PRELIMINARY CONTROL TECHNOLOGY SURVEY

on

ROCKWELL INTERNATIONAL CORPORATION
Electronic Devices Division
Newport Beach, California

to

U.S. ENVIRONMENTAL PROTECTION AGENCY
Industrial Environmental Research Laboratory
26 West St. Clair Avenue
Cincinnati, Ohio 45268

and

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
Division of Physical Sciences and Engineering
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by

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PLANT SURVEYED:	Rockwell International Corporation Electronic Devices Division 4311 Jamboree Road Newport Beach, California 92660
SIC CODE:	3674
SURVEY DATE:	January 18, 1982
SURVEY CONDUCTED BY:	Gary J. Mihlan Battelle Columbus Laboratories Robert D. Willson, CIH PEDCo Environmental, Inc. Paul E. Caplan, CIH NIOSH
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1.0 ABSTRACT

A preliminary control technology assessment survey was conducted at Rockwell International Corporation, Electronic Devices Division, Newport Beach, California, on January 18, 1982. The survey was conducted by Battelle Columbus Laboratories under a U.S. Environmental Protection Agency contract funded by an Interagency Agreement with the National Institute for Occupational Safety and Health. The facility manufactures p-channel and n-channel metal oxide semiconductor integrated circuits.

The process operations performed by Rockwell International include: 1) thermal oxidation of purchased silicon wafers; 2) photolithography to define circuit patterns, including photoresist application, substrate exposure, and photoresist development; 3) wet chemical etching and cleaning; 4) plasma etching; 5) diffusion; 6) ion implantation; 7) low pressure chemical vapor deposition (LPCVD) of silicon nitride, silicon dioxide, and polycrystalline silicon; and 8) metalization, including radio frequency (RF) sputtering for aluminum and gold deposition and electron beam evaporation for silicon/aluminum deposition. Non-fabrication processes, such as wafer assembly and packaging, are performed at another facility. Several process operations are employed more than once in the fabrication sequence and some equipment is used for more than one process operation. The process operations for integrated circuit fabrication are performed in a clean room environment with high efficiency particulate air (HEPA) filtration of the air supply.

Engineering controls used at the facility vary by process operation and process equipment. Several process operations are performed in sealed reaction chambers that isolate the process from the workers. The isolation technique is used in plasma etching, ion implantation, low pressure chemical vapor deposition, metalization, and some wet chemical operations. Shielding is used in ion implantation to control X-ray emissions, in plasma etching and RF sputtering to control radio frequency emissions, and in substrate exposure to control ultraviolet light emissions. Local exhaust ventilation removes process gases and byproducts from photolithography processes (photoresist application, photoresist developing, photoresist stripping), wet chemical cleaning and etching operations, diffusion, and thermal oxidation. Local

exhaust ventilation is also used at storage cabinets containing toxic, flammable, or corrosive gases.

Several process operations are automated and controlled by microprocessors. These operations include photoresist application, ion implantation, diffusion, thermal oxidation, low pressure chemical vapor deposition, and metalization.

Continuous area monitoring for phosphine is performed with a Matheson® phosphine monitoring system. The facility does not have a continuous combustible gas monitoring system.

Personal protective equipment controls operator exposures during normal process operations and maintenance activities. Rockwell International is developing worker training programs in chemical safety, spill cleanup, and emergency response. The facility employs consultants in industrial hygiene.

A variety of process operations used at the facility should be considered for detailed investigation. These include plasma etching, low pressure chemical vapor deposition, ion implantation, and metalization. Additional areas that should be evaluated include the gas handling system, the ventilation system, and the safety interlocks associated with each.

2.0 INTRODUCTION

A preliminary survey was conducted at Rockwell International, Electronic Devices Division, Newport Beach, California, on January 18, 1982 as part of a control technology assessment of the semiconductor manufacturing industry. The study was performed under U. S. Environmental Protection Agency Contract No. 68-03-3026 through an Interagency Agreement with the National Institute for Occupational Safety and Health. The survey was conducted by Battelle Columbus Laboratories, Columbus, Ohio. Mr. Paul E. Caplan, NIOSH Division of Physical Sciences and Engineering, accompanied the survey team.

The following plant representatives supplied information at Rockwell International:

1. Jerry Meade, Supervisor, Health and Safety
2. Dennis H. Hawkins, Manager, Process Engineering
3. Casey S. Strozewski, Manager, Facilities, and
4. Sylvia Curran, Employee Representative, IBEW Local 2125

The study protocol was provided to Mr. Jerry Meade before the survey. During an opening conference the study objectives and methods were described. Plant staff provided a detailed description of the health and safety programs at the facility, including a review of the plant construction, monitoring systems, gas handling systems, ventilation systems, and chemical storage facilities.

Following the opening conference, the research team surveyed the wafer fabrication area. A closing conference was held following the survey.

3.0 PLANT DESCRIPTION

3.1. General

The Rockwell International Electronic Devices Division manufactures p-channel and n-channel metal oxide semiconductor (PMOS and NMOS, respectively) integrated circuits. The facility occupies a two story, 240,000 sq. ft. building with 120,000 sq. ft. per floor. The building has concrete walls and was constructed in 1968. Wafer fabrication started in 1975 at the facility in two fabrication clean rooms, approximately 7,000 to 10,000 sq. ft. each. The fabrication areas are located on the second floor. Additional operations performed at the facility include the production of mechanical filters and testing and assembly of telecommunications equipment. Two additional wafer fabrication areas are under construction.

The facility employs 572 people in the wafer fabrication area with 351 involved in production, 158 in administration and technical services, and 63 as clerical support or supervisors. The production staff include 271 females and 80 males, the administrative/technical staff include 26 females and 132 males, and 25 females and 38 males in clerical/supervisory staff. The facility operates three shifts per day, with 300 employed in the first shift, 147 on the second shift and 125 on the third shift. The work shifts include a staggered employee work week that allows operation over the weekend.

