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IN-DEPTH SURVEY REPORT

CONTROL TECHNOLOGY FOR GALLIUM ARSENIDE PROCESSING

AT

Morgan Semiconductor
Garland, Texas

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INTRODUCTION

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

Since 1976, ECTB has conducted a number of assessments of health hazard control technology on the basis of industry, common industrial process, or specific control techniques Examples of these completed studies include the foundry industry, various chemical manufacturing or processing operations, spray painting, and the recirculation of exhaust air The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for or availability of an effective system of hazard control measures

These studies involve a number of steps or phases Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concepts or techniques Next, in-depth surveys are conducted to determine both the control parameters and the effectiveness of these controls The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury

This research study of control technology for Gallium Arsenide processing was prompted by a growing interest in silicon alternatives for the semiconductor industry For years, silicon had been the primary semiconductor material for integrated circuits However, demands for higher speed devices for communication and military purposes led to an anticipated surge in the gallium arsenide technology Gallium arsenide provides higher electron speeds, lower power consumption, and higher radiation resistivity than silicon Because of the increased demands for gallium arsenide and the fact that arsenic, considered a human carcinogen, is used in the gallium arsenide production process and also can dissociate from gallium arsenide in the body, there is a need to identify what hazard controls are necessary Since this industry is growing, it will be useful to know if different or additional controls are needed in comparison to silicon-based processes

PLANT AND PROCESS DESCRIPTION

FACILITY DESCRIPTION

Morgan Semiconductor, a subsidiary of Ethyl Corporation since 1985, is a small (50 employees) gallium arsenide crystal grower founded in 1974 Their product is sliced and polished wafers, which are supplied to gallium arsenide optoelectronics, microwave, and integrated circuit manufacturers In addition, Morgan supplies some gallium arsenide wafers with epitaxial layers of gallium aluminum arsenide

Morgan has two separate buildings, one for administrative purposes and the other for production purposes Morgan employs the Liquid Encapsulated Czochralski (LEC) and Horizontal Bridgeman (HB) techniques for crystal growing Other operations include ampoule loading, synthesis, grinding/sawing, polishing, and epitaxy areas A layout of the plant is shown in Figure 1

PROCESS DESCRIPTION

Process Flow

At Morgan, gallium arsenide (GaAs) is synthesized prior to crystal growth In the ampoule loading room, elemental arsenic and liquid gallium are loaded into a vessel which is then sealed The load room operator transports the sealed vessel to the synthesis room and places it in a synthesis furnace to be heated After synthesis, the vessel is opened and the polycrystalline GaAs charge is removed The charge is then etched with a solution of ammonium hydroxide, hydrogen peroxide, and water and rinsed in deionized water Oxides are removed in the cut-off room using a sandblaster and the ends of the charge are cut off with a saw prior to crystal growth

In the LEC process, the charge, along with boron oxide, is loaded into the crystal puller crucible by an LEC operator The puller is heated, melting the GaAs and boron oxide The boron oxide floats on the melt and serves as a liquid encapsulant to prevent arsenic vapor from escaping The melt chamber is pressurized with argon A seed crystal is lowered into the crystal puller and the desired single crystal GaAs is obtained

The duties of an LEC operator include monitoring the crystal pullers approximately every 5 minutes, loading and cleaning the crystal pullers, and general housekeeping The floors in the LEC area are cleaned at the end of each shift and the puller surfaces are wiped down

For the HB process, a synthesized polycrystalline GaAs charge is broken up in a glove box and loaded with a seed crystal of single crystal GaAs into a quartz boat, which is then placed in a quartz ampoule The ampoule is then evacuated and sealed, loaded into an HB furnace, and selectively heated at the proper temperature gradients to initiate single crystal growth

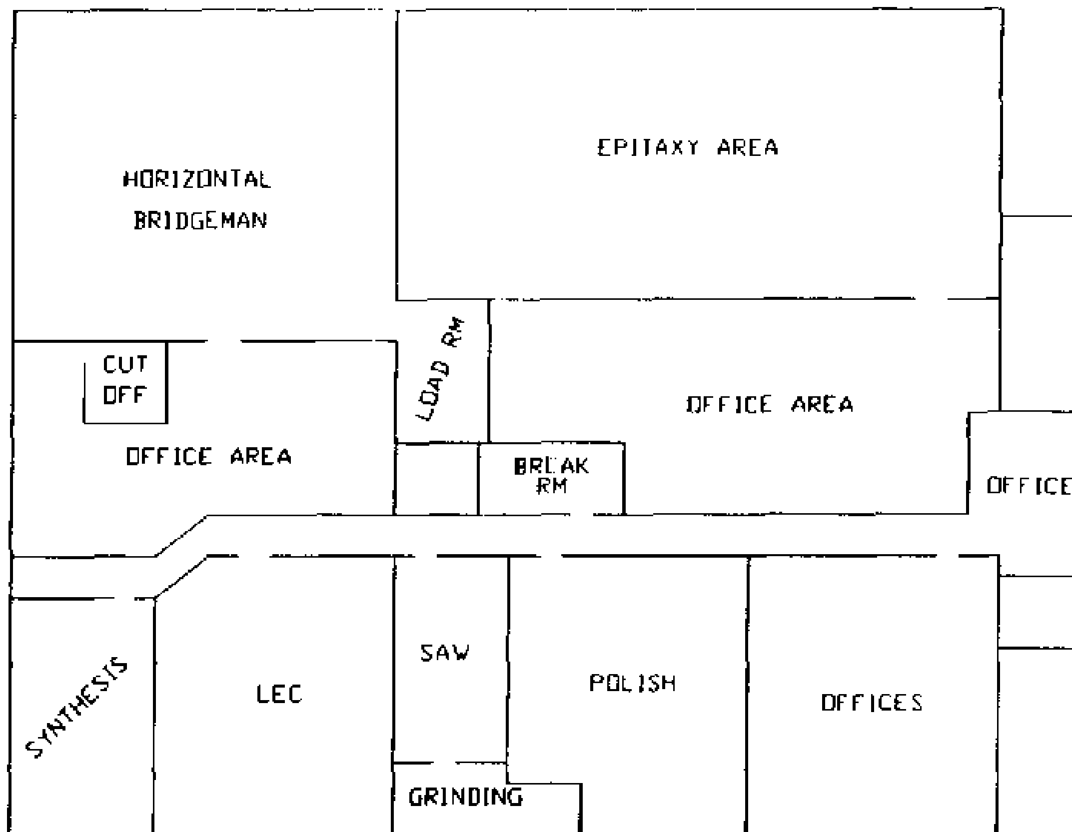


Figure 1

Plant Layout

The quartz boats from the HB process are cleaned with a diluted hydrofluoric acid and then rinsed with deionized water Occasionally, a quartz ampoule may crack and vent in the HB furnace, the furnaces must then be cleaned with a high efficiency particulate air (HEPA) filter vacuum cleaner once the boat cools down The furnace room may also have to be cleaned if the ampoule has vented outside the furnace

