IN-DEPTH SURVEY REPORT:

CONTROL TECHNOLOGY FOR THE MICROELECTRONICS INDUSTRY AT FAIRCHILD SEMICONDUCTOR SOUTH PORTLAND, MAINE

by

Leslie J. Ungers, C.I.H.
PEDCo Environmental, Inc.
11499 Chester Road
Cincinnati, Ohio 45246

Gary J. Mihlan, C.I.H.
BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

James H. Jones, C.I.H.
National Institute for Occupational Safety and Health
Division of Physical Services and Engineering
Engineering Control Technology Branch
4676 Columbia Parkway
Cincinnati, Ohio 45226

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NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
Division of Physical Sciences and Engineering
Engineering Control Technology Branch
4676 Columbia Parkway
Cincinnati, Ohio 45226

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PLANT SURVEYED:	Fairchild Semiconductor 333 Western Avenue South Portland, Maine 04106
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SURVEY CONDUCTED BY:	Leslie J. Ungers, C.I.H., Gary J. Mihlan, C.I.H., James H. Jones, C.I.H., Robert Willson, C.I.H, Paul Manna
EMPLOYER REPRESENTATIVES CONTACTED:	Rip Dyer, Safety and Industrial Hygiene Coordinator (207) 775-8490
EMPLOYEE REPRESENTATIVES CONTACTED:	None
ANALYTICAL WORK PERFORMED BY:	PEDCo Environmental, Inc. 11499 Chester Road P.O. Box 46100 Cincinnati, Ohio

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. 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 control 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 hazard control measures. Ultimately, the information gathered from these research activities forms a publicly available data base on hazard control techniques 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 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 indicated that substances like arsine might pose an arsenic hazard to microelectronics workers.

BACKGROUND FOR THE FAIRCHILD SEMICONDUCTOR SURVEY

This in-depth survey was performed as part of a larger data gathering effort to characterize basic exposures and describe the processes and controls so that an assessment can be made of the hazard control technology applied within the microelectronic 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 Fairchild Semiconductor facility at South Portland, Maine, was selected for study on the basis of a preliminary walk-through survey conducted on December 4, 1981 (NIOSH 1983). This facility (which is operated by the Fairchild Digital Products Division) allowed NIOSH representatives to observe the fabrication of integrated circuits, an operation that involves a range of process and control technologies.

Six of the many process operations common to the fabrication of integrated circuits were studied in detail: photolithography, wet chemical etching, diffusion doping, ion implantation, 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 Fairchild Semiconductor 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 will address discrete operations and will interrelate those operations only when necessary to improve the reader's understanding. Throughout the discussion the reader will be referred to information sources that provide more detailed descriptions of the fabrication steps if such details are desired.

GENERAL DESCRIPTION

Fairchild's South Portland, Maine, plant was constructed in 1961. The facility, which consists of two concrete block buildings with a combined area of 220,000 square feet, manufactures digital bipolar integrated circuits. Operations include circuit design, wafer fabrication, lead fabrication, assembly, packaging, and research and development activities.

Of a total of 1360 employees, 890 work in the production area (531 on the first shift, 215 on the second shift, and 146 on the third shift). The remaining 270 employees hold administrative positions.

Approximately 230 of the production workers are in the wafer fabrication area. The remaining production employees are in integrated circuit testing, wafer sorting, die scribing and separation, die bonding, packaging, reliability testing, and film production (Beta Film).

CHEMICAL STORAGE

Chemical supplies for the fabrication area are stored in an individual container chase adjacent to the clean room fabrication area. Liquid chemicals are supplied in 1-gallon containers and are transported in carts to the fabrication area, where they are placed in exhausted cabinets that have sprinklers in the walls.

GAS HANDLING SYSTEM

Process gases are supplied in cylinders, which are stored in ventilated cabinets in or near the process equipment. Process gases are distributed to the equipment in welded stainless steel lines and are connected to the equipment with compression fittings. Nitrogen is supplied from a bulk storage tank. This supply, known as house nitrogen, is used as a purge gas. Dual check valves with a relief valve between them are used in the nitrogen lines to prevent contamination of house supplies, cylinder gas supply lines have flow-limiting valves. Dual cylinders of arsine and diborane are provided with regulatory assemblies that automatically switch gas flow from an empty cylinder to a full one. There are emergency hydrogen shutoffs for each area using hydrogen.

Gas cylinders are replaced by workers wearing air-line-supplied respirators. The cylinders are leak-tested by use of a soap bubble test (SNOOP®) or by an ammonium hydroxide vapor test if cylinders contain chlorine compounds (hydrogen chloride, dichlorosilane, silicon tetrachloride, boron trichloride, etc.). Solenoid valves, which stop gas flow in the event of a power failure, are incorporated in the gas handling system within the epitaxial reactor.

The following gases are supplied in cylinders: 1) arsine, 50 ppm in hydrogen and 20,000 ppm (2 percent) in nitrogen; 2) phosphine, 20 ppm and 50,000 ppm (5 percent) in hydrogen; 3) diborane; 4) boron trichloride; 5) hydrogen chloride; 6) silicon tetrachloride; 7) dichlorosilane; 8) silane, 15 percent and 100 percent; 9) ammonia; 10) hexafluoroethane (Freon 116); 11) carbon tetrafluoride (Freon 14); 12) sulfur hexafluoride; 13) Argon; 14) boron trifluoride; 15) nitrous oxide; 16) trichlorofloromethane (Freon 11); and 17) both 15 percent arsine and phosphine in lecture bottles.

MONITORING SYSTEMS

Arsine and phosphine are monitored with a Matheson® Model 8040 located in the service aisle at the rear of the diffusion furnace area. Air sampled from the diffusion furnace area is pulled through a filter tape impregnated with chemical reagents sensitive to arsine or phosphine, manifested by a chemiluminescent reaction that is monitored by the unit. The unit sounds an alarm in the furnace area only when arsine or phosphine levels exceed the Threshold Limit Value (50 ppb and 300 ppb, respectively) (ACGIH 1983).

The facility is installing a TELOS® continuous multipoint arsine/phosphine monitoring system. This system is capable of monitoring 16 remote locations throughout the gas storage and wafer fabrication areas.

Hydrogen is monitored with an MSA® combustible gas detection system at 18 remote sampling points throughout the wafer fabrication area. The unit is calibrated once every 3 months.

VENTILATION SYSTEM

The ventilation system consists of air treatment and supply, air recirculation, and local exhaust ventilation. The wafer fabrication room supply air is cleaned by passing air through a fiberglass prefilter followed by a charcoal bed and high-efficiency particulate absolute (HEPA) filter. The filtration system is housed in the penthouse on top of the building. The air pressure in the clean room is positive to the surrounding areas in the building.

Recirculation of clean room air is restricted to the photolithography area. The room air is supplied through ceiling grates, and return air is exhausted through louvers located in the wall of the room, approximately 3 feet above the floor. Twenty-five percent of the recirculated air supply is fresh makeup air, which is again passed through the filtration system before being distributed. The quantity of air that is supplied or recirculated in the fabrication areas was not reported.

Air is exhausted from the wafer fabrication area either by exfiltration from the room or by local exhaust ventilation of the process equipment. Exhaust air from the arsenic trioxide diffusion furnaces is passed through a fiberglass prefilter, a bag filter, and a HEPA filter. The unit handles 2310 cubic feet of air per minute from the two diffusion furnace stacks. Exhaust from wet chemical benches using nitric and hydrochloric acid is passed through a wet scrubber for treatment. The system treats 4500 cfm of air exhausted by four benches. Additional air treatment includes the use of oil separators that trap oil from pump exhausts. This system, which is reported to be 99.5 percent efficient in the removal of oil from the exhaust air, is used on most oil-sealed pumps.

Supply air intakes are located on top of the penthouse. The nearest exhaust stack is located approximately 100 feet away.

WASTE MANAGEMENT

Liquid process wastes are categorized as acids containing fluorides, all other acids, chlorinated hydrocarbon solvents, Freons, and all other nonchlorinated organic solvents. Wastes are either collected by an operator and transferred to a storage or treatment area or collected by a drain system that connects to a storage tank or treatment facility.

Acids containing fluoride are collected by a separate drain system and stored in two 4200-gallon tanks located within a polypropylene containment tank in a diked area. The collected waste acid is removed by a waste management firm for disposal. Other acids are collected by another separate drain system and directed into an acid tank in which the pH is adjusted with anhydrous ammonia. The treated acids are then released to a publicly operated treatment facility. Chlorinated hydrocarbon solvents, such as 1,1,1-trichloroethane, are directed into still another separate drain system and collected in a 100- to 200-gallon tank. This waste is transferred into 55-gallon drums, which also are collected by a waste management firm for offsite disposal. Freon wastes are collected separately and stored in 55-gallon drums for recycling by a waste management firm. Also collected separately, photoresist wastes are added to the waste nonchlorinated organic solvents.

Waste pump oils are collected and stored in 55-gallon drums. These waste oils are treated as hazardous and disposed of offsite by a waste management firm.

Solid hazardous wastes, such as arsenic trioxide and antimony trioxide, are collected and stored in 55-gallon drums for offsite disposal by a waste management firm. These wastes originate from the diffusion furnace area and from diffusion furnace exhaust air filters. Roughing filters, bag filters, HEPA filters, and personal protective clothing (coveralls) worn by the workers who change the filters are placed in drums for collection and disposed of offsite by a waste management firm.

Fairchild has instituted a pre-production drain authorization program to determine the method and location of a liquid waste disposal for wastes that originate in the fabrication area. Under this system, liquid wastes can only be disposed of in drains specifically identified for that particular substance.

PROCESS DESCRIPTIONS

The fabrication sequence used for the manufacture of bipolar integrated circuits varies with the specific type of device being manufactured. The specific sequence in which these process operations are performed is not presented. A general processing sequence for bipolar integrated circuits is provided by Colclaser (1980) and should be consulted for a more detailed review of the fabrication process. Several process operations occur more than once in the fabrication sequence, and some equipment is used for more than one process operation.

Thermal Oxidation

The silicon wafers used as a substrate for device fabrication are purchased. In the thermal oxidation process, the wafers are oxidized at a high temperature (approximately 900° to 1200°C) in a diffusion furnace assembly that uses a pyrophoric water (hydrogen and oxygen) atmosphere. Hydrogen chloride gas is added to the gas stream periodically for cleaning or gettering both the growing oxide and the oxidation tube of sodium ion contamination (Colclaser 1980). The wafers are loaded into carriers (referred to as boats) that are inserted into the diffusion furnace. The furnace tube is heated to the operating temperature by electrical resistance while the tube is purged with nitrogen. Hydrogen and oxygen are introduced into the tube at a controlled rate. The furnace operating conditions (including temperature, processing sequence, and tube temperature) are adjusted by direct digital control (DDC). The furnace is automatically controlled by feedback control loops that monitor the furnace performance and adjust the conditions to programmed specification (Douglas 1981).

Photolithography

Following thermal oxidation, the wafers are ready for photolithography, which includes 1) primer and photoresist coating, 2) pre- or soft-bake, 3) mask alignment and exposure, 4) development, 5) post- or hard-bake, 6) etching, and 7) photoresist stripping. The wafer is first coated with a primer (which acts as a surfactant) by spin application using either hexamethyldisilizane (HMDS) or bistrimethylsilyacetamide (BSA) in xylene, methyl ethyl ketone, or Freon carrier. The photoresist, which contains a proprietary mixture of organic polymers in a xylene carrier, is spun onto the wafer, and the coated wafer is baked in a resistance-heated oven. At Farichild, this operation takes place in both manual (Type I) and automated (Type II) processes. Automated processes require that the operator only load and unload the cassettes.

The mask pattern is transferred to the coated wafer by ultraviolet light (365 to 415 nm) by use of either projection mask alignment or contact printing. The operator aligns the wafer with the mask by viewing through a split-field binocular microscope. In projection mask alignment, a lens is interposed between the mask and the wafer, and the ultraviolet light source is located behind the mask. Masks used for projection mask alignment are supplied by vendors, whereas those used for contact printing are fabricated by Fairchild from a chrome submaster mask produced by a vendor. The contact mask is a precision glass plate coated with a silver halide emulsion. The mask pattern is transferred from the submaster with ultraviolet light. Exposed masks are developed with a hydroquinone-based solution.

The exposed wafers are developed either by immersion in a developer tank or by spin-on application of the developer. A mixture of n-butyl acetate and xylene develops the negative photoresist, and a potassium hydroxide solution develops the positive photoresist. The developed wafers are rinsed with deionized water and "hard-baked" in a resistance-heated oven.

Wafer Etching

The exposed layer not covered by photoresist may be etched by use of either wet chemical etching or plasma etching techniques. Wet chemical etching is performed by immersing the wafers in an etching solution of: 1) hydrogen peroxide, for etching titanium/tungsten alloy; 2) hydrofluoric acid and ammonium fluoride, for etching silicon dioxide; 3) phosphoric acid, for etching silicon nitride; 4) nitric acid and iodine, for etching silicon; 5) nitric, phosphoric, and acetic acid, for etching aluminum; and 6) nitric and hydrochloric acid, for metal etching. The etching operations are performed in tanks recessed in polypropylene benches (equipped with splash shields) similar to laboratory-type hoods. The acid tanks are located in the rear of the benches. Local ventilation of the tanks is provided by slots around the tank perimeter and/or by slots located across the rear of the bench and through perforated plates in the bench top.

Plasma etching is performed by placing wafers in a field of plasma formed by a radio frequency power source operating at 13.56 MHz. The plasma contains ions, free radicals, and free electrons, which are reactive with the layer to be etched. Selection of the gas used for creating the plasma is based on the individual layer and includes 1) freon and oxygen, for etching silicon dioxide; 2) carbon tetrachloride for etching aluminum; and 3) oxygen, for stripping photoresist. The plasma is formed in a sealed reaction chamber at a vacuum of approximately 0.1 to 20 torr created by an oil-sealed mechanical pump.

Wafer Doping

Doping introduces impurities into the wafer, and alters the electrical properties of the doped area. Wafers are doped at various stages of the processing sequence, either by diffusion or ion implantation. Diffusion is accomplished by exposing the wafer to a high-temperature atmosphere containing the dopant. The operation is performed in a diffusion furnace assembly that uses a solid (arsenic, antimony trioxide, boron nitride), liquid (phosphorus oxychloride, boron trichloride, phosphorus tribromide), or gaseous (arsine or diborane) dopant source. Fairchild uses both direct-digital-control (DDC) diffusion furnaces and hybrid-control diffusion furnaces.

