WALK-THROUGH SURVEY REPORT: CONTROL TECHNOLOGY FOR INTEGRATED CIRCUIT FABRICATION

at

INTEL CORPORATION
Chandler, Arizona

Prepared by
Gary J. Mihlan, Russell K. Smith and Leslie J. Ungers

Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

Report No. 115-11a
May 31, 1983

U.S. Environmental Protection Agency
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

and

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

PLANT SURVEYED: Intel Corporation
5000 W. Williams Field Rd.
Chandler, Arizona 85224

SIC CODE: 3674

SURVEY DATE: August 12, 1981

SURVEY CONDUCTED BY: Mr. Gary J. Mihlan, Battelle-Columbus Laboratories
Dr. Ralph I. Mitchell, Battelle-Columbus Laboratories
Mr. Russell K. Smith, Battelle-Columbus Laboratories
Mr. Leslie J. Ungers, PEDCo Environmental
Mr. James H. Jones, National Institute for Occupational Safety and Health
Mr. Robert Hartley, U.S. Environmental Protection Agency
Mr. Eugene Harris, U.S. Environmental Protection Agency

EMPLOYER REPRESENTATIVES CONTACTED:

Mr. Edward J. Sawicki, Corporate Safety Manager
Mr. Ed Boleky, Plant Manager
Mr. Jerry O'Neal, Senior Facilities Engineer
Mr. Bill Taylor, Safety Engineer
Mr. Steve Kopp, Site Safety/Security Manager

EMPLOYEE REPRESENTATIVES CONTACTED:

Mr. Steve Schuster, Safety Committee Chairman

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

1.0 ABSTRACT

A preliminary control technology survey was conducted at Intel Corporation, Chandler, Arizona on August 12, 1981 by Battelle's Columbus Laboratories, Columbus, Ohio. The survey was conducted as part of a project under a U.S. Environmental Protection Agency contract funded through an Interagency Agreement with the National Institute for Occupational Safety and Health. Intel Corporation manufacturers n-channel metal oxide semiconductor (N-MOS) integrated circuits. The Chandler facility opened in 1980 and is at less than half production capacity.

The process operations in the manufacture of integrated circuits at Intel are contained within a Class 100 clean room. Particulate control is performed by filtration of inlet air through HEPA filters. Local air filtration is provided in the clean room by laminar flow benches with HEPA filtration. Process equipment is generally located in the laminar flow benches.

Process operations employed at Intel Corporation in MOS integrated circuit manufacture include: 1) thermal oxidation of purchased pre-doped silicon wafers, 2) chemical vapor deposition of silicon nitride, polycrystalline silicon and silicon dioxide, 3) photolithographic processes for defining circuit patterns, including wafer cleaning, photoresist coating, soft-bake, projection mask alignment exposure, wafer developing, hard bake, plasma etching, and photoresist stripping, 4) doping, including diffusion and ion implantation, 5) hydrogen alloying, and 6) metalization, including electron beam evaporation and direct current (DC) sputtering.

Engineering controls used at the facility vary by process operation. General engineering controls include gas storage in ventilated cabinets or in secured covered areas outside of the building, and gas lines of welded stainless steel construction or stainless steel in PVC lines. Local exhaust ventilation is provided for removing process gases by local exhaust take-offs located at the source of the emission or by removal of process gases from enclosed systems employing vacuum pumping systems. Shielding and electrical interlocks are used to control X-ray emissions from ion implantation.

Environmental monitoring of toxic gases in the clean room area is performed by a Miran® 801 multicomponent multistation system. Hydrogen monitoring is performed by a Bacharach® Model CD850 and by an IST® sensor.

Process operations are generally automated and controlled by microprocessors. The process sequences generally require that workers load and unload wafers from the equipment.

Intel Corporation has developed a comprehensive worker training program. Worker education and training is required of all new employees. The programs cover equipment operations, safety practices, hazardous properties of chemical agents and personal protective equipment. Plant safety program personnel have the primary responsibility for worker health and safety. A detailed emergency response plan has been developed for the facility.

Areas which warrant further study include: 1) review of ventilation system design, testing, and maintenance, 2) review of data from environmental monitoring systems, 3) documentation of work practices including worker training programs, and 4) evaluation of maintenance activities including identification of hazards and controls employed during maintenance activities.

2.0 INTRODUCTION

A preliminary survey was conducted as part of the control technology assessment of the electronic components industry (SIC 3674). The study was conducted for U.S. Environmental Protection Agency contract through an Inter-agency Agreement with the National Institute for Occupational Safety and Health. The preliminary survey was conducted to identify and evaluate the control technology used to control emissions and work exposures. The information obtained from the preliminary survey will be used to select sites for the detailed control technology assessment.

The preliminary survey was conducted on August 12, 1981, at Intel Corporation, 5000 W. Williams Field Road, Chandler, Arizona. The survey was conducted by Battelle Columbus Laboratories with assistance from Mr. James Jones, NIOSH. Mr. Bob Hartley and Mr. Gene Harris, U.S. EPA/Industrial Environmental Research Laboratory, Cincinnati, Ohio, accompanied the research team as observers.

The following individuals were contacted at Intel:

1. Mr. Edward J. Sawicki, Corporate Safety Manager
2. Mr. Ed Boleky, Plant Manager
3. Mr. Jerry O'Neal, Senior Facilities Engineer
4. Mr. Bill Taylor, Safety Engineer
5. Mr. Steve Kopp, Site Safety/Security Manager
6. Mr. Steve Schuster, Safety Committee Chairman

The study protocol was provided to the corporate safety manager prior to the preliminary survey. An opening conference was held with plant representatives. The study objectives and methods were described. A detailed description of the health and safety programs at the plant was provided by the plant staff. The plant structural design and layout, process description, unit operations, monitoring systems, gas handling systems, and chemical storage facilities were reviewed.

Following the opening conference a detailed tour of the facility was conducted. Production areas, gas and chemical storage areas, air handling systems, waste management systems, and medical facilities at the plant were reviewed. A closing conference was held following the survey. All information provided by the plant that was considered confidential was identified by plant representatives.

3.0 PLANT DESCRIPTION

3.1. General

The plant is an integrated circuit fabrication facility located in a two-building complex. It consists of a 150,000 sq. ft. building, with a 34,000 sq. ft. Class 100 clean room, of tilt-up construction, Type 3N, (Uniform Building Code). The plant was opened in 1980 and is at less than half production capacity. The plant produces N-MOS type integrated circuits.

Approximately 300 people are employed on three shifts at the plant as follows: 194 first shift, 84 second shift, and 22 third shift.

3.2. Chemical Storage

Chemicals are stored in a chemical warehouse and transported to the facility via common carrier. Chemicals stored at the plant are segregated as acids and solvents (organics). Storage rooms are approximately 6 inches below the surrounding floor level. Separate storage rooms are used for acids and solvents. Acids are received as boxed shipments and stored on wooden pallets. Chemical spill kits are available in the storage rooms.

Solvents are received as boxed shipments or drums. The solvent storage room is mechanically ventilated with ventilation take-offs located at floor level. A trench is located in the storage room. Drums are placed on the grating above the trench, grounded, and connected to an automatic pumping system.