After LEC or HB crystal growth, the GaAs ingot is annealed in a dilute arsenic atmosphere furnace to relieve radiation induced stress in the crystal lattice The crystal orientation is then determined using potassium hydroxide, and a solution of bromine and methanol The ends of the GaAs ingot are cut off with an outer diameter (O D) saw in the grinding/sawing room and one side of the ingot is ground flat, to mark the crystal orientation, using an O D grinding machine Epoxy and graphite are mounted to the flat side of the ingot in order to mount it on automated saws used to slice the wafers The wafers are then cleaned in the polishing room with acetic acid and the epoxy and graphite are removed Finally, the wafers are beveled with an edge-beveler in the grinding/sawing room and sent back to the polishing room to be polished with colloidal silica, deionized water, bleach, and a commercially available detergent An etching process follows An ammonium hydroxide, hydrogen peroxide, and water solution is used for the etching process Finally, the wafer is ready to be packaged

Additionally, Morgan uses GaAs wafers as substrate material for the epitaxial growth of thin layers of doped GaAlAs with the proper electrical characteristics Before loading the wafer or wafers into the epitaxial reactor, a portable Matheson monitor is used to check for arsine The door is cracked open and the monitor is employed for approximately three minutes The door is then fully opened and the reactor is checked over once again with the monitor The wafer or wafers are inserted into the reactor and the bell jar and base plate are vacuumed with a Nilfisk GS-JF HEPA filter vacuum cleaner After vacuuming, the door is then closed A mixture of arsine gas (10 percent concentration), trimethyl aluminum vapor, and trimethyl gallium vapor is metered into the reactor chamber with silane and/or diethyl zinc gas dopants The GaAlAs is then formed with either silicon or zinc doping and a layer deposited on the wafer

LEC Cleaning

The crystal pullers are cleaned following each LEC production run Cleaning is an integral part of the LEC process All internal surfaces of the pullers are vacuumed with the Nilfisk GS-81 HEPA filter vacuum cleaner and wiped using towels (Kay Dry absorbent wipes) with isopropyl alcohol The crystal pulling room is designated as a regulated area during cleaning operations

Two operators are in the LEC room during cleaning--one operator does the actual cleaning, while the second operator continues to monitor the operating crystal pullers Just before the cleaning operation begins, the doors of the LEC room are closed and a sign is hung outside the door indicating no one is admitted without proper respiratory protective equipment The operator who is cleaning dons either a MSA half-face pressure demand supplied-air respirator or a MSA full-face pressure demand supplied-air respirator, while the other

operator wears a half-face air-purifying respirator (HSA Type H) Air for the supplied-air respirator is delivered from bottles through 1/2-inch diameter hose at approximately 165 psi The operator also wears a disposable Tyvek coverall with bootlets, head covering, safety glasses, and rubber gloves while cleaning

Cleaning of the puller begins by moving a cart with the tools and supplies next to the puller Ten bolts are loosened with an air-powered wrench to open the vertical top portion of the puller After the panel is opened by hand, the vacuum is turned on and the inside of the panel is vacuumed using the 3-inch diameter hose attachment The inside walls of the vertical cavity and the connecting rod inside the cavity containing a blackish-grey dust, are then vacuumed The cavity is semicircular, about 8 inches deep, 8 inches wide, and about 2-1/2 feet high After vacuuming the inside walls, the cavity is wiped using towels (Kay Dry absorbent wipes) with isopropyl alcohol While wiping the surfaces, the operator leaves the vacuum running and either lays the vacuum hose on the floor or puts the hose into a garbage can previously placed next to the puller

Next, the operator loosens the center rod with a pliers, lifts up the top vertical part of the puller and rotates it out of the way, moves a garbage can under this top vertical section, and vacuums the underside of the circular top of the puller He then wipes the underside and viewing screen with isopropyl alcohol and throws the dirty towels into the garbage can

Several inner liners from the lower part of the puller are removed and vacuumed inside and out Several more liners and graphite parts including the crucible are removed but not vacuumed, the crucible is emptied into the garbage can and placed in a nitrogen-purged dry box We observed that the entire inside wall of the 2-foot high cylindrical section of the puller was covered with dust The operator vacuums and wipes the inside wall and bottom of the cylinder with isopropyl alcohol Lastly, he scrubs the inside with Scotch Brite pads, but lays the contaminated pad on the outside of the puller The outside of the puller is not vacuumed or wiped While cleaning the bottom of the puller, the operator has to reach a full arm's length into the cylinder so that his face is in the opening at the top of the cylinder much of the time

The vacuum is then turned off and the operator puts the graphite parts and liners back into the cylindrical part of the puller, and the thermocouple is cleaned, greased, and inserted back into the puller The operator takes off his suit and respirator and leaves the room About 5 minutes after LEC puller cleaning is finished, other workers enter the room without respirators

Process Rooms

Both low-pressure crystal pullers and high-pressure crystal pullers were located in the LEC room The low-pressure pullers were situated on a base and the lower cylindrical portion of the puller was stainless steel, approximately 2 feet high It contained a series of insulating liners made of graphite and a boron nitride crucible This lower cylindrical portion of the puller also

contained a crystal pull rotation rod and a thermocouple The upper portion of the puller was semicircular, about 8 inches deep, 8 inches wide, and about 2-1/2 feet high A viewing screen was provided for each puller, thus enabling the operator to monitor all aspects of the crystal growth process

The high-pressure pullers were segregated, but not isolated from the rest of the room, by a polyvinyl chloride (PVC) screen High- and low-pressure pullers have the same basic components, however, for the high-pressure pullers, the thermal control is more complex In addition, the pressure in a high-pressure system is about an order of magnitude greater than in the low-pressure environment The high-pressure pullers were monitored remotely from a computer control console located on the other side of the PVC screen

There were several HB crystal growth furnaces in two parallel rows in the HB room Ventilation consisted of ceiling fans that exhaust air through the roof to the outside There was no local exhaust ventilation

Two wet chemical stations and a glove box were located in the ampoule load room Local exhaust ventilation was employed for the wet chemical stations and the glove box The glove box was used for loading the elemental arsenic and liquid gallium into quartz ampoules

Equipment in the synthesis room consisted of vertical synthesis furnaces, and annealing furnaces Argon gas cylinders are also stored in the synthesis room Each vertical furnace is approximately 7 feet high by 2-1/2 feet square Each of the vertical furnaces is equipped with a 4-inch flexible duct which enters a central plenum ducted to the roof Exhaust air from the vertical furnaces is not treated (no collector) and is discharged 2 feet above the roof line The horizontal ingot annealing furnaces are approximately 6 feet high, 1-1/2 feet wide, and 8 feet long These serve as multipurpose furnaces and contain three layered, horizontal sections The top level is used for bake out, the second level is used for annealing, and the third level is used for storage of the thermocouples

Automated, inside diameter (I D) saws and an outer diameter (O D) grinder were located in the front room of the grinding/sawing room The saws were equipped with local exhaust ventilation and the grinder was enclosed with local exhaust ventilation Exhaust air for each of the saws and the grinder was discharged through 3-inch diameter flexible pipes to an exhaust fan, then through the roof by a single straight exhaust duct There was no collector or scrubber A make-up air supply opening was located in the ceiling near the center of the room