When doping is accomplished by ion implantation, a source material is ionized and passed through an analyzing magnet that collects, accelerates, and implants the desired ions into a target wafer. The ion source, the analyzing and accelerating chamber, and the wafer exposure station are operated at vacuum conditions of approximately 10^{-6} torr. This vacuum is maintained by two sets of pumps, either an oil-sealed pump and a diffusion pump or an oil-sealed pump and a cyrogenic pump. The dopant source is either a gas (boron trifluoride) or a solid (elemental arsenic or phosphorus). The process operation sequence requires the operator to load wafers into the load station of the ion implantation unit individually or in cassettes. Individual wafers are automatically removed from the cassette to a load-lock chamber, transferred to the exposure chamber that is pumped to vacuum with an oil-sealed mechanical pump and implanted with dopant ions. The dosage received by the wafer is automatically controlled. The implanted wafer is either automatically transferred into a cassette or manually removed and loaded into cassettes following implantation. As a final step, the doped wafers are heated in a nitrogen or oxygen atmosphere in a diffusion furnace. The furnace assembly is similar to that of the previously described thermal oxidation.

Epitaxial Growth

A single crystal layer of silicon is deposited on the wafer surface by epitaxial growth in an enclosed chamber. The single crystal silicon layer is deposited during the reaction of dichlorosilane and hydrogen, or silicon tetrachloride and hydrogen. A doped silicon layer is deposited by introducing arsine or phosphine to the reaction chamber. Epitaxial silicon is deposited at high temperature (approximately 950° to 1250°C) in a reaction chamber at atmospheric pressure and heated by either radiant heat or radio frequency radiation. This automatically controlled operation sequence requires the operator to load wafers onto a metal platen or barrel which is then inserted into the reactor chamber. For more detail, the reader should consult Atherton (1981) and Hammond (1978), both of which provide descriptions of epitaxial silicon deposition.

Chemical Vapor Deposition

Another process operation that occurs during the fabrication sequence is the deposition of a thin film on the wafer surface by chemical vapor deposition, in which the solid products of a vapor-phase chemical reaction are deposited on the substrate. Low-pressure chemical vapor deposition (LPCVD) is used to deposit silicon nitride during the reaction of ammonia and dichlorosilane. The operation is performed in a sealed diffusion furnace tube evacuated to approximately 0.4 to 3.0 torr (Baron and Zelez 1978). This process operation requires the operator to load cassettes containing wafers into the furnace. The furnace door is closed, and the sequence and operating parameters are then controlled by microprocessor.

Plasma-enhanced chemical vapor deposition (PECVD) is also used to deposit silicon nitride by the reaction of either 2 percent silane and nitrogen or 100 percent silane and ammonia. The plasma is created by introducing the gases in a 13.65 MHz radio frequency field. The operation is performed under vacuum conditions in a sealed chamber or tube at approximately 0.2 to 1.0 torr. Two PECVD systems are used for silicon nitride deposition at Fairchild. These include an in-line cassette-to-cassette unit and a furnace assembly similar to a diffusion furnace with a radio frequency power source, sealed chamber tube, vacuum system, and a wafer boat. The boat consists of a set of parallel vertical metal plates onto which the wafers are mounted.

The operation sequence requires the operator either to load cassettes containing wafers into the unit (cassette-to-cassette system) or to mount wafers on a series of parallel vertical plates, which are then loaded into the furnace tube. Both types of equipment are automatically controlled by a system microprocessor.

Atmospheric pressure chemical vapor deposition (CVD) is used to deposit a phosphorus-doped silicon dioxide layer by the reaction of 100 percent silane, oxygen, and phosphine. The operation sequence requires the operator to load wafers onto flat plates or platens and then insert them into the unit. Once the platens are inside the unit the sequence is automatically controlled. A metal layer is deposited on the wafer surface by radio frequency sputtering, electron beam evaporation, or thermal evaporation. The metal is deposited on the wafer surface in a sealed reaction chamber or bell jar that is maintained at a vacuum of approximately 10^{-6} torr by an oil-sealed mechanical pump and an oil diffusion pump or a cryogenic pump. Radio frequency sputtering (at 13.56 MHz) is used to deposit aluminum, aluminum/copper, platinum, titanium/tungsten, and gold; electron beam evaporation is used to deposit aluminum; and thermal evaporation is used to deposit gold. The process operation sequence requires the operator to load the wafers in a planetary structure or platen and then place it inside the process equipment. From this point on the process operation is automatically controlled by a system microprocessor.

Photoresist Etching

Process operations such as photolithography, doping, metalization, and chemical vapor deposition may be repeated several times during wafer fabrication. Between these processing steps, wafers may be cleaned by use of a solution consisting of nitric and sulfuric acid, nitric and hydrochloric acid, or hydrofluoric acid. Photoresist may be stripped by oxygen plasma etching or by wet chemical methods. The latter method may entail the use of 1) phenol and perchloroethlyene, 2) sulfuric acid and hydrogen peroxide, 3) 1,1,1-trichloroethane, or 4) isopropanol. These wet chemical operations are performed in partially enclosed bench stations (equipped with splash shields) similar to laboratory hoods. The stations are ventilated by local exhaust slots at the rear of the benches, around the perimeter of the immersion tank, and through perforations in the bench surface.

Metalization

Following gold sputtering onto the wafer surface, a photoresist laminate film is applied to the wafer, which is then exposed to a mask pattern by using ultraviolet light. The pattern exposes areas of the wafer that will serve as electrical interconnections to the individual die. The exposed wafer is developed by the use of 1,1,1-trichloroethane to uncover the underlying gold layer. A gold film is then plated onto the exposed areas in a potassium cyanide gold electroplating process. The laminate is stripped from the wafer with methylene chloride, and the exposed gold layer is etched by use of a cyanide solution. A titanium/tungsten layer exposed by the gold etching process is then stripped using hydrogen peroxide. The process produces gold bumps that provide contacts with the film carrier in the final package. A detailed review of this process, known as wafer bumping, is provided by Liu et al. (1980).

Final Processes

The final step in the wafer fabrication sequence is backside grinding of the wafer. The wafers are first cleaned with isopropanol, then mounted (backside exposed) on a metal plate that has a laminate sheet adhesive. The exposed backside of the wafer undergoes a process known as Blanchard grinding, after which the wafers are removed and cleaned with isopropanol. Additional operations that may be performed include backside diffusion and backside gold deposition.

Following wafer fabrication, each die (i.e., an individual integrated circuit) on the wafer is electrically tested. The wafer is scribed, and each individual die is attached to a Beta film carrier. Most of them are shipped overseas. Film leads are attached to the gold bumps on the die, and the device is encapsulated and placed in a ceramic package.

The Beta film (i.e., beam tape) carrier is manufactured by Fairchild in a separate area adjacent to the clean room wafer fabrication area. The carrier consists of a copper film with an adhesive and polyimide layer. Initially, the adhesive-coated polyimide film is cut and perforated, and then a copper film is laminated to it. The laminated film is cured in a nitrogen-purged oven at 120°C. The copper is cleaned with sulfuric acid, followed by sodium persulfate and water. The photoresist laminate film is applied to the tape with a heated roller. The film carrier pattern is transferred to the film by exposure with ultraviolet light at 380 nm. The exposed film is developed with butyl Cellosolve, rinsed, and dried. The backside of the film is coated with silk screen ink in an acetone carrier by use of a roller coating process. The film is cured in a nitrogen purged oven and cleaned with sodium persulfate. The exposed copper film is then etched with an ammonium hydroxide spray, water-rinsed, and air-dried. The remaining photoresist and backside coat film is stripped, rinsed in acetone, dried, and then inspected before shipment. The process is a continuous automated operation. A detailed review of beam tape carrier fabrication is provide by Cain (1978) and Hayakawa et al. (1979).

METHODOLOGY

The in-depth survey at Fairchild's South Portland plant included sampling for chemical agents, monitoring for physical agents, and measuring of control parameters. The sampling apparatus, instrumentation, and analytical methods used during this in-depth survey are presented herein.

WORKPLACE MONITORING FOR CHEMICAL AGENTS

Several chemical agents were sampled during the in-depth survey. 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 1982).

Antimony

Antimony concentrations in the workplace air were determined by using the NIOSH reference method for trace metals (P&CAM 173). Antimony compounds were collected by drawing a measured volume of air through a 0.8-μm 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 9.0 µg was achieved during these analyses. The analytical results were corrected for reagent and filter blanks. The sampling results were reported in micrograms per cubic meter.

Arsenic (Collected as Arsenic Trioxide)

Arsenic concentrations in the workplace air were determined 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-µm mixed-cellulose ester membrane filter (Millipore MCE or equivalent) using 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 rotometer setting used to determine the sample flow rate and volume was 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 (50-200 ml/min) stroke pump (SKC model number 222-3). The analyte was desorbed with nitric acid and analyzed by using 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 adsorbed 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^R 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 rotometer setting used to determine the sample flow rate and volume was corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Hydrogen Fluoride

Breathing zone samples were taken during the first (primary) production workshift of the day. 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-µg detection limit. The analytical results were corrected for sample and reagent blanks. The rotometer setting used to determine the sample flow rate and volume was corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Sulfuric Acid

Sulfuric acid concentrations in the workplace air were determined by using the NIOSH Reference Method for sulfuric acid (S174). Sulfuric acid mist was collected on a 0.8-µm mixed-cellulose ester-membrane filter (Millipore type MCE or equivalent) by drawing air through the filter with a personal high-flow pump (Dupont P2500, MSA Model G, or Bendix BDX-55-HD). The analyte was extracted from the filter with a solution of distilled water and isopropyl alcohol. The pH of the extract was adjusted with dilute perchloric acid and titrated with 0.005M barium perchlorate. Thorin was used as an indicator. A detection limit of 18 µg was achieved during these analyses. The analytical results were corrected for filter and reagent blanks. The rotometer setting used to determine the sample flow rate and volume was corrected for changes in temperature and pressure. The sampling results were reported in micrograms per cubic meter.

Nitric Acid

Nitric acid concentrations in the workplace air were determined by using the NIOSH Reference Method for nitric acid (nitrate ion) (S319). Nitric acid mist was collected in distilled water 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 content of the impinger was analyzed by direct potentiometry using an ion-specific electrode; a detection limit of 500 µg was determined. The analytical results were corrected for reagent blanks. The rotometer setting used to determine the sample flow rate and volume was 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 using an adsorption on charcoal, desorption with CS_2, and analysis by mass spectroscopy. Organic compounds were collected by drawing a measured volume of air through a charcoal tube with a low-flow (50-200 ml/min) stroke pump (SKC Model No. 222-3). The analyte was desorbed with 1 ml of CS_2 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 detection limit for this method varies with the organic compound being analyzed. However, an OR column detection limit of 20 nanograms can usually be achieved. 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.

WORKPLACE MONITORING FOR PHYSICAL AGENTS

Two physical agents were monitored during the in-depth survey: radio-frequency radiation and gamma or X-radiation. 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 Nuclear Chicago Model 2650, Serial Number 2009 (Battelle ID 86531) Geiger-Müller 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 mrems). The Geiger-Müller survey results were reported in milliroentgens per hour (mR/hr), and the dosimeter readings were reported in millirems (mrem) for the specific time period monitored.

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® Model 441 air velocity meter. The measurement results were reported in feet per minute (fpm). A multi-point 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, safe work practices, and the use of personal protective equipment.

In general, a system that includes these control measures is required to provide worker protection under normal operating conditions as well as under conditions of process upset, failure, and/or maintenance. Process and workplace monitoring devices, 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 proper use and 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 application of these measures at the Fairchild Semiconductor facility for the product of bipolar integrated circuits is discussed.

DESCRIPTION OF PROGRAMS

Industrial Hygiene

The facility has a full-time industrial hygienist, who is responsible for industrial hygiene, safety, security, training, and medical. The corporate headquarters in Mountain View, California, provides additional assistance in industrial hygiene and safety.

Worker exposure has been monitored during normal operations, maintenance, and emergency conditions (such as chemical spills). The monitoring equipment includes a portable infrared analyzer (MIRAN® 1A), direct-reading detector tubes, midget impingers, and charcoal tubes. X-ray radiation emissions and operator exposures in the ion implantation area are monitored by the use of radiation film badges and a Geiger-Müller survey meter.

Measurements of the ventilation system are limited to the monitoring of face velocities of local exhaust ventilation systems with a swinging vane anemometer. The air exhausts from some operations also require careful monitoring to assure product quality. Facility engineering personnel and an industrial hygienist perform these measurements.

Scheduled renovations to the wafer fabrication area will include the use of magnehelic gauges to monitor local exhaust ventilation from the diffusion furnaces. The ventilation system design drawings have recently been updated to trace all process ventilation systems from the point of exhaust to the air cleaner and/or exhaust fan. This documentation was required for emergency response planning and to identify all the agents that could potentially be exhausted through a given system. It was also used to determine whether the exhaust system was compatible with the planned facility renovations.

An emergency response team has been organized to handle chemical spill hazards and emergency evacuation. Emergency drills are performed twice a year. Fairchild has also established an internal emergency telephone number for reporting accidents or hazardous situations. Telephones are accessible throughout the wafer fabrication area. The communication system is also on emergency power, and safety personnel and chemical spill teams, as well as other key supervisors, are provided with two-way radios.

Education and Training

Fairchild's training programs cover safety practices, materials handling, the use of personal protective equipment, emergency response, and hazard reporting. Included are chemical safety, handling and labeling of hazardous wastes, use of self-contained breathing apparatus and respirators, and emergency evacuation procedures. The training programs are offered upon employment and twice a year thereafter as a refresher.

A 1-hour weekly chemical training program is offered to all new employees. Specialized training for new employees or employees new to a specific production area is the responsibility of the area supervisor. Supervisors instruct the new employees on safety items, which are also outlined on a safety review checklist, including 1) specific job safety requirements; 2) emergency evacuation procedures; 3) required action in response to specific alarms; 4) the location of emergency showers, eye wash stations, fire extinguishers, and telephones; 5) the safety function of exhaust fume hoods; 6) eating and smoking policies; 7) working alone policy; 8) proper chemical storage procedures; 9) aisle clearance; 10) medical department location; 11) accident or hazardous situation reporting; and 12) housekeeping practices. Training is also provided by other facility supervisors, and a 2-hour tour is conducted by the industrial hygienist.

Respirators and Other Personal Protective Equipment

The safety and medical departments at Fairchild have specific personal protective equipment requirements for each area in the plant, including production, maintenance, support facilities, and office areas. The requirements cover the use of safety glasses, contact lenses, ear and head protection, and the designation of radiation and nonsmoking areas. The general requirements are supplemented by specific task or job functions within the areas, and safety specifications are written for each piece of process equipment.

Workers are required to wear safety glasses in the wafer fabrication area. Open-toe shoes and contact lenses are prohibited. Specific requirements by job category or task include the following: 1) apron, gloves with gauntlets, and face shields for operators, 2) aprons, acid gloves with gauntlets, face shields, and boots for chemical technicians who transport or mix chemicals, 3) air line-supplied respirators for technicians who change gas bottles, 4) respirators (1/2-face with goggles) for maintenance workers who change arsenic and antimony air filters and clean silicon dioxide deposits from the vapor-phase deposition system, and 5) air line-supplied respirators for technicians who change the plasma etching system cold trap.

