyed during normal photolithographic operations. The photometer's detection cell was positioned at eye level in the direction of the UV light source. During this measurement, the cabinet panel on the front left-hand side of the instrument was left open. Leaving panel doors open is a common practice within the industry. It is done to promote easy access to the instrument's internal wafer handling system and to improve ventilation of the UV light source. A survey was also performed on a Perkin Elmer 140 instrument undergoing maintenance. The maintenance technician had completely removed the cabinet enclosure to reach and view the various internal components. The UV monitoring was performed at eye level and at a distance from the source where maintenance technicians were likely to be. The results of both survey measurements are presented in Table 2.

TABLE 1. SUMMARY OF RESULTS OF AREA AND PERSONAL MONITORING FOR SOLVENT EXPOSURES FROM PHOTOLITHOGRAPHIC OPERATIONS

Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentrations (ug/m ³)					
			Hexamethyl- disilizane	Acetone	n-butyl acetate	Xylene	Cellosolve acetate	Methyl cellosolve
Area monitor at mask alignment and exposure unit (near wafer track)	2:38	30.34	468.5	1009.7	9.9	19.8	198.0	-
Area monitor at mask alignment and exposure unit (near wafer track)	2:37	16.80	*	863.1	-	6.0	71.4	-
Area monitor at mask alignment and exposure unit	1:56	22.85	-	517.5	-	-	72.3 [†]	-
Area monitor at photoresist application line	2:36	12.67	559.0	1803.1	7.9	15.7	283.5 [†]	-
Area monitor at photoresist application line	2:36	16.07	217.4	1391.3	6.2	18.6	130.4 [†]	-
Area monitor at photoresist application line	2:02	23.42	-	709.4	-	-	55.6 [†]	-
Area monitor at photoresist application line	1:56	22.74	-	594.7	-	-	72.3 [†]	-
Area monitor at photoresist application line	4:00	47.12	74.3	53.1	-	17.0	12.7	-
Area monitor at photoresist application line	4:02	24.89	-	52.2	-	20.1	28.1	-
Personal monitor on operator in photolithography area	1:11	7.59	-	6092.1	-	-	250.0 [†]	-
Area monitor in e-beam mask production room	1:42	10.50	-	38.1	19.0	-	76.2 [†]	-
Area monitor in e-beam photoresist application area	2:31	19.90	-	-	-	45.2	30.2	-
Area monitor in e-beam photoresist application area	1:49	14.34	-	55.9	21.0	35.0	28.0 [†]	-
Area monitor in e-beam photoresist application area	3:26	40.38	-	101.5	-	-	14.8	-
Area monitor in e-beam photoresist application area	3:17	37.44	-	29.4	-	5.3	16.0	-
Area monitor in e-beam mask cleaning area	1:05	8.58	-	104.6	46.5	-	46.5	-
Area monitor in e-beam solvent storage area	4:10	14.91	-	1910.2	-	25.0	10.4	-
Area monitor in e-beam solvent storage area	3:16	37.58	-	16.0	2.6	18.6	31.9 [†]	-
Area monitor in e-beam solvent storage area	3:23	38.98	-	92.8	-	7.1	21.4 [†]	-
Area monitor in e-beam solvent storage area	3:20	38.40	-	26.0	-	-	5.2	-

* Dash indicates that the solvent content of the sample was below the detection limit of the analytical method. The following detection limits were achieved during this analysis: hexamethyldisilizane - 3.5 ug, acetone - 0.1 ug, n-butyl acetate - 0.1 ug, xylene - 0.1 ug, cellosolve acetate - 0.1 ug, and methyl cellosolve - 0.1 ug.

[†] Analysis of charcoal sampling tube detected a breakthrough concentration equal to or exceeding 25 percent of the forward charcoal portion.

TABLE 2. SURVEY OF ULTRAVIOLET RADIATION EMISSIONS
FROM MASK ALIGNMENT-EXPOSURE UNITS

Equipment	Irradiance, [*] mW/cm ²
Perkin Elmer 120 (with left side panel up)	0.03
Perkin Elmer 140 (with entire cabinet removed)	0.15 (measured at back of unit)

* The irradiance values given represent the average emission detected over a 2- to 3-minute period. The spectral response of the monitoring instrument used during this survey is limited to the near ultraviolet spectral region.

Ventilation

The three photolithographic areas monitored during this survey are located in separate equipment aisles serviced by vertical laminar-flow ventilation with HEPA filters. The aisles are designed to maintain a Class 10-100 clean room environment. These aisles are separated by limited-access service chases that enclose both the ventilation ducting and utility services to the photolithographic equipment.

The first photolithographic area contains the e-beam lithography production of photomasks. A wet bench (designed as an exhausted, vertical, laminar-flow work station) is located in the e-beam aisle. The bench contains five sinks surrounded by a perforated work surface, and four exhaust slots are located along the back of the bench, opposite the worker. The work area is serviced by an overhead, vertical, laminar-flow, HEPA filtering unit.

The two remaining aisles contain equipment representative of a contemporary automated photolithographic operation. These aisles are serviced by both ceiling and local overhead laminar-flow HEPA filter units. Each aisle is served by seven in-ceiling units. The air returns for the ceiling units are located along the floor of the aisle. The Wafer Trak[®] units in the two aisles are serviced by three local overhead HEPA filters. Tables 3 and 4 summarize the ventilation measurements taken in the photolithography aisles with two-lane and four-lane Wafer Trak[®] systems.

TABLE 3. SUMMARY OF VENTILATION MEASUREMENTS IN PHOTOLITHOGRAPHY AISLE WITH AN AUTOMATED FOUR-LANE WAFER TRAK[®]

Description	Ventilation component	Average measured air flow velocity (fpm)	Exhaust take-off area (ft ²)	Volumetric flow rate (cfm)
Vertical laminar-air-flow, HEPA filter units in photolithography aisle	Three HEPA-filter units over 4-lane wafer track	90	~20.89	1880
		92	~20.89	1922
		98	~20.89	2047
Estimate of air flow from work station onto worker	Air flow under fixed hanging sash	52	49.33	2565
	HEPA-filter ceiling units	211	3.32	700
Total volumetric air flow in aisle	HEPA-filter units over wafer track			5849
	HEPA-filter ceiling units (seven)			4900

TABLE 4. SUMMARY OF VENTILATION MEASUREMENTS IN PHOTOLITHOGRAPHY AISLE WITH AN AUTOMATED TWO-LANE WAFER TRAK[®]

Description	Ventilation component	Average measured air flow velocity (fpm)	Exhaust take-off area (ft ²)	Volumetric flow rate (cfm)
Vertical laminar-air-flow, HEPA filter units in photolithography aisle	HEPA-filter units over two-lane wafer track	53	14.10	747
		90	22.85	2056
		129	22.85	2948
Estimate of air flow from work station onto worker	Air flow under fixed hanging sash	59	37.67	2222
	Typical HEPA-filter ceiling units	246	3.32	817
Total volumetric air flow in aisle	HEPA-filter units over wafer track			5751
	HEPA-filter ceiling units (seven)			5719

The Wafer Trak[®] units are equipped with internal exhaust ventilating systems designed to reduce the fugitive emissions of solvent or surfactant aerosols generated during the lithographic process. Central to this internal ventilation is the photoresist spin-on wafer chuck unit. Enclosed in a plastic hood, the wafer chuck is serviced by a 1.25-inch diameter exhaust duct with a face velocity of approximately 400 fpm. The wafer chuck exhaust produces an effective volumetric exhaust air flow of 3.2 cfm. Exhaust air from this duct is vented into the main exhaust ducting for the fabrication area and exits into the ambient outside air.

Work Practices

Work activities in the photoresist application aisle consist of loading and unloading wafer cassettes in the wafer-processing unit, replacement of photoresist and HMDS containers, and activation of push-button controls to initiate the processing sequence. Workers in the photolithography aisle also perform other related activities, including wafer exposure, wafer and mask inspection, mask cleaning, and wafer developing. Consequently, the potential for exposure to chemical or physical agents is lower than if the operator worked at one specific process operation for an entire shift.

During normal operations, mask-alignment workers are seated at the projection mask aligner. It was common to see these employees operate the equipment with one or more of the equipment panels open. When the panels are open, a blue light is visible around the unit.

Workers in the wafer development area transfer cassettes containing exposed wafers from the projection mask aligner to the developer station. They are also required to manually change developer solution containers, which serve as reservoirs for the system.