The back room of the grinding/sawing area was separated from the front room by double doors It contained 2-inch and 3-inch wafer edge bevelers without local exhaust ventilation, an enclosed grinder without local exhaust ventilation, and an O D saw, a grinder, and a saw each with local exhaust ventilation The O D saw was enclosed, but the door was open during much of the survey Exhaust air from the O D saw and the grinder were discharged through 4-inch flexible ducts and air from the saw was discharged through a 3-inch duct to the roof The total exhaust airflow for the grinding/sawing

area was 3,600 cubic feet per minute (cfm) A wet chemical station was also located in the back room of the grinding/sawing area

A Pictorous abrasive cut-off saw, a wet vapor hone, and a sandblast unit were employed in the cut-off room The Pictorous saw was used to remove the ends of the synthesized charge before crystal growth This was a wet process The wet vapor hone and sandblast unit were used interchangeably to remove oxides from the synthesized charge before crystal growth

The polish room consisted mainly of two 24-inch double-side polishers and two single-side polishers A wet chemical station was also located in this room for hypochlorite use

Two epitaxial reactors (Spire and Cambridge) were employed in the Class 100 (100 particles or less per cubic foot of air) epitaxial clean room The Cambridge was down for maintenance during the survey The Spire consisted of a quartz bell jar reaction chamber sitting on a base plate, a nitrogen-filled glove box for loading, unloading, and handling of wafers, an instrumentation monitoring panel, a cabinet housing gas lines and stainless steel containers for trimethyl aluminum and trimethyl gallium within a vented negative pressure enclosure, and a computer terminal through which the operator could control, monitor, and document all aspects of the growth process

EVALUATION CRITERIA

Arsenic requires stringent controls to minimize exposures to the current OSHA permissible exposure limit (PEL) of 10 $\mu g/m^3$, the OSHA action level of 5 $\mu g/m^3$, and the NIOSH recommended exposure limit (REL) of 2 $\mu g/m^3$ (ceiling) The plant must establish regulated areas in cases where inorganic arsenic exposures exceed the permissible exposure limit These regulated areas must be demarcated and segregated from the rest of the workplace, access must be limited to authorized persons, and appropriate respirators must be worn [1,2,3] Chronic exposure to arsenic may cause malaise, fatigue, peripheral neuropathy, and perforation of the nasal septum Arsenic is also suspected of causing skin and respiratory tract cancer [4]

The OSHA PEL for arsine is 200 $\mu g/m^3$, the NIOSH REL for arsine is the same as the NIOSH REL for arsenic [1,3] Arsine is an extremely toxic gas that can produce massive hemolysis and renal failure, and exposures as low as 10 ppm have caused coma and death Early effects from an exposure are characterized by giddiness, headache, shivering, and abdominal pain [5] Arsine has a slight garlic odor which is only detectable above safe levels [4]

Other commonly used materials at Morgan include silane, trimethyl aluminum, trimethyl gallium, and diethyl zinc Silane, trimethyl gallium, trimethyl aluminum, and diethyl zinc are pyrophoric and, therefore, present a fire and explosion hazard [5] Little is known about their toxicity

Hydrochloric, hydrofluoric, and nitric acids are also employed in GaAs wafer production The NIOSH REL/OSHA PEL is 7,000 $\mu g/m^3$ (15-minute ceiling) for HCl, 2,500 $\mu g/m^3$ (TWA) for HF, and 5,000 $\mu g/m^3$ (TWA) for HNO_3 [6] These acids

may cause burning and scarring of the skin and mucous membranes Chronic inhalation may cause bronchitis and pulmonary edema [5]

Amorphous silica is usually considered to be of low toxicity, however if it is contaminated with crystalline silica, pulmonary fibrosis of the lungs may result [6] The OSHA PEL for amorphous silica is 80 mg/m^3 divided by the percent silica (TWA) The OSHA PEL for respirable crystalline silica is 10 mg/m^3 divided by the percent silica plus two (TWA), the NIOSH REL is 50 μg/m^3 for respirable crystalline silica [6,7]

METHODOLOGY

AIR SAMPLING AND ANALYSIS

Personal and area samples for arsenic and gallium were collected on 37 mm diameter cellulose ester 0 8 μm pore size filters The filters were pretreated with sodium carbonate and glycerol and dried by drawing sufficient air volume through them to break the initial pressure drop prior to the conduct of the survey

Two sampling trains were used for the collection of arsenic and gallium as shown in Table 1 The first train consisted of a treated filter in series with a charcoal tube and a DuPont P-2500 pump operated at a flow rate of approximately 0 5 liters per minute (Lpm) This type of sampling train was employed because in the presence of heated arsenic sources, arsenic trioxide vapors or volatilized arsenic material may be present in the air, monitoring solely with conventional filters would underestimate total arsenic exposures The charcoal tubes consisted of 400 mg of activated coconut-based charcoal in

Table 1 Sampling and Analytical Methods

Sample Train	Flow Rate (Lpm)	Analyte	Analytical Method
Filter	1 7	Arsenic, Gallium	Graphite Furnace AA According to NIOSH Method 7901
Filter and Charcoal Tube	0 5	Arsenic, Gallium	Graphite Furnace AA According to NIOSH Method 7901 (filter) Graphite Furnace AA According to NIOSH Method 6001 (tube)
Prefilter and Charcoal Tube	0 1	Arsine, Arsenic	Graphite Furnace AA According to NIOSH Method 7901 (filter) Graphite Furnace AA According to NIOSH Method 6001 (tube)

the main section and 200 mg of activated charcoal in the backup section The larger (400 mg/200 mg) charcoal tube was used instead of the 100 mg/50 mg charcoal tube provided for in NIOSH Method 6001 [8] For personal samples, the charcoal tube was placed in a sorbent tube holder in series with a treated filter The tube holders were pretested for leaks prior to the conduct of the survey The other sampling train for arsenic and gallium consisted of a treated filter and a DuPont P-4000 pump operated at a flow rate of approximately 1 7 Lpm

Arsine vapors were collected using a coconut-based charcoal tube (400 mg/200 mg) with a treated prefilter (37 mm, 0 8 µm) Arsine personal and area samples were taken in the epitaxy area at a flow rate of approximately 0 1 Lpm using DuPont P-200 pumps The prefilter was analyzed for arsenic and gallium, and a number of the samples were also analyzed for aluminum and zinc Several samples collected at a flow rate of 1 7 Lpm on treated filters were also analyzed for aluminum and zinc in addition to arsenic and gallium For samples analyzed for all four metals, detection limits were 0 2 µg/filter for arsenic, 0 07 µg/filter for gallium, 9 µg/filter for aluminum, and 0 2 µg/filter for zinc Limits of quantitation were 0 50 µg/filter for arsenic, 0 23 µg/filter for gallium, 30 µg/filter for aluminum, and 0 61 µg/filter for zinc On samples that were only analyzed for arsenic and gallium, limits of detection ranged from 0 02 to 0 05 µg/filter for arsenic and 0 02 to 0 04 µg/filter for gallium Limits of quantitation ranged from 0 05 to 0 14 µg/filter for arsenic and 0 035 to 0 11 µg/filter for gallium Limits of detection for charcoal tubes analyzed for arsenic ranged from 0 01 to 0 02 µg/tube