Medical Program

The facility employs two nurses full time and one part time to provide health services on all three production shifts. Emergency care services and health education are provided by the nurses. The facility also has a physician on the premises on a part-time basis.

All personnel are required to undergo a preplacement medical examination and a periodic examination (every 1 to 2 years). Fabrication area workers and chemical mix operators are required to have chest X-rays. Workers in areas where noise levels are greater than 85 dB(A) receive periodic hearing examinations, and vision testing is required for all employees. All fabrication area workers are required to have blood tests, including a full blood profile. All workers in areas where arsenical compounds are used must give urine samples to determine urinary arsenic levels.

Housekeeping

Housekeeping and maintenance activities are a necessary part of maintaining product quality. Specific housekeeping procedures that were identified by the plant as preventing worker exposures to chemical agents include the use of a portable vacuum system to clean areas where antimony trioxide powder is used. The system is used for routine cleaning and to control dry spills.

PHOTOLITHOGRAPHY

Photolithography includes the following operations: 1) spin-on application of one of two primers, bis-trimethyl silyacetamide (BSA), or hexamethyldisilizane (HMDS); 2) drying; 3) spin-on of photoresist; 4) soft-baking; 5) wafer exposure by projection mask alignment or contact printing; 6) spin-on application of a developer solution, either potassium hydroxide or n-butyl acetate and xylene; 7) hard-baking; and 8) wafer inspection. At Fairchild these operations are contained in tunnel-like work areas. The two different tunnel designs observed during the survey are presented in Figure 1. The lithographic process equipment is located on both sides of an access aisle (Type I) or on one side of the aisle (Type II). HEPA filtration systems are located in the air supply intake to the photoresist application

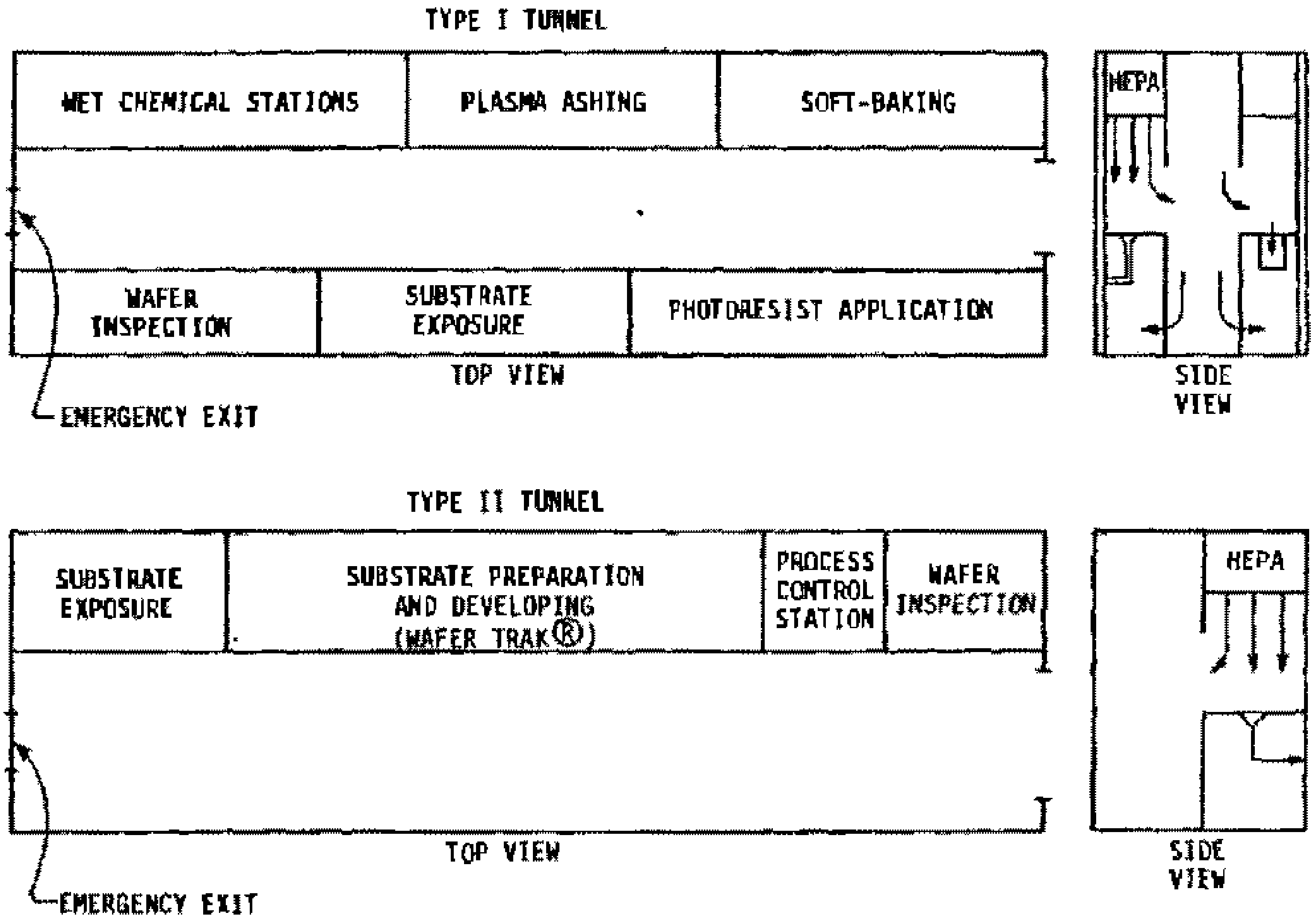

Figure 1. Tunnel layout of photolithography operations.

and substrate exposure stations in Type I tunnels and above all process operations in Type II tunnels.

Type I Tunnels

Air is removed from the room at the floor level through slots running the length of the side walls of the tunnel, which act as return air plenums. The single HEPA filters above the work stations deliver approximately 1660 cfm of air downward onto the process equipment at an average velocity of 80 fpm. The air is directed downward by clear plastic shields hanging from the front edge of the units. The estimated quantity of air exiting the unit from the front work area is 2020 cfm (average velocity is 105 fpm).

Type II Tunnels

Air is supplied to the work station through vertical laminar flow HEPA filter units located above all the process equipment. The air is directed downward by clear plastic panels that hang across the front of the work area. Air is removed from the tunnel by return-air slots located at three levels along the opposite wall--6 inches above the floor, at a height of 4 feet, and at the ceiling. Each slot runs the length of the tunnel along the side wall opposite the process equipment. Air also leaves the tunnel through panels located at the base of the emergency exit door at the closed end of each tunnel. This air exhausts into a closed corridor that acts as a return-air plenum servicing five photolithography tunnels.

Approximately 4800 cfm of air is supplied to the Type II tunnels through HEPA filter units. Air velocity measured at the face of the work area between the shield and the work surface is 200 fpm, with an estimated air flow of 6080 cfm. Return-air removed from the tunnel by exhaust slots along the rear tunnel wall is estimated to be 7960 cfm, which indicates that some air is being drawn into the tunnel from the personnel entrance. Local exhaust ventilation in Type II tunnels includes the exhaust of three spin platforms. The flow rate of the platform exhausts could not be calculated because the exhaust ducts were inaccessible. Face velocity at the platform could not be determined because of the nature of the enclosure and the effect that air flow from the HEPA filter has on the measured flow.

Monitoring Results

The workplace air in both Type I and II photolithographic tunnels was monitored for seven organic substances: HMDS, acetone, methyl ethyl ketone (MEK), n-butyl acetate, xylene, Cellosolve acetate, and methyl cellosolve. The Type I tunnels represent old process technology and control system configurations; the Type II tunnels represent photolithographic operations with a more state-of-the-art approach to product protection and emission control.

Results of Monitoring Conducted in Type I Photolithographic Tunnels--

Two Type I tunnels were monitored using area sampling methods. The results are presented in Table 1. The two tunnels are identified in Table 1 as Aisle B and Aisle C. Eight individual samples

TABLE 1. SUMMARY OF AREA MONITORING FOR ORGANIC SUBSTANCES IN TWO TYPE I PHOTOLITHOGRAPHIC TUNNELS

				Measured concentrations						
Monitoring method	Job description or location of monitor	Charcoal Sample duration (h min)	Sample volume (liters)	Hexamethyl-disilizane (ppm)	Acetone (ppm)	n-butyl acetate (ppm)	Xylene (ppm)	Cellosolve acetate (ppm)	Methyl Cellosolve (ppm)	Methyl ethyl ketone (ppm)
Area	Aisle B photo-lithographic operation	3 25 3·01	21 1 18 7	0.31 0 14	0 06 0 04	0 04 0 07	2 34 2 38	nd nd	nd nd	nd nd
	Aisle B photo-lithographic operation	2 35 3 48	29 41 43.36	nd 0 08	0 06 0 08	0 07 0 07	1.74 2.39	nd nd	nd nd	nd nd
	Aisle C photo-lithographic operation	3 36 3 17	23.3 21 3	0 17 0 09	0 05 0 05	0 06 0 06	4 55 3.08	nd nd	nd nd	nd nd
	Aisle C photo-lithographic operation	2 27 3 31	27.5 39 5	0.22 0.03	0 10 0 12	0.07 0.07	5.39 4 55	nd nd	nd nd	nd nd

nd - No concentration of solvent was found above the detection limit of the analytical method. Detection limits achieved during this analysis were hexamethyldisilizane - 8 μg, acetone - 1 μg, n-butyl acetate - 1 μg, methyl cellosolve - 1 μg, and methyl ethyl ketone - 1 μg were taken during the survey of Type I photolithographic tunnels. The duration of these area samples ranged from a low of 2 hours and 27 minutes, to a high of 3 hours and 48 minutes. The average sample volume was approximately 28 liters.

Results of Monitoring Conducted in Type II Photolithographic Tunnels--

Two Type II tunnels were monitored by both area and personal sampling methods. The results are presented in Table 2. The two tunnels are identified in Table 2 as either Mod. 6 or Mod. 4.

Area samples were taken only in one Type II tunnel (Mod. 6) between the wafer checking stations and the automated Wafer-Trak® and between the Wafer-Trak^R and the alignment and exposure station. The duration of the area samples was limited to just a little over an hour.

Personal samples were taken in both Type II tunnels. The samples were taken on four workers involved in wafer checking, three workers performing mask alignment and exposure of wafers, and one maintenance worker. Sample durations ranged in length from 2 hours and 4 minutes to 5 hours and 38 minutes.

Work Practices

The work practices and activities of workers involved in photolithographic operations vary according to whether the operations are being performed in a Type I or Type II tunnel. This difference is directly related to the process technology being used in each of the tunnels.

TABLE 2. SUMMARY OF PERSONAL AND AREA MONITORING FOR ORGANIC SUBSTANCES IN TWO TYPE II PHOTOLITHOGRAPHIC TUNNELS

Monitoring method	Job description or location of monitor	Sample duration (h min)	Sample volume (liters)	Measured concentrations					
				Hexamethyldisilizane (ppm)	Acetone (ppm)	n-butyl acetate (ppm)	Xylene (ppm)	Cellosolve acetate (ppm)	Methyl Cellosolve (ppm)
Personal	Wafer checking in Mod 6, M20 aisle	2 41 2 54	17 4 18 8	nd nd	0 05 0 07	0 03 nd	0 01 0 01	nd nd	nd nd
	Time-weighted average concentration				0 06	0 01	0 01		
	Wafer checking in Mod 6, M20 aisle	3 09 2 48	35 3 31 4	nd nd	nd 0 59	0 01 0 02	0 08 0 15	nd nd	nd nd
	Time-weighted average concentration				0 28	0 01	0 12		
	Alignment and exposure of wafers in Mod 6, M20 aisle	2 35 4 07	22 6 36 0	nd nd	0 06 0 20	0 03 0 02	0 14 0 09	0 04 nd	nd nd
	Time-weighted average concentration				0 15	0 02	0 11	0 02	
	Alignment and exposure of wafers in Mod 6, M20 aisle	5 18 5 14	129 8 128 0	nd nd	nd 1 28	0 01 0 01	0 08 0 10	nd 0 01	nd nd
	Time-weighted average concentration				0 64	0 01	0 09	<0 01	
Area	Wafer checking station Mod 6, M20 aisle	1 16	13 6	nd	3 74	nd	0 21	nd	nd
	Alignment and exposure station in Mod 6, M20 aisle	1 20	15 3	nd	0 39	nd	0 06	nd	nd
Personal	Wafer checking in Mod 4, M14 aisle	3 01 5 38	73 9 138 0	nd nd	nd 0 02	0 01 0 01	0 05 0 34	nd nd	nd nd
	Time-weighted average concentration				0 01	0 01	0 24		
	Wafer checking in Mod 4, M14 aisle	2 55 3 31	33 3 40 1	nd nd	0 07 0 15	0 09 0 07	0 15 1 90	nd nd	nd nd
	Time-weighted average concentration				0 12	0 08	1 11	nd	
	Alignment and exposure of wafers in Mod 4, M14 aisle	1 18 2 36	17 4 16 1	nd nd	nd	0 07 0 05	0 07 0 10	nd	nd nd
	Time-weighted average concentration					0 06	0 08		
	Maintenance in Mod 4, M14 aisle	2 28 2 05	28 23 23 69	nd nd	2 53 1 25	0 02 0 02	0 36 0 33	nd nd	nd nd
	Time-weighted average concentration				1 55	0 02	0 35		

nd - No concentration of solvent was found above the detection limit of the analytical method Detection limits achieved during this analysis were hexamethyldisilizane - 8 µg, acetone - 1 µg, n-butyl acetate - 1 µg, methyl cellosolve - 1 µg, and methyl ethyl ketone - 1 µg

In Type I tunnels the area samples were taken near the photoresist application station. The air sampling pump was located at "head" level between the photoresist spin-on equipment and wafer-baking unit. During the sampling effort, as many as four workers would be operating equipment in the Type I tunnel. Workers in Type I photolithographic tunnels do not remain positioned in front of the photoresist application station for long periods of time. A majority of their workday is spent at other work stations in the tunnel. A worker begins a work activity cycle by loading wafers into the spin-on operation. Following load-in, the worker starts the process equipment, observes its operation to assure that the desired treatment of the wafers is being achieved, and then leaves the area to attend to other tasks within the tunnel. The worker will return periodically to observe the process operation and finally to assist in the load-out of wafers from the baking oven.

Sampling in the Type II photolithographic tunnels was conducted by both personal and area monitoring methods. Area sampling was conducted at each of the two work stations located in the Type II tunnels. Personal samples were collected from alignment and exposure workers, wafer checkers, and a maintenance worker. Because operations in Type II tunnels are more automated than in Type I tunnels, only two full-time process workers are required.

The alignment and exposure workers remain seated at their work stations for most of the workday. Short excursions from their seated work activities occur when it is necessary to load wafers into the Wafer-Trak® system or check on its operation.

The wafer checkers also remain seated at their work stations throughout most of the workday. Some excursions are made to load or unload wafers, to check on the operation of the Wafer-Trak® system, or on occasion, to leave the tunnel to transfer wafers to the plasma etching station.