3.3. Gas Handling System

Production gases are provided either in cylinders or as bulk shipments. Gas cylinders are stored outside of the facility in a covered secured area. Cylinders are segregated into four major categories:

flammable, toxic, pyrophoric, and oxidizer. Most cylinders have excess flow control valves to automatically close the line when gas flow exceeds a preset flow limit. A purge gas cylinder is located beside the process gas cylinder. Control assemblies for gas purging are mounted above the gas cylinders.

Bulk storage tanks are used for nitrogen and oxygen, and are located outside of the building. Gases supplied by cylinders include arsine, Freon®, phosphine, hydrogen chloride, silane, dichlorosilane, boron trifluoride, and ammonia. Hydrogen chloride, hydrogen, and dichlorosilane are stored in ventilated cabinets located indoors. Gas control systems have excess flow valves. Cabinets have local exhaust ventilation and are located in fenced, locked enclosures. Gases are piped to process operations using welded stainless steel lines. Hydrogen is supplied to process operations in a double-line of welded stainless steel tubing enclosed in PVC. The interstice contains nitrogen, which is purged toward a combustible gas monitor. Process gas for ion implantation is supplied in lecture bottles located in a ventilated gas storage cabinet in the ion implantation unit.

Natural gas is piped through a seismic protection valve into the plant. Cylinder gases are purchased in size K and T bottles and piped into the building.

3.4. Monitoring Systems

Two types of monitors are used for monitoring gases. Hydrogen is monitored by both a Bacharach® Model CD 850 and by an IST® sensor. The Bacharach® sensor is used to monitor lines for explosive concentrations. The IST® unit is employed near the ion implantation units. The alarm from this system (10 ppm) will identify a toxic gas leak. This is a combustible mixture alarm that will activate for combustible compounds, such as hydrogen and alcohols. The Bacharach® sensor and the IST® sensor have been in use since early 1981.

A second toxic gas monitoring system is the Miran® 801. This system is a multistation, multicomponent monitoring system. The system is used to monitor for arsine, phosphine, hydrogen chloride, nitrogen dioxide, hydrogen fluoride, xylene, n-butyl acetate, and acetic acid. Isopropanol, water, and carbon monoxide are interference compounds which are also monitored. Each line is prepurged before it is sampled so that the gas analyzed is representative of that present at the sampling location during the period analyzed.

Local exhaust ventilation is monitored through visual alarms. Velocity, temperature, humidity, and pressure are measured at key points, such as ventilation ducts and upstream of the scrubber. Breathing zone monitoring of workers for arsenic and organics is also performed.

Alnor velometers are used to measure ventilation flow rates on a periodic basis. The ventilation system power is backed up for full flow capability on the emergency power system.

4.0 PROCESS DESCRIPTION

The plant purchases pre-doped p- and n-type silicon wafers. Photomasks used for defining circuit patterns in the wafer are produced for the plant by another manufacturer. Process operations performed at the facility include thermal oxidation, chemical vapor deposition (silicon nitride, polycrystalline silicon, and silicon dioxide), photolithography (wafer cleaning, photoresist coating, soft-bake, wafer exposure, develop, hard bake, etching, and photoresist stripping), doping (diffusion, ion implantation, and hydrogen alloying), and metallization (electron beam evaporation and DC sputtering).

Several process operations utilize similar types of equipment for different process steps. Thermal oxidation, silicon nitride and polycrystalline silicon deposition, hydrogen alloying, and doping (diffusion) are performed in direct digital control furnaces. The processes vary in the types of source gases used, furnace temperatures, processing time, and sequencing of operation.

Similar process steps may be performed with a variety of process equipment. Chemical vapor deposition is performed in a direct digital control furnace and a continuous vapor phase system. Plasma etching is performed in both a planar etching system and a barrel or tunnel etching system.

The production area is designed as a Class 100 clean room with temperature and humidity controlled. All operations, except electron beam evaporation of gold, are performed in the clean room.

The purchased wafers are loaded into quartz boats and placed in an open end tube called an elephant. The elephant is manually attached to the direct digital control (DDC) furnace. The furance consists of a horizontal quartz tube heated by electrical resistance. One end of the tube has a ground glass joint with a removable cap.

The direct digital control furnace is operated by a microprocessor, which controls gas flow, tube temperature, the rate of wafer loading, and unloading and process time. Once the elephant is attached to the furnace, the boats containing the wafers are automatically inserted into the furnace at a programmed rate. Depending on the process step, the gases introduced into the furnace include oxygen (for thermal oxidation), dichlorosilane and ammonia (for silicon nitride deposition), silane (for polycrystalline silicon deposition), phosphorous oxychloride (for doping or junction formation), and hydrogen (for hydrogen alloying). The DDC furnace is used to deposit a layer on the wafer (silicon dioxide, polycrystalline silicon, or silicon nitride), and to promote diffusion of dopants into the wafer surface. Those processes in which a layer is deposited on the wafer surface by a chemical vapor are known as chemical vapor deposition or CVD. These CVD processes include silicon nitride, polycrystalline silicon, and silicon dioxide deposition. Silicon dioxide is deposited in a vapor phase reactor with silane and oxygen.

Wet chemical processes are used at various steps in integrated circuit fabrication. Sulfuric acid and hydrogen peroxide are used to clean wafers by immersion in the heated mixture. The immersion baths are located in laminar flow hoods in molded plastic benches. Local exhaust ventilation of the baths is provided by slots located at the top of the bath and at the rear of the bench. Hydrofluoric acid is used to remove silicon dioxide.

The first step in the photolithographic process is wafer preparation. The photoresist layer, consisting of an organic polymer in a xylene or cellosolve acetate solvent, is spun onto the wafer and soft-baked in an electrical resistance heated oven. The soft-baked wafer is loaded into wafer carriers and transferred to the projection mask aligner for pattern definition. The wafer is automatically removed from the carrier and mounted against a photomask. The circuit pattern is transferred to the wafer by exposure of the wafer to ultraviolet light. The exposed wafer is returned to the carrier and the process is repeated for the remaining wafers. The treated wafer is then submerged in a wet chemical bath to remove the photoresist. Depending on the type of photoresist used (positive or negative) the layer removed is either the unexposed or exposed area. The exposed wafers are treated in a post- or hard-bake oven.

A dopant may then be diffused into the wafer surface. Dopants are introduced into the substrate by gas diffusion or ion implantation, or as a solid dopant, which is then heat treated in a DDC furnace. Diffusion is performed in the direct digital control furnaces. Wafers are inserted, and heated, and a gas mixture of nitrogen and phosphorous oxychloride is introduced to the furnace. Ion implantation uses a focused ion beam. The ions are generated by an electrical arc discharge in a vacuum system containing the doping gas (phosphine, arsine, or boron trifluoride). The ions are targeted at the individual wafer and implanted into the substrate. The ion implantation occurs under high vacuum conditions.

The exposed underlying layer may then be etched using plasma etching systems. Plasma etching is a dry chemical etching method using a plasma gas containing reactive ions which remove material from the wafer surface. The operation is performed under high vacuum conditions. Wafers are loaded into the system, which is sealed and pumped to vacuum. A plasma containing reactive fluoride ions is created by passing a reactant gas through a radio frequency field created inside the sealed chamber. Planar plasma etching and barrel or tunnel reactor plasma etching systems are used at Intel.