The plant has two emergency generators that provide power for continuous operation of the exhaust system and for some equipment. The utility that supplies power to the facility can obtain power from an additional utility in the event of a power failure.

3.2 Chemical Storage

The chemical storage area was not observed during the survey due to time constraints. The following information was provided by the facility manager. Liquid chemicals are segregated by U. S. Department of Transportation class and are stored in a covered concrete pad located near the facilities supply. The pad is diked with drains provided for some parts of the pad. The pad is manned 24 hours per day. Flammable or temperature-sensitive chemicals are stored in a temperature-controlled room that is diked and constructed with explosion-proof walls. Dispensing and mixing of chemicals is done in a chemical mix room on the second floor of the building. Chemicals in glass 1-gallon bottles are transported from the storage area to the mix room in plastic carriers. A new chemical storage, mixing and dispensing area is being planned for the facility.

3.3 Gas Handling System

Gases used in wafer fabrication are supplied from cylinders and from bulk house supplies. Hydrogen is supplied to a facility bulk tank by a pipeline and is distributed in copper and stainless steel lines. The hydrogen supply lines do not have seismic valves. Nitrogen gas and liquid nitrogen are supplied to the fabrication area from separate bulk tanks located outside of the plant and are also distributed in stainless steel and copper lines. Liquid oxygen is supplied from a bulk tank and is distributed in stainless steel lines.

Gases supplied in cylinders are stored in a covered pad area and are segregated by class. The cylinders are transferred from the storage area to ventilated storage cabinets near the point of use. The cabinets are seismically anchored. Gases stored in ventilated cabinets include 100 percent phosphine and 100 percent hydrogen chloride. Phosphine is supplied in a small cylinder that is placed in a separate ventilated cabinet located inside a larger cabinet. The cabinet exhaust is vented through stacks to the atmosphere. A continuous phosphine monitor is interlocked to solenoid valves on the phosphine gas line and will shut off gas flow in case of an emergency. A door switch on the cabinet is interlocked to the gas supply line and will shut off gas flow if the door is opened. Flow-limiting valves are also used on gas lines and will shut off gas flow if the flow exceeds a preset limit. The gas supply is also interlocked to the exhaust system and will shut off if the exhaust system fails. Purging of all toxic gas lines is done manually. The source of the purge gas (i.e., house supply or cylinder) was not specified.

3.4 Monitoring Systems

The facility uses four Matheson® Model 8040 continuous phosphine monitoring systems, two in each fabrication area. In each area, one monitor is located above the LPCVD furnace and another above the gas storage cabinet. Air sampled from the area is pulled through a filter tape impregnated with chemical reagents sensitive to phosphine. A chemiluminescent reaction is produced by reaction of phosphine with the chemical reagent and is monitored by the unit. Output from the monitoring system is interlocked to a solenoid valve and will shut off the phosphine gas supply if phosphine is detected. The plant is planning to replace the unit with a continuous monitoring system using emission spectroscopy (TELOS® Labs, Inc.).

False alarms have been a problem with the unit and are presumed to be due to methane emissions from a sewage treatment plant adjacent to the Rockwell International plant. The facility does not have a hydrogen monitoring system.

3.5 Ventilation System

The ventilation system consists of air treatment and supply air recirculation, and local exhaust ventilation. The two fabrication areas are served by separate air handlers, each supplying approximately 100,000 cfm with 40,000 cfm fresh makeup air and the remainder recirculated air. The supply air enters a common ceiling plenum above the fabrication area and is distributed to the fabrication area through high efficiency particulate air (HEPA) filters located across one wall of the fabrication area. The air is recirculated through ceiling grills to the common ceiling plenum. Local exhaust ventilation removes 40,000 cfm of air from each of the fabrication areas. The exhaust is vented directly to the atmosphere without treatment.

There is one air change every 2 to 2.5 minutes. Each exhaust fan has pressure switches to sense loss of suction and is interlocked through solenoid valves in toxic gas lines to shut off gas flow if the exhaust system fails. The pressure sensors will also activate an audiovisual alarm if the exhaust system fails. Smoke sensors, located in exhaust ducts and at the intake of the recirculation fan, will shut off supply air handlers and speed up exhaust fans to clear smoke from the area.

Plastic curtains are used on most wet chemical stations to reduce the open area and increase face velocities at the opening into the station. Face velocities are reportedly 100 to 150 fpm at most of the stations that do not include vertical laminar flow HEPA filtration units in the station. For those stations with the HEPA filtration units, face velocities at the front of the hood are 70 to 100 fpm. The wet chemical stations were modified to obtain a face velocity of 150 fpm. Quality assurance personnel perform a monthly measurement of face velocity for each wet station. Exhaust ducts handling acid exhausts from wet chemical stations are steel with vinyl coating on the inside. The ducts are resistant to corrosion and have passed fire safety ratings.

The plant has two separate utility power feeds and two emergency generators that keep the exhaust fans and some process equipment running in the event of a power failure.

3.6 Waste Management System

Liquid wastes are each handled separately and may be categorized as acids and organic solvents. Acids are aspirated from the wet chemical stations into a central acid drain that flows into a three compartment neutralization tank. The pH is automatically adjusted by the addition of anhydrous ammonia, and the neutralized waste is sent to a publicly operated treatment works. Acids containing fluorides do not undergo special treatment but are handled in the same way.

Waste organic solvents are drained to a central waste holding tank that is periodically removed and replaced by an outside contractor. The central drain system is used for organic solvents, hexamethyldisilizane, and photoresist wastes.