Specific work practices employed in the electron beam lithography process operation were not observed.

Workers are required to wear normal clean-room attire, consisting of shoe covers, lab coat, hood, latex gloves, and safety glasses or goggles. Except for safety glasses or goggles, the equipment is required for control of product quality. Figure 3 presents the approximate location of key workers in the photolithographic operations.

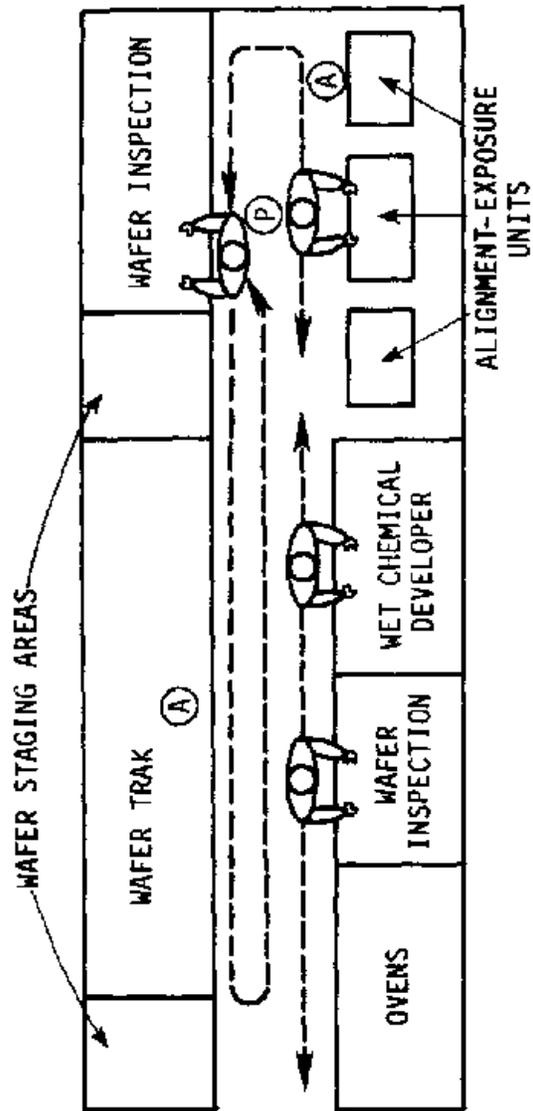
WET CHEMICAL STATIONS

At the Xerox facility wet chemical stations are used to perform two tasks: (1) etching or cleaning of wafers by immersion in an acid bath and (2) solvent cleaning.* Wet chemical stations that were evaluated during the in-depth survey include two ventilated polyethylene plastic benches with recessed solution tanks for cleaning, etching, or stripping wafers by immersion in acid, and two ventilated stainless steel benches for solvent cleaning.

Acid Baths

The two acid-etching operations observed were performed in polypropylene benches with overhead laminar-flow, HEPA-filter

* Solvent cleaning, as it is used in this report, refers both to a cleaning or degreasing-type operation and solvent use during e-beam photomask processing.



-  PRIMARY WORK STATION, LOCATION OF WORKER DURING MOST OF THE PHOTOLITHOGRAPHIC OPERATION
-  SECONDARY WORK STATIONS, MOVEMENT OF WORKER DURING PROCESS OPERATION
-  LOCATION OF AREA SOURCE SAMPLING EQUIPMENT
-  IDENTIFICATION OF PROCESS WORKERS WITH PERSONAL MONITORS

Figure 3. Diagram of work activities and location of area and personal monitors during photolithographic operations.

units; slot exhaust ventilation along the back of the bench; and ventilation down through the perforated work surface.

The acid baths are covered by clear plastic lids. A spill plenum is exhausted by a slot located below the work surface across the rear of the plenum. This plenum, located below the perforated bench surface of each unit, catches spilled acid and diverts the liquid to a waste acid drain. The operator flushes the plenum with water. Figure 4 presents the basic design of a polypropylene wet bench.

The purpose of having a HEPA-filter unit located over each of the benches is to provide for a curtain of Class 100 clean air over the products. This air curtain approach to ensuring product quality is fundamental throughout the Xerox fabrication process. The HEPA-filter units are designed to maintain a face velocity of 150 fpm downward and across the work surface. Although it controls particulate levels over the products very effectively, the air curtain results in a net outflow of air from the acid etch tanks across the work station into the workers environment. The volumetric flow rates for the two wafer etching benches are presented in Figure 5. Air velocity and dimension measurements taken during the in-depth survey indicate that approximately 40 to 60 percent of the Class 100 clean air supplied to the work station is pushed out from below the splash shield into the work environment at velocities of 63 to 97 fpm. During periods when the worker is away from the etching bench, the capture distance provided by the slots and perforations extends across the face of