An aluminum layer, deposited on the wafer by DC sputtering under high vacuum conditions, acts as a metallic connect. Wafers are loaded onto platens and placed in a load chamber. The load chamber is pumped to a vacuum and the platens are automatically transferred to the sputtering chamber. The sputtering chamber consists of a bell jar and DC sputtering source. The bell jar is lowered and a high vacuum seal is formed. The aluminum is contained in a target material, which is in the bell jar assembly. The aluminum is deposited on the wafer surface by removing surface molecules of the metal from the source target. This deposition is accomplished by the ionizing energy supplied by a DC power source, which is applied to the target. A gaseous glow discharge is established between the anode (containing the wafers) and the target (containing the material to be deposited). The aluminum atoms are sputtered from the target to the wafer surface. After deposition of the metal, the photolithographic sequence is repeated to define the metal pattern. Etching is used to remove the exposed aluminum and establish the contact pattern.

The last step in the fabrication process is the deposition of a gold layer on the wafer backside. This layer promotes bonding of the integrated circuit chip during packaging and is deposited through electron beam evaporation. The wafers are loaded into the planetary. The bell jar is lowered and the unit is pumped to a high vacuum. Gold is evaporated from a target source using an electron-beam field applied to the gold source material. High vacuum conditions (10^{-2} torr) are created with an initial rough pumping of the bell jar using a mechanical roughing pump. Lower pressures are obtained using a cryogenic or diffusion pump. The diffusion pumps utilize a low boiling hydrocarbon fluid. Molecules of the hydrocarbon vapor are heated in the pump bottom and ejected downward, sweeping gas molecules from the chamber. A cryogenic trap is used to remove water vapor present in the chamber air.

The above steps may be repeated several times to produce an integrated circuit. The differences in electrical properties of the layers and the arrangement and sequence of the layers forms the transistors, capacitors, resistors, and conductors, which constitute the integrated circuit.

5.0 DESCRIPTION OF PROGRAMS

5.1. Industrial Hygiene

The plant employs a full-time safety engineer. An industrial hygienist employed at corporate headquarters is also available. Consultants are used as necessary in the areas of industrial hygiene, health physics, medicine, and toxicology. Corporate staff were involved in the initial design of the plant.

The work area is monitored with personal and area sampling methods. A monitoring system has been developed which samples workroom air from 24 remote locations with analysis at a central location using the Miran® 801 for the agents and interference compounds listed in the discussion of monitoring systems (Section 3.4).

The results from area sampling are reported on computer printouts. Analytical results are reported as 8-hour, time weighted averages and peak concentrations by location of sampling stations. Sampling probes were located based on results of smoke tests. A hydrogen monitoring system is also present with sampling points near areas of hydrogen use (e.g., hydrogen alloying furnace).

Personal monitoring has been conducted at the plant for production and maintenance workers. Verbal and/or written results of personal monitoring are provided to employees. Monitoring records were available, but were not reviewed during the survey. Personal monitoring has been conducted for numerous chemical agents, including arsenic. Plant personnel indicated that personal breathing zone samples of workers exposed to arsenic have not been above 1 $\mu g/m^3$ (limit of detection). Monitoring of exposures to physical agents, including X-rays, radio frequency radiation, and ultraviolet radiation, has been conducted.

Local exhaust ventilation is monitored with Alnor® velometers. In-house systems are equipped with audible and visual alarms should a ventilation failure occur. Ventilation systems are backed up with emergency generators.

Standard operating procedures are defined for normal production and maintenance operations. Work practices are listed for all job classifications. Chemical transport in-house is limited to individuals specifically trained in chemical handling. Maintenance personnel are trained for specific pieces of equipment. Written maintenance procedures are available. Material safety data sheets are available for chemicals used at the facilility. Detailed procedures have been developed for chemical spills, confined area entry, chemical handling, earthquakes, electrical maintenance and lockout, electrical safety, and gas cylinder storage.

Emergency response equipment is available at the facility. A loss control team has been established to respond to emergencies, to facilitate plant evacuation, and to safely shut-down building services and utilities as needed. Written procedures for emergency response have been established.

The facility has established a radiation safety program, administered by a radiation safety officer. The program requires controlled access to high radiation areas. Permissible levels of exposure are adapted from 29CFR1910.96.

5.2. Education and Training

All new employees must complete a 20-hour new hire technical orientation. The orientation includes sections on safety practices, tools, equipment, and technology. General facility safety practices are described. Personal protective equipment and emergency procedures are provided. Potential chemical and physical hazards in the plant, the effects from exposure to these agents, and the appropriate first aid treatment are described. Maintenance procedures for equipment are also outlined. Gas handling procedures and training in changing cylinders, calibrating cylinders, assembling regulators, and leak testing cylinders are part of the training program. The hazards of gases used at the facility are also described.

Training of employees occurs every 6 months. All employees are continuously monitored for safety. The safety practices of new employees are carefully monitored for the first 3 months to identify unsafe work practices.

5.3. Respirators and Other Personal Protective Equipment

Personal protective equipment required by the plant includes safety glasses or goggles, bunny suits (coveralls) with hoods, safety shoes, and latex gloves. Additional protective equipment used during the handling of acids includes aprons with sleevelets and face shields. Self-contained breathing apparatus with a full facepiece operated in a pressure demand mode used when changing lecture bottles for ion implantation. Self-contained breathing apparatus (SCBA) are also accessible for emergencies within the plant. Those performing maintenance requiring any type of respiratory protection use a self-contained breathing apparatus described above.

The plant respiratory protection program requires employees using respirators to undergo a medical examination to determine their ability to use this equipment. The program administrator is the employees' supervisor. The correct respirator is selected by the supervisor, and the employee is trained in the use, inspection, assembly, disassembly, cleaning, and sanitizing of the respirators. Respirators are tested by the employee using a negative pressure test. A logbook is provided for each respirator which details its use, cleaning, and inspection. Only self-contained breathing apparatuses were used at the plant. Engineering controls preclude the need to use other respiratory protection.

The facility is equipped with acid suits, disposable acid resistant coveralls and SCBA with full facepiece operated in a pressure demand mode for emergencies.

5.4. Medical Program

The plant employs a full-time registered nurse during the first and second shifts, and a physician is available from the corporate headquarters. Furthermore, security personnel are trained in first aid and cardiopulmonary resuscitation. Medical treatment is available at a nearby hospital.

The medical program requires only a medical history with visual tests of employees also being performed. Baseline tests of urinary arsenic levels are required of all employees working with arsenic compounds. A pre-placement medical examination of all new employees began on September 1, 1981 and physical examinations will be required on an annual basis. This program includes a medical history questionnaire, vital signs, routine urinalysis, blood tests, and back analysis (Kraus-Weber fitness exam and X-ray).

Emergency equipment available at the plant includes showers, eye wash stations, and oxygen supply.

5.5. Housekeeping

As noted, the production area is a Class 100 clean room (100 particles per cubic foot). Dust levels in the rooms are controlled by passing room air through HEPA filters. Also, as stated earlier, production workers are required to wear bunny suits with hoods, booties, gloves and safety glasses or goggles. Individuals with facial hair are required to wear masks. These controls are designed to limit particulate levels in the fabrication area.