4.0 PROCESS DESCRIPTION

The fabrication sequence used for MOS integrated circuit manufacture varies depending upon the specific type of device manufactured. Process operations seen at the facility are discussed below. The specific sequence in which the process operations are performed is not presented. A general processing sequence for MOS integrated circuits is provided by Colclaser (1980) and Elliott (1982) and should be consulted for a more detailed review of the fabrication process. Several process operations are employed more than once in the fabrication sequence and some equipment is used for more than one process operation. The silicon wafers used as a substrate for device fabrication are purchased.

In the thermal oxidation process, wafers are oxidized at high temperatures (approximately 800 to 1000°C) in an atmospheric pressure diffusion furnace assembly using a pyrophoric (hydrogen and oxygen) atmosphere. Hydrogen chloride is added to the gas stream to minimize electrical defects in the layer (Colclaser, 1980). The operation consists of loading wafers into carriers that are inserted into the diffusion furnace tubes. The furnace tubes are heated by electrical resistance to the operating temperature while the tube is purged with nitrogen. Hydrogen and oxygen are introduced into the tubes at a controlled rate. The furnaces are controlled either with a direct digital control (DDC) system or a hybrid system. The DDC system monitors and adjusts the furnace operating parameters, including temperature, process sequencing, and gas flow by feedback control loops (Douglas, 1981). The hybrid control system utilizes automatic control of process operating parameters that require visual monitoring of the system and manual adjustment by the operator.

Following thermal oxidation, the wafers are ready for photolithography that consists of: 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 by spin application using hexamethyldisilizane (HMDS). A positive photoresist, containing a proprietary mixture of organic polymers in a carrier solvent containing n-butyl acetate, xylene, and cellosolve acetate, is spun onto the wafer. The coated wafer is baked in a resistance-heated oven. The operation is automated and only requires that the operator load and unload the cassettes.

The mask pattern is transferred to the coated wafer by ultraviolet light (395 nm) using either projection mask alignment or stepping projection alignment. The operator aligns the wafer with the mask by viewing through a split-field binocular microscope (projection mask alignment) or by viewing a video display terminal adjacent to the unit (stepping projection alignment). In projection mask alignment, a lens is interposed between the mask and the wafer with the ultraviolet light source located behind the mask. In stepping projection alignment, a set of transfer and condenser optics is interposed between the mercury light source and the mask with the wafer located opposite the mask. Masks used for both systems are purchased.

The exposed wafers are developed by spray application of the developer solution onto the wafers. An aqueous solution containing tetramethyl ammonium hydroxide develops the positive photoresist. The operation is performed in an enclosed spray chamber. After developing, the wafers are rinsed with deionized water and hard-baked in a resistance-heated oven.

The exposed underlying layer may be etched using either wet chemical etching or plasma etching techniques. Wet chemical etching is performed by immersing the wafers in an etching solution. The etching methods include: 1) hydrofluoric acid and ammonium fluoride for etching silicon dioxide, 2) nitric, phosphoric, and acetic acid for etching aluminum or silicon/aluminum, and 3) phosphoric acid for etching silicon nitride. The etching operations are performed in tanks recessed in polypropylene benches similar to laboratory-type hoods. Additional wet chemical operations include cleaning of wafers with sulfuric acid, stripping of photoresist with sulfuric acid and hydrogen peroxide, and cleaning process equipment with hydrofluoric and hydrochloric acid.

Plasma etching is performed by placing wafers in a plasma gas formed by a radio frequency power source operating at 13.56 MHz. The plasma gas contains ions, free electrons, and free radicals that are reactive with the layer to be etched. The gas used for creating the plasma is selected based upon the individual layer and includes 1) Freon and oxygen for etching silicon nitride and polycrystalline silicon, 2) silicon tetrafluoride for etching silicon nitride, 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.

Doping introduces impurities into the wafer, altering the electrical properties of the doped area. Wafers are doped at various stages of the processing sequence either by diffusion or ion implantation. Diffusion is accomplished by exposing the wafer to a high temperature atmosphere containing the dopant. The operation is performed in a diffusion furnace assembly using a liquid (phosphorus oxychloride or boron tribromide) or solid (arsenic trioxide) dopant source. The liquid source is supplied in bubblers whereas the solid source is spun onto the wafer surface before insertion into the diffusion furnace. An oxidation step using a pyrophoric atmosphere may also be performed in the furnace during the diffusion operation.

Wafers are also doped using ion implantation. A source gas (either 15 percent phosphine in hydrogen or 100 percent boron trifluoride) is ionized and passed through an analyzing magnet where the desired ions are collected, accelerated, and implanted into an individual wafer held in a vacuum chamber. The ion source, the analyzing and accelerating chamber, and the wafer exposure station are operated at vacuum conditions of approximately 10^{-6} torr. This vacuum is maintained by a two stage pumping system consisting of an oil-sealed mechanical (roughing) pump and a diffusion pump. The process operation sequence requires the operator to load a cassette into the load station of the ion implantation unit. Individual wafers are automatically removed from the cassette to a load lock chamber which is pumped to vacuum with an oil-sealed mechanical pump. The wafer is transferred to the exposure chamber where the dopant ions are implanted. The dosage received by the wafer is automatically controlled. The implanted wafer is transferred through a second load lock chamber and then into a cassette. A description of ion implantation is provided by Burggraaf (1981) and should be consulted for more detailed information.

During the fabrication sequence, a thin film is deposited on the wafer surface by chemical vapor deposition from the solid products of a vapor phase chemical reaction. Low pressure chemical vapor deposition (LPCVD) is used to deposit 1) silicon nitride by the reaction of dichlorosilane and ammonia, 2) polycrystalline silicon by the reaction of silane, and 3) phosphorus-doped silicon dioxide by the reaction of silane, oxygen and phosphine (100 percent). The operations are performed in a sealed diffusion furnace tube evacuated to approximately 0.4 to 3.0 torr (Baron and Zelez, 1978). The process operation requires the operator to load cassettes containing wafers into the furance. The furnace door is closed and the sequence and operating parameters are then controlled by microprocessor.