Sampling duration was based on the adsorptive capacity of the tubes for the contaminant to be sampled Approximate full-shift samples were taken for the filter cassettes, however, when this was not possible or practical, shorter samples (4 to 5 hours) were taken Additionally, short-term sampling for arsenic and gallium was performed specifically for the duration of the LEC cleaning operation The charcoal tubes were changed every 2 to 3 hours in order to avoid breakthrough

Air sampling was also performed for silica and various acids Silica was collected on 37 mm 5 µm pore size polyvinyl chloride (PVC) filters preceded by 10 millimeter nylon cyclones at a flow rate of 1 7 Lpm using MSA Model G pumps for personal and area samples For personal samples, filter cassettes and cyclones were attached to the workers Tyvek suit as close to the breathing zone as practical Samples were taken for approximately a full shift Mineral acid tubes (400 mg/200 mg) were used to sample for nitric, hydrochloric, and hydrofluoric acids in the ampoule loading room with DuPont P-2500 pumps at a flow rate of approximately 0 5 Lpm for the collection of acids

All filter samples for arsenic and gallium were analyzed by graphite furnace AA in accordance with NIOSH Method 7901 [9] The graphite furnace was determined more appropriate for the desired sensitivity than the ICP method for these metals Filter samples in the polishing room were also analyzed for aluminum and zinc by flame AA in accordance with NIOSH Method 7901

Charcoal tubes were analyzed by NIOSH Method 6001[8] for arsine. NIOSH Method 7500[9] was used for the analysis of the PVC filters for quartz, cristobalite, and tridymite. NIOSH Method 7903[9] was employed for the analysis of the mineral acid tubes.

Wipe Samples

Wipe samples were also taken to measure arsenic surface contamination. Wearing polyethylene gloves, an investigator removed a Whatman 42, 7 cm (1.8-inch) diameter filter from the box. The filter was moistened with 0.4 milliliters of triple distilled deionized water using a pipette. Areas of 100 cm^2 or 500 cm^2 were wiped with the moistened filter. Plexiglas® templates or masking tape were employed to measure off the areas. The filter was folded in half with the exposed side in and folded again to form a 90° angle in the center of the filter. It was placed, angle first, in a clean glass vial and capped. In order to determine the degree of variability in a measurement, side-by-side replicate wipe samples were taken for several of the initial wipes. In addition, for several samples, the same area was wiped a second time with another filter paper in order to determine a collection efficiency.

Wipe samples were collected in the LEC, grinding/sawing, and HB areas. These samples were analyzed in accordance with NIOSH Method 7900.[10]

OBSERVATIONS

During the sampling survey, effective work practices and use of personal protective equipment were documented, in particular during the LEC cleaning operation. Additionally, control configurations and production equipment were sketched and discussed.

CONTROL TECHNOLOGY

PRINCIPLES OF CONTROL

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

In general, a system comprised of the above control measures is required to provide worker protection under normal operating conditions as well as under

conditions of process upset, failure, and/or maintenance Process and workplace monitoring devices, personal exposure monitoring, and medical monitoring are important mechanisms for providing feedback concerning effectiveness of the controls in use Ongoing monitoring and maintenance of controls to ensure proper use and operating conditions, and the education and commitment of both workers and management to occupational health are also important ingredients of an effective control system

These principles of control apply to all situations, but their optimum application varies from case to case The application of these principles are discussed below

RESULTS/DISCUSSION

Arsenic Air Samples

Personal arsenic results for five gallium arsenide process areas are presented Table 2 These areas include LEC, HB, grinding/sawing, cut-off room, and load room In the LEC, except during cleaning, the average exposure was 4 8 $\mu g/m^3$ There was no difference in average arsenic exposures between the two LEC operators on the day shift based on 4 days of sampling In the grinding/sawing area, arsenic exposures averaged 5 3 $\mu g/m^3$ Slightly higher levels were found in the ampoule load room area, averaging 7 3 $\mu g/m^3$, one of the four samples was above the OSHA PEL of 10 $\mu g/m^3$ Higher exposures, averaging 24 $\mu g/m^3$, were found in the HB room and extremely high levels

Table 2 Personal Exposures to Total Arsenic by Process

Area Worked	No of Samples	Average Sample Duration (min)	Arithmetic Mean ($\mu g/m^3$)	Geometric Mean ($\mu g/m^3$)	Range ($\mu g/m^3$)
LEC	10	254	4 8	4 2	1 4-8 2
Horizontal Bridgeman	4	295	24	12	4 4-75
Grinding/Sawing	4	312	5 3	4 8	2 1-7 2
Cut-Off Room[a]	3	190	890	810	550-1,500
Ampoule Loading	4	239	7 3	6 4	3 4-14
OSHA PEL			10 $\mu g/m^3$		
NIOSH REL			2 $\mu g/m^3$		

[a]Full-face air-supplied respirator worn

averaging 890 μg/m³ were measured in the cut-off room One worker was sampled for 3 consecutive days in the cut-off room This worker spent about 3 hours each day in the cut-off room His lowest exposure was 550 μg/m³ and the highest was almost 1,500 μg/m³ His average 8-hour TWA exposure was 340 μg/m³ The worker wore an air-supplied respirator, but had he not worn personal protective equipment, his exposures would have been more than 30 times the OSHA PEL for arsenic

Average personal arsenic exposures were above the NIOSH REL of 2 μg/m³ in all five process areas shown in Table 2 In the grinding/sawing, HB, and load rooms, all personal samples were above the NIOSH REL Since all five process areas had personal arsenic exposures above the NIOSH REL as well as the OSHA action level, these areas need to be regularly monitored Prudent practice indicated that efforts should also be made to improve engineering controls

Average area arsenic levels for four process areas are shown in Table 3 In grinding/sawing, the average area arsenic concentration (5 3 μg/m³) was the same as the average arsenic concentration for the personal samples (5 3 g/m³) The average area arsenic concentration was 4 1 μg/m³ in the synthesis room (a regulated area, as defined earlier) Because workers only occasionally entered this room, no personal samples were taken there The average arsenic concentration in the synthesis room was below the OSHA action level but above the NIOSH REL, all area samples in this room were below the OSHA PEL Because workers spend little time in the synthesis room and the highest area arsenic concentration was 6 μg/m³, it may not be necessary to regulate this room during routine operation

Table 3 Area Sample Total Arsenic Concentrations (By Process)

Room	No of Samples	Average Sample Duration (min)	Arithmetic Mean (μg/m³)	Geometric Mean (μg/m³)	Range (μg/m³)
LEC	10	279	4 0	3 6	1 3-7 5
Horizontal Bridgeman	4	399	3 1	2 5	1 0-6 0
Grinding/Sawing	4	389	5 3	4 2	1 7-10
Synthesis	6	320	4 1	4 0	2 7-6 0
Other[a]	12	371	1 4	1 3	0 7-2 1

[a] These samples were collected 20 to 60 feet from GaAs production rooms Excludes samples collected at 0 1 Lpm