The maintenance worker monitored during this survey remained in a Type II tunnel for most of the sampling period. The maintenance activity was limited to the Wafer-Trak® system; the maintenance worker had partially disassembled the Wafer-Trak® system to observe, clean, and adjust the equipment.

Figure 2 is a diagram showing the position of photolithographic workers, the location of area and personal samplers, and the range of worker movement during normal work activities.

WET CHEMICAL STATIONS

Wet chemical stations are used at Fairchild to clean wafers, to etch or strip deposited layers, or to clean components of certain process equipment (see wafer-etching section under Plant Process Description). Wet chemical stations that were evaluated during the in-depth survey included 1) ventilated stainless steel benches for cleaning photolithography equipment parts with xylene, and 2) ventilated plastic benches with recessed wells for cleaning, etching, or stripping wafers by immersion in an acid solution.

The xylene cleaning station is a stainless steel bench in a laboratory-type hood. The exhaust hood encloses the unit on

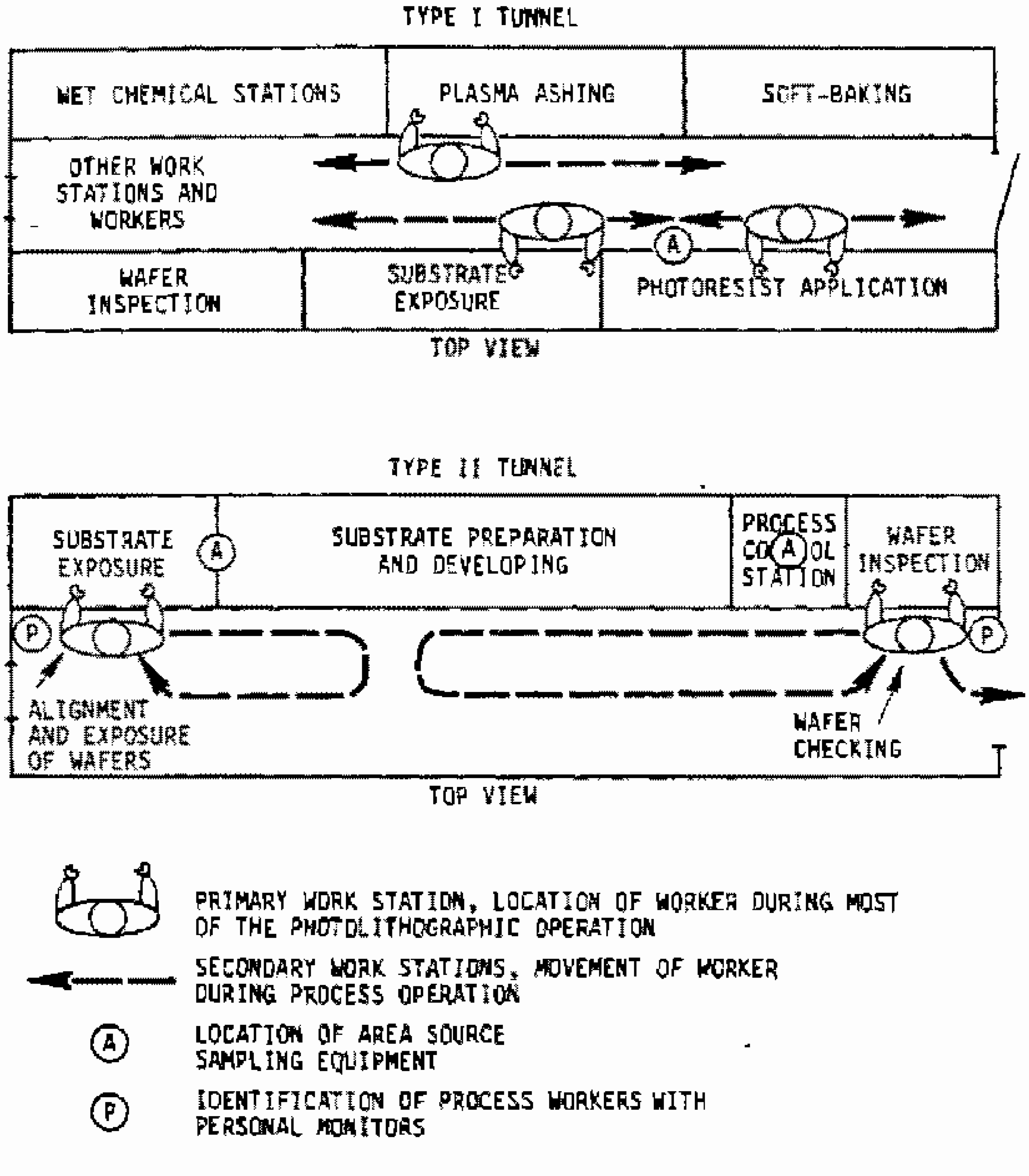

Figure 2. Pictorial diagram of work activities and location of area and personal monitors during photolithographic operations.

three sides, and a flexible plastic shield runs across the front of the bench. The shield is used to decrease the open-face area of the bench. The open-face area is 500 in.^{2} with the shield down, the average face velocity is 83 fpm, and the estimated volumetric flow rate is 290 cfm. Measurements obtained with the shield up resulted in an open-face area of 1356 in.^{2} and an average face velocity of 44 fpm.

The xylene cleaning bench is vented by two slots (17 x 1.75 in.) located at the rear of the bench. The average slot velocity ranged between 750 and 975 fpm for a combined estimated volumetric air flow of 360 cfm. A solvent well in the bench surface contained a tank of xylene at room temperature (22°C). Although a set of slots were located around the perimeter of the well to control solvent vapor emissions, no air flow was detected.

Etching, cleaning, or stripping of wafers is achieved by immersing the wafers in an appropriate solution. The operations are performed in plastic benches with local exhaust ventilation provided by slots across the rear of the bench, around each solution tank perimeter, and through a perforated deck that is vented to an exhaust plenum below the work surface. The basic design of the wet chemical bench is shown in Figure 3, with variations of the bench design as indicated. Measurements taken at the bench include face velocity, slot velocity, tank slot velocity, and air velocity at the perforated deck.

Dimensions of both acid and solvent benches and local exhaust ventilation were obtained and the air flow was estimated in cubic feet per minute. These results are summarized in Table 3.

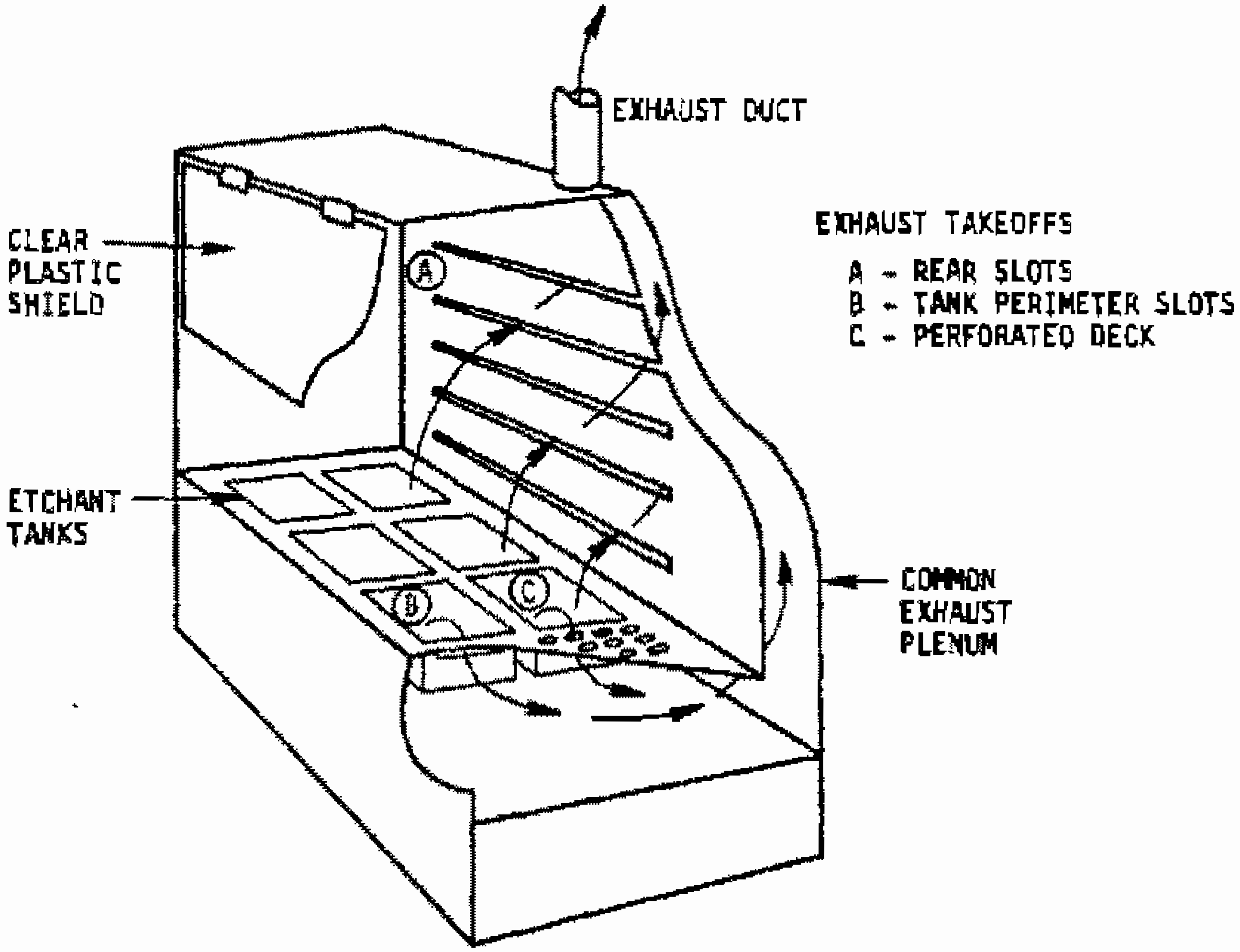

Figure 3. Cut-away view of wet chemical station.

TABLE 3. SUMMARY OF VENTILATION MEASUREMENTS FOR WET CHEMICAL STATIONS

Bench type	Face velocity (fpm)	Air flow (cfm)	Slot velocity (fpm)	Air flow (cfm)	Tank slot velocity (fpm)	Air flow (cfm)	Agents
Cleaning station	80	350	750-975	200-360	Neg.	0	Xylene
Acid cleaning	120	1420	1190-3100	480	170	110	HF
					70	60	H_2SO_4/H_2O_2
					105	100	HNO_3/HCl
Metal etching	110	1240	625-1900	210	70	30	HF
					100	40	HF
					90	80	H_3PO_4/HNO_3
					100	80	H_3PO_4/HNO_3
Acid cleaning	165	1180	780-1560	550	30	30	HF
					50	30	H_2SO_4/HNO_3
					50	40	HNO_3/HCl
Acid cleaning[*]	130	790	700-1450	390	50	30	HF
					55	30	NH_4OH/H_2O_2
					50	40	HF
Acid cleaning[†]	140	1280	1350-1500	900	65	100	$H2^{SO_4}/H_2O_2$
					70	100	H_2SO_4/H_2O_2
Acid Cleaning	120	1400	1390-2000	390	55	40	$HNO3/^{H_2SO_4}$
					120	110	HF
					125	80	HNO_3/HCl

[*] Additional local exhaust ventilation provided by an exhaust plenum below a perforated deck with an average face velocity of 150 fpm and air flow of 70 cfm

[†] Additional local exhaust ventilation provided by an exhaust plenum between perforated deck along the front edge of the bench with an average face velocity of 180 cfm and air flow rate of 60 cfm.

Monitoring Results

Three chemical substances were monitored at wet chemical stations during the survey of the Fairchild integrated circuit fabrication facility: hydrofluoric acid, sulfuric acid, and nitric acid. Personal sampling methods were used to monitor for hydrofluoric and sulfuric acids. Area monitoring was conducted only on wet chemical stations where nitric acid was used. The area source monitoring for nitric acid was performed both inside and outside of the hooded acid baths in an attempt to estimate the hood efficiency of the wet chemical station.

Table 4 presents the results of the personal sampling for both hydrofluoric and sulfuric acid. Personal monitoring of workers for exposure to hydrofluoric and sulfuric acids was conducted on four employees. Personal samples for hydrofluoric acid were taken on a worker involved in wafer etching and on a chemical handler.

Two of the nitric acid samples were taken just inside the plastic shield located on the hooded wet chemical station and two samples were taken outside the plastic shield. The results of the area sampling effort to detect nitric acid concentrations proved unsuccessful because all of the analyses showed nitric acid to be below the detection limit (500 µg) of the NIOSH Reference Method (S319).

Work Practices

The jobs of the two workers (the operator and the chemical handler) monitored for exposure to hydrofluoric acid are markedly

TABLE 4. SUMMARY OF PERSONAL MONITORING FOR HYDROFLUORIC AND SULFURIC ACIDS AT WET CHEMICAL STATIONS

Chemical agent	Monitoring method	Job description	Sample duration (h:min)	Sample volume (liters)	Measured concentration ($\mu g/m^3$)*	Time-weighted average concentration ($\mu g/m^3$)
Hydrofluoric acid	Personal	Wafer etching	1.02	65.7	19.8	
			0.45	47.7	14.7	
			1:01	64.7	9.3	14.6
		Chemical handling	1:08	71.4	26.6	
			0:59	62.0	12.9	
			1:01	64.0	12.5	17.6
Sulfuric acid	Personal	Photoresist etching	1:25	204.0	1470	
			1.29	213.6	<84†	0.09
			1:38	199.9	<90†	
			2:17	279.5	<64†	
			1.29	181.6	<99†	0.0

* Measured concentration determined as (sample - field blank)/sample volume.

† Analytical results below detection limit of 18 µg.

different. Their exposures represent both controlled and uncontrolled situations. The operator involved in wafer etching spends only a small portion of the workday at the wet chemical station (estimated by the operator to be 20 percent). The remainder of this individual's time is spent at stations opposite the wet chemical station. The work performed at the wet chemical station consists of loading and unloading wafer cassettes from etching and deionized water baths.

The chemical handler spends a portion of time at the chemical wet stations (estimated by the operator to be 50 percent) and the other half is spent transferring acid containers to and from storage. The chemical handler loads or replenishes etchant baths with acid, an activity that often involves tasks (i.e., pouring) that require reaching inside the hooded wet station. This work activity has the potential to disrupt air flow to the exhaust slots and to cause some release of acid fumes to the workplace air.

Two photoresist etching workers were monitored for exposure to sulfuric acid. The photoresist etching is performed in the photolithography tunnels as part of the wet chemical operation. The diagrams presented in Figure 4 summarize these work activities.