Additional engineering controls have been included in the design of the facility which eliminates many housekeeping problems. These engineering controls are defined in detail in Section 7.0 and include distribution lines for pumping process chemicals from a central storage area to the specific unit operation, and suction lines and waste drains for transporting waste liquids from wet chemical areas to waste storage and treatment facilities. Pump oils and filtration media from roughing pumps are replaced by reversing the pump flow and pumping wastes into a container. The pumping oil and filtration media are changed every 1 to 4 months. Written maintenance procedures have been established for process equipment. Equipment maintenance operations were not evaluated during the survey.

Hazardous wastes generated at the facility are transported to a Class I hazardous waste landfill for disposal. Hydrofluoric acid wastes are transported to an acid treatment facility. Other acid wastes are diluted to an acceptable pH level and disposed of in the sewer system for treatment by the public sewage treatment plant.

6.0 SAMPLE DATA FROM PRELIMINARY OR PREVIOUS PLANT SURVEYS

Sample data from previous plant surveys and equipment evaluations conducted by Intel staff have been compiled by plant staff but were not reviewed at the preliminary survey. Monitoring data available include results of the plant area monitoring network, personal monitoring of worker exposures, and equipment evaluations.

7.0 DESCRIPTION OF CONTROL STRATEGIES FOR PROCESS OPERATIONS OF INTEREST

A variety of strategies are used at Intel to control emissions and work exposures. Control strategies used include local and general exhaust ventilation, process modification, process substitution, process isolation, process and environmental monitoring, personal protective equipment, and work practices. The following is a detailed description of each process operation and the control strategies applied.

7.1. Chemical Vapor Deposition

Chemical vapor deposition (CVD) is the formation of a stable compound on a heated substrate by the thermal reaction or decomposition of gaseous compounds. Examples of CVD observed at the plant include silicon nitride deposition, polycrystalline silicon deposition, and silicon dioxide deposition. The deposition of silicon nitride is performed in a direct digital control furnace. Silicon dixoide is deposited in a continuous vapor phase system. A general description of the direct digital control furnace is given below. The description is applicable to those operations which use the DDC furnace (silicon nitride deposition, thermal oxidation, diffusion, and hydrogen alloying).

The direct digital control furnace system includes a microprocessor, which organizes the overall furnace processing using feedback control loops. The control loops are used to insert and withdraw wafer carriers at a specified rate, to raise or lower the furnace temperatures at a specified rate, to adjust the various gas flows as a function of time, and to monitor the actual temperature profile inside the furnace as a function of time (Douglas, 1981). The microprocessor can automatically clean the furnace, perform an automatic calibration cycle, and tailor the dynamic performance of the furnace to a given process step. The advantage of the direct digital control furnace is the high degree of process reproducibility possible with the system. A disadvantage is that all control is lost if the computer fails.

The primary components of the system include an electronics enclosure, jungle cabinet, load station, furnace modules, and source cabinet. The source cabinet is used for the diffusion furnace bubbler system, source dopant system, and as a location where the gas systems interfaces with the furnace tube.

Wafers are received in fused silica boats. The boats are loaded in queue onto a carrier and the carrier is placed into a silica glass tube. The entire task is performed by a single operator at a laminar flow work bench close to the furnace. A glass plug is removed from the furnace tube and the elephant is manually lifted into the furnace loading station and attached to the furnace. The loading station is enclosed with movable panels, which allows access during loading and unloading of the elephant.

The silica glass elephant is ground at one end to promote a fairly tight seal with the furnace tube. A small round opening at the opposite end of the elephant receives a silica glass tube called a boat puller. The boat puller is used to advance the boats into the furnace at a programmed rate. The boat puller also retrieves the boats upon completion of the cycle.

Local exhaust ventilation consists of a local exhaust take-off at the furnace tube opening. The face velocity at the ventilation take-off was reported to be 600 to 1300 lineal feet per minute.

The chemical vapor deposition of silicon nitride is used in both bipolar and MOS technologies. In the production of bipolar integrated circuits the silicon nitride deposition provides for passivation. In MOS integrated circuits it is used for multilayered insulators.

Silicon nitride is formed on silicon wafers in a direct digital control furnace. The deposition of silicon nitride on silicon wafers is similar to that described above. The wafers are loaded into boats, placed in a carrier, and inserted into the elephant. The elephant is attached to the furnace and the boats are automatically loaded into the furnace. The processing sequence is controlled by the system microprocessor, as described above. The wafers are heated in an atmosphere of dichlorosilane and ammonia. An amorphous silicon nitride film grows on the wafer surface and hydrogen gas is liberated during the reaction.

Silicon dioxide deposition is a form of chemical vapor deposition (CVD) where a stable SiO_2 layer is formed on a heated substrate (single crystal silicon wafers) by the thermal reaction or decomposition of gaseous compounds. The SiO_2 layer is deposited by the oxidation of silane with oxygen. The SiO_2 glass deposition system observed at the Intel plant was a continuous vapor-phase oxidation system. The system is a low-temperature cold wall reactor operating at atmospheric pressure. It includes a reaction chamber, gas control system, time and sequence control system, heat source, and effluent handling system. Time and sequence of gas input (SiH4, O_2 and PH_3) are computer controlled.

Prior to loading wafers into the system, the wafers are cleaned with a degreasing solvent, followed by acid cleaning (sulfuric hydroxide - H_2SO_4 and H_2O_2) and drying. The wafers are manually loaded in the SiO_2 glass deposition system. Wafers are automatically transported through a nitrogen purge to the preheat zone and into the reaction chamber. The SiO_2 film is deposited by the oxidation of silane (SiH_4) with oxygen. Phosphine is added to the reaction chamber gases and is deposited with the SiO_2 as a dopant. After the deposition sequence is completed, the wafers are removed and placed in wafer carriers.

7.1.1. Engineering Controls. Local exhaust ventilation of the DDC furnace consists of a takeoff located at the furnace tube opening. Air flow is directed from the source cabinet through the furnace tube to the furnace opening. A nitrogen purge of the furnace tube opening provides dilution of the reactant gases released from the furnace.

The furnace loading station is enclosed by movable panels. The elephant containing the wafer carriers is placed in the loading station and attached to the furnace. The panels are closed and the load station is automatically purged with nitrogen. The source cabinet containing the bubbler system, source dopant system, and gas interface systems is enclosed.

The continuous vapor phase reactor consists of a preheat zone, main SiO_2 deposition zone, and a post heat zone. The wafers are manually fed to the reactor. Wafers enter a nitrogen purge in the preheat zone and pass through a nitrogen curtain prior to the main deposition zone. Phosphorus-doped silicon dioxide is deposited on the wafer surface in the main zone. The system consists of a heater block, dispersion tubes, gas controls, and local exhaust ventilation of the reactor. Wafers with a deposited silicon dioxide layer pass through the nitrogen curtain and nitrogen purge. Loading and unloading stations are normally covered during operations. The metal covers are manually removed when loading or unloading wafers.

The reactor is located in a protective enclosure. The gas control systems for silane, oxygen, nitrogen, and phosphine are located at the front of the process unit. Wafer loading and unloading is from the side of the equipment.

7.1.2. Monitoring. The DDC furnace is microprocessor controlled. The microprocessor controls the process cycle directing loading and unloading of the furnace, gas flow, temperature, calibration, and cleaning. A specific "recipe" is programmed for the individual process step.