Average personal and area sample arsenic concentrations were comparable in the LEC (during routine operation) and grinding/sawing areas Because personal exposures were not much higher than area concentrations, this suggests that the personal exposure level is due to the general background levels in the area, not from a specific emissions source or work practice Therefore, the use of improved ventilation to minimize emissions and good housekeeping rather than improvements in work practices might be a better initial approach for lowering arsenic levels In the load room, personal concentrations were much above area arsenic concentrations Higher personal exposures were possibly the result of work practices, thus improved work practices should be investigated in order to lower the exposure levels here The area sample results from the HB room averaged 3 1 $\mu g/m^3$, or one-eighth the average personal sample concentration of 24 $\mu g/m^3$ But the high personal exposure for arsenic was due to one very high personal sample (75 $\mu g/m^3$) Therefore, the higher mean arsenic exposures in the HB room may have been caused by an unusual event or a nonroutine work practice or activity by the operator on that day Should this high exposure be repeated, efforts should be made to identify and eliminate the exposure source

Area arsenic samples collected in breakrooms and offices, 20 to 60 feet from the process rooms, showed average concentrations of 1 4 $\mu g/m^3$ This level indicates cross-contamination between production and nonproduction areas and may have resulted from general airflow patterns whenever doors to the LEC grinding/sawing and horizontal Bridgeman rooms are left open A separate ventilation system for the breakroom and office areas and less traffic into and out of production areas should help reduce arsenic levels found in nonproduction areas

Personal samples collected on the cleaning operator during LEC puller cleaning averaged 1,070 $\mu g/m^3$ (Table 4) and ranged from 250 $\mu g/m^3$ to 2,700 $\mu g/m^3$ During the survey, a typical LEC puller cleaning took 45 to 90 minutes and a total of five LEC puller cleanings were sampled over 3 days The cleaning operator wore an air-supplied respirator During the LEC cleaning, a second operator, wearing a half-mask air-purifying respirator, monitored the crystal pullers but did not clean His potential personal exposures averaged 12 $\mu g/m^3$ during cleaning

Area samples collected in the LEC room during cleaning averaged 31 $\mu g/m^3$ of arsenic Area arsenic concentrations during LEC cleaning varied little among sample locations, but were slightly higher near the puller being cleaned Area samples taken during LEC cleaning in the hall outside the LEC room averaged 7 4 $\mu g/m^3$ Other samples were collected away from process areas in rooms or hallways where the presence of arsenic in the air was not expected, unless recirculated by the building ventilation system or a nonprocess (e g , outside) source of arsenic existed A sample concentration taken in the breakroom (about 25 feet from the LEC room) during cleaning was 0 2 $\mu g/m^3$ total arsenic

In LEC cleaning, extremely high exposures resulted for the LEC operator performing the cleaning This operator wore an air-supplied respirator with either a half-mask or full-mask which should reduce his exposure to an acceptable level These high arsenic levels averaged greater than

Table 4 Total Arsenic Concentrations During LEC Cleaning

Sample Type	No of Samples	Average Sample Duration (min)	Arithmetic Mean ($\mu g/m^3$)	Geometric Mean ($\mu g/m^3$)	Range ($\mu g/m^3$)
Operator who is cleaning[a] (personal samples)	5	71	1,070	760	250-2,700
Operator not cleaning[b] but is in room during cleaning (personal samples)	5	79	12	12	7 3-19
Area Samples during cleaning	20	89	31	14	1 4-110
Samples in hall during LEC cleaning	2	71	7 4	6 5	3 9-11
Sample in break room during LEC cleaning and LEC operation	1	317	0 2	--	--

[a] Air-supplied respirator worn
[b] Air-purifying respirator worn

1,000 $\mu g/m^3$, contrasted with the noncleaning operator whose average exposure was 12 $\mu g/m^3$ (7 3 to 19 $\mu g/m^3$) arsenic This two orders of magnitude difference indicates that the greatest exposure to the cleaning operator came from wiping and vacuuming techniques and other job tasks, rather than general room levels during cleaning Because of these high arsenic levels, the LEC room should remain a regulated area after cleaning for an extended period and tests should be run to determine when levels have dropped sufficiently in order to reenter the room without personal protective equipment

Arsenic levels measured in the hall outside the LEC room during cleaning averaged 7 4 $\mu g/m^3$, compared to 0 2 $\mu g/m^3$ in the break area This indicates arsenic dust or fume was released into the halls from the LEC room during and immediately after LEC crystal puller cleaning Workers frequently went in and out of the LEC room during cleaning which probably contributes to the release of arsenic into the hall

Our sample results showed that in some process areas a large amount of arsenic passed through the filter and was collected on the charcoal tube The percentage of arsenic (in the total sample) collected on the charcoal tubes ranged from 0 to 79 percent These results were based on 28 personal and 43 area samples collected using a filter followed by a charcoal tube (Any samples where either the charcoal tube value or the filter value were detectable were included) The arithmetic mean percentage of arsenic collected on the charcoal tubes in the LEC, grinding/sawing, and synthesis room and

during LEC cleaning are presented in Figure 2 Seven area samples in the synthesis room showed that an average 60 percent of the arsenic was on the charcoal tubes In grinding/sawing, 46 percent of the arsenic was collected on the charcoal tube, and in LEC, during regular operations, 31 percent of the arsenic was found on the tubes During LEC cleaning, however, only 2 percent of the arsenic was collected on the charcoal tubes In the HB area, the percentage of arsenic on the charcoal tube was 16 The fraction of arsenic on the charcoal tubes was almost the same for personal and area samples for the same process area

Samples for vapor phase arsenic collected in the epitaxial area (Table 5) were, except for one sample, below the detection limit of 1 3 $\mu g/m^3$ This is below the NIOSH REL of 2 $\mu g/m^3$ for arsenic Arsenic was also not detected on the filters of the samples collected in epitaxy These results indicate current controls for arsine/arsenic in epitaxy are preventing routine exposure to airborne arsenic and arsine

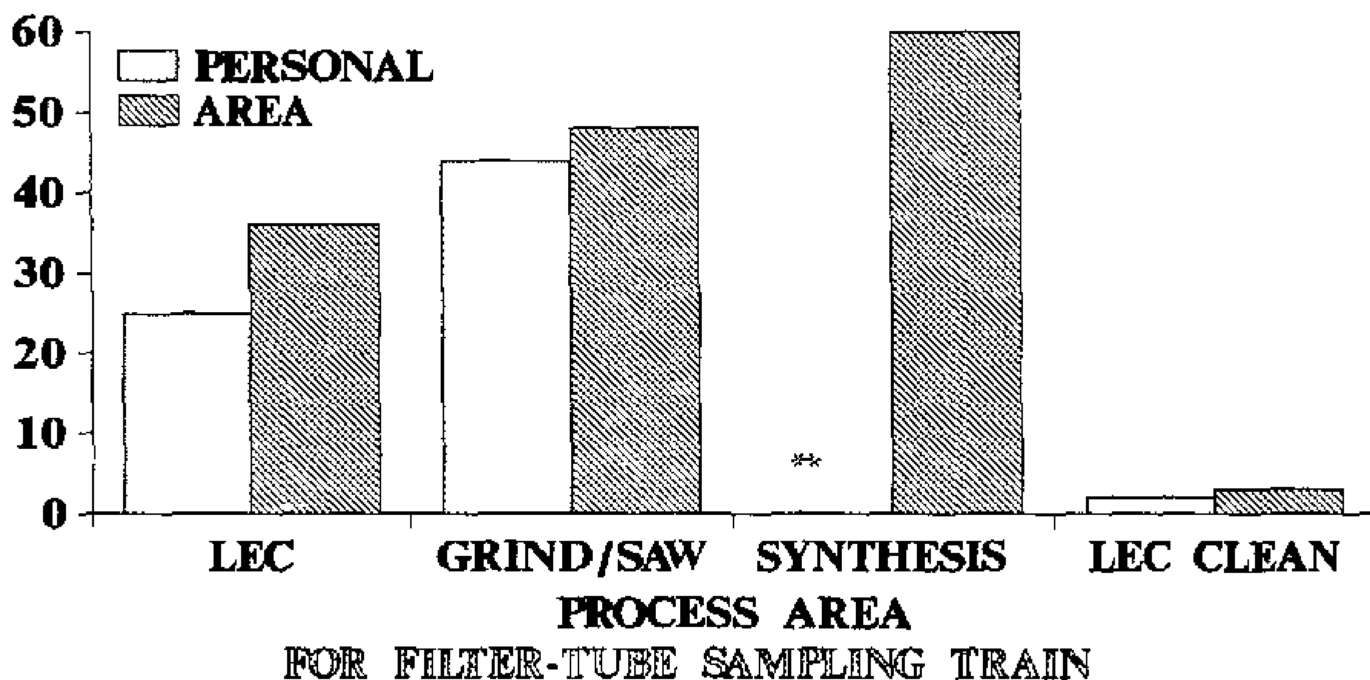
Table 5 Air Sample Results for Epitaxy Production