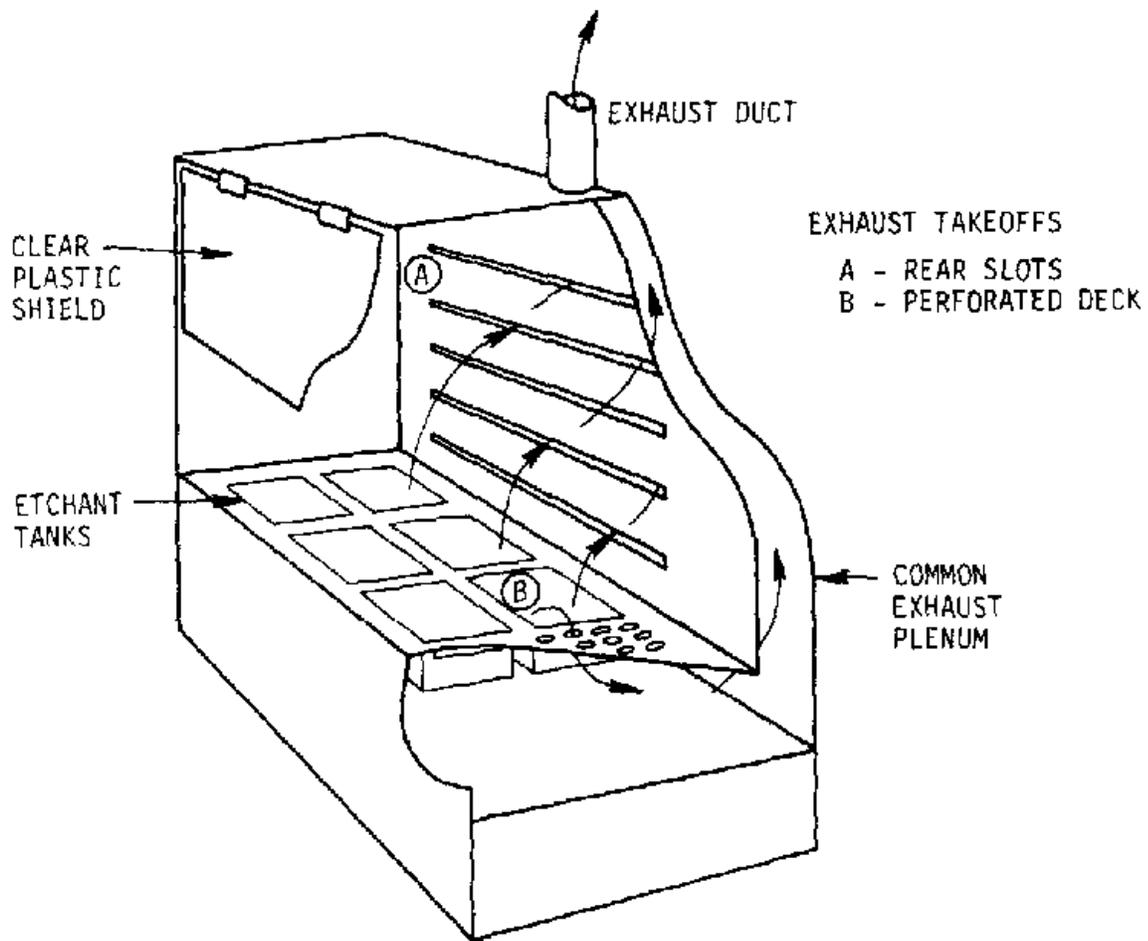


Figure 4. Cutaway view of wet chemical station

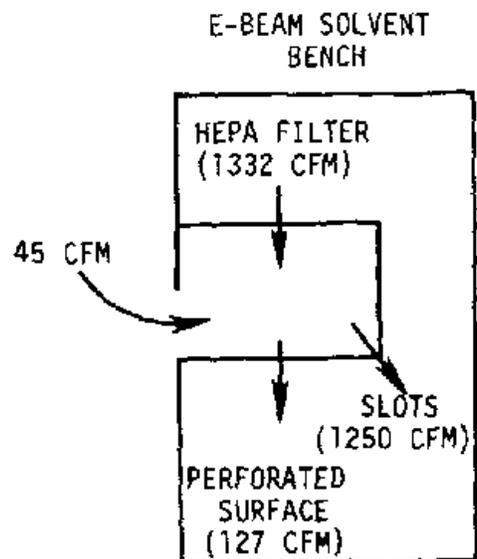
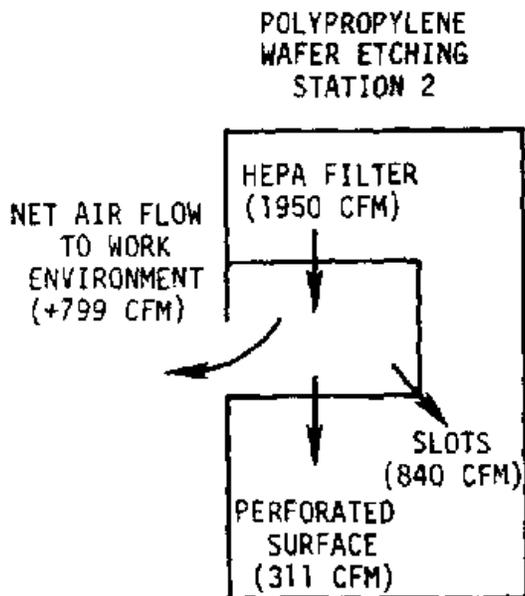
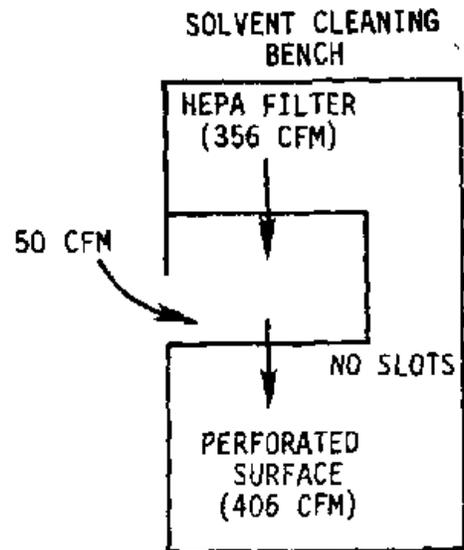
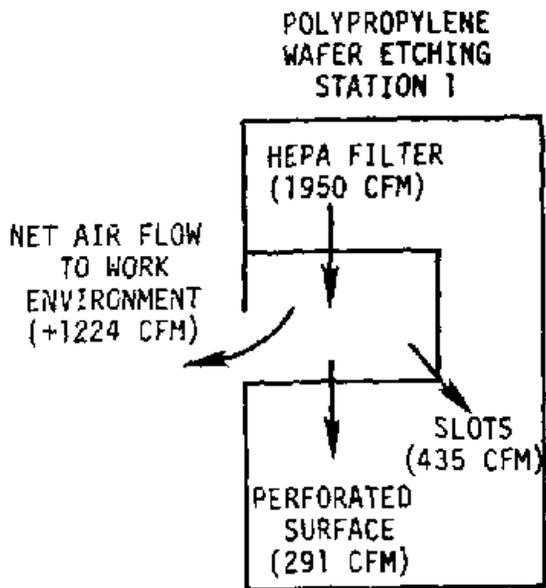


Figure 5. Estimated volumetric flow rates for wet chemical wafer etching and solvent cleaning benches.

the acid baths and appears to be successful in exhausting most of the acid vapors. Under these conditions, the excess HEPA-filtered air does not appear to disrupt the efficiency of the slot and perforated-work-surface exhausts. During removal or replacement of wafer cassettes, however, the worker may disrupt the air flow enough to defeat the exhaust ventilation. In an effort to measure the extent of this disruption, air samples were taken both inside and outside of the wafer-etching benches (see Table 5). The bubbler solutions were analyzed for hydrogen fluoride in an attempt to estimate the relative efficiency of the exhaust ventilation while characterizing workplace exposures. Concentrations in all samples taken were below the detection limit of the method employed to perform the analyses.

Solvent Baths

Solvent use at Xerox includes the cleaning of wafer-handling equipment and the treatment of e-beam produced photomasks. Solvent cleaning removes organic contaminants from wafer-handling equipment. The solvent tanks are contained within stainless steel tanks enclosed in a fireproof case that is serviced by local exhaust ventilation. Ultrasonic sound is used to assist in the cleaning process. Solvent compounds, such as acetone or isopropanol, are supplied to the individual tanks from pressurized solvent containers located beneath the bench. Waste solvent is drained by aspiration to a solvent-collection system and stored in a holding tank.

TABLE 5. SUMMARY OF AREA MONITORING FOR HYDROGEN FLUORIDE AT WET CHEMICAL WAFER ETCHING STATIONS

Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentration * (mg/m ³)	Time-weighted average concentration (mg/m ³)
Wet chemical etching station (inside hood)	1:01	51.8	<1.2	NA [†]
Wet chemical etching station (inside hood)	1:04	54.7	<1.1	NA
Wet chemical etching station (outside hood)	1:00	66.6	<0.9	NA
Wet chemical etching station (outside hood)	1:03	69.9	<0.9	NA

* Based on a detection limit of 60 µg.

† NA = not applicable.

The solvent bath and fireproof enclosure are exhausted through perforations in the work surface of the bench. Exhausted air is vented to the facility's scrubber system. Although similar in design to the acid etching benches, the solvent benches are constructed of stainless steel. The solvent benches also maintain a net volumetric air flow rate into the bench and away from the work environment (see Figure 5). Results of air monitoring conducted at the e-beam solvent bench were presented previously in Table 1, in the section on photolithography. The results indicate that the bench is only partially successful in the prevention of emissions of organic solvent vapors into the work environment.*

ION IMPLANTATION

Ion implantation is a "doping" process performed under high vacuum conditions (10^{-5} torr). The vacuum is established by a mechanical roughing pump followed by a cryogenic trap and a diffusion pump. The vacuum creates negative pressure conditions which limit the release of the dopant ions into the workroom air during the implantation step. Wafers are targeted through load locks that are evacuated with a mechanical pump. The dopant sources or implant gases (boron trifluoride, diborane, phosphine, and arsine) are stored in a ventilated gas cabinet located inside the ion implantation unit. The ion beam source is contained

* It should be noted that the bench was not the only source of potential solvent vapors. The solvent storage cabinet (although enclosed and exhausted) is located in the same aisle as the bench.

within a double lead-shielded cabinet to prevent x-ray leakage. Access to the source is through panels which are electrically interlocked to the system.

Two classes of ion implanters were monitored during this survey: the cassette-type and the pallet-type. The designations refer to the manner in which the instrument handles the target wafers. Cassette-type implanters accept the wafers in standard cassettes. These ion implanters automatically select and target individual wafers one at a time. The finished wafer is automatically loaded into a waiting cassette.

Pallet-type ion implanters accept 25 to 50 wafers at one time. The wafers are removed from cassettes and manually loaded onto one of two pallets. Once loaded, the pallets are automatically positioned in front of the beam, and all wafers are targeted at once. The finished wafers are then manually removed from the pallet into cassettes.

Monitoring Results

The ion implantation process was monitored for exposures to dopant substances (or their products) and X-radiation. Ion implanters monitored during the in-depth study were using arsine, phosphine, and boron trifluoride gases as dopants. The maintenance of the ion source chamber is an auxiliary operation associated with implant procedures. This maintenance includes the bead-blasting of metallic arsenic and arsenic trioxide residuals from the chamber components. Arsenic, measured either as elemental particulate arsenic or arsine gas, was monitored during

the ion source change and the bead blasting operation. The results of monitoring for metallic arsenic and arsine are presented in Table 6. The results of monitoring for boron and phosphine are presented in Tables 7 and 8, respectively.