Environmental monitoring of the workroom is performed with multi-station, multicomponent sampling, and central analysis by the Miran® 801. Sampling ports are located in the clean room area above the gas jungle cabinets. Specific details of the gas monitoring system are described in Section 3.4.

7.1.3. Personal Protective Equipment. Personal protective equipment requirements include normal clean room attire consisting of hoods, booties, clean suit, latex gloves, chemical safety goggles or safety glasses, and safety shoes. Heat protective gloves are used by workers unloading wafers from the continuous vapor phase reactor. A heat resistant handle is used to remove the ground glass cover from the furnace tube.

7.1.4. Work Practices. Computer control of the DDC furnace results in limited contact of the worker with the furnace. After loading of the elephant, the process is completely automated, requiring only that the worker initiate the program.

Detailed written maintenance procedures have been established for the continuous vapor phase reactor.

7.2. Thermal Oxidation

The oxidation of silicon to silicon dioxide is an important process in both bipolar and MOS monolithic integrated circuit technology. Thermal oxides are used in both technologies as barriers to the diffusion of doping agents. Oxide areas, which have been defined by photolithography, are used to establish the boundaries of the circuit pattern. Silicon dioxide is also used in MOS technology as the dielectric gate material.

Silicon wafers are oxidized by a wet oxidation process. Deionized water vapor in a nitrogen carrier gas is introduced into the furnace as the oxidant. Silicon dioxide is formed on the wafer in a direct digital control furnace. The furnace design and processing steps are similar to those described for chemical vapor deposition of silicon nitride. The wafers are loaded into boats placed on a carrier, and inserted into the elephant. The elephant is attached to the furnace and the boats are automatically inserted into the furnace. The processing sequence is controlled by the furnace system microprocessor.

7.2.1. Engineering Controls. Thermal oxidation is performed in DDC furnaces using a wet oxidation process of deionized water vapor. Engineering controls for the DDC furnace are summarized in Section 7.1.1.

7.2.2. Monitoring. General clean room monitoring is performed with remote sampling ports and analysis by the Miran® 801. The monitoring system is described in Section 3.4. The process control of the DDC furnace is described in Section 7.1.

7.2.3. Personal Protective Equipment. Personal protective equipment requirements for thermal oxidation include chemical safety goggles or safety glasses, safety shoes, and heat protective gloves. General clean room attire is also required.

7.2.4. Work Practices. Work practices for operation of the DDC furnace are described in Section 7.1.4.

7.3. Doping and Hydrogen Alloying

Doping is the process of introducing impurities into the substrate to produce changes in its electrical properties. These impurities are referred to as dopants. Two specific doping methods observed at the plant are diffusion and ion implantation. Hydrogen alloying of the substrates is also performed to remove radiation damage from the metalization process and to promote good electrical contact between the metal and silicon.

Gaseous dopants used at Intel include boron trifluoride, arsine and phosphine. Doping of substrates with gaseous dopants is performed in direct digital control diffusion furnaces. These dopants are used for diffusion and ion implantation. The dopant gases are introduced to the diffusion furnace at atmospheric pressure. The gas flow is controlled by the system microprocessor.

Arsine, phosphine, and boron trifluoride dopant gases are used in a high vacuum ion implantation system. Gas flow and other process variables are controlled by the system microprocessor. Ion implantation gases are stored in ventilated gas storage cabinets located within the ion implantation unit.

Diffusion operations introduce impurities into the substrate to produce changes in the electrical properties of the substrate. Dopants used at the plant include n-type electron donors ($POCl_3$). Doping of the substrate is performed in a direct digital control furnace.

Prior to doping, a layer of silicon dioxide is deposited on the substrate. Photolithographic processes are used to define the mask pattern. The wafers with the silicon dioxide mask are loaded onto a carrier and placed into a silica glass tube or elephant. The elephant is placed in the load station of the furnace and connected to the furnace with a ground glass seal. A small round opening in the opposite end of the elephant receives a silica glass tube which is used to insert the carrier into the furnace at a programmed rate. The doping agents, introduced into the furnace in nitrogen, diffuse into areas of the substrate where the mask layer has been removed from earlier photolithographic processes.

Diffusion of the dopant into the substrate is determined by the temperature, gas flow, time sequence, and type of dopant. The dopant ($POCl_3$) is contained in a quartz bubbler placed in the source cabinet of the furnace. Nitrogen is bubbled through the liquid. The resulting gas contains sufficient $POCl_3$ for doping. The $POCl_3$ reacts with oxygen in the furnace to produce P_2O_5.

Ion implantation is used in both bipolar and MOS technologies to introduce selected impurities into semiconductor wafers. This technique allows greater control over the amount of dopant being introduced and operates at much lower temperatures than diffusion processes.

Ion implantation uses the focused ion beam of a source gas to dope semiconductor material. The beam is generated at the ion source. The source consists of a Freon cooled arc chamber (anode) surrounding a tungsten filament source (cathode). An electrical arc discharge is maintained by passing a source gas (or vaporized liquid) through the chamber. The ion beam is drawn from the arc chamber by an extraction electrode and directed to the analyzing magnet. The magnet analyzes, resolves, and focuses the beam and selects only the desired species of ions required for implantation.

The selected ions are then targeted through the acceleration tube in the direction of the wafer target. The acceleration tube optimizes both the focusing and transmission of the selected ion beam. The selected beam enters the lens and scavenger box, where it is further focused and deflected toward the wafer target. The scanner has the capacity to move the ion beam in a raster pattern to cover the entire target area with the smaller ion beam diameter. The focused beam finally enters the target chamber, where a silicon wafer has been automatically removed from a standard wafer cassette (boat) and positioned for impact. Each target wafer enters the chamber via an input vacuum lock. The locks are sealed and vented before a wafer enters or leaves the target chamber. The ion implanter scans the beam across the target wafer, implanting the desired ion species at a preferred concentration.

Three types of source gases are commonly used during ion implantation: boron trifluoride, BF_3; phosphine in hydrogen; or arsine in hydrogen. The source gases are supplied in lecture bottles located in the nitrogen purged gas box.

The ion implanter maintains three independent vacuums: the source, beam line, and end station (or target). Typically, each vacuum is produced by a mechanical roughing pump and a diffusion pump. The input and output vacuum locks are serviced independently by two roughing pumps. Cryogenic pumps may be used in the source and end station regions. The beamline and end station are isolated from the beam regions of the instrument using liquid nitrogen locks. Each pumping system is fully automatic and will shutdown the implantation process in event of a vacuum leak.

The instrument and gas box are vacuum vented using dry nitrogen. The target chamber and wafer handling mechanisms are ventilated by a vertical laminar flow hood at 600 cfm.

Hydrogen alloying is the process of heating the subst:ate in a hydrogen or hydrogen/nitrogen atmosphere. It is performed to remove radiation damage from metalization and to minimize contact resistance between aluminum and silicon. Hydrogen alloying is performed in direct digital control furnaces identical to those used for chemical vapor deposition of silicon nitride.

The wafers are loaded into carriers, placed in an elephant, and connected to the furnace. The wafers are automatically inserted into the furnace. Wafer loading/unloading, temperature, gas flow, and process time are automatically controlled by a microprocessor control unit. Following insertion into the furnace, the wafers are heated in a pure hydrogen atmosphere for a specified time. The furnace is purged with nitrogen and the wafers are automatically removed.