A metal layer is deposited on the wafer surface by either radio frequency sputtering or electron beam evaporation. The metal, either aluminum or silicon/aluminum, 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 a second unspecified high vacuum pump.

Radio frequency sputtering of aluminum is a continuous operation in which wafers are loaded onto platens by the operator. The platens are automatically conveyed through a loadlock chamber into the deposition zone. The radio frequency power source operates at 13.56 MHz. The system is also used to deposit gold on the wafer backside. A description of sputtering is provided by Aronson (1978) and should be consulted for more detailed information.

Electron beam evaporation of silicon/aluminum is a batch operation in which wafers are loaded into a planetary by the operator. The chamber is sealed and evacuated and the metal is deposited. Both operations are automatically controlled.

Process operations such as photolithography, doping, metalization, chemical vapor deposition, and etching may be repeated several times during wafer fabrication. Between these processing steps wafers may be cleaned using wet chemical methods previously described.

5.0 DESCRIPTION OF PROGRAMS

5.1 Industrial Hygiene

A full-time safety engineer is employed at the facility with responsibility for industrial hygiene and safety. At the time of the survey the plant was interviewing for an industrial hygienist and now have hired a chemical engineer. Additional assistance is provided by consultants in industrial hygiene and emergency response planning.

Monitoring of emissions and operator exposures to chemical and physical agents has been performed at the plant. The monitoring has included area sampling for sulfuric acid, nitric acid, phosphine, and hydrogen chloride using direct-reading, colorimetric detector tubes. Wipe samples, area samples, stack samples, and personal samples of arsenic from the dopant spin-on operation have been obtained by consultants. Noise measurements have been obtained using a sound level meter and an octave band analyzer. Radio frequency radiation monitoring has been conducted by the California Division of Occupational Safety and Health. Measurements of local exhaust ventilation performance are conducted by facility engineering. Measurements include checks of local exhaust ventilation capture velocity and air supply velocity from laminar flow HEPA filter units.

5.2 Education and Training

Rockwell International has developed training programs in worker safety, personal protective equipment, emergency response, and hazard reporting. Two safety committees have been formed at the plant. One committee consists of the production manager, line managers and safety engineer. The second committee consists of employee representatives from all three production shifts, the union representative, and the safety engineer. The employee safety committee meets every month to review current problems in the plant, and every three months conducts a walk-through survey to identify safety hazards.

Newly hired employees undergo a chemical hazard orientation of approximately 1 hour duration. The orientation includes reviews of the effects of exposure to the chemicals and of proper handling procedures. The plant is developing a chemical safety training program that will cover materials handling and spill cleanup. Each month department meetings are held which include safety training. The training consists of chemical burn hazards, use of fire extinguishers, and other safety issues as needed. Supervisors provide instruction in the use of personal protective equipment. A forklift training program has also been established.

The plant has established an emergency telephone line for reporting any hazardous situation or spill to plant security. The plant recently initiated a program to determine the necessary actions for handling emergency responses.

5.3 Respirators and Other Personal Protective Equipment

Personal protective equipment requirements depend upon the job activity. Operators at wet chemical stations and chemical mix technicians are required to wear acid-resistant aprons, gloves, and face shields. Chemical handlers and maintenance technicians are required to wear safety shoes. Chemical mix technicians are required to wear self-contained breathing apparatus (SCBA) when changing liquid dopant bubblers and when changing hydrogen chloride cylinders. Operators performing arsenic trioxide dopant spin-on operations use a Wilson respirator. All operators are required to wear safety glasses. All employees are required to wear product-protective equipment consisting of smocks, head covers, and booties. Training in the use of personal protective equipment is provided by the supervisor.

5.4 Medical

The facility employs a full-time nurse on one shift only. A physician is available at a nearby industrial medical clinic. A preplacement medical examination is required for newly hired workers. The examination includes pulmonary function, blood, audiometric, and vision tests. Periodic physical examinations are required for inspectors, executive personnel, operators working with arsenic, and operators exposed to radiation. Operators working with arsenic are required to undergo a chest X-ray and a 24-hour urinary arsenic level test.

Emergency medical care is provided by the nurse, by employees trained in first aid and cardiopulmonary resuscitation, by the industrial medical clinic, and by an area hospital. Available workroom emergency equipment includes emergency showers, emergency eye wash stations, breathing oxygen, and a self-contained breathing apparatus.

5.5 Housekeeping and Maintenance

Housekeeping and maintenance activities are required to maintain product quality. Specific housekeeping and maintenance procedures employed at the facility could not be identified for all operations in the time allotted to the preliminary survey. Maintenance includes periodic draining and replacement of pump oil by a maintenance technician in all oil-sealed mechanical pumps used in ion implantation, low pressure chemical vapor deposition, plasma etching, and metalization.

Process technicians periodically pull and clean diffusion furnace tubes with hydrochloric acid or hydrofluoric acid.

A vacuum system is present for general housekeeping. Equipment and work areas are periodically cleaned by wiping. Floors in the fabrication area are cleaned by wet mopping.

6.0 SAMPLE DATA FROM PRELIMINARY OR PREVIOUS PLANT SURVEYS

Sampling for chemical and physical agents released by process operations was not performed during the preliminary survey nor were measurements of the ventilation system taken. Discussions during the preliminary survey with the plant indicated that previous monitoring had been performed by industrial hygiene consultants and by the California Division of Occupational Safety and Health. Physical agents monitored included noise and radio frequency radiation.

Arsenic trioxide emissions and worker exposures have been monitored with area and personal samples, wipe samples, and stack samples.