X-ray emissions were monitored during implantation operations. This X-ray monitoring was performed in two steps. An initial survey of the work areas around the implanter was performed by using a Geiger-Muller counter with a thin film probe. The purpose of the initial survey was to identify points of high emissions or "hot spots". Once identified, the hot spots were monitored for a 2-week period by using film badge dosimetry. The badges were located at points of high emissions, left exposed for 2 weeks, and then taken down and developed to obtain an integrated exposure estimate. The results of both the initial Geiger-Muller survey and the film badge dosimetry monitoring are presented in Table 9.

The ventilation system associated with the ion implanters was not monitored.

Work Practices

Although the work characteristics and practices of ion implantation workers do not vary greatly with the implanter or type of dopant being used, employees' work practices are affected by the physical state of the dopant source. Sources can be in gaseous, liquid, or solid states. Because of the potential for release and dispersion into the work environment, gaseous and liquid sources present the greatest hazard to workers. Work practices around gaseous and liquid sources are more regimented, and specific precautions must be taken before certain tasks are

TABLE 6. SUMMARY OF RESULTS OF AREA AND PERSONAL MONITORING FOR ARSINE (AsH₃) AND ELEMENTAL ARSENIC EXPOSURES FROM ION IMPLANTATION OPERATIONS

Substance	Job description or location of monitor	Sample duration (h min)	Sample volume (liters)	Measured concentration (µg/m ³)*	Time-weighted average concentration (µg/m ³)
Arsenic	Personal monitor on worker performing bead blasting of source from DF-4	0 30	60 60	<0 3	0
Arsine	Area monitor at controls of the Extrion BQ10 ion implanter	1 18	15 30	<0 7	NA†
Arsine	Area monitor at wafer loading station of Extrion BQ10	1 28	17 30	<0 6	NA
Arsine	Area monitor at source location during source change of Extrion BQ10	1 28	9 05	87 37	NA
Arsine	Personal monitor on operator during maintenance of manipulator of Extrion BQ10	0 56	7 39	<1 4	NA
Arsine	Area monitor at ion implanter controls of DF-4	2 22	27 89	<0 4	NA
Arsine	Area monitor at wafer loading station of DF-4	2 24	15 45	<0 6	NA
Arsine	Area monitor at source location during source change of DF-4	1 20	8 59	<1 2	NA
Arsine	Personal monitor on operator during source change of DF-4	2 23	28 27	0 36	0 35
Arsine	Personal monitor on worker performing bead blasting of source from DF-4	0 30	3 21	<3 1	0
Arsine	Personal monitor on DF-4 operator during normal operations	2 48	33 04	<0 3	} 0 45
Arsine	Personal monitor on DF-4 operator during normal operations	0 59	11 65	1 79	
Arsine	Area monitor at wafer loading station of DF-4	5 15	33 68	<0 3	NA
Arsine	Area monitor at wafer loading station of DF-4	1 36	10 30	1 01	NA

* Values based on a minimal detection limit of 0 01 µg for arsine and 0 02 µg for arsenic

† NA = Not applicable

TABLE 7. SUMMARY OF RESULTS OF AREA AND PERSONAL MONITORING OF PHOSPHINE (PH₃) EXPOSURES FROM ION IMPLANTATION OPERATIONS

Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentration* (µg/m ³)	Time-weighted average concentration (µg/m ³)
Area monitor at wafer-loading station of Extrion 8010	0:46	9.08	<220	NA [†]
Area monitor at operator controls of Extrion 8010 ion implanter	0:35	6.86	<292	NA
Personal monitor on operator during normal operation of Extrion 8010	2:44	16.89	219.06 (as phosphate) 78.42 (as PH ₃)	219 (as phosphate) 78 (as PH ₃)
Area monitor at loading station of DF-4 ion implanter	2:48	32.26	<62	NA
Area monitor at loading station of DF-4 ion implanter	1:42	19.58	<102	NA

* Based on a minimal detection limit of 2 µg

† NA = Not applicable.

TABLE 8. SUMMARY OF RESULTS OF AREA AND PERSONAL MONITORING OF BORON EXPOSURES FROM ION IMPLANTATION OPERATIONS

Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentration* ($\mu\text{g}/\text{m}^3$)	Time-weighted average concentration ($\mu\text{g}/\text{m}^3$)
Area monitor at controls of 20-A ion implanter	1:40	104.50	26.79	NA [†]
Area monitor at loading station of 20-A ion implanter	1:45	110.88	<2.87	NA
Area monitor at controls of 20-A ion implanter	4:07	241.07	<1.24	NA
Area monitor at controls of 20-A ion implanter	2:43	159.09	7.54	NA
Area monitor at loading station of 20-A ion implanter	4:04	257.66	<1.16	NA
Area monitor at loading station of 20-A ion implanter	2:43	172.13	<1.74	NA

* Based on a minimal detection limit of 0.3 μg .

[†] NA = Not applicable.

TABLE 9. SUMMARY OF G-M SURVEY AND DOSIMETER MEASUREMENTS OF X-RAY EMISSIONS FROM ION IMPLANTATION OPERATIONS

Unit	Monitor location or worker responsibility	Distance from suspected source (ft)	G-M survey (mR)	Total dose (mrems)	Weekly dose (mrems)
Extrion 8010*	Manipulator	~0.5	20	150	NA [†]
	High-vacuum valve near ion source	~0.5	†	14,850	NA
	Water-distribution panel	~0.5	3	§	<5
	Operator	-	0	§	-
Varian DF-4	Wafer-loading station	~3.0	0	§	NA
	Window on source cabinet	~3.0	0	§	NA
	Control panel	~3.0	0	§	NA
	Operator	-	0	§	<5
	Maintenance	-	0	§	<5
	Maintenance technician	-	0	§	<5
	Maintenance technician	-	0	§	<5
	Maintenance technician	-	0	§	<5

* Extrion 8010 was operating at 80 KeV during G-M survey.

† NA = Not applicable.

‡ Reading on G-M survey meter went off scale.

§ Emission was below the 10-mrem detection limit of the dosimeter.

performed. These regulated tasks are associated with the maintenance of the ion implanter and the changing of source material.

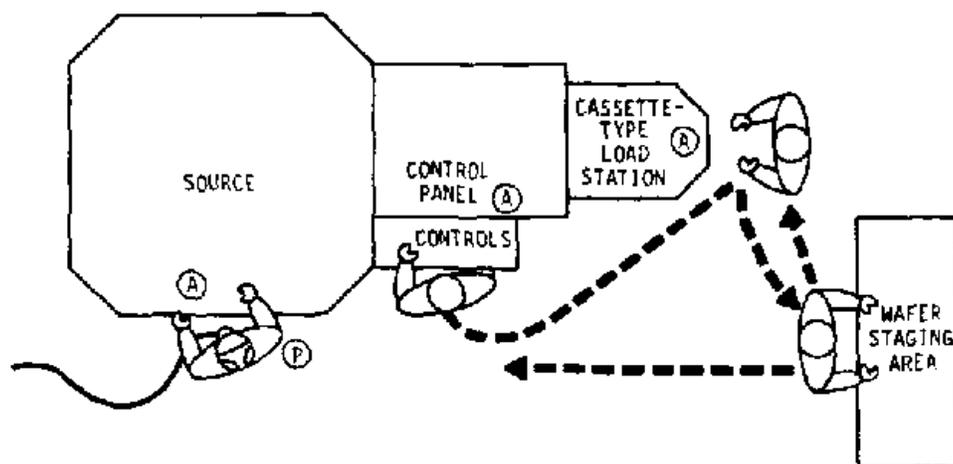
The work practices can be divided into two categories: operational and maintenance. Operational work practices consist of equipment startup, operation, and shutdown. The transfer of wafers to and from the wafer load-in station is an example of an operational work practice. Figure 6 depicts work practices for implanters with two types of load-in stations--cassette-type load-in stations and pallet-type stations.

Maintenance or source change activities are often performed by the equipment operators or engineers responsible for the ion implantation portion of the process. Maintenance activities include changing of the source, replacement of pump oils, and general mechanical repairs. For source changes a worker must wear either a self-contained breathing apparatus or a full-face air-line respirator. An ancillary maintenance activity not presented in Figure 6 involves the breakdown and bead-blasting of the ion source removed from the implanter. This activity requires the worker to transfer the ion source to a glove box to perform the bead-blasting operation.