The elephant containing the wafers is attached to the furnace at a loading station that is enclosed by movable panels for access during loading and unloading. The furnace tube is sealed with a removable quartz cap when not in production. A ground glass seal on the tube end provides the connection for attaching the elephant or cap to the furnace. The system is purged with nitrogen during the alloying process to dilute hydrogen gas escaping from the seal.

Local exhaust ventilation is provided at the furnace opening. A ventilation take-off is located adjacent to the furnace tube opening. Hydrogen sensors are located in the source cabinet, at the load station, and exhaust duct, and above the jungle cabinet. Hydrogen gas is supplied to the furnace in a double jacketed stainless steel/PVC line. This line is purged with nitrogen from the furnace back to the storage cabinet. A hydrogen monitor is located in the storage cabinet.

7.3.1. Engineering Controls. As described, diffusion and hydrogen alloying are performed in a DDC furnace. Engineering controls for the furnace are described in Section 7.1.1. DDC furnaces used for diffusion require the use of liquid dopant sources. Quartz bubblers containing $POCl_3$ are mounted in the enclosed source cabinet. Air flow from the cabinet is directed to the diffusion furnace. Local exhaust ventilation of the DDC furnace is located at the furnace tube opening near the loading station.

DDC furnaces used for hydrogen alloying do not require the quartz bubbler system. Hydrogen is supplied to the furnace from cylinders stored in ventilated gas storage cabinets located in the basement. The hydrogen is piped to the furnace entering at the source cabinet. Hydrogen lines are double jacketed stainless steel in PVC.

Ion implantation is performed in high vacuum conditions (10^{-5} torr). The vacuum is established by a mechanical roughing pump followed by a cryogenic trap and a diffusion pump. The vacuum creates negative pressure conditions which limit the release of the ions into the workroom air. Individual wafers are loaded into the ion implantation unit through load locks which are evacuated with a mechanical pump. Prior to loading or unloading wafers, the lock is purged with nitrogen. Ion implantation gases (boron trifluoride, phosphine, and arsine) are stored in a ventilated gas cabinet located inside the ion implantation unit.

The ion beam source is lead shielded to prevent X-ray leakage. The ion source is contained within two lead shielded cabinets. Access to the source is through panels which are electrically interlocked to the system. The cabinets are electrically grounded.

7.3.2. Monitoring. Interlocks on the ion implantation vacuum system will shut down the unit if leaks occur in the vacuum system. Process monitoring is performed by a microprocessor, which controls wafer cycling and determines the implanted dose.

Environmental monitoring of the workroom environment is provided by a sampling port located above the ion implanter. The workroom air is sampled and analyzed by the Miran® 801 system described in Section 3.4.

Hydrogen alloying performed in the DDC furnaces is monitored using combustible gas detectors placed in the load station, source cabinet, and heat exhaust duct. A detector is located in the ventilated gas cylinder cabinet where the hydrogen cylinder is stored.

Hydrogen is monitored at the ion implantation unit. The hydrogen is used as a carrier for the source gas. Hydrogen is monitored to determine if a leak condition exists for the more toxic gases. A hydrogen sensor is located in the exhaust stack of the gas storage cabinet located in the ion implanter.

7.3.3. Personal Protective Equipment. Personal protection requirements for workers operating the ion implantation unit, and DDC furnace consist of standard clean room attire. This attire includes hood, clean suit, booties, chemical safety goggles or safety glasses, latex gloves, and safety shoes.

Individuals responsible for changing gas bottles for the ion implanter are required to wear pressure demand self-contained breathing apparatus.

Workers handling quartz bubblers containing $POCl_3$ must wear acid-resistant gloves, chemical aprons, and face shields.

7.3.4. Work Practices. Handling of lecture bottles used in ion implantation is limited to specially trained workers. Workers are required to wear positive pressure SCBA when handling ion implant lecture bottles.

Pump oils for the oil roughing pump are changed by reversing the flow of the pump and pumping out oils into a container. The oil is manually replaced. Freon for the diffusion pump is manually charged.

Phosphorous oxychloride is supplied in sealed quartz bubblers. Standard operating procedures have been established for handling the bubblers. Bubblers are only changed by trained personnel. The bubblers are received in metal containers packed in wooden boxes. The containers are removed from the boxes and transferred to a laboratory hood. The quartz bubbler containing the liquid $POCl_3$ is removed from the metal can. The used bubbler is removed from the source cabinet, placed in a chemical carrier bucket, and transported to the laboratory hood, where it is packed into the metal can, sealed, and stored for hazardous waste disposal. The replacement bubbler is transferred to the furnace in a chemical carrier bucket. The bubbler is placed in the source cabinet and attached to the furnace.

Emergency procedures for corrosive spill cleanup of the bubbler solution have been established.

7.4. Wet Chemical Cleaning Processes

The silicon wafer cleaning process is performed to obtain a clean, uniform, and stable surface. The cleaning operations are performed in Class 100 enclosures using ultrapure, electronic grade chemicals.

The initial step during the cleaning process is the immersion of a cassette of wafers in a solution of sulfuric acid and hydrogen peroxide, commonly referred to as sulfuric peroxide. The exact proportions of sulfuric acid to hydrogen peroxide were not specified at Intel. However, typical solutions used in industry contain approximately nine parts concentrated H_2SO_4 to one part H_2O_2. Nitric or hydrochloric acid may be added in small amounts. The initial solution is designed to remove organic residue, which may have accumulated on the wafers during handling.

A second wet chemical cleaning process is designed to remove unwanted silicon dioxide formed during the cleaning processes. The clean wafers (in cassettes) are submerged in a solution of one part hydrofluoric acid to ten parts deionized water. When oxide etching is completed, the wafers are rinsed in pure deionized water.

Following the deionized water rinse, the wafers are removed from the cassettes and dried by spinning under a nitrogen blow-off. This portion of the process is automated.

The cleaning baths, oxide etch, rinse baths, and nitrogen blow-off system are located under laminar flow ventilation. Baths or etching tubs used in the cleaning process are equipped with take-off vents around the tank perimeter. The vents are used to maintain a constant down draft across the face of each tub.

Spent solutions used in the cleaning process are aspirated out of the tubs. New solutions are manually added.

7.4.1. Engineering Controls.

Wet chemical benches are of plastic construction. The benches are located under laminar flow hoods. Air is passed through HEPA filters. Acid tanks and deionized water tanks are recessed in the wet chemical benches. The acid tanks are heated by electrical resistance. Local exhaust ventilation of the tank is through slots located inside the tank around the top perimeter. Local exhaust ventilation of the entire bench is provided by slot ventilation with take-offs located at the rear of the bench. Air flow for the bench is directed down from the HEPA filters across the work bench to the rear ventilation take-off.

Waste chemicals are removed from the tanks by aspirators located in the bench. Waste acid lines are plumbed from the aspirator to a central waste acid tank located outside of the building.

7.4.2. Monitoring. Sampling ports for the MIRAN® 801 monitoring system described in Section 3.4 were located at ceiling height (approximately 8 feet). The sampling ports in the wet chemical bench areas were located based on smoke tests conducted by Intel.