7.0 DESCRIPTION OF CONTROL STRATEGY FOR PROCESS OPERATIONS OF INTEREST

A variety of control strategies is used at Rockwell International to control emissions and worker exposures. The control strategies include local and general exhaust ventilation, process isolation, process and environmental monitoring, and personal protective equipment. Devices or work stations that contain toxic materials considered of potentially immediate danger to life and health are all controlled by local exhaust ventilation, monitoring systems, personal protective equipment, and work practices. Additional engineering controls used include process isolation and process substitution.

Specific engineering control strategies for individual process operations are described below. Monitoring systems are described in Section 3.4 and are briefly described below for the specific process operation. General personal protective equipment requirements are described in Section 5.3; specific requirements for each process are described below.

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

Specific descriptions are given below for control strategies employed for thermal oxidation, photolithography processes, wet chemical cleaning and etching, plasma etching, diffusion, ion implantation, low pressure chemical vapor depostion (LPCVD), and metalization.

7.1 Thermal Oxidation

A diffusion furnace assembly is used to oxidize purchased silicon wafers. The operation is performed by exposing wafers to a pyrophoric atmosphere (by the combustion of hydrogen in an oxygen atmosphere) in the furnace tube.

The diffusion furnace assembly consists of: 1) a load station where carriers containing wafers are loaded and unloaded in the furnace tube; 2) a furnace cabinet containing the furnace tubes and electrical resistance heat source; 3) a source cabinet that encloses the furnace tube end and the gas control assemblies; and 4) an electrical cabinet containing the system controls. Process gases enter the furnace tube through gas supply lines that connect to the furnace through the source cabinet. The furnace cabinet acts as a protective barrier against hot contact surfaces of the furnace tube. Processing gases include hydrogen, oxygen, and hydrogen chloride. Hydrogen chloride is added to the gas stream as a method of removing sodium ion concentration (i.e., getter) for both the growing oxide and the furnace tube (Colclaser, 1980).

The diffusion furnace assembly is ventilated at two sites, 1) the source cabinet, and 2) the furnace tube loading end at the load station. The source cabinet encloses the gas assemblies and the ends of the furnace tubes and is vented by a local exhaust duct at the top of the cabinet. The furnace tube opening is vented by a scavenger box that encloses the opening. The exhaust is vented through a stack directly to the atmosphere.

Nitrogen, hydrogen, and oxygen are provided from house supplies described in Section 3.3. Hydrogen chloride is supplied in cylinders stored in a ventilated cabinet described in Section 3.3.

The operation is performed by placing wafers in carriers that are loaded into the furnace. The quartz tube temperature is increased (the specific temperature depends on the operation performed) and the tube is purged with nitrogen followed by the introduction of the process gases. After completion of the process sequence, the operator removes the carriers. The facility uses both hybrid control and direct digital control (DDC) units. With the DDC units, the operating parameters, including tube temperature, gas flow, process sequence and duration, and other operating conditions are controlled by feedback control loops that monitor and adjust the dynamic performance of the furnace (Douglas, 1981). In hybrid control furnaces, the operating parameters are preset by the operator and require that the operator monitor and adjust the equipment as needed.

No monitoring systems are present in the area for routinely evaluating emissions or operator exposures to chemical or physical agents. General personal protective equipment requirements are outlined in Section 5.3 and include heat-protective gloves used by operators to unload wafers from the furnaces. Specific work practices for controlling emissions or operator exposures were not observed during the preliminary survey.

7.2 Photolithography

The photolithography process consists of three basic steps: 1) substrate preparation 2) substrate exposure, and 3) substrate developing. Following developing, the exposed underlying layer may be etched using either a wet chemical or plasma etching operation described in Section 7.3 and 7.4, respectively. The photolithography process may be repeated several times during the processing sequence.

7.2.1 Substrate Preparation.

The operations involved in substrate preparation include: 1) spin-on application of hexamethyldisilizane (HMDS); 2) spin-on application of a positive photoresist; and 3) soft-bake of the coated wafer in a resistance-heated oven. The operations are then performed consecutively in a microprocessor-controlled, in-line cassette-to-cassette unit. Wafers are automatically transferred from one processing step to the next. The cassette system is located beneath laminar flow HEPA filtration units with electrostatic eliminators (Simco®). The only non-automated portion of substrate preparation is the manual loading of cassettes into the unit.

Individual wafers are automatically removed from the cassettes and transported to a spin platform. The wafer is rotated and hexamethyldisilizane (HMDS) is applied to its surface. Positive photoresist in an n-butyl acetate, xylene, and cellosolve acetate solvent is then applied to the spinning wafer. The coated wafer is transported through a resistance-heated drying oven and loaded onto a cassette. HMDS and the photoresist are automatically dispensed onto the wafer from pressurized metal containers or siphoned from the original container. The chemicals are stored in a ventilated chemical storage cabinet separate from the spin operation unit.

Local exhaust ventilation for the unit is provided by a duct below the spin platform. The HMDS and photoresist wastes are drained through the exhaust duct to the organic solvent drain system. The chemical storage cabinet is also ventilated by a local exhaust duct. Both ventilation systems go to a scrubber.

Monitoring systems for evaluating emissions or worker exposures to chemical or physical agents are not present. No personal protective equipment is used by operators. Personal protective equipment requirements for chemical technicians responsible for transporting chemicals to the station are described in Section 3.4.

7.2.2 Substrate Exposure. A mask pattern is transferred to the photoresist-coated wafers by projecting the mask image with ultraviolet (UV) light either by scanning projection alignment or stepping projection alignment. Both systems are described by Elliott (1982); that reference should be reviewed for more detailed information.

The scanning projection alignment system uses reflective optics and a mercury lamp providing UV light at a peak wavelength of 395 nm. Both manual and automatic loading systems are used at Rockwell International. The manual system requires operators to load individual wafers manually and to align the photomask and wafer by viewing through a split-field binocular microscope. The automatic alignment system requires operators to load cassettes containing wafers into the unit. Individual wafers are automatically removed and mounted on the stage for manual alignment of the photomask and wafer by the operator. With both systems the operator is seated at the unit.