	Arsine		Arsenic	
	No of Samples	Arithmetic Mean ($\mu g/m^3$)	No of Samples	Arithmetic Mean ($\mu g/m^3$)
Personal Samples	7	<1 3	4	<6 1
Area samples in epitaxy room	7	<1 3	8	<4 3
Samples outside epitaxy	7	<1 1	4	<5 2
OSHA PEL				10
NIOSH REL				2

NOTE Arsine sample duration averaged about 3 hours
Arsenic sample duration averaged about 5 hours

Arsenic Wipe Samples

Wipe samples for arsenic were collected on various surfaces in the LEC, grinding/sawing, Horizontal Bridgeman, and ampoule loading rooms These sample results, in micrograms of arsenic per 100 square centimeters ($\mu g/100\ cm^2$), are presented in Table 6 The highest arsenic levels were found on the top of the base of an LEC puller 1,500 $\mu g/100$ cm before LEC cleaning and 710 $\mu g/100$ cm after cleaning Arsenic surface contamination averaged a relatively high 330 $\mu g/100$ cm on the control console of an LEC puller The lowest arsenic surface contamination in the LEC room was measured on the top of a table next to a puller (4 7 $\mu g/100\ cm^2$) and on the top of a table in the middle of the room (1 9 $\mu g/100\ cm^2$)



**No Personal Samples Collected.

Figure 2

Table 6 Wipe Samples Results for Arsenic

Process	Sample Location	Number of Samples	Sample Area (cm^2)	Arsenic Surface Contamination ($\mu g/100\ cm^2$)
LEC	Control console for LEC puller	2	100	330
	Table top at LEC puller	2	500	4 7
	Table top in middle of room	1	500	1 9
	Floor in front of LEC puller	2	500	31
	Nitrogen purge dry box (outside surface)	1	100	80
LEC Cleaning	Top of LEC puller base before cleaning	1	100	1,500 (repeat 160)
	Top of LEC puller base after cleaning	1	100	710 (repeat 110)
Grinding/Sawing	Door between sawing and grinding areas	2	500	33
	Saw oil pan	1	100	88
	Skirting on saw	1	100	580
Horizontal Bridgeman	Top of heat shield on HB furnace	1	100	76
Load Room (ampoules)	Table top	1	100	230
	Balance table	1	100	420
	Top of wet bench hood	1	100	36

In the grinding/sawing area, relatively high arsenic surface contamination (580 $\mu g/100\ cm^2$) was found on the skirting around the saw Arsenic on the oil pan surface was 88 $\mu g/100\ cm^2$ A lesser amount of arsenic (33 $\mu g/100\ cm^2$) was measured on an inside door in grinding/sawing, however, this is a relatively large amount of arsenic for a surface not directly affected by the process

One wipe sample, taken in the HB room on the top of the HB furnace heat shield, showed 76 $\mu g/100\ cm^2$ of arsenic In the ampoule loading room relatively high arsenic surface contamination (420 $\mu g/100\ cm^2$) was measured on the balance table in the ampoule loading room and 230 $\mu g/100\ cm^2$ were found on another table in this room Arsenic on the top of the hood for the wet bench was 36 $\mu g/100\ cm^2$ Arsenic on the wet bench hood probably came from airborne arsenic dust, whereas arsenic on the table tops probably resulted

from operator activities such as loading the ampoules   Blank wipe samples collected at this plant were below the detection limit of 0 2 $\mu g/100\ cm^2$

Gallium Air Samples

Gallium air sample concentrations are presented in Appendix A, Table A-1 Personal sample gallium concentrations are summarized in Table 7 for five GaAs process areas and the LEC cleaning operation   All personal TWA gallium concentrations were 2 $\mu g/m^3$ or less in the LEC and ampoule load room, and less than 5 $\mu g/m^3$ in the grinding/sawing area   One of four personal samples in the HB room was above 5 $\mu g/m^3$, this sample showed a gallium concentration of 86 $\mu g/m^3$ (the arsenic concentration for this sample was 75 $\mu g/m^3$)   Higher average exposures for gallium were found during LEC cleaning (45 $\mu g/m^3$) and in the cut-off room (820 $\mu g/m^3$)   There is no OSHA PEL or NIOSH REL for gallium, however, NIOSH recommends that worker exposure to gallium arsenide be controlled to the NIOSH REL for inorganic arsenic of 2 $\mu g/m^3$ (ceiling)

Table 7   Personal Exposures to Gallium by Process

Area Worked	No of Samples	Average Sample Duration (min)	Arithmetic Mean ($\mu g/m^3$)	Geometric Mean ($\mu g/m^3$)	Range ($\mu g/m^3$)
LEC	10	254	0 7	0 6	0 2-1 6
Horizontal Bridgeman	4	295	23	4 6	0 7-86
Grinding/Sawing	4	312	2 1	1 7	0 82-4 1
Cut-Off Room[a]	3	190	820	720	470-1,500
Ampoule Loading	4	239	1 5	1 5	0 8-2 0
LEC Cleaning[a]	5	71	45	33	13-98

[a] Air-supplied respirator worn

In general, the amount of gallium was less than that of arsenic for the same filter, however, this depended greatly on the process area sampled as demonstrated in Figure 3   In the LEC during routine operations, gallium concentrations averaged 15 percent of the arsenic concentrations, and during LEC cleaning gallium averaged 9 percent of the arsenic concentrations   On the other hand, in the grinding/sawing area gallium averaged 82 percent and in the cut-off room 97 percent of the arsenic concentration   The almost one to one gallium to arsenic ratio was expected for the latter two process areas, since the starting material for the grinding/sawing and cut-off room operations is gallium arsenide, and these two processes do not involve the use of elemental arsenic or heating or melting as in the LEC process