DIFFUSION FURNACE ASSEMBLIES

Diffusion furnaces operating at atmospheric pressure are used for 1) thermal oxidation of the wafers; and 2) doping of wafers, which involves the use of boron trichloride, phosphorus

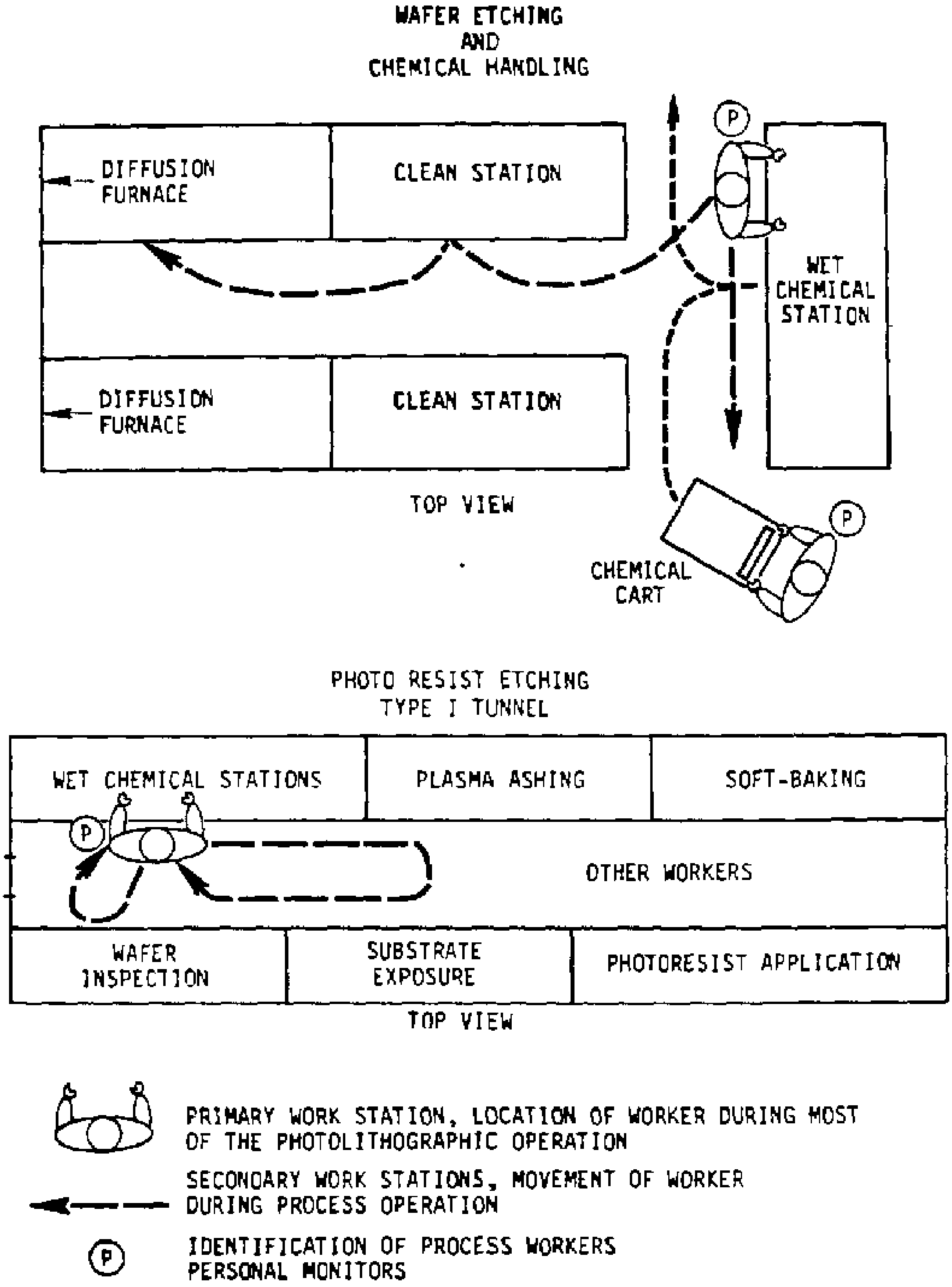

Figure 4. Pictorial diagram of work activities and location of personal monitors during wet chemical operations.

tribromide, phosphorus oxychloride, antimony trioxide, boron nitride, arsine, and diborane. The diffusion furnace assemblies consist of a furnace cabinet containing the furnace tubes and heating elements, a clean station where wafers are manually or automatically loaded into the furnace, a source cabinet, and a control console. The source cabinet is enclosed and vented by a local exhaust. A ventilated scavenger box positioned at the furnace tube end provides control of gas and particulate emissions from the tube opening. The furnace cabinet is also enclosed and ventilated. Several variations of this basic diffusion furnace design that were observed throughout Fairchild's facility are described in the following subsections. Figure 5 presents the basic components of a diffusion furnace and its associated work stations.

Work Practices

The characteristics of the work activities of furnace operators generally do not change with the type of material being diffused; the basic interaction of worker with equipment remains much the same. Because of the basic similarities between the activities of workers at various diffusion furnace assemblies, these activities are described only once in this section. The results of monitoring for various toxic substances around the diffusion furnace work areas are presented later in this report under specific subtitles.

During the in-depth survey it was noted that one worker was responsible for a single bank of diffusion furnaces (i.e., four

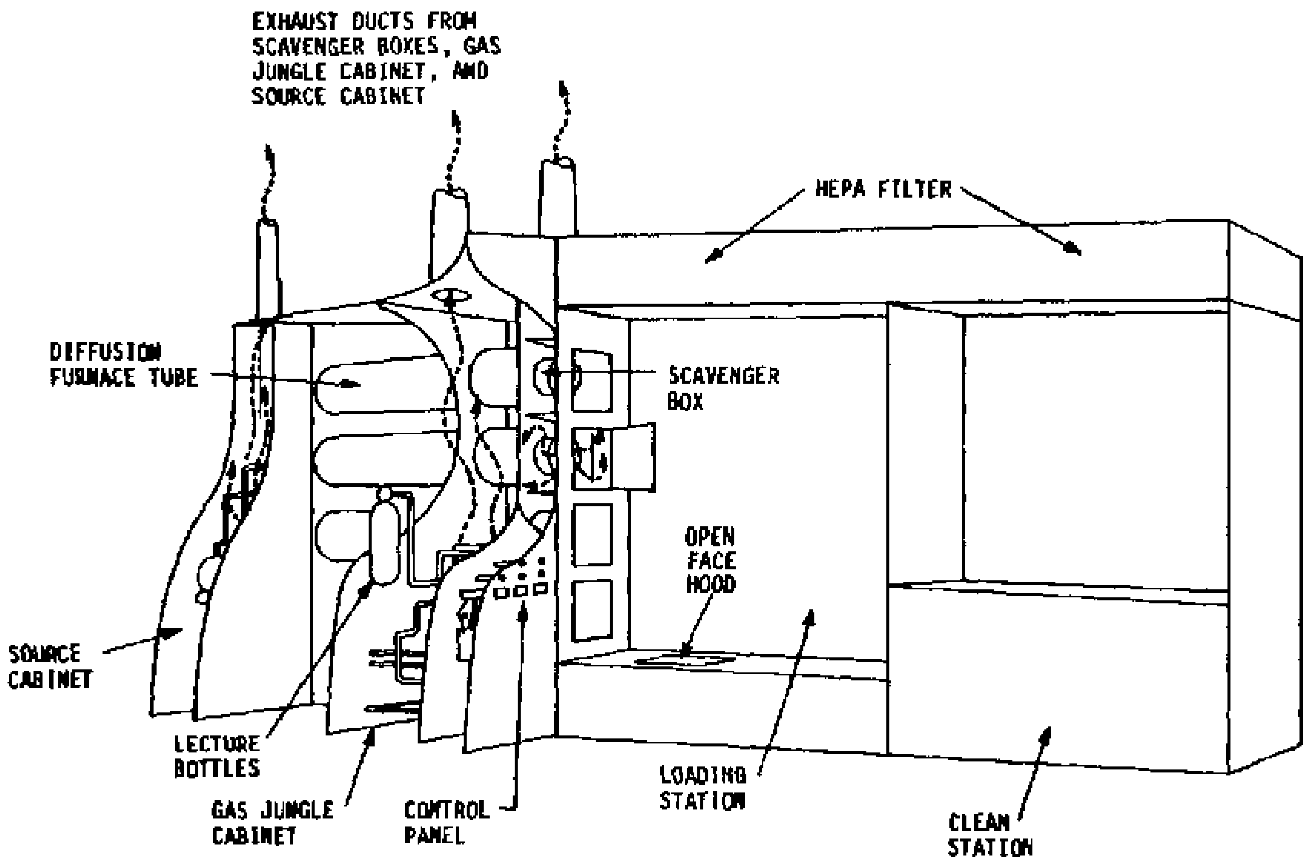

Figure 5. Diffusion furnace and associated work stations.

diffusion tubes). In some cases, however, more than one process worker was performing tasks in the vicinity of the diffusion furnace tubes. For this reason, the sampling results may reflect workplace exposures for other workers in the fabrication area. The employee responsible for a bank of diffusion furnaces spent a majority of the workday at two primary work stations: 1) the loading station, where wafer boats were loaded in and out of the tube furnaces; or 2) at the adjacent clean station, where incoming wafers were removed from cassettes and transferred to boats or finished wafers were removed from the boats and transferred back into cassettes. The operators frequently leave these primary work stations, but only for short periods of time. Diffusion furnace operators periodically leave the furnace area to obtain new quantities of wafers or to transfer finished wafers to a holding station. It was also common to see the worker approach the furnace control panel and make adjustments. Figure 6 presents a pictorial diagram of a diffusion furnace work area, the location of work stations, and the placement of both area and personal monitors.

Three-inch Diffusion Furnaces

Forty diffusion tubes are arranged in 10 banks of 4 tubes each. The banks are located parallel to furnace loading stations and positioned under vertical laminar flow HEPA filters. The furnace cabinets and source cabinet are enclosed in a separate room, which also contains ventilated gas storage cabinets and a ventilated chemical sink for filling liquid source bubblers.

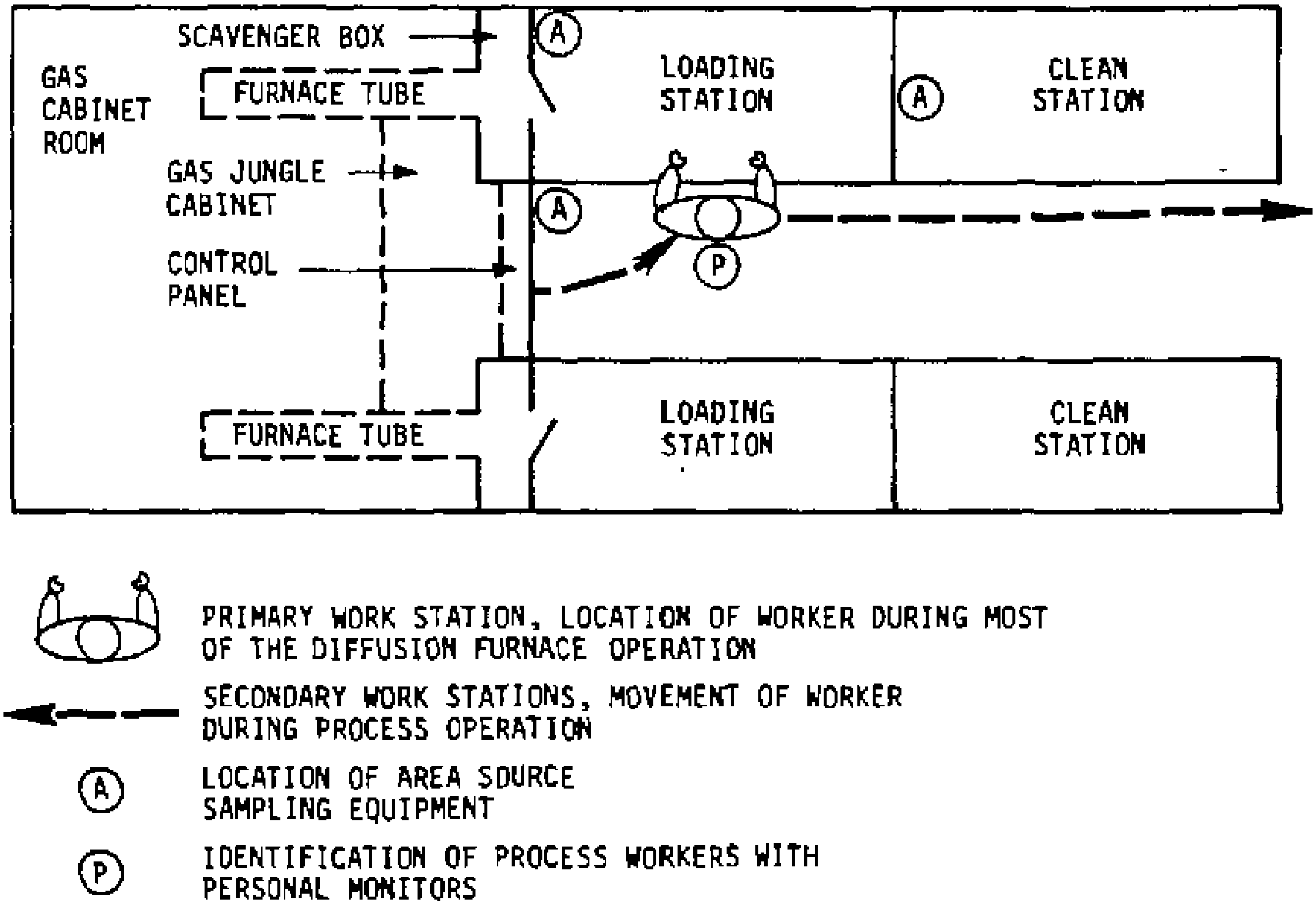

Figure 6. Pictorial diagram of work activities and the location of area and personal monitors during diffusion furnace operations.

Access to the room is from the fabrication area through a door normally kept closed during operation. Employees are not required to enter the source cabinet room during normal operations.

The results of ventilation measurements taken near the 3-inch diffusion furnaces are summarized in Table 5.

HEPA filters located over the furnace tube openings provide a clean air curtain that prevents particulates from settling on the wafers. The HEPA filter air flow varied from low velocities (approximately 4 fpm) at one station to high velocities (approximately 84 fpm) at another station. Average volumetric flow rates for the HEPA filters ranged around 1010 cfm.

During the in-depth survey, it was noted that some diffusion processes require the operator to pull the wafer carriers from the furnace quickly. During this quick pull operation, tube furnace gases may escape or be emitted from the wafers. When this occurs, the air flow from the HEPA filters may contribute to the dispersion of doping agents into the surrounding workplace air.