Engineering controls used to control emissions or operator exposures to chemical or physical agents includes shielding of the UV light source by the cabinet. The mercury lamp is enclosed within a chamber that is vented to the room atmosphere.

The stepping projection alignment system is a direct step-and-repeat exposure of the wafer using refractive optics and a mercury lamp providing UV light at a peak wavelength of 395 nm. The alignment system is located in a separate environmentally controlled chamber. The system is located in a small room in the photolithography area but is maintained at higher pressure than the remainder of the area. The operator is seated at a video display terminal located adjacent to the chamber. The operation is automatically controlled except for the chamber loading and unloading of cassettes by the operator.

The operator depresses a button on the control console and a wafer is automatically mounted in the stage. The operator then aligns the wafer with the mask using push-button and "joystick" controls.

Emissions of ultraviolet light from the mercury lamp are controlled by shielding provided by the lamp enclosure and the environmental chamber which contains the exposure system. However, access doors to the chamber may be opened during operation. The doors are not interlocked to the lamp. A potential for operator exposure to ultraviolet light is likely but the extent is unknown.

No continuous monitoring systems are present for evaluating emissions or operator exposure to ultraviolet light. Operators are not required to use personal protective equipment. Work practices that may affect emissions or operator exposures were not observed during the survey.

7.2.3 Substrate Developing. Photoresist-coated wafers that have been exposed to the mask pattern are developed by spray application of the developer onto the wafers in a sealed chamber. The developer solution is a proprietary mixture containing tetramethyl ammonium hydroxide in a water carrier solution. A cassette containing wafers is placed by the operator into a spray chamber. The chamber is sealed, and purged with nitrogen, and the discs are fed one at a time to the spin unit where they are spun while the developer solution is sprayed. After developing, the wafers are rinsed with deionized water and dried. The process sequence is automatically controlled requiring only that the operator load and unload cassettes.

The developer solution is stored in two reservoirs located in the base of the unit. The developer solution sprayed onto the wafers is recycled. The used solution is collected from the spray chamber in a reservoir and cleaned by filtering. New make up developer is added to the solution after cleaning.

The spray chamber is operated at atmospheric pressure. The chamber is vented to a scrubber. The developer solution is replaced by a chemical technician and waste developer is removed from the system by a drain.

Following the developing operation the wafers are hard-baked in a resistance-heated oven. The operation is performed in a continuous, in-line system described in Section 7.2.1 or in an oven as a batch operation. The continuous, in-line oven is not ventilated. The individual oven used in batch drying is purged with nitrogen and vented to the outside air.

Monitoring systems for evaluating emissions or worker exposures to chemical or physical agents were not present in the area. Required personal protective equipment for chemical technicians includes acid-resistant aprons, gloves, and face shields. Operators are required to wear only normal clean room attire described in Section 5.3.

7.3 Wet Chemical Cleaning and Etching

Wet chemical operations are used to clean wafers, to etch deposited layers, and to clean process equipment. The operations are performed in polypropylene benches. The etching and cleaning chemicals include: 1) hydrofluoric acid and ammonium fluoride (known as "buffered oxide etch" or BOE) for etching silicon dioxide, 2) sulfuric acid for cleaning wafers before other process operations, 3) sulfuric acid and hydrogen peroxide for stripping photoresist, 4) nitric, phosphoric, and acetic acid for etching aluminum or silicon/aluminum, 5) phosphoric acid for etching silicon nitride, and 6) hydrochloric and hydrofluoric acid for cleaning quartz furnace tubes. The wafer etching and cleaning operations are performed by immersing cassettes containing wafers into the acid solutions. The acids are contained in tanks that are recessed in the wet chemical bench. The acid solutions are heated to increase the rate of etching; buffered oxide etch and sulfuric acid are heated to 30 to 50°C and phosphoric acid and sulfuric peroxide are heated to approximately 100°C. The acid may be agitated by introducing nitrogen bubbles into the solution.

The wet chemical stations are of polypropylene construction. The tank containing the acid is located in a well that is recessed in the bench surface and the unit is ventilated by slots in the well around the tank perimeter. A spill plenum is located beneath the surface of the bench and acts as an exhaust plenum for the bench. In addition to the acid etch bath, a water rinse tank and spin drier are located in the station. A vertical laminar flow HEPA filter unit is located above the wet station with clear plastic splash shields attached to the front edge of the laminar flow unit to direct air flow downward onto the work surface. Waste acid is removed from the tanks by aspiration to a neutralization tank. Acid waste treatment procedures are described in Section 3.6. Additional engineering controls include a water-cooled lid placed over the phosphoric acid etching tank to control evaporation of the heated acid.

Aluminum or silicon/aluminum is etched from the wafer by immersion of the wafers in a solution containing phosphoric, nitric, and acetic acid maintained at an elevated temperature (approximately 35°C). The operation is performed in an automated batch etch system that is enclosed and maintained under vacuum conditions. The etching unit consists of a plastic cabinet with a recessed well containing the immersion tank. Access to the tank is by a clear plastic door directly above the tank. Controls for the unit are located at the top rear of the cabinet. The etching solution is stored in a reservoir located in the base of the cabinet. A vacuum pump (specific type was not identified) creates a negative pressure in the recessed well. The operation sequence requires the operator to open the access door and place cassettes containing wafers into the empty immersion tank. The door is closed and the operator initiates the process by pushbutton. A vacuum is then established in the process chamber and acid is drawn from the holding tank into the chamber. The acid level is controlled by a float valve that prevents overflow of the unit. After the wafers have been etched, the vacuum in the process chamber is automatically released and the acid returns to the holding tank. The process chamber is then automatically filled with deionized water and the wafers are rinsed. The water is drained from the chamber and the cassettes are removed.