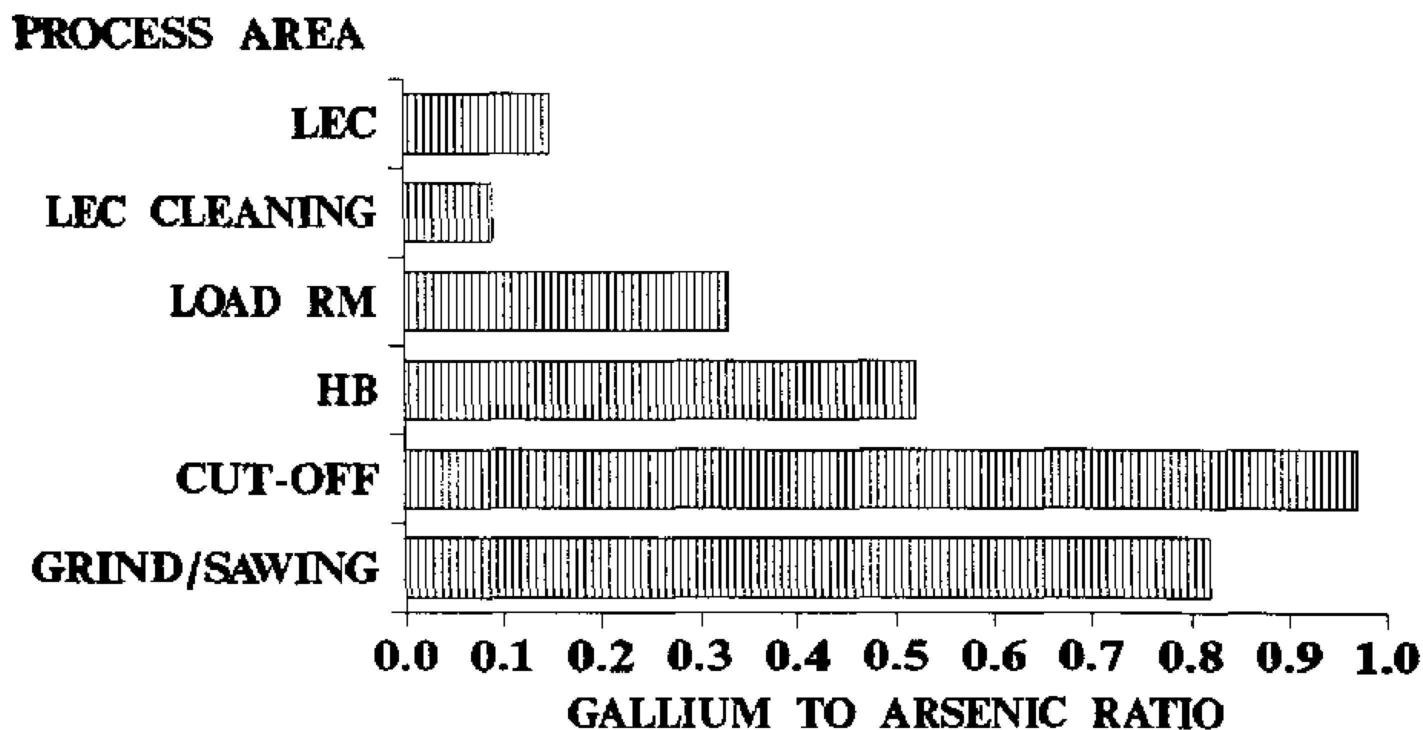


Figure 3

Inorganic Acid Results

Five area samples for hydrogen chloride, hydrogen fluoride, and nitric acid (Table A-2) were collected in the ampoule load room near the wet bench over a 3-day period Average concentrations are shown in Table 8 Generally, two consecutive 4-hour samples were taken each day Hydrogen fluoride and nitric acid concentrations were well below the OSHA PEL and the NIOSH REL, however, hydrogen chloride concentrations ranged up to 11,000 $\mu g/m^3$, which is higher than the OSHA PEL and NIOSH REL of 7,000 $\mu g/m^3$ (ceiling) These data indicate local exhaust ventilation at the wet bench may not be adequate for the control of hydrogen chloride emissions

Table 8 Inorganic Acid Concentration in Ampoule Load Room by Wet Bench[a]

Sample Location	Parameter	HCl[b]	HF	HNO_3
	No of Samples	5	5	5
Ampoule load room near wet bench	Arithmetic mean ($\mu g/m^3$)	2,500	11	400
	Standard Deviation ($\mu g/m^3$)	4,100	6 5	680
	Range	230-10,700	6 7-24	26-1,800
	Avg sample duration (minutes)	237	237	237
	OSHA PEL ($\mu g/m^3$)	7,000 (ceiling)	2,500 (TWA)	5,000 (TWA)
	NIOSH REL ($\mu g/m^3$)	7,000 (ceiling)	2,500 (TWA)	5,000 (TWA)

[a] Blank corrected
[b] Relatively high blank values were found for HCl (7-17 μg)

Free Silica Exposure

Personal and area samples for respirable free silica (see Appendix A, Table A-3) were collected in the polishing room over 4 days Personal samples were collected for an average of 5 hours per day The NIOSH REL for respirable free silica is a time-weighted average concentration of 50 $\mu g/m^3$ Personal samples for quartz and tridymite were below the detection limit of 30 $\mu g/m^3$, three of four personal samples for cristobalite were below the detection limit of 30 $\mu g/m^3$ with one sample at the detection limit These levels indicate free silica exposures in the polishing room were satisfactorily controlled Area respirable free silica concentrations in the polishing room were approximately the same as the personal sample concentrations

CONCLUSIONS AND RECOMMENDATIONS

1 Arsenic exposures are a potential problem in gallium arsenide production at this plant Five process areas evaluated showed personal exposures above the NIOSH REL of 2 $\mu g/m^3$ and the OSHA action level of 5 $\mu g/m^3$, and three areas showed potential exposures above the OSHA PEL of 10 $\mu g/m^3$ As a result of these exposures, we recommend that the current industrial hygiene program with the following components should be continued environmental monitoring, medical surveillance, posting of exposure areas, personal protective equipment and work clothing, employee training, work practices, sanitation practices, and recordkeeping

2 Extremely high levels of arsenic were found in the cut-off room Although the operator wore an air-supplied respirator, such high levels (greater than 1,000 $\mu g/m^3$) are still a major concern and should be reduced by better design of the enclosures for the sandblaster and saws and improved ventilation Exhaust from the cut-off room should be treated before discharge to the atmosphere

3 There was almost no difference in arsenic exposures between the two-day shift LEC operators On the other hand, arsenic exposures among the LEC cleaning operators varied by as much as an order of magnitude This difference may have been due to various degrees of difficulty in cleaning certain LEC pullers as well as differences in the work practices of individuals

Personal and area arsenic concentrations during routine LEC operations did not vary greatly from day to day, but were lowest on Thursday and highest on Friday During LEC cleaning, personal arsenic concentrations were similar on all 3 days, however, area arsenic concentrations were much higher on Thursday and Friday than on Wednesday

4 All arsine/arsenic exposures (collected on charcoal tubes) in epitaxy were below the detection limit of the sampling and analytical method

5 High levels of arsenic were found during the LEC cleaning operation Air-supplied respirators with either a half-mask or full-mask should continue to be worn in this area during LEC reactor cleaning