Access to each furnace tube is through a vented scavenger box. A stainless steel door is present on the front of each scavenger box at the 3-inch assemblies. This door is usually closed during operation, and the closed box forms a trap that contains and removes air escaping from the furnace tube. The door provides a loose seal, which allows outside air to bleed into the scavenger box. A bleed-in is also provided through a

TABLE 5. SUMMARY OF VENTILATION MEASUREMENTS TAKEN AT 3-INCH DIFFUSION FURNACES

	HEPA filter		Scavenger box		Source cabinet		
	Average velocity (fpm)	Air flow (cfm)	Average velocity (fpm)	Air flow (cfm)	Average velocity (fpm)	Air flow (cfm)	Agent(s)
3-inch Diffusion Furnaces 1 and 2	84	1010	190	12	1520	130	AsH_3
			200	13			
			500	36			
			430	28			
			160	10			
			360	23			
			280	18			
			500[*]	55			
3-inch Diffusion Furnaces 3 and 4	4	40	260	17	†	†	B_2H_6, H_2, N_2, O_2
			280	19			
			260	17			
			300	20			
			350	23			
			510	33			
			460	30			
			160	11			
3-inch Diffusion Furnaces 9 and 10[‡]	†	†	240	32	†	†	PBr_3, $POCl_3$, N_2, H_2, O_2
			460	60			
			420	55			
			390	51			
			310	40			
			530	70			
			420	54			
			370	48			

[*] Measurement obtained at duct takeoff from scavenger box Measurements at the scavenger surface indicated a velocity of 124 fpm and an estimated air flow of 82 cfm

[†] Measurements were not taken

[‡] Additional exhausts include 380 cfm (1012 fpm) and 430 cfm (1138 fpm) from two slots in the furnace

double panel in the door, which allows air to enter via an effective area of 0.04 to 0.07 ft^2. Estimates of air flow rates through the bleed-in range from 6 to 37 cfm, with air velocities of 160 to 530 fpm, respectively.

Open-faced hoods (10 in. x 5 in.) are often located at the base of the furnace tube-loading stations. The open-face hoods are used to control chloride emissions from furnace end caps when the furnace is using phosphorus oxychloride as a doping agent. The end caps are removed from the tubes and placed in front of the hoods. Although not presented in Table 5, average face velocities of the hoods were measured at 1010 to 1140 fpm, with estimated volumetric air flow rates of 380 to 430 cfm.

Two diffusion furnace stacks containing four tubes each are used for diffusion with boron trichloride. The boron trichloride is supplied from lecture bottles that are stored adjacent to the unit in a partially enclosed, ventilated cabinet located between the diffusion furnace stacks. The cabinet contains gas supply lines, regulator assemblies, and floor controllers for the diffusion furnaces. It is vented by two 4-inch diameter ducts. Air velocities of 3200 and 1710 fpm measured at the duct openings resulted in an estimated volumetric air flow rate of 280 and 150 cfm, respectively. The source cabinet at the rear of each tube bank is enclosed and vented by a 4-inch diameter duct. The average velocity measured at one cabinet was 2790 fpm, which resulted in an estimated flow rate of 240 cfm.

The front end of the furnace, which includes the control panel display and wafer loading station, is located in the clean room fabrication area. Access to the rear of the control panel, the lecture bottles, and the source cabinet is located in a separate room.

Antimony Diffusion Furnace

The layout of the antimony diffusion furnace differs slightly from the furnaces just described. The primary difference is in the design of the source cabinet. A small source furnace is connected to each of the larger tube furnaces. Antimony trioxide is loaded onto a hand-held small paddle at the loading station before being transferred into the source furnace. The antimony diffusion furnaces are combined in banks of three tubes. Access to each tube was possible through loading stations at the rear of the assembly. A clear plastic door (27 in. x 41 in.) is opened when measured dopant has to be added to the source furnace. The paddle is used to introduce the powdered antimony trioxide into the source furnace, which is located in an enclosed, ventilated source cabinet. Access to the source furnace is through a loading station at the back of the diffusion furnace assembly. The source furnace work station is ventilated by a 17 in. by 15 in. duct. The duct opening, which is directly parallel to the working surface, provides the source cabinet with general exhaust ventilation.

The ventilation characteristics of two source cabinet loading stations were assessed. The face velocity at one loading station was 81 fpm and the estimated volumetric air flow rate was 620 cfm. The air velocity at the face of the work surface slot exhaust was 490 fpm and the estimated volumetric air flow rate was 140 cfm. The face velocity at the second loading station was 47 fpm and the estimated flow rate was 360 cfm. The air velocity at the face of the second slot exhaust was 567 fpm and the estimated flow rate was 160 cfm. The low face velocity and flow rate of the second loading station were due to a less-than-effective enclosure of the source cabinet, which resulted in leakage of air into the system.

As in the case of all diffusion furnaces, wafers are loaded into the furnace tube opening opposite the source cabinet. These forward furnace tube openings are also ventilated by scavenger boxes. The scavenger boxes act as exhaust plenums with two exhaust takeoffs. One takeoff is permanently open, and the other is automatically opened whenever the furnace access door is opened. At one furnace tube, air velocity at the face of the scavenger box with the door open was 123 fpm and the estimated flow rate was 65 cfm. When the access door is closed, air enters the scavenger box through a circular slot in the door. The average air velocity measurements taken from five furnace tubes on which the doors of the scavenger boxes were closed ranged from 60 to 131 fpm and estimated flow rates ranged from only 2 to 5 cfm.

It is believed that the scavenger box face velocities can be affected by the air movements from the vertical laminar flow HEPA filter located over the loading station. The air velocity measured at the face of one of the two HEPA filters was 124 fpm and the estimated air flow rate was 1330 cfm. The values were 111 fpm and an estimated air flow of 1190 cfm on the other. Ventilation measurements taken at an antimony diffusion furnace bank are summarized in Table 6.

Four-inch Diffusion Furnaces

The 4-inch diffusion furnaces do not vary greatly from 3-inch furnaces in terms of assembly layout. Some differences exist in the enclosure characteristics of the gas "jungle" cabinet (one with a maze of lines), source cabinet, or the furnace tubes; however, these different configurations do not appear to affect the function of the exhaust ventilation systems. As a rule the 4-inch furnace assemblies are designed to have higher scavenger box and source cabinet exhaust flow rates than either the 3-inch or antimony diffusion furnaces. One significant difference associated with some of the 4-inch furnaces is the absence of a door on the scavenger box. The ventilation measurements for the 4-inch diffusion furnaces are presented in Table 7.

Monitoring Results

The work areas associated with the diffusion furnace operations were monitored for diborane, arsine, arsenic trioxide, and antimony. The selection of a monitoring technique (personal versus area) to be used at a particular furnace assembly during the in-depth survey was influenced greatly by practical considerations. Horizontal surfaces were not always available for locating area monitors. In many cases, locating sampling pumps

TABLE 6. SUMMARY OF VENTILATION MEASUREMENTS TAKEN AT AN ANTIMONY DIFFUSION FURNACE

Furnace type	HEPA filter		Scavenger box		Source cabinet		Agent(s)
	Velocity (fpm)	Flow (cfm)	Velocity (fpm)	Flow (cfm)	Velocity (fpm)	Flow (cfm)	
Antimony diffusion furnace	124	1330	60* 80* 131*	2 3 5	47 face 567 slot 42 rear	360 160 140	Sb_2O_3
	111	1190	60* 123† 74*	2 7 3	81 face 490 slot 103 back	620 140 340	Sb_2O_3

* Door closed.

† Door open.

TABLE 7. SUMMARY OF VENTILATION MEASUREMENTS ON 4-INCH DIFFUSION FURNACES

Four-inch diffusion furnace	HEPA filter		Scavenger box		Source cabinet		Agent(s)
	Velocity (fpm)	Flow (cfm)	Velocity (fpm)	Flow (cfm)	Velocity (fpm)	Flow (cfm)	
Bank D	184	3030	78*	43	†	-	H_2, N_2, O_2
			43*	24	†	-	H_2, N_2, O_2
Bank C	178	2930	175*	98	†	-	BN, H_2, N_2, O_2
			126*	71	†	-	BN, H_2, N_2, O_2
			330*	185	3000	-	B_2H_6, H_2, N_2, O_2
			300*	168	2675	130	B_2H_6, H2, N_2, O_2

* Measurements taken with furnace tube loading end doors open.

† Measurement not taken.

near the furnace tube areas would have interfered with normal work activities. It was often possible to accomplish personal sampling with less disturbance to the work activities.

Diborane--

Personal sampling was conducted on an employee responsible for both 3- and 4-inch diffusion furnaces. Area monitoring was conducted both at 3-inch furnaces equipped with scavenger box doors and 4-inch diffusion furnaces without doors. Samplers were set at distances of 12 and 24 inches from the opening of the 3-inch furnace scavenger box openings. A single sample was taken at a distance of 10 feet from the 4-inch diffusion furnace. The results of the sampling and analysis of worker exposure to diborane are presented in Table 8.

Arsenic Trioxide--

Two personal samples were taken on an employee responsible for the operation of a bank of 3-inch diffusion furnaces using arsine gas as a dopant. In addition to the personal samples, area monitoring was conducted on four occasions at a stationary location 24 inches from the opening of the furnace scavenger boxes. The results of both the personal and area monitoring are presented in Table 9. Arsenic trioxide concentrations on all the filter samples proved to be below the minimal detection limit of 0.035 µg.

TABLE 8. SUMMARY OF PERSONAL AND AREA MONITORING FOR DIBORANE

Monitoring method	Job description or location of monitor	Sample duration (hr:min)	Sample volume (liters)	Measured concentration ($\mu g/m^3$)[*]	Time-weighted average concentration ($\mu g/m^3$)
Personal	Loading, unloading of 3- and 4-inch diborane diffusion furnaces	2:09	140.6	32.7	
		2:46	180.9	<1.4[†]	14.4
	Loading, unloading of 3- and 4-inch diborane diffusion furances	2:01	131.9	<1.9[†]	
		2:48	183.1	<1.4[†]	
Area	12 inches from opening of 3-inch diborane diffusion furnace	1:00	66.6	147.1	
		2:12	132.0	30.3	
		3:16	196.0	13.8	39.9
	10 feet from opening of 4-inch diborane diffusion furnace	1:14	82.1	82.0	

[*] Measured concentration determined as (sample - field blank)/sample volume.

[†] Analytical results were below the detection limit of 0.25 μg.

TABLE 9. SUMMARY OF PERSONAL AND AREA MONITORING FOR ARSENIC TRIOXIDE

Monitoring method	Job description or location of monitor	Sample duration (hr:min)	Sample volume (liters)	Measured concentration (µg/m³)*	Time weighted average concentration (µg/m³)
Personal	Operation of 3-inch diffusion furnace	6:02 6:00 7:13	716.8 362.0 883.3	<0.09† <0.10† <0.04†	<0.06
Area	24 inches from opening of 3-inch diffusion furnace scavenger box	6:51 6:45	845.7 767.5	<0.04† <0.05†	

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* Measured concentration determined as (sample - field waste)/sample volume.

† Analytical results were below the detection limit of 0.035 µg.

Antimony--

Three personal samples were taken on an employee responsible for the operation of an antimony diffusion furnace. Two area samples were taken at locations midway between the two diffusion furnace tube banks. The results of both the personal and area monitoring are presented in Table 10. Antimony concentrations on all the filter samples were below the minimal detection limit of 9.0 µg.

ION IMPLANTATION

Two major types of ion implanters are commonly used within the electronics industry: cassette-type implanters and pallet-type implanters. Figure 7 presents a basic illustration of both types. Although Fairchild has both types of implanters, only the pallet-type implanter was operating during the survey.

Scheduled preventive maintenance of the ion implantation unit includes periodic cleaning of the ion source, changing of the beam manipulator, and periodic replacement of the vacuum pump oils. The ion source is located within a sealed source chamber maintained at pressures below atmospheric. When it is necessary to access the ion source, the chamber is purged and backfilled to atmospheric pressure before it is opened. During the opening the chamber is vented by a duct located above the ion source. The average face velocity at the duct was 1500 fpm, and the estimated air flow was 120 cfm. During maintenance, the ion source is removed and taken to a laboratory-type, ventilated cleaning bench. This stainless steel bench has an open face of 7.42 ft^2

TABLE 10. SUMMARY OF PERSONAL AND AREA MONITORING FOR ANTIMONY

Monitoring method	Job description or location of monitor	Sample duration (hr:min)	Sample volume (liters)	Measured concentration (µg/m³)*	Time-weighted average concentration (µg/m³)
Personal	Diffusion furnace operation	6:02	716.8	<12.6†	
		6:00	362.0	<24.9†	
		7:13	883.3	<10.2†	
Area	Over control panel between diffusion tube banks	6:51	845.7	<10.6†	
		6:45	767.5	<11.7†	<11.2

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[*] Measured concentration determined as (sample - field blank)/sample volume.

[†] Analytical results were below the detection limit of 9.0 µg.

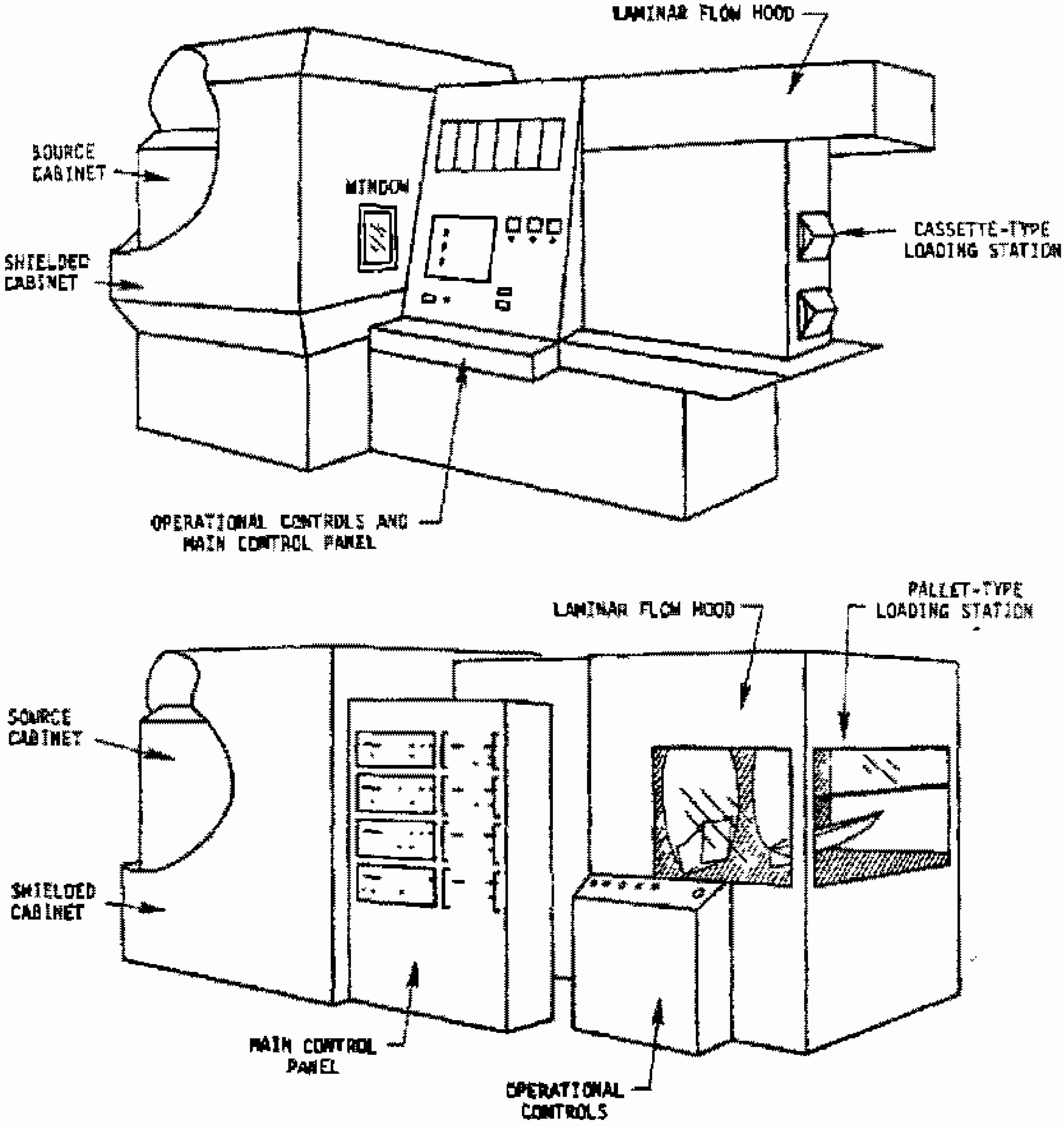

Figure 7. Cassette- and pallet-type ion implanters.