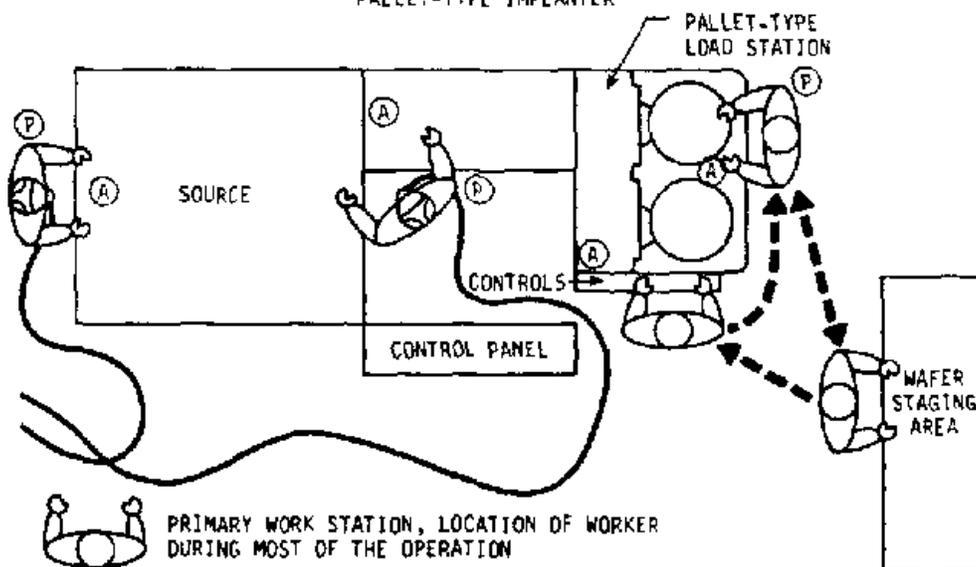
CHEMICAL VAPOR DEPOSITION

Chemical vapor deposition at Xerox was monitored to detect the presence or absence of decomposition byproducts emitted from the furnace assembly. The low-pressure chemical vapor deposition (LPCVD) furnaces were monitored for emissions of hydrogen chloride (HCl), a likely decomposition product during polycrystalline

CASSETTE-TYPE IMPLANTER



PALLET-TYPE IMPLANTER



- PRIMARY WORK STATION, LOCATION OF WORKER DURING MOST OF THE OPERATION
- PRIMARY WORK STATION, LOCATION OF WORKER WITH LINE RESPIRATOR DURING MAINTENANCE ACTIVITY OR SOURCE CHANGE
- SECONDARY WORK STATIONS, MOVEMENT OF WORKER DURING PROCESS OPERATIONS
- (P)** IDENTIFICATION OF WORKERS EQUIPPED WITH PERSONAL MONITORS
- (A)** IDENTIFICATION OF AREA MONITOR LOCATIONS

Figure 6 Pictorial diagram of work activities and location of personal and area monitors during ion implantation operations at implanters with cassette-type (top) and pallet-type (bottom) loading stations.

silicon deposition. The results of this monitoring are presented in Table 10. The results of the monitoring indicate that workers are not exposed to HCl decomposition products from the LPCVD operations.

Ventilation measurements were conducted at the scavenger box openings during normal LPCVD operations. Measurements taken with the scavenger box open showed an air velocity of 50 fpm. Based on an estimated open area of 1.2 ft^2 , a volumetric flow rate of 60 cfm was calculated. During the actual deposition of polycrystalline silicon, the scavenger box doors were closed, which resulted in a reduction of the opening to a small slot approximately 0.01 ft^2 in area. The measured air velocity at the opening was approximately 830 fpm. The scavenger box exhaust duct located inside the box maintained an air velocity of approximately 750 fpm over an opening of approximately 0.06 ft^2 .

DIFFUSION FURNACES

One diffusion furnace operation was being performed during the in-depth survey. Figure 7 presents a typical diffusion furnace assembly. At Xerox, phosphorus oxychloride (POCl_3) was used to dope wafers with phosphorus. A likely byproduct of this operation would be the formation of phosphate upon contact of the dopant with the workplace air. The air around the phosphorus diffusion furnaces was monitored for phosphates.

Monitoring Results

The results of this monitoring are presented in Table 11.

TABLE 10. SUMMARY OF AREA MONITORING FOR HYDROGEN CHLORIDE AT LOW-PRESSURE CHEMICAL VAPOR DEPOSITION (LPCVD) FURNACES

Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentration* (mg/m ³)	Time-weighted average concentration (mg/m ³)
Scavenger box opening of LPCVD furnace during loading of wafer boats (door open)	0:15	15.0	<2.7	NA [†]
Scavenger box opening of LPCVD furnace during loading of wafer boats (door open)	0:16	16.0	<2.5	NA
Scavenger box opening of LPCVD furnace during loading of wafer boats (door open)	0:15	15.0	<2.7	NA
Scavenger box opening of LPCVD furnace during unloading of wafer boats (door open)	0:15	15.7	<2.6	NA

* Based on a minimal detection limit of 40 µg

† NA = Not applicable.

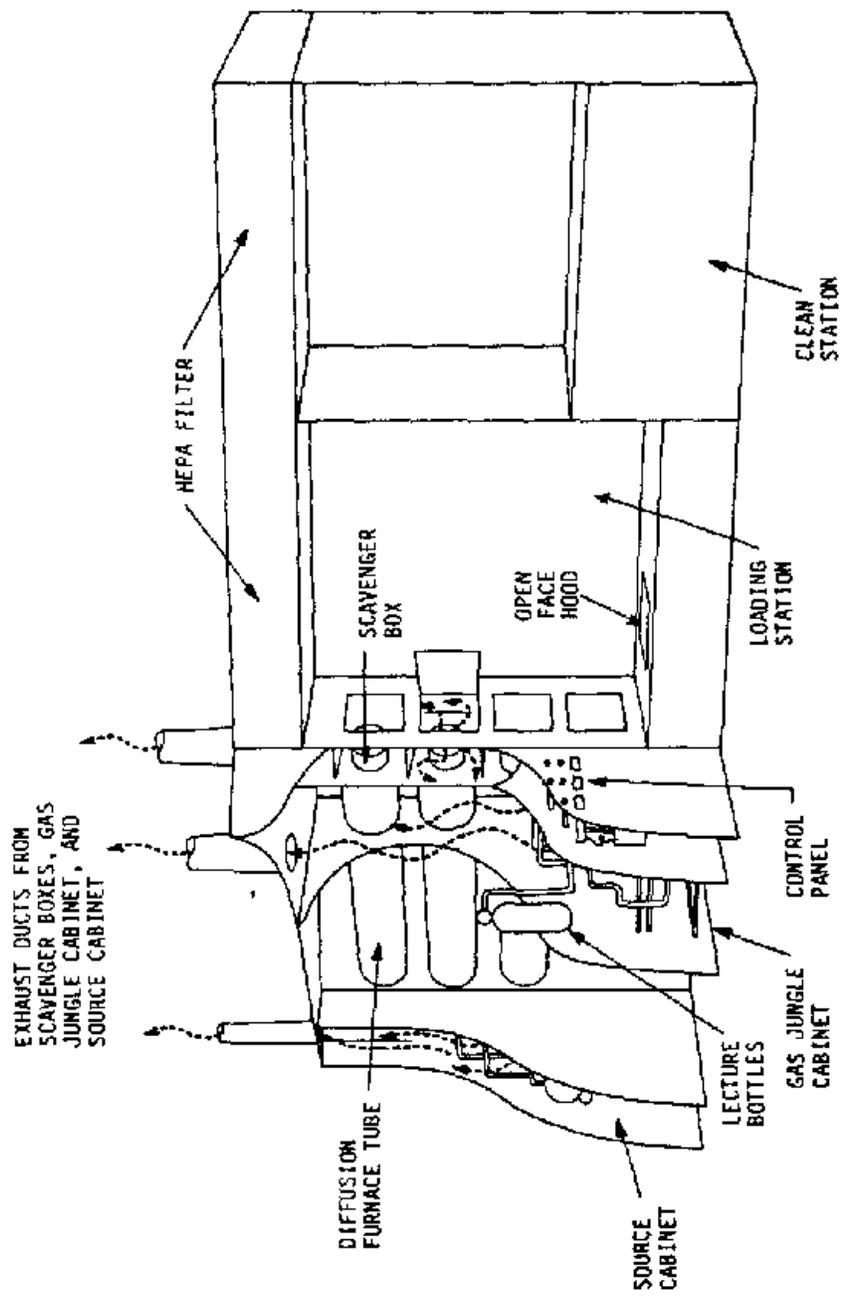


Figure 7. Diffusion furnace and associated work stations.