7.4.3. Personal Protective Equipment. Workers are required to wear normal clean room attire consisting of booties, clean suit, hood, latex gloves, chemical goggles or safety glasses, and hard toe shoes. Workers replacing chemical solutions are required to wear face shields and chemical aprons.

7.4.4. Work Practices. Wafers are contained in carriers of plastic construction. Plastic handles are attached to the carrier and the unit is dipped into the bath. Release of the handle is by hand squeezing of the grip. Individuals mixing solutions for the wet chemical areas are specially trained in chemical handling.

7.5. Photolithography

Photolithography includes the following process operations: 1) photoresist application, 2) substrate exposure, and 3) a photoresist development. These operations are outlined below.

Microelectronic technology uses photosensitive organic compounds to delineate the circuit patterns on silicon wafers. Exposure to light, in particular light at ultraviolet (UV) wavelengths, alters the chemical resistive characteristics of these photoresist compounds. The photoresists are grouped into two separate classes depending on their reaction to UV light exposure. Negative photoresists become insoluble or resistant to etching chemicals on exposure. Positive photoresists become soluble or nonresistent when exposed. Negative UV sensitive photoresists are most frequently used during the production of integrated circuits.

Intel uses both positive and negative photoresists during integrated circuit production. Since negative photoresists were used during the survey, they will be the model for this process description. The application is actually a series of individual "job shop" operations presented as one process for simplicity.

The first operation is the actual application of photoresist material to each clean, dehydrated wafer. A uniform coat of photoresist is spun onto the wafer. The use of either positive or negative photoresist depends on the requirements of the circuit pattern. In either case the procedures for application will be the same. The photoresist is deposited in a uniform layer by spinning at speeds of several thousand rpm's. Chemical exposures for this operation are most often associated with the photoresist solvent; at Intel the negative photoresist solvent was xylene, the positive was cellosolve acetate. During the spin process excess photoresist will be expelled from the wafer surface. Redeposition of the expelled material is prevented through the maintenance of a downdraft at the wafer perimeter. In addition to the local downdraft, laminar flow ventilation is used to establish a clean area around the application/spinning equipment.

The photoresist coated wafers are transfered in cassettes to a pre- or soft-baking oven. The purpose of the pre-bake is to drive off the remaining photoresist solvent prior to wafer exposure. Laminar air flow is provided at the pre-bake work station. Intel used a nitrogen atmosphere, resistance heated oven for the pre-bake.

Substrates coated with a soft-baked photoresist layer are exposed using a projection mask alignment system. Cassettes containing substrates are manually loaded into the alignment system. Single wafers are automatically removed from the cassette. The substrate is held in a vacuum chuck, which is part of an x-y table with rotational adjustment. A single wafer is aligned with the mask using split field optics, which permit simultaneous viewing of the wafer and mask. After alignment the substrate is clamped to the mask, the microscope is moved away, and the substrate is exposed to ultraviolet light. A mercury vapor lamp is used as the UV source. The alignment system exposes the substrate from a 1:1 mask by successive sweeps of an exposure slit. Exposed substrates are automatically returned to the cassette.

An operator is seated at the alignment system to load and unload cassettes and to check mask alignment. The mask alignment system has internal environmental controls, which heat the air and filter particulates.

The development process consists of rinsing away the dissolvable portions of the exposed photoresist film from the surface of the silicon wafer. The dissolvable portion of negative photoresist is the area covered by the mask which has not been exposed to UV light. In the case of positive photoresist, the portion removed is the exposed film surface. The rinsing process usually consists of chemical dissolution of the soft photoresist and finish rinsing in deionized water. The developed photoresist is finally heat treated in a post- or hard-bake oven to improve its hardness and adhesion characteristics.

The photoresist development process at Intel receives the exposed wafers in a standard cassette carrier. The cassettes are manually submerged in the dissolution chemical and deionized water baths. A mixture of n-butyl acetate and various mixed isodecanes are used to remove unexposed negative photoresist. Exposed positive photoresist is removed using a solution of sodium hydroxide. Both dissolution baths are followed by rinses in deionized water.

Post- or hard baking at Intel is performed using a resistance heated batch oven. Laminar air flow is present at the oven and work station. No additional local ventilation was observed.

7.5.1. Engineering Controls. Wafer cleaning, heating, application of photoresist, soft-bake, projection mask alignment, and hard bake are done under laminar flow hoods with HEPA filtration. The spin-on process for application of photoresist is automatically controlled. Local exhaust of the operation directs air downward around the perimeter of the spinning platform to a local exhaust take-off located at the base of the platform. Air enters the enclosure through openings in the rear of the enclosure.

The mask alignment system contains internal environmental controls. The wafer exposure area is enclosed to prevent contamination of the mask and wafer and to limit ultraviolet light emission. Interlocks of the projection mask aligner are also designed to prevent ultraviolet light emissions.

7.5.2. Monitoring. Sampling ports for the MIRAN® 801 monitoring system are located in the photolithography area. The system is described in Section 3.4.

Monitoring of process operations is through automated control of the process cycle. The process cycle for application of the photoresist is automatically controlled to provide uniformity.

7.5.3. Personal Protective Equipment. Personal protective equipment used in the photolithography area consists of the normal clean room attire of hood, clean suit, latex gloves, booties, chemical safety goggles or glasses, and safety shoes.

7.5.4. Work Practices. The handling of individual wafers requires the use of vacuum wands or tweezers. Removable handles are used to place the wafer cassettes in the developing and rinse tanks. Paper towels wetted with isopropanol are used by workers for general equipment cleaning.

7.6. Plasma Etching

Plasma etching is a dry chemical etching method used to remove a specific material or layer from the wafer surface. It is used in the fabrication of semiconductor devices where fine line widths are required. The wafer to be etched may be a thermal SiO_2 layer, aluminum or aluminum alloy thin films, silicon nitride or silicon. A photoresist layer is spun onto the wafer, baked, and exposed. The wafer is then developed and hard-baked. The wafer at this point contains a baked photoresist layer with areas of the underlying substrate exposed from the developing process. The substrate is then ready for etching. The gas used in plasma etching is selected based on the specific substrate material to be etched.

As noted in Section 4.0, two types of plasma etching systems are used at Intel, planar plasma etching and barrel reactor plasma etching. Both etching processes are located in Class 100 clean rooms under laminar flow hoods. The planar plasma etching system consists of a reaction chamber with parallel electrode plates. The top electrode acts as a cathode to establish a radio frequency (RF) field in the chamber, while the lower electrode (anode) holds the wafers. Wafers are loaded on platens and inserted into the reaction chamber. The chamber is sealed, purged with nitrogen, and evacuated to approximately 0.1 to 10 torr. A plasma is created between the plates by passing a reactant gas through the radio frequency field. Ultraviolet radiation generated from the plasma may be released from the reaction chamber through the glass viewing port.

The plasma consists of a variety of ions and free radicals. The free radicals chemically attack the substrate but do not appreciably attack the protective photoresist. The reaction products are removed from the chamber by the exhaust system. A Freon gas is used as the reactant gas for the planar plasma etching system. The fluoride ions produced are reactive with silicon dioxide.