(44.5 in. x 24 in.) and is vented by a slot located at the rear of the bench. The average face velocity of the bench was 172 fpm, and the estimated air flow was 1280 cfm. The slot face velocity was 1463 fpm, and the estimated air flow was 1490 cfm.

Gases used for ion implantation are stored in a ventilated gas cabinet located within a lead-lined cabinet that encloses the ion source and gas cabinet. The gas cabinet is vented by a 6.5-inch duct. Average velocity measured at the duct face was 2680 fpm and the estimated air flow was 570 cfm. Measurements were taken with the cabinet door open. The door, which is normally closed, does not provide air intake vents or slots to facilitate the movement of air into the cabinet.

Monitoring Results

Radiation film badges were used to monitor X-radiation emissions from high energy sources within the ion implanter. A Geiger-Muller survey meter with a thin window probe was used to identify "hot spots" or areas of X-ray emission above background. After the detection of "hot spots," radiation dosimetry badges were placed at the location of the emission. The badges remained in place for a period of 37 days. The results of the monitoring for X-radiation are presented in Table 11.

Arsine and arsenic trioxide emissions were monitored during the normal operation of the equipment and during specific maintenance activities. Personal monitors were placed on one worker during the operation of an ion implanter that incorporated a pallet-type wafer-loading station. An area source monitor was

TABLE 11. RESULTS OF MONITORING FOR X-RADIATION FROM ION IMPLANTERS

Equipment type	Location of badge	Total dose (mrems)	Weekly dose (mrems)*
Varian 80-10	Wafer loading station (work environment)	Neg.[†]	-
	Beam window (interior of equipment)	Neg.[†]	-
	Inside shielding around ion source (interior of equipment)	140	26
	Outside shielding around ion source (work environment)	70	13
Varian DF-4	Wafer loading station (work environment)	Neg.[†]	-
	Observation window on shielded source cabinet near control panel (work environment)	Neg.[†]	-
	Inside shielding around ion source (interior of equipment)	Neg.[†]	-

[*] Weekly dose = total dose x 7d/37d.

[†] Less than the detection limit of 10 mrems.

also located in the area of the work station where the wafers were being transferred from cassettes to individual positions on the pallet. The results of this sampling effort are presented in Table 12.

In addition to the monitoring of work exposures during normal operation of the ion implanter, three types of maintenance activities associated with this equipment were monitored for exposure to arsine. An area sample was taken above the ion source in the open source chamber during removal of the ion source unit. This sample was taken from a relatively small, confined space in front of the worker. Although the concentration measured undoubtedly contributes to the workers' area exposure, the magnitude of the workers' actual exposure can only be inferred from these results.

A similar area sample was taken in the shielded cabinet over the receptacle for the beam manipulator, and these results are also presented in Table 12. As in the case of the ion source, concentrations monitored during the removal of the receptacle reflect neither a personal nor area concentration, but they do indicate the general severity of the exposure problem.

Sampling for arsenic trioxide was performed at a laboratory hood used for cleaning the ion source apparatus. The results of the sampling for arsenic trioxide are presented in Table 12.

Work Practices

Although the work characteristics and practices of ion implantation workers do not vary greatly with the type of dopant

TABLE 12. SUMMARY OF PERSONAL AND AREA MONITORING FOR ARSENIC (as arsine gas)

Monitoring method	Job description or location of monitor	Sample duration (h:min)	Sample volume (liters)	Measured concentration (μg/m³)*	Time-weighted average concentration (μg/m³)
Personal	Loading station wafers from ion implanter	1:40	14.6	<2.40†	1.11
		2:31	22.1	1.85	
Area	Opening at loading station of ion implanter	2:25	14.9	1.27	0.43
		4:45	29.4	<1.19†	
	Sampling at manipulator	2:00	28.8	14,361.0	Not applicable
	Sampling above ion source	0:53	21.7	51.2	Not applicable
	Opening of laboratory hood used for ion source cleaning	7:27	916.4	<0.04†	<0.04

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[*] Measured concentration determined as (sample - field blank)/sample volume.

[†] Analytical results were below the detection limit of 0.035 μg.

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 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 8 depicts work practices for implanters with two types of load-in stations--cassette-type load-in stations and pallet-type stations. In the cassette-type station, the operator must load and remove a cassette of 25 wafers; in pallet-type stations, the operator manually places 50 individual wafers on two circular holders or pallets.

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

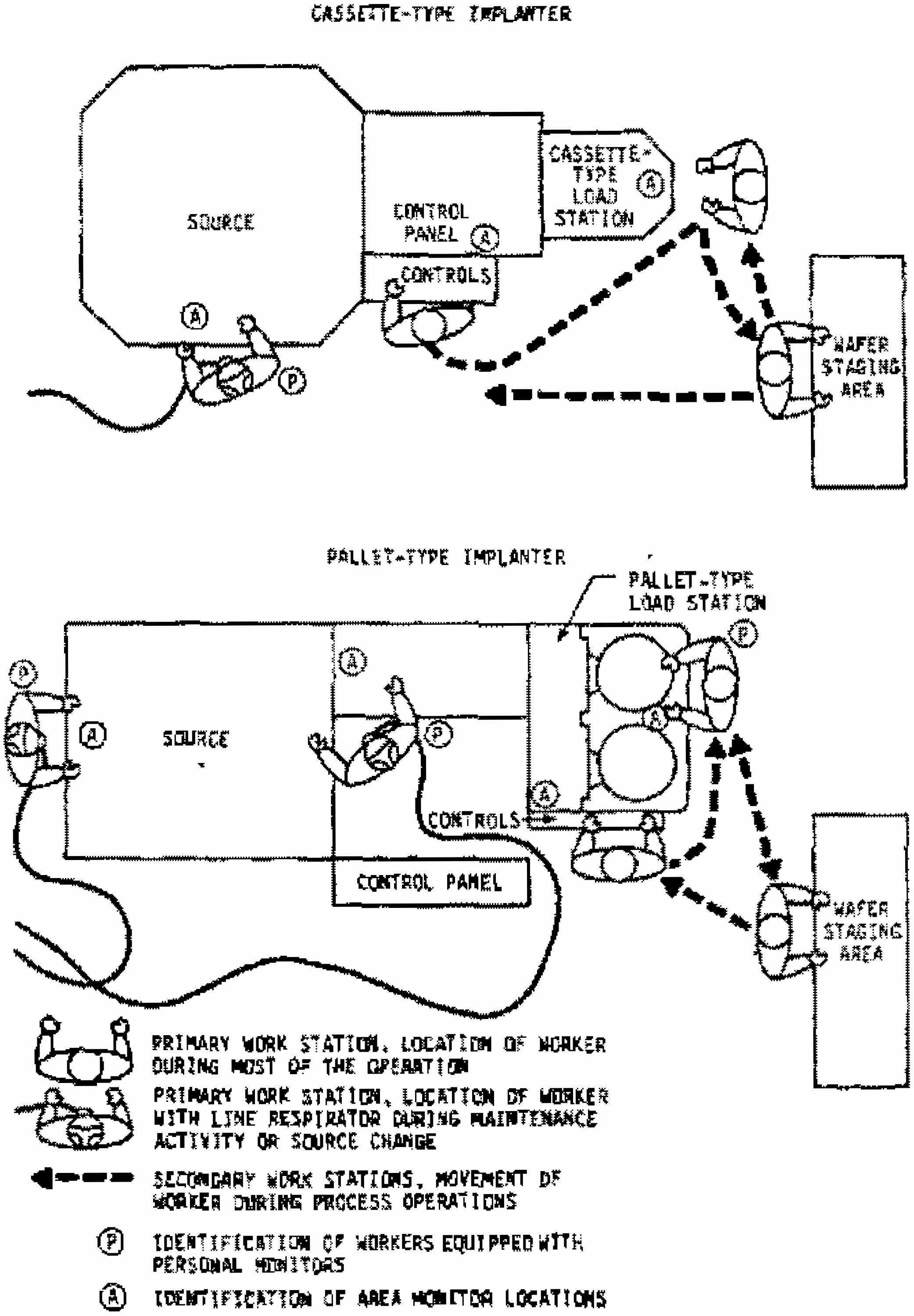

Figure 5. Pictorial diagram of work activities and location of personal and area monitors during ion implantation operations at implanters with cassette-type (top) and pallet-type (bottom) loading stations.

presented in Figure 8 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 container or glove box for transport to an enclosed bead-blasting operation. The transfer is performed in the vicinity of the ion implanter under protection of a supplied-air respirator.

RADIO-FREQUENCY RADIATION SOURCES

Radio-frequency (RF) radiation is used in the following process operations: 1) plasma etching/ashing, 2) radio-frequency sputtering, 3) plasma-enhanced chemical vapor deposition, and 4) direct current (DC) sputtering (metallization). The RF monitoring results obtained during this survey are presented in Table 13.

The batch processes dedicated to plasma etching/ashing operations use 13.56-MHz RF sources at 200 to 800 watts. The RF sources for plasma etching are operated intermittently for 5 to 65 minutes, depending on the equipment and process requirements.

Radio-frequency sputtering is performed in both batch and continuous processes. The batch operations use 13.56-MHz RF sources at 350 to 1500 watts. The continuous operations use 13.56 MHz RF sources at 250 watts. The RF power sources used in batch sputtering operate continuously. In the continuous RF sputtering process, the RF source is on for 30 seconds during each 70-second cycle, and the cycle is repeated continuously over the entire period that the equipment operates.

Radio-frequency radiation is also used during the plasma etching step in the DC sputtering process. The system operates

TABLE 13. SUMMARY OF RADIO-FREQUENCY RADIATION EMISSIONS FROM RF SOURCES USED IN THE MANUFACTURING OF INTEGRATED CIRCUITS

Equipment manufacturer and model	Frequency	Operating power (watts)	Maximum duration of RF emissions	Maximum electric field (V^2/m^2)	Maximum magnetic field (A^2/m^2)
LFE Corp. PFS/PDS/PDE 1002	13.56 MHz	200 and 400	26.9 min	500	0.04
LFE Corp. PFS/PDS/PDE 1002	13.56 MHz	300	6.0 and 5.2 min	400	0.07
LFE Corp. PDS 504	13.56 MHz	500	65 min	500	0.02
LFE Corp. PDS 504	13.56 MHz	520	65 min	None	0.05
LFE Corp. PDS 504	13.56 MHz	550	25 min	None	0.05
LFE Corp. PDS 504	13.56 MHz	500	25 min	None	0.05
LFE Corp. PDS 504	13.56 MHz	500	45 min	None	0.07
LFE Corp. PDS 504	13.56 MHz	500	45 min	300	0.03
LFE Corp. PDS 504	13.56 MHz	500	75 min	None	0.07
LFE Corp. PDS 504	13.56 MHz	500	20 min	200	0.08
LFE Corp. System 8000	13.56 MHz	100	5 min†	500	0.05
LFE Corp. System 8000	13.56 MHz	100	5 min†	1000	0.03
ASM America, Inc. Micon III	450 kHz	300	100 min	None	‡

(continued)

TABLE 13 (continued)

Equipment manufacturer and model	Frequency	Operating power (watts)	Maximum duration of RF emissions	Maximum electric field (V^2/m^2)	Maximum magnetic field (A^2/m^2)
ASM America, Inc. Micon III	450 kHz	400	100 min	4000[#]	[‡]
Orytek, Inc. Model 100[*]	13.56 MHz	850	Continuous	500[#]	0.37[#]
Varian Associates, Inc. Model 3180	13.56 MHz	250	160 sec[†]	None	None
Varian Associates, Inc. Model 3180	13.56 MHz	250	160 sec[†]	300	None
Perkin Elmer PE 3400	13.56 MHz	350	5 min[†]	400	0.01
Perkin Elmer PE 3400	13.56 MHz	500	5 min[‡]	500	0.05
Perkin Elmer PE 4400[*]	13.56 MHz	1500	22.4 min	2500	9.2
Perkin Elmer PE 4400[*]	13.56 MHz	1500	1.5 min[**]	62000	7.2
Perkin Elmer PE 4400	13.56 MHz	1000	1.5 min[**]	1500	[††]
Perkin Elmer PE 4410[*]	13.56 MHz	1500	26.4 min	2500	25.0

[*] Source has potential to cause an exposure in excess of the ACGIH TLV for magnetic field strengths at 13.56 MHz.

[†] Maximum duration of operation during any 6 minute period.

[‡] Probe cannot measure magnetic fields at 450 kHz

[#] Measurements with access doors open.

[**] Radio frequency used in plasma etch step of DC sputtering operation.

[††] Measurements not obtained.

with a 13.65-MHz RF source at 1500 watts for 1.5 minutes during a 17-minute process cycle.

Radio-frequency radiation emissions (magnetic and electric fields) were found along the seams of adjoining metal plates or mesh screens that form the cabinet enclosure, through openings in the cabinet enclosure (the result of missing screws), and around the cabinet's cable access ports. Initial measurements of these emissions or leakage were made at 10 cm (6 inches) from the enclosure cabinets. Once elevated RF measurements were identified, additional measurements were made at greater distances from the emission source. A level of 0.26 A^2/m^2 RF magnetic field was noted at 30 cm (12 inches) from one RF sputtering system, which decreased to below the detection level at 61 cm (24 inches). This leakage, which was measured in front of the operator's viewing port, appeared to be due to a screw missing from the cabinet assembly and not from leakage through the glass port. The RF radiation measured at the screw holes was 7.0 A^2/m^2 when the process equipment was operating in the bias sputtering mode and 3.2 A^2/m^2 when it was operating in the etching mode. The difference in measured RF emissions is due to the application of a portion of the electrical energy from the cathode to the anode supporting the wafers. The operator may be exposed to either of these levels for only brief periods (≤ 1 minute) while observing the operation through the viewing port.