TABLE 11. SUMMARY OF RESULTS OF AREA MONITORING FOR
PHOSPHATES AT DIFFUSION FURNACES

Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentration * ($\mu\text{g}/\text{m}^3$)	Time-weighted average concentration ($\mu\text{g}/\text{m}^3$)
Scavenger box opening of furnace	2:51	33.7	<59	NA [†]
Scavenger box opening of furnace	1:38	25.0	<80	NA
Scavenger box opening of furnace	4:50	74.0	<27	NA

* Based on a minimal detection limit of 2 μg .

† NA = Not applicable.

The diffusion furnace operations are conducted in an area of the fabrication process where wafers are periodically checked for surface flaws with a UV light source. A worker responsible for the wafer checking would be exposed to three potential sources of UV light: (1) direct emissions of UV from the light source, (2) indirect emissions of UV from reflection of the light, and (3) potential UV emissions from nearby furnace-tube openings. Ultraviolet light emissions were detected from each of these sources, as shown in Table 12.

The measurements around the wafer-checking work area cannot be directly related to worker exposure because the exact work schedule and practices of the employees in this area of the plant could not be ascertained. Under the present production scenario at Xerox, it is unlikely that any process workers would be exposed to levels of UV light in excess of the TLV.

Ventilation

Ventilation measurements were also conducted on the scavenger box openings during normal diffusion furnace operations. The air velocity of each scavenger box was measured with the doors closed. Measurements of 1150, 450, 450, and 625 fpm were detected at each of the four POCl_3 furnaces. Based on an opening of 0.14 ft^2 , (with doors open), respective volumetric flow rates of 161, 63, 63, and 88 cfm for each of the scavenger boxes were calculated.

TABLE 12. RESULTS OF SURVEY OF ULTRAVIOLET RADIATION EMISSIONS
FROM WAFER CHECKING OPERATIONS

Equipment	Irradiance,* mW/cm ²
Wafer-checking station (direct exposure at a distance of 12 inches from source)	10-20
Wafer-checking station (indirect reflective exposure at a distance of 12 inches from the source)	0-10
Diffusion furnace (emissions from furnace opening)	0.01

* The irradiance values given represent the average emission detected over a 2- to 3-minute period. The spectral response of the monitoring instrument used during this is limited to the near ultraviolet spectral region.

Work Practices

The work practices of fabrication workers involved in both the diffusion furnace operations and wafer checking were not observed during the in-depth survey at Xerox.

RADIO-FREQUENCY RADIATION SOURCES

At the Xerox facility, radio-frequency (RF) radiation is used in the following process operations: (1) plasma etching, (2) radio-frequency sputtering, and (3) mask production. The RF monitoring results obtained during this survey are presented in Table 13.

The plasma etching systems are located under laminar-flow hoods with HEPA filters. Vacuum pumps for each process unit are located in the equipment chase immediately behind the units. The barrel reactor photoresist stripping system is mounted in the equipment chase, with only the load door and controls in the clean room work area. Process gases are stored in a ventilated storage cabinet in the equipment chase. Vacuum pump exhausts are vented to the scrubber system through stainless steel ducts.

The sputtering units used during the metalization process are located in the fabrication clean room. Sputtering and filament deposition are performed in sealed stainless steel or glass chambers under high-vacuum conditions (chamber pressure negative to the room).

The sputtering unit is mounted in the equipment chase wall with access to the unit from the clean room and the equipment

TABLE 13. SURVEY OF MONITORING FOR RESULTS OF RADIO-FREQUENCY RADIATION EMISSIONS FROM RF SOURCES

Equipment manufacturer and model	Frequency	Operating power (watts)	Maximum duration of RF emission (min)	Maximum electric field (V ² /M ²)	Maximum magnetic field (A ² /M ²)
Applied Materials AME-8100 oxide etcher	13.56 MHz	750	25	None	0.06
Varian 3180 Metal sputterer	13.56 MHz	125	1.5	None	None
IPC Branson 2000 Plasma stripper	13.56 MHz	300-400	60	4.0x10 ⁵ *	0.044
stripchart recorder	-	-	-	1.0x10 ⁴	0.055
IPC Branson 3000 Plasma stripper	13.56 MHz	300	30-45	0.013	None
Technics plasma unit 500-II (e-beam)	450 kHz	400	6	3.2x10 ⁴	+
Tegal 700 plasma etcher	13.56 MHz	100	2	None	None

* Electric field levels in excess of the TLV for RF radiation at 13.56 MHz (1.8 x 10⁴ V²/M² for a six minute exposure).

† Magnetic field levels could be measured with probes available at the time of the survey.

chase. Pumps systems for the unit are also located in the equipment chase. The planetary is mounted in the reaction chamber through the access door in the clean room, which is under a laminar-flow, HEPA-filter, work station. Nitrogen is supplied to the unit in cylinders, which are stored in the equipment chase. The cylinders are chained upright to the load-bearing wall.

Both the etching and sputtering systems employ oil-sealed mechanical roughing pumps, cryogenic traps, and diffusion pumps. The pump exhaust is vented to a process vent system and directed to a water-circulating scrubber. The air is then exhausted to the atmosphere.

Each of these systems are automated operations, in which worker contact with the process is limited.

Monitoring Results

Batch processes dedicated to plasma etching operations use 13.56-MHz RF sources at 100 to 400 watts. The plasma etching RF sources are operated continuously for 25- to 60-minute cycles. The metal sputtering operations performed at Xerox use 13.56-MHz frequency RF sources operating at 125 watts (Varian 3180). The RF source on the metal sputtering units run continuously for 1.5-minute cycles. A 450-kHz plasma etching unit is used during the mask production associated with the e-beam lithographic process. This unit operates at 400 watts over cycle times of less than 6 minutes.

Radio-frequency radiation emissions (both magnetic and electric fields) were found along the seams of adjoining metal plates, at viewing windows equipped with metal screens, and near

auxiliary instrumentation connected to the process equipment. Initial measurements of the RF emissions were made at a distance of 10 cm (4 inches) from the individual pieces of equipment. Once elevated RF measurements or "hot spots" were identified, additional measurements were made at greater distances from the source until the survey instrument readings dropped to zero. At all the process equipment monitored during the in-depth study, the magnetic and electric field emissions of energy dropped off to zero at or before reaching 100 cm (39 inches) from the source.

Only one RF source appeared to present a potential hazard to process workers. Xerox uses an IPC Branson 2000 series plasma stripper to remove silicon nitride with a plasma created from oxygen and Freon. Both the maximum electric field and magnetic field measurements taken at this equipment's viewing window exceed the recommended TLV for 13.56-MHz sources. Also, a remote stripchart recorder that was connected to the IPC Branson 2000 unit appeared to conduct and emit electric and magnetic field energies. The stripchart recorder was not grounded.

The seriousness of the RF radiation emitted from a majority of the process equipment listed in Table 13 is minor. The largest potential source of RF emissions (the IPC Branson 2000 unit and its stripchart recorder) does not present a whole-body exposure problem because, under normal operating conditions, the operator responsible for loading the plasma stripper is only near the unit (within 100 cm or 39 inches of the RF source) for very short

periods of time (less than 30 seconds). An exposure potential does exist for maintenance personnel who repair and closely observe the operation of this equipment for several minutes. A potential electrical field hazard appears to exist near the IPC Branson 2000 unit and stripchart recorder. This stripchart recorder and other ungrounded metal objects near the unit may strongly couple to the RF field and present a shock or burn hazard.

Protection from radio-frequency hazards are achieved through two engineering control approaches. The RF emissions from the reactor chamber are contained by equipping each plasma etcher with a metal screen over the viewing window. The single noteworthy RF source documented previously was not equipped with such a control measure, but Xerox has since installed a metal screen on the troublesome unit. Electric field emissions from metal objects near the process equipment were negated by grounding. Grounding of the remote stripchart recorder eliminated the shock potential previously posed by the coupling of this instrument to the nearby plasma stripper.