Furnace tube cleaning is performed by immersing the quartz tubes in a solution containing hydrochloric and hydrofluoric acid. The tubes are removed from the furnace by a process technician and cleaned by a wet chemical station operator. The cleaning operation is performed manually in a separate room, but was not observed during the survey due to time constraints.

Monitoring systems for evaluating emissions or operator exposure to chemical or physical agents were not present. All operators at the wet chemical stations, and chemical mix technicians who are responsible for mixing, delivering, and pouring chemicals are required to wear acid-resistant gloves, aprons, and face shields. Chemical mix technicians are also required to wear safety shoes.

7.4 Plasma Etching

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

Plasma etching is performed with the reaction chamber pressure negative to the room pressure. The vacuum is approximately 0.1 to 20 torr and is maintained by an oil-sealed mechanical pump. The plasma gases, containing the volatile species formed by the plasma ions reacting with the substrate, are exhausted from the unit by the mechanical roughing pump. The pump exhaust is vented to the atmosphere.

The oil-sealed mechanical pumps are stored below the etching units in an area that is either open to the room or enclosed in a ventilated storage cabinet. A maintenance technician changes the pump oils by draining the used pump oil into a container and replacing it with fresh oil. The frequency with which the oil is changed was not stated. Gases are supplied in cylinders that are stored in ventilated cabinets near the process equipment. The cabinets are vented to the atmosphere.

Personal protective equipment is not required for operators. Monitoring systems for evaluating emissions or worker exposures to chemical or physical agents were not present. Radio frequency radiation emissions from the plasma etching systems have been monitored by the California Division of Occupational Safety and Health. Monitoring results were not available. During the survey visible light emissions were observed at an observation window for one of the barrel etching units. Previous studies (Wang and Gelernt, 1981) have identified optical emissions of blue light (peak wavelengths of 431.5 nm and 306 nm) from plasma photoresist stripping processes using a Freon/oxygen plasma. Operators viewing the operation through the window may be exposed to the light emissions.

Work practices that may affect worker exposures include the use of automated controls which limit the need for operator interaction with the equipment. The operator is required to load and unload cassettes and to start the processing sequence with pushbuttons and is not required to be at the unit for the entire work shift. The operator is then intermittently free to perform other tasks such as wet chemical cleaning and etching or to operate other automated units. Any exposures to specific chemical or physical agents would be for relatively short time periods throughout the shift.

7.5 Diffusion

Diffusion of dopants into the wafer is performed in a diffusion furnace assembly similar to that described in Section 7.1 for thermal oxidation. The wafers are heated to a high temperature (approximately 600 to 1200°C depending on the source used), and a dopant is introduced that diffuses into the wafer. The dopant is supplied as either a liquid, such as phosphorus oxychloride ($POCl_3$) and boron tribromide (BBr_3), or a solid, such as arsenic trioxide in an isopropanol carrier. An oxidation step using a pyrophoric water (hydrogen and oxygen) atmosphere is part of the diffusion process sequence.

Liquid source dopants are supplied in quartz bubblers that are placed in the source cabinet of the furnace assembly and connected to the furnace tube. The solid source arsenic trioxide dopant is supplied in a liquid that is spun onto the wafer before it is loaded into the furnace. The arsenic is spun onto the wafer surface in an automated enclosed system similar to the photoresist spin operation described in Section 7.2.1. A cassette containing wafers is loaded onto the spin applicator unit. The spin platform, cassette, and dispensing nozzles are enclosed with a clear plastic cabinet that covers the entire unit. The enclosure is vented to the plant exhaust system which goes to a scrubber. The ventilation system is monitored to identify low exhaust velocities and will alarm if the velocity is below a preset limit. The duct takeoff is located on top of the unit with a slot in the enclosure to allow air flow into the unit. The quantity of air exhausted or the duct velocity were not known. The enclosed spin-on system is, in turn, located beneath a vertical laminar flow HEPA filtration unit. The dopant solution is supplied in a pressurized metal container stored in the bottom cabinet of the unit.

Engineering controls present in the diffusion furnace are outlined in Section 7.1. Additional engineering controls are used as required by the dopant source. Liquid source bubblers are placed in the ventilated source cabinets and connected to the furnace tube. Generally, there were plastic access doors in these cabinets in order to change the source bubblers without opening the main cabinet doors. Where maintenance operations were being performed, the panels that enclosed the source cabinet were removed.

Monitoring systems to evaluate emissions or operator exposures to chemical or physical agents associated with the diffusion operation were not present. Required personal protective equipment includes heat-protective gloves for operators unloading wafer carriers and for process technicians removing furnace tubes for cleaning.

Work practices reported that may reduce potential operator exposures include prescribed procedures for handling the liquid source bubblers. Chemical technicians handling the bubblers are required to unload the bubblers from the shipping container in a special laminar flow work area that includes local exhaust ventilation. The technician wears a disposable mask (type not specified). The source bubbler is mounted in the source cabinet by a technician wearing a self-contained breathing apparatus.

7.6 Ion Implantation

Ion implantation is used to introduce impurities or dopants into the wafer surface. The impurities are p- or n-type ions created by a confined electric discharge sustained by a dopant gas. The ion beam is drawn from the arc chamber by an extraction electrode and directed toward the analyzing magnet. The magnet resolves and focuses the ion beam and selects only the desired ion species for wafer implantation. The selected ions are targeted through an acceleration chamber and focused to produce a uniform dose to the substrate. The ion implantation is performed in a sealed chamber at vacuum conditions of approximately 10^{-6} torr. The unit has an operating power range of 20 to 200 keV.

The source of the dopant ion is either phosphine (15 percent in hydrogen) or boron trifluoride (100 percent) supplied in lecture bottles that are stored in a ventilated cabinet within the ion implantation unit.