The automation of the process equipment results in limited operator exposure to RF radiation. Operators are required to load wafers or cassettes into the process equipment. The operator then initiates the operation by dial or push-button control and may remain at the equipment for short periods (~1 minute) to observe the operation with the RF power on. The operator is at other work stations in the area during the rest of the process cycle.

Plasma-enhanced chemical vapor deposition is performed as a batch operation, which uses a 450-kHz RF source at power levels of 300 to 400 watts, and as a continuous cassette-to-cassette operation, which uses a 13.56-MHz RF source at 100 watts. The RF source in the batch operation is on 24 to 27 minutes for deposition and 100 minutes during a process etch cycle that is performed once every 10 runs. During the continuous process operation mode, the RF source is on for 115 seconds during a 145-second cycle.

GAS HANDLING SYSTEM

Toxic, corrosive, pyrophoric, and flammable process gases are supplied in cylinders, which are stored in ventilated gas cabinets. The cabinets contain two to four cylinders, secured by straps. The gas piping system (see Figure 9) for each cylinder is mounted above the cylinders. The cabinets are vented by 4 to 8 inch diameter galvanized steel ducts that exit the top of the cabinets. The cabinets used at this facility generally are not equipped with air supply vents. Table 14 summarizes the average velocity and estimated volumetric air flow for each gas cabinet duct. Estimated average air velocities ranged from 930 to 3130

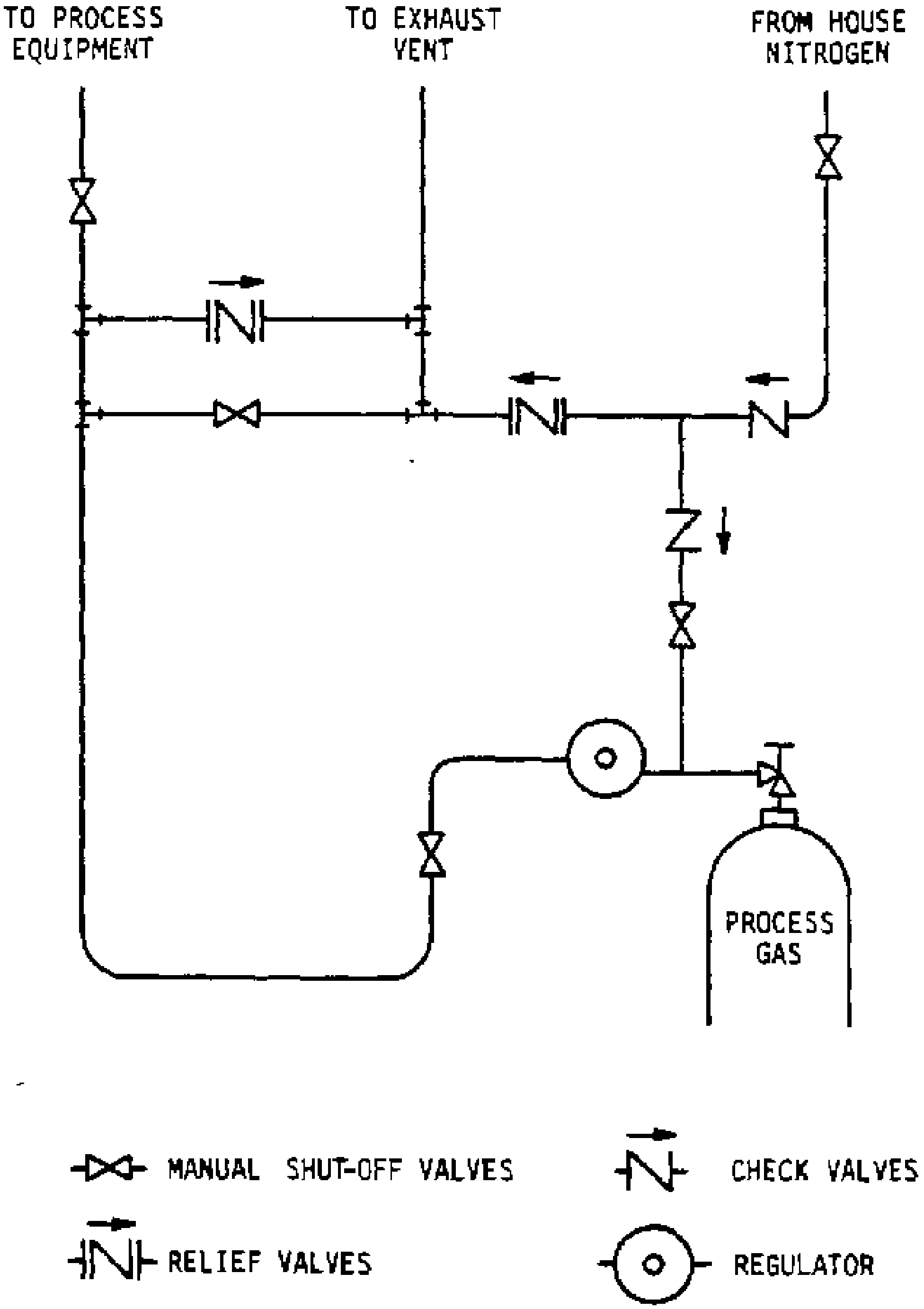

Figure 9. Gas distribution system.

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

Gas	Duct diameter, inches	Average velocity,* fpm	Volumetric flow rate, cfm
SiH_4	6	1980	390
N_2O	6	3060	600
CF_4/O_2	5	2700	370
B_2H_6	6	3130	620
NH_4	6	2880	570
SiH_4	6	2010	390
PH_3, SiH_4	6	1510	300
AsH_3	8	1460	510
B_2H_6	6	2980	590
HCl, AsH_3	6	930	180†
HCl, AsH_3	6	2800	550
HCl, AsH_3	6	2480	490
AsH_3	6	2480	350†
BCl_3 control cabinet	4	3200	280
BCl_3, control cabinet	4	1710	150
H_2/O_2 source lab	4	3380	300
AsH_3 source lab	4	1520	130

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* Average velocity determined with access doors open, using a thermal anemometer. Three to five traverse points were taken to determine the average value.

† Damper partially closed.

feet per minute, which result in estimated air volumetric flows of 180 to 620 cubic feet per minute. The lowest velocities and volumetric flow rates were from gas cabinets that had partially closed dampers in the ventilation ducts.

GAS DISTRIBUTION SYSTEM

A general diagram of the gas piping system used at this facility is presented in Figure 9. A regulator assembly is attached to the process gas cylinder, and a nitrogen purge line enters the assembly just prior to the regulator. Gas is distributed from the regulator through a Swagelok^{R} flexible hose to 3/16-inch stainless steel line. The final control of the process gas occurs just prior to where the stainless steel lines connect to the process equipment. Gas from the cylinders is controlled at the process equipment through a manually controlled Whitey^{R} valve. The stainless steel line is protected from overpressurization by a relief valve that exhausts to a 3/8-inch stainless steel vent. A second Whitey^{R} valve allows gas to exhaust from the system to a 3/8-inch stainless steel vent.

House nitrogen is used as a purge gas. The gas is distributed through 3/8-inch copper or stainless steel lines, and it passes through a nitrogen regulator, a Whitey^{R} valve, and two check valves before it enters the process gas system in front of the process gas regulator.

A variation of the above system included the use of "pig-tails" in place of the flexible hose. A "pig-tail" is a circular coil of stainless steel line that gives the system some degree of structural flexibility in the connecting or disconnecting of gas cylinders. Air-operated valves may be used in place of manual shutoff valves to switch the gas supply from an empty to a full cylinder. Cylinders may contain liquified pressure. Any gas in the exhaust vents is released directly to the external plant atmosphere.

CONCLUSIONS

The results of the in-depth survey lead to the following conclusions, which 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 Fairchild facility involve the movement of process chemicals from storage or holding areas into the circuit fabrication process area. Toxic or hazardous gases used at Fairchild 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) exhausted gas cabinets for safe storage of gas cylinders, 2) flow-limiting and emergency shutoff valves, and 3) welded stainless steel lines that contain a minimum of compression fittings. Worker exposures to leaks and gas releases during cylinder changing operations are further controlled through the used air line-supplied respirators.

Worker exposures during the transfer of liquid chemicals are controlled through the use of personal protective equipment. Chemical handlers (chemical technicians) are provided with personal protective equipment consisting of 1) chemical-resistant aprons, 2) acid- or chemical-resistant gauntlets or 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. The intermediate storage areas consist of exhausted cabinets with automatic sprinkler systems.

PROCESS CONTROLS

In most instances it was not possible to assess the effectiveness of more than one control option, either because of the lack of variation in control solutions at Fairchild or because of the limits that budgetary considerations imposed on the sampling effort. The controls that were observed were assessed in terms of their effectiveness at reducing or eliminating 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 in both the Type I (old technology) and the Type II (new technology) tunnels proved to be less than the TLV's for these substances (see Tables 1 and 2). Area monitoring in Type I tunnels detected acetone, n-butyl acetate, and xylene at levels equal to or less than 5 percent of their respective TLV's. Although Cellosolve acetate, methyl Cellosolve, and methyl ethyl ketone were used in the process, they were not detected during the in-depth survey. Hexamethyldisilizane (for which a TLV has not yet been established) was detected at levels between 0.03 and 0.31 ppm. No personal monitoring was conducted in the Type I photolithographic tunnels.

Area and personal monitoring in Type II tunnels detected acetone, n-butyl acetate, xylene, and Cellosolve acetate at levels less than 1 percent of their respective TLV's. Hexamethyldisilizane, methyl Cellosolve, and methyl ethyl ketone were not detected during either the area or personal sampling.

Although neither photolithographic operations (Types I or II) presented an exposure hazard to the fabrication workers, the newer process equipment in the type II tunnel (i.e., the Wafer Trak^R System) appears to provide a fivefold reduction in workplace exposure.

Wet Chemical Stations

Worker exposures to hydrofluoric, sulfuric, and nitric acids 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 the bench, slots around the perimeter of each solution tank, and a perforated deck serviced by an exhaust plenum below the work surface. The workers involved in wafer etching at these benches and the chemical handlers responsible for replenishing the acid tanks were exposed to aerosol levels representing less than 1 percent of the TLV's for hydrofluoric and sulfuric acid (see Table 4). No nitric acid was detected at the wet chemical stations where nitric acid solutions were used.

Diffusion Furnaces

Diffusion furnace operators and their work areas were monitored for diborane, arsenic trioxide, and antimony. A majority of the diffusion furnace banks studied incorporated the use of four ventilation control measures: 1) ventilation of the enclosed source cabinets, 2) ventilation of the furnace tube bank and gas supply line "jungle," 3) ventilated scavenger boxes equipped with closing doors, and 4) open-faced hoods located at the base of the furnace tube loading stations. The 4-inch furnaces were the single exception; although ventilated, the scavenger boxes on these furnaces had no doors.

Emissions of boron compounds (possibly diborane) were detected in personal and area samples taken at the 3- and 4-inch diffusion furnaces using diborane. The results of personal samples taken on furnace operators ranged between zero and 14 percent (14.4 $\mu g/m^3$) of the diborane TLV. An area monitor located 12 inches from the opening of a 3-inch furnace was used to collect three air samples (see Table 8). Assuming that the boron compounds collected were diborane contents of 2.7, 4.0, and 9.8 µg, respectively, were found in 196, 132, and 67 liters of collected air. Another area monitor, located 10 feet from the opening of a 4-inch furnace, collected 6.8 µg of diborane from an 82-liter sample of air. The results of the sampling effort identified the potential for the emission of diborane.* The results also suggest that the variation in scavenger box design between the 3-inch and 4-inch furnaces does not affect the level of dopant or process gases escaping in the workplace.

Scavenger box face velocities were measured at values as low as 60 fpm. It is possible that under some circumstances the removal of wafer boats combined with the downdraft of air from overhead HEPA filters could reduce the effectiveness of the scavenger box exhaust.

A similar concern arises about air velocities measured at source cabinets. Readings as low as 47 fpm were observed on diffusion furnace source cabinets containing toxic dopants. Personal and area samples taken at furnaces using arsenic trioxide or antimony dopants failed to detect either arsenic or antimony in the workplace air (see Tables 9 and 10).

Ion Implantation

Ion implantation operators and maintenance personnel were monitored for both arsenic (measured as arsine gas) and X-rays.

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* At Fairchild's request, another set of diborane samples were analyzed to verify the presence of boron (measured as diborane). In this second set, all results were below the detection limit of the method. Although exactly the same process operations may not have been performed during the second sampling effort as during the first, no explanation was found for the discrepancy. It is suggested that any person having a particular concern about diborane exposures in the fabrication area should conduct independent sampling to verify the presence or absence of diborane.

The ion generating mechanisms of implanters are housed in a lead-shielded cabinet. This shielding provides protection against the emission of harmful levels of X-ray generated during the application of high-voltage electrical energy to the ion source. Dosimetry badges were placed at four locations on the implanter cabinet outside of the shielding and at three locations inside the shielding. Three out of the four workplace locations registered negligible emission levels (see Table 11). At just one location outside the shielding a total dose of 70 mrem (approximately 13 mrem/week) was detected. Another dosimeter placed in the same location, but just inside the shielding, registered a total dose of 140 mrem (approximately 26 mrem/week).

The dosimetry data indicate that the shielding greatly attenuates the level of X-ray emissions that reach the workplace. At the point of greatest potential exposure (close to the ion source, but outside the protective shielding) the attenuation was limited to 50 percent.

During the routine performance of manning the equipment, ion implantation operators appear to be exposed to very low levels of arsine gas (less than 1 percent of the TLV) (see Table 12).

Maintenance personnel involved in the removal of ion sources or the repair of graphite components (i.e., beam manipulation) are confronted with large emissions of arsenic (presumed to be in the form of arsine gas). During one sampling period area monitors located over the graphite receptor of the ion source and the beam manipulator collected 413 and 1.1 μg of arsine, respectively.

This sampling effort was the first verification of suspected arsenic exposures during source maintenance efforts. As an established precaution, Fairchild's maintenance personnel are required to wear full-face airline-supplied respirators during maintenance activities. As an additional protective measure, the ion sources are quickly transferred upon removal to air-tight glove boxes for maintenance or repair. This precaution is designed to prevent the suspected "out-gassing" of arsenic or arsenic compounds from graphite material components.

Radio Frequency (RF) Sources

Radio-frequency or microwave radiation emissions were detected near most RF generating sources (Table 13). Several of the metallization units produced magnetic near-field energy levels that could result in exposures above the TLV for 13.56 MHz sources. The work habits of Fairchild 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. In contrast to the exposure potential to magnetic-field emissions, only one source had the potential for overexposure to electrical field energy.

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

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