Work Practices

Operators use tweezers or vacuum wands to load the wafers into carriers in a laminar-flow HEPA-filtered staging area adjacent to the plasma etching and sputtering operations. Workers are required to load and unload wafer carriers and to initiate the process sequence. Processing is automatically controlled to allow workers to perform other job activities; for this reason, workers spend very little time in proximity to the equipment.

The barrel plasma reactor system for stripping photoresist is manually cleaned with isopropanol. Pump oils are manually drained and replaced. Process gases supplied in cylinders are changed by trained technicians. The procedures used for maintenance and cleaning activities were not observed during the in-depth survey. The automated control of the process equipment does not require an operator to be present during the operation. Therefore, if the plasma etching unit is emitting radio-frequency radiation, the operator is unlikely to be at the unit during an entire shift, but normally will be some distance away from the source. The operator's distance away from the source and variation in tasks during a work shift would both be considered controls that decrease worker exposure.

Workers are required to wear normal clean room attire, consisting of shoe covers, lab coat, hood, latex gloves, and safety goggles. Except for safety glasses or goggles, the equipment is required to control product quality. Workers replacing gas cylinders are required to wear gloves and full-face, supplied-air respirators.

GAS HANDLING SYSTEM

As previously discussed in the section on Plant, Process, and Program Descriptions, most of the toxic or hazardous process gases are stored in the toxic gas storage room. This storage room provides approximately 500 ft³ of storage space and is exhaust-ventilated to the outside. Make-up air is provided through a louvered panel in the access door. The panel provides

approximately 0.5 ft^2 of area at an average air velocity of 656 fpm, which provides for a volumetric flow rate of 328 cfm (see Table 14). In addition to the toxic gas storage room, two gas cabinets located in the equipment chases of the fabrication area were examined. These cabinets contain compressed gas cylinders of etchant gases for the Tegal and Branson plasma etchers. The gas cabinet supplying the Tegal etcher contained sulfur hexafluoride, and was vented through a 4-inch duct at an air velocity of 1120 fpm. It is estimated that the cabinet provides a volumetric exhaust rate of approximately 98 cfm (see Table 14). A similar gas cabinet which supplies silicon tetrafluoride oxygen and Freon 14 to the Branson etchers was vented through a 4-inch duct at an air velocity of 1000 fpm. This cabinet is estimated to deliver a volumetric exhaust rate of 87 cfm (see Table 14).

GAS DISTRIBUTION SYSTEM

Figure 8 presents a general diagram of a typical gas distribution system used at this Xerox facility. The process gas cylinder is enclosed in an exhausted gas cabinet. Process gas is first supplied to the system through a flow-limiting valve that is designed to shut off the gas flow when the pressure exceeds or drops below a specified range. The process gas enters a welded stainless steel cross, which acts as a four-way intersection for the process gas or nitrogen purge gas. To the left of the intersection is a manual purge valve that supplies bottled nitrogen to the gas distribution system when purging of the system is required. It is against company policy to connect purge lines to the house

TABLE 14. SUMMARY OF AIR FLOW CHARACTERISTICS OF
VENTILATED GAS CYLINDER STORAGE CABINETS AND
TOXIC GAS STORAGE ROOM

Gas	Duct diameter (inches)	Average velocity (fpm)	Volumetric flow rate (cfm)
AsH ₃ , PH ₃ , SiH ₄ , BF ₃ , N ₂ , SiF ₄ , H ₂ SiCl ₂ , SiF ₆	-	656	328
SF ₆	4	1120	98
SiF ₄ /O ₂	4	1000	87

* Process gases stored in a 500 ft³ toxic gas storage room
that is vented to the outside.

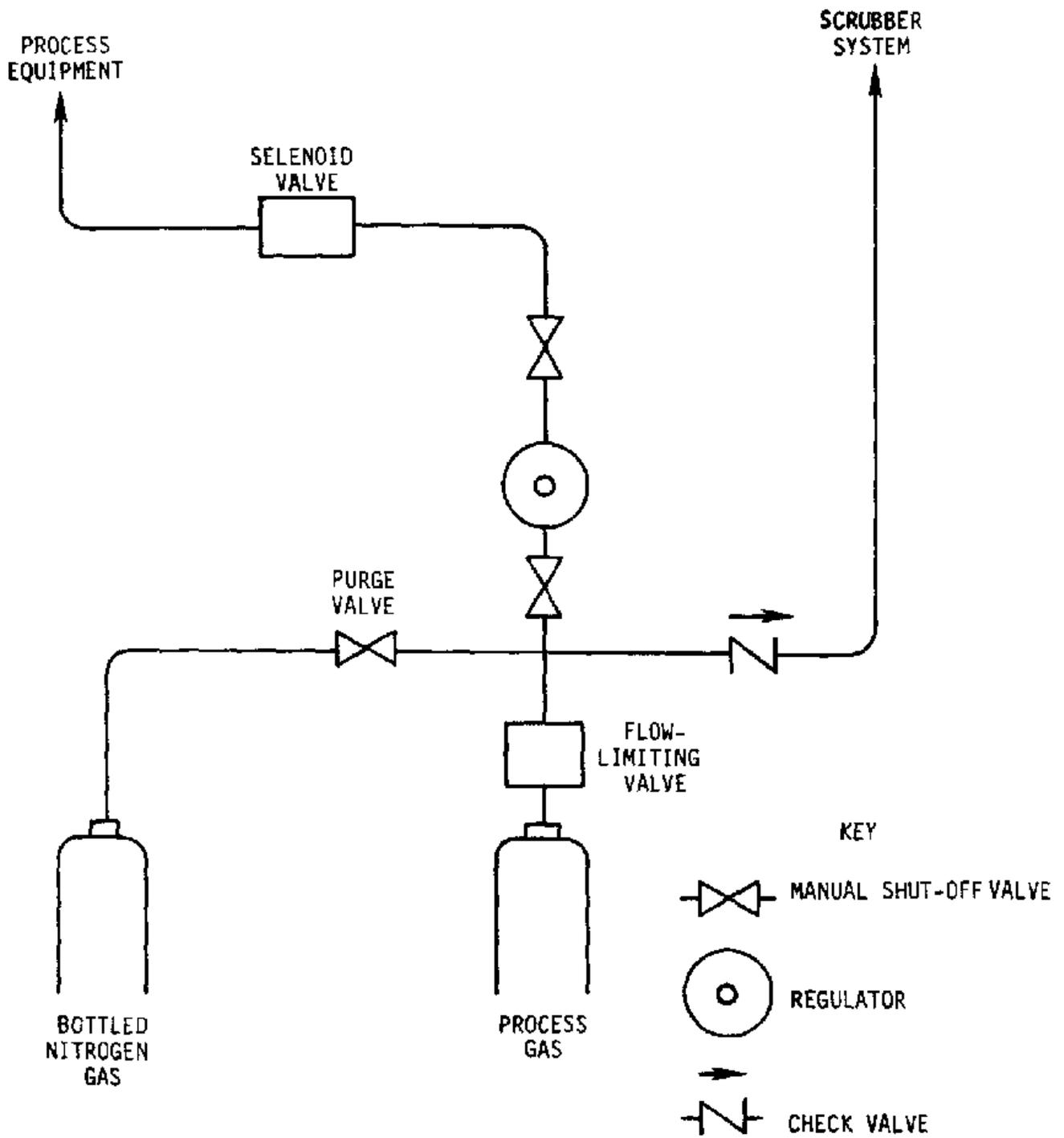


Figure 8. Gas distribution system

nitrogen. To the right of the intersection is a manual relief valve. This valve can be opened to purge or flush the gas cylinder system to the scrubber system. Over the intersection is the first of two manual shutoff valves located on the line leading to the process equipment. The other shutoff valve is positioned after the gas regulator. Xerox has installed pressurized-air activated solenoid valves in all toxic gas lines prior to the process equipment. The solenoid valves automatically shut down process gas service to the equipment as a result of one or more of the following: (1) a power failure occurs, (2) fire is detected in the facility, or (3) the process gas pressure drops. Manual activation of the solenoid can occur at the solenoid or in the gas-distribution piping to the process equipment.

CONCLUSIONS

The following conclusions have been drawn from the in-depth survey. These conclusions correspond to each work activity or process operation discussed in the control technology section of this report.