The barrel reactor system consists of a cylindrical chamber. The wafers are vertically mounted in a fused silica carrier. A plasma is created by an RF coil outside the reactor chamber. A perforated cylinder surrounds the substrates which shunts the RF field and confines the plasma between the reactor wall and the cylinder (Colclaser, 1980). The reacting species pass through the perforated cylinder and chemically etch the substrate. The chemically active free radicals in the plasma react with the wafer surface causing etching through a reduced-pressure adsorption-reaction-desorption process (Douglas, 1981). The sequence of events prior to the etching is similar to that described above. A Freon gas is introduced into the barrel reactor and a radio frequency field is established which generates a plasma that is reactive with silicon nitride, silicon dioxide, and polycrystalline silicon. The etch is believed to be the result of atomic fluorine, which diffuses to the silicon surface, forming a volatile SiF_4 that diffuses away from the surface.

The advantage of the planar plasma etch system over the barrel reactor plasma etch system is its ability to produce anisotropic etching where the etch is primarily in one direction (generally perpendicular to the substrate surface). Wet chemical etching methods and barrel reactor plasma etching systems produce isotropic etching profiles where the etch rate is equal in all directions. Isotropic etching results in undercutting of the resist layers.

7.6.1. Engineering Controls. Plasma etching processes operate under vacuum conditions. The vacuum is created using a mechanical roughing pump. The system pressure is negative to room pressure. The plasma gases are exhausted from the pump through local exhaust. Pump oils are continuously filtered.

The plasma etching systems are located under laminar flow hoods. They may be considered as substitutes for wet chemical acid etching where hydrofluoric acid is used to etch the wafers. Plasma etching uses Freon as a source of fluoride atoms. Reactive fluoride ions are formed in an RF field.

7.6.2. Monitoring. No specific environmental monitoring systems for plasma etching are used. Process monitoring of the plasma etching systems is by automatic control of the equipment.

7.6.3. Personal Protective Equipment. Personal protective equipment used at the plasma etching systems consist of normal clean room attire. Specific equipment used for the process operation was not identified.

7.6.4. Work Practices. Wafers are mounted on platens or in carriers and manually placed in the reaction chamber. Specific practices used for the operation of the equipment were not observed.

Mechanical pump oil is changed by reversing the pump flow and pumping the oil into a waste container. Oil is manually added from portable containers.

7.7. DC Sputtering

Aluminum is deposited on the wafer surface by removing surface molecules of the metal from a source material (target) by bombardment with energetic ions. The ionizing energy is supplied by a direct current (DC) power supply. The sputtering process occurs in a vacuum system. The system operates under high vacuum conditions (approximately 30 - 70 x 10^{-3} torr). The high vacuum conditions are created in the bell jar by pumping first with a roughing pump, then a cryogenic pump.

The wafers are cleaned and dried prior to loading on the anode, which is done through a loadlock attached to the sputtering chamber. The loadlock is closed and pumped to vacuum. The wafers are automatically loaded into the bell jar, where a high vacuum is formed. Argon is introduced to the chamber and the DC current is applied. A gaseous discharge of metal atoms is sputtered from the target to the wafers, producing a thin film of aluminum on the wafer. The chamber is then automatically unloaded and the wafers are transferred to the loadlock, where they are ready for photoresist application and further processing. The sputtering sequence is automatically controlled.

7.7.1. Engineering Controls. The DC sputtering system is located in the general clean room environment. The process operates at a pressure which is negative to that of the room. The pump exhaust is vented through the local exhaust ventilation system. The metalization system employs two chambers, a loading chamber and a bell jar chamber. The separate loading chamber minimizes contamination of the sputtering chamber bell jar. The process is automatically controlled.

7.7.2. Monitoring. Specific environmental monitoring systems to evaluate emissions from the process are not present. The process is monitored by automatic control of the process cycle. Interlock is provided to stop the cycle if the hood chamber door is obstructed. A vacuum interlock system will shut down power if the chamber vacuum is not achieved.

7.7.3. Personal Protective Equipment. Personal protective equipment consists of normal clean room attire. Specific equipment used for the process operation includes gloves used during chamber cleaning with potassium hydroxide.

7.7.4. Work Practices. Equipment maintenance requires removal of the bell jar and internal reactor assembly for cleaning. The bell jar is cleaned with potassium hydroxide. Metal sputtering parts are bead-blasted for cleaning.

7.8. Electron-Beam Evaporation

Gold is deposited on the substrate by heating the gold in a high vacuum and condensing the vapor on a cooler substrate. A focused electron beam provides the heat necessary to vaporize the metal. The wafers are placed above the source in a movable fixture called a planetary. During evaporation the wafers are rotated to ensure maximum uniformity of the deposited layer. A glass bell jar is lowered over the fixture and a high vacuum is pumped.

The gold deposition process occurs in a basement area separated from other fabrication activities but not in a Class 100 clean room. Equipment ventilation is limited to exhaust for the vacuum pumping system. The vacuum system is similar to that previously described. The vacuum is created by an initial rough pumping followed by a liquid cold trap and diffusion pump.

7.8.1. Engineering Controls. The system operates under high vacuum conditions, resulting in a chamber pressure which is negative to that of the room.

7.8.2. Monitoring. No specific environmental monitoring systems are used to evaluate work room emissions from the process. The process cycle is monitored through microprocessor control. The entire vacuum cycle is automatically controlled.

7.8.3. Personal Protective Equipment. Personal protective equipment used during electron beam evaporation was not identified. The unit was not in operation during the preliminary survey.

7.8.4. Work Practices. Work practices specific to the operation were not identified.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The production of integrated circuits at Intel is performed in an environment established to control product quality and provide a safe work environment. Individual engineering controls are used within this clean room environment to control product quality and protect the workforce. Individual process operations may be located in the clean room within a laminar flow bench with HEPA filtration. These process operations have associated engineering controls. These process specific engineering controls include operation at negative pressure (vacuum conditions), local exhaust ventilation, automated process control (microprocessor), enclosure (other than vacuum conditions), shielding, and interlocks of the operation.

Work practices, environmental and process monitoring systems, and personal protective equipment are used by Intel to complement engineering controls. Intel appears to have a well-engineered, state-of-the-art facility, with a comprehensive health and safety program to ensure protection of the health and safety of the workforce.

Areas that warrant further study include:

1. Ventilation System Design--It would be beneficial to document how the overall system is designed, how balance is achieved in the system, and how the adequacy of the ventilation system is determined. Procedures and work practices in maintenance of the system should be evaluated in more detail. The general design for adding processes and capacity should also be discussed.
2. Monitoring Systems--The calibration and testing of the Miran® 801 and the combustible gas monitoring systems should be detailed. The analysis of output data trends should be evaluated. Results of personal monitoring conducted by Intel should be evaluated since the data may be useful in documenting the effectiveness of the control technology.
3. Work Practices--Intel appears to excel in establishing safe work practices. Documentation of the overall training philosophy, training methods, and cost of training (administrative burden and employee time) would be beneficial.

4. Maintenance Activities--The maintenance activities of the integrated circuit manufacturing processes should be investigated. Work practices should be identified. Methods used in controlling emissions and worker exposures during maintenance activities should be detailed.

9.0 REFERENCES

Colclaser, R. A. Microelectronics: Processing and Device Design. John Wiley and Sons. New York. 1980.

Douglas, E. C. Advanced Process Technology for VLSI Circuits. Solid State Technology. 24(5):65-72. 1981.