The power source, ion source, and analyzing magnet are contained in a lead-shielded cabinet for the control of X-ray radiation emission. The cabinet is located within a second lead-lined enclosure that is electrically grounded and interlocked to the power supply. A glass window is present in the outer cabinet near the control console to allow the operator to view gauges within the cabinet. Any effect that the window may have on the effectiveness of X-ray shielding is unknown.

Three independent vacuum systems are used to maintain vacuum conditions: 1) an oil-sealed mechanical pump that evacuates the load lock chambers, 2) an oil-sealed mechanical pump and oil diffusion pump that evacuate the target chamber, and 3) an oil-sealed mechanical pump and oil diffusion pump that evacuate the ion source. The pump exhausts are vented directly to the atmosphere through the plant ventilation system described in Section 3.5. Pump oil is added to the oil diffusion pumps by a maintenance technician because a small amount is vaporized during the pumping sequence.

Radiation film badges have previously been used for monitoring X-ray exposures of operators. However, the radiation monitoring program was discontinued because results indicated that worker exposures were at background levels. No personal protective equipment was used by the operators. Although the operation is automatically controlled, operators must be present in the area to load and unload the system and to monitor the operation. Chemical technicians changing dopant gas lecture bottles wear self-contained breathing apparatus.

7.7 Low Pressure Chemical Vapor Deposition

Low pressure chemical vapor deposition (LPCVD) is used to deposit polycrystalline silicon, silicon nitride, and silicon dioxide. The operation is performed in a diffusion furnace assembly similar to that described in Section 7.1 but operated at low pressure (approximately 0.1 to 3.0 torr). The LPCVD furnace consists of a furnace tube with mechanically sealed doors, gas control enclosure, gas flow control, electronic control, and vacuum pumps. The process operation is controlled by a microprocesser using feedback control loops and programmed "recipes". The system controls the furnace temperature profile, gas flow, vacuum pumping and purging, and process sequence. The furnace tube vacuum is maintained by an oil-sealed mechanical pump that is located in a ventilated cabinet at the source end of the furnace. The pump exhaust is vented to the atmosphere without treatment.

Process gases include: 1) silane for polycrystalline silicon deposition, 2) dichlorosilane and ammonia for silicon nitride deposition, and 3) silane, oxygen, and phosphine (100 percent) for silicon dioxide deposition. Hydrogen chloride is used to clean or getter the furnace tube. Process gases are stored adjacent to the LPCVD systems in ventilated cabinets which are vented to the atmosphere.

The process operation requires the operator to load wafers onto carriers that are inserted into the furnace. The operator initiates the operation by push-button control. Following deposition of the desired layer, the operator removes the carriers from the furnace.

Engineering controls include local exhaust ventilation of the source cabinet containing the gas manifolds and gas flow controllers. The cabinet is vented by a duct off the top of the unit. A part of the source cabinet houses the vacuum pump and is also vented by the local exhaust duct at the top of the cabinet.

The furnace tube is sealed with a stainless steel door that is interlocked by the microprocessor control unit to the vacuum pump to prevent operation of the pump while open. A pressure interlock prevents reactive gases from flowing if the system malfunctions. The process gas flow is controlled by mass flow controllers that are centrally controlled by the system microprocessor unit. The phosphine monitoring system controls solenoid valves on the phosphine supply line and will shut off flow in an emergency. The phosphine monitor is located above the gas storage cabinet and the furnace assembly.

Personal protective equipment requirements include heat-protective gloves for unloading wafers. Operator work practices that may affect emissions or hazardous agents were not observed.

7.8 Metalization

Silicon/aluminum is deposited on the wafer surface as an electrical contact. The metal is deposited by radio frequency (RF) sputtering in a sealed reaction chamber at very low pressure (approximately 10^{-7} torr). The wafers are loaded onto a metal platen which is placed on a conveyor. The platens are automatically transported to a load lock chamber that is evacuated with an oil-sealed mechanical pump. The platen is then transported through the deposition chamber where the metal is deposited by radio frequency sputtering. The deposition chamber is evacuated by a second unspecified high vacuum pump. The coated wafer is then transported through a second load lock chamber that purges the system to atmospheric pressure. The above system is also used to deposit gold on the wafer backside.

Silicon/aluminum is also deposited by electron beam evaporation in a sealed reaction chamber (bell jar). The operator mounts wafers on a planetary structure that is then loaded into the bell jar. The operation is automatically controlled with the operator required to initiate the process by push button. After the process is completed, the bell jar is raised and the wafers are removed from the planetary.

The radio frequency field for sputtering is formed by an RF generator operating at 13.56 MHz. The power level for the sputtering unit and electron beam evaporation unit are not known.

No continuous monitoring systems for evaluating emissions or operator exposures to chemical or physical agents were present in the area. No personal protective equipment is required.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The fabrication of integrated circuits at Rockwell International is representative of the present state-of-the-art in wafer processing. Process operations observed that may also be indicative of future processing trends include plasma etching, low pressure chemical vapor deposition, ion implantation, metalization, and automation of some photolithography processes. Specific observations and recommendations are outlined below.

1. Rockwell International should consider installing a combustible-gas monitoring system to monitor hydrogen in fabrication areas where it is used.
2. Substitution of silicon tetrafluoride in the plasma etching process with a less toxic gas should be investigated (such as carbon tetrafluoride/oxygen) (Bersin, 1976; Elliott, 1982; Tolliver, 1980).
3. The effectiveness of shielding used to control radio frequency emissions from plasma etching systems and radio frequency sputtering systems should be evaluated.
4. Rockwell International should consider re-establishing the radiation film badge monitoring of workers potentially exposed to X-ray radiation in the ion implantation area.

If a detailed survey is performed at the Rockwell International facility it should also document the gas handling system, the ventilation system and the safety interlocks associated with each system.

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