CHEMICAL HANDLING

Most of the chemical-handling tasks performed at the Xerox facility involve the movement of process chemicals from storage or holding areas into the circuit fabrication process area. Toxic or hazardous gases used at Xerox were transferred from compressed gas cylinders to process machinery through a gas handling system. This system is an example of "good" contemporary engineering design. It incorporates (1) a central exhausted toxic gas storage room or exhausted gas cabinets for safe storage of gas cylinders, (2) flow-limiting, emergency shutoff valves and automatic solenoid valves, and (3) welded stainless steel lines that have a minimum of compression fittings. Worker exposures to leaks and gas releases during cylinder changing operations are further controlled through the use of supplied-air line respirators.

Worker exposures during the transfer of liquid chemicals are controlled through the use of personal protective equipment.

Chemical handlers are provided with personal protective equipment consisting of (1) chemical-resistant aprons, (2) acid- or chemical-resistant gloves, (3) chemical-splash goggles and face shields, and (4) protective boots. The overall potential for accidental exposure to liquid chemicals is further reduced by limiting the supply vessels to 1-gallon containers that are transported from intermediate storage areas to ventilated wet chemical benches in the fabrication area.

PROCESS CONTROLS

In most instances it was not possible to assess the effectiveness of more than one control option because of the lack of variation in control solutions at Xerox. The controls that were observed were assessed in terms of how effectively they reduced or eliminated an exposure problem. Although the sampling approach taken during the in-depth survey was not designed specifically to calculate 8-hour time-weighted averages, a comparison of such values with recommended threshold limit values (TLV's) will provide a quantitative assessment of process control effectiveness.

Photolithography

Worker exposures to organic substances from photolithographic operations around the automated Wafer Trak[®] systems at Xerox proved to constitute only a fraction of the recommended TLV's (see Table 1). Both the area and personal monitoring efforts detected acetone, n-butyl acetate, Cellosolve acetate (2-methoxyethyl acetate), and xylene at levels less than 1

percent of their respective TLV's. Hexamethyldisilazane (for which a TLV has not yet been established) was detected at levels between 74.5 and 559.0 $\mu\text{g}/\text{m}^3$.

Ultraviolet (UV) light emissions from Perkin-Elmer mask alignment-exposure units were measured to estimate potential worker exposures to UV radiation during both normal and maintenance activities (see Table 2). The photoelectric cell used during this study to detect UV light has a frequency response range of 300 to 400 nm, with a peak response at 365 nm. Because the monitoring instrument operates in the near ultraviolet spectrum, a TLV of 1 mW/cm^2 for a 16-minute exposure was selected for the purpose of assessing UV emissions from the mask alignment-exposure units. Based on this value, workers at Perkin-Elmer 120 units involved in normal wafer exposure tasks (with the left-side panel up) would not be exposed to UV levels in excess of the TLV. Maintenance workers (although exposed to UV levels 5 times that experienced by the equipment operators) are also unlikely to receive exposures in excess of the TLV.*

Wet Chemical Stations

Worker exposures to hydrofluoric acid (HF) were monitored at the wet-chemical wafer-etching stations, which use a "laboratory type" chemical bench design. This type of design includes a plastic splash shield, local exhaust slots across the rear of

* This assessment of UV exposures is based on an evaluation of UV radiation in the near spectral range. The emission in the actinic region (200 to 315 nm) could not be measured. Consideration of actinic UV light emission might well reverse the conclusions of this assessment.

the bench, plastic covers over each acid bath, and a perforated deck serviced by an exhaust plenum below the work surface. Based on the area monitoring results (see Table 5), workers involved in wafer etching at these benches were not exposed to detectable levels of HF. Two attempts to judge the efficacy of the bench design by sampling for HF both inside and outside of the hood proved to be inconclusive because no HF was detected in any of the samples.

Worker exposures to organic compounds from the e-beam solvent bench were assessed by using area monitors (see Table 1). The sampling results indicate that these workers are exposed to very low airborne concentrations of the solvents (less than 1 percent of their TLV's). The e-beam solvent bench appears to be effective in containing and exhausting solvent emissions.

Ventilation measurements taken at the acid-etching benches (see Figure 4) indicate that the use of laminar-flow HEPA filters designed to protect the product may contribute to the potential for worker exposure. The use of laminar-flow HEPA filters over these benches results in a new outflow of air from the bench into the work environment. The solvent cleaning benches are equipped with HEPA filters similar to those used over acid benches; however, these work stations have a net inflow of air from the workplace to the bench.

Ion Implantation

Ion implantation operators and maintenance personnel were monitored for exposures to elemental arsenic, arsine, phosphine, boron, and X-rays. During the routine performance of manning the ion implanters, operators are exposed to arsenic (measured as arsine gas) in the range of 0.4 to 1.8 $\mu\text{g}/\text{m}^3$. Maintenance personnel involved in the removal of ion sources or the repair of graphite components are confronted with large emissions of arsenic (presumed to be in the form of arsine gas). During area monitoring of an Extrion 8010 ion source change, arsine was measured near the source at levels of 87 $\mu\text{g}/\text{m}^3$. Workers performing the source change wear full-face air-line respirators and therefore are not exposed to these emissions of arsine.

Area and personal monitoring for phosphine gas was conducted during normal ion implantation operations (see Table 7). Based on these results, it appears that operators performing normal work activities on the Extrion 8010 are periodically exposed to levels of 78 $\mu\text{g}/\text{m}^3$ phosphine gas or approximately 20 percent of the TLV.

Area monitoring was conducted for boron (see Table 8). Monitors located at the controls of the Varian 20-A ion implanters, which use boron trifluoride as a dopant source, detected levels of boron as high as 27 $\mu\text{g}/\text{m}^3$ or less than 5 percent of the TLV (if measured as boron trifluoride).

The results of the Geiger-Muller survey and personal dosimetry monitoring for X-rays indicate that under normal operating conditions ion implantation operators are not exposed to harmful levels of radiation. Area dosimetry measurements indicate, however, that maintenance workers performing tasks or observing the operation of the Extron 8010 could be exposed to elevated levels of X-ray emissions (see Table 9). The actual potential for exposure is not known because maintenance work activities were not observed during the time period over which the dosimetry measurements were being conducted.

Chemical Vapor Deposition

Decomposition product in the form of hydrogen chloride (HCl) was monitored at low-pressure chemical vapor deposition (LPCVD) furnaces. The purpose of the monitoring was to assess the adequacy of scavenger box exhaust ventilation of the furnace openings. Although the potential for HCl emissions from LPCVD furnaces has not been defined (i.e., an uncontrolled process scenario could not be monitored), no emissions of HCl were measured near the LPCVD furnaces when exhaust ventilation was in effect. These results are inconclusive as to the effectiveness of the scavenger box system; the results do indicate that workers are not exposed to HCl during CVD operations.

Diffusion Furnaces

Diffusion furnace operations at Xerox were monitored for airborne phosphate emissions during doping of silicon wafers with phosphorus oxychloride (POCl_3). The diffusion furnace bank

monitored incorporated the use of three ventilation control measures: (1) ventilation of the enclosed source cabinets, (2) ventilation of the furnace tube bank and gas supply line "jungle," and (3) ventilated scavenger boxes equipped with closing doors.

Phosphate emissions were not detected in area samples taken at the diffusion furnaces using POCl_3 (see Table 11). Because no uncontrolled operation scenario could be conducted, the monitoring results are inconclusive as to the effectiveness of furnace controls; the results do indicate, however, that workers are not exposed to POCl_3 or airborne phosphate. Air velocity measurements taken at the scavenger box openings ranged between 450 and 1150 fpm.

Ultraviolet light emissions from wafer-checking operations in the area of the diffusion furnace present a potential exposure hazard at levels measured during the in-depth survey (see Table 12). The extent of this exposure could not be assessed because employee work practices were not observed.

Radio Frequency (RF) Sources

Significant radio-frequency or microwave radiation emissions were detected near one RF generating source (Table 13). This source (an IPC Branson 2000 plasma stripper) produced magnetic and electric near-field energy levels that could result in exposures above the TLV for 13.56-MHz sources. The work habits of Xerox employees, however, prevented any such exposures. Their work regimen prevents them from spending any more

than 1 or 2 minutes near enough to the equipment to be exposed to the levels measured during the in-depth survey.

Emissions due to the electrical field for 450-kHz sources were below the recommended TLV's.

An item of particular interest was the detection of the emission of both magnetic and electrical field hazards from a stripchart recorder attached to the IPC Branson 2000 plasma stripper. The recorder appears to be drawing energy from the plasma stripper and radiating it into the workplace.

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