6 The LEC cleaning operators' average exposure was approximately 100 times the average arsenic exposure of the noncleaning operator This indicates that the specific job tasks involved in reactor cleaning are a major factor influencing exposures The LEC cleaning operators' exposure should be reduced by controlling emission sources during cleaning A major source of emissions is the wiping of the inside walls of the pullers Other potential sources include unbolting the LEC crystal puller using an air-powered wrench, and dropping the LEC vacuum hose on the floor or in a garbage can during cleaning Wet wiping, applying local exhaust ventilation while wiping and removing graphite liners and other internal parts, and wet wiping the contaminated section of the vacuum hose between each use should reduce emissions of arsenic The

feasibility of transferring liners and internal parts of the crystal puller to a ventilated hood or of isolating individual pullers should be investigated Additionally, the LEC room should remain a regulated area for a longer time following LEC crystal puller cleaning, and egress and access to the LEC room during cleaning and "clearing" should be strictly limited

7 In the synthesis room, 60 percent of the arsenic was collected on a charcoal tube following a filter In several process areas, a large portion of the arsenic in a sample were collected on charcoal tubes following the filter This represents arsenic that would not be collected using the traditional filter-only sampling method for arsenic

8 Relatively high levels of arsenic surface contamination were found on top of the base of an LEC puller, on the control console of an LEC puller, on the skirting around a saw (in the grinding/sawing room), and on the top of two tables in the ampoule load room The lowest arsenic surface contamination was measured on the tops of several tables in the LEC room These lowest levels are two to three orders of magnitude lower than the arsenic levels on the surfaces of the LEC pullers and puller console

9 Area hydrogen chloride air concentrations in the ampoule loading room were high enough (one area sample was higher than the OSHA PEL for HCl) to warrant increased ventilation at the wet bench Nitric acid and hydrofluoric acid emissions were well controlled in the ampoule loading room

10 Respirable free silica levels were well controlled in the polishing room indicating low potential for excess free silica exposures in this area

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Appendix A - Table A-1 Arsenic and Gallium Air Sample Results for Morgan Semiconductor

Date	Time (min)	Volume (liters)	Sample Number	Sample Type	Room	Location Code	Arsenic Mass (μg)	Gallium Mass (μg)	Arsenic Conc ($\mu g/m^3$)	Gallium Conc ($\mu g/m^3$)
03/23/87	269	134	3126	P	LEC		0 38	0 1	7 61	0 75
03/23/87	73	36 6	3128	P	LEC		0 1	0 029	4 07	0 79
03/23/87	312	155	3134	A	LEC	L2	0 25	0 029	5 54	0 19
03/23/87	308	155 2	3139	A	LEC	L1	0 42	0 029	7 47	0 19
03/23/87	190	95 6	3102	P	GS		0 21	0 09	7 22	0 94
03/23/87	243	410 7	3150	A	LEC	L3	1	0 05	2 43	0 12
03/23/87	304	516 8	3131	A	LEC	L4	0 88	0 09	1 70	0 17
03/23/87	199	338 3	3141	P	CUT-OFF		220	160	650	470
03/23/87	289	144 7	3124	A	GS	GS3	038	0 29	6 50	2 00
03/23/87	292	496 4	3140	A	GS	GS1	1 3	1 2	2 62	2 42
03/23/87	288	489 6	3111	A	GS	GS2	0 91	0 8	1 86	1 63
03/23/87	104	52 1	3148	A	COMP	CP2	0 13	0 03	5 95	0 58
03/23/87	102	50 8	3144	A	COMP	CP1	0 11	0 03	5 51	0 59
03/23/87	261	130 2	3117	A	BCKGRD	BREAK	0 07	0 03	1 80	0 23
03/23/87	263	447 1	3123	A	BCKGRD	OFFICE	0 72	0 53	1 61	1 19
03/23/87	262	131 2	3104	A	BCKGRD	OFFICE	0 12	0 06	1 46	046
03/23/87	169	16 9	3047	P	EPITAXY		0 15	0 06	<8 88	<3 55
03/23/87	168	16 8	3015	A	BCKGRDe	EPI	0 15	0 06	<8 92	<3 57
03/23/87	166	16 6	3026	A	EPITAXY	E2	0 15	0 06	<9 04	<3 61
03/23/87	159	270 3	3013	A	EPITAXY	E2	0 15	0 06	<0 55	<0 22
03/23/87	175	297 5	3020	P	LOAD RM		1	0 5	3 36	1 68
03/23/87	296	503 2	3005	A	LOAD RM	LR1	0 1	0 06	0 20	0 12
03/23/87	300	510	3014	A	HB	HB1	5 4	5 4	10 59	10 59
03/23/87	299	508 3	3021	A	HB	HB3	1 4	1	2 75	1 97
03/23/87	302	151	3001	A	HB	HB2	0 35	0 16	2 84	1 06
03/23/87	227	113 5	3011	P	HB		0 59	0 41	6 33	3 61
03/23/87	288	489 6	3007	A	POLISH	P2	0 15	0 06	<0 31	<0 12
03/24/87	453	227	3125	P	LEC		0 29	0 05	3 21	0 22
03/24/87	452	227 4	3123	P	LEC		0 4	0 15	4 31	0 66
03/24/87	453	225 1	3106	A	LEC	L2	0 26	0 029	3 59	0 13
03/24/87	448	224 3	3103	A	LEC	L1	0 79	0 029	5 82	0 13

(Continued)

Appendix A - Table A-1 (Continued)

Date	Time (min)	Volume (liters)	Sample Number	Sample Type	Room	Location Code	Arsenic Mass (μg)	Gallium Mass (μg)	Arsenic Conc ($\mu g/m^3$)	Gallium Conc ($\mu g/m^3$)
03/24/94	444	754 8	3113	A	LEC	L3	0 69	0 04	0 91	0 05
03/24/94	443	753 1	3135	A	LEC	L4	0 71	0 11	0 94	0 15
03/24/94	317	158 8	3137	P	GS		0 15	0 13	2 14	0 82
03/24/94	423	723 3	3112	A	GS	GS1	0 45	0 32	0 62	0 44
03/24/94	423	719 2	3147	A	GS	GS2	0 37	0 24	0 51	0 33
03/24/94	411	204 8	3142	A	GS	GS3	0 2	0 17	2 79	0 83
03/24/94	166	282 2	3115	P	CUT-OFF		420	410	1490	1450
03/24/94	170	289	3120	A	CUT-OFF	C01	160	170	550	590
03/24/94	259	440 3	3107	A	CUT-OFF	C01	1 9	2	4 32	4 54
03/24/94	325	163 8	3101	A	BCKGRD	BREAK	0 13	0 1	1 64	0 61
03/24/94	412	205 2	3130	A	BCKGRD	OFFICE	0 19	0 16	1 15	0 78
03/24/94	413	702	3122	A	BCKGRD	OFFICE	0 78	0 61	1 11	0 87
03/24/94	459	229 3	3133	A	COMP	CP1	0 17	0 029	3 56	0 13
03/24/94	459	229	3110	A	COMP	CP2	0 17	0 03	3 32	0 13
03/24/94	160	80 3	3145	P	LEC		0 16	0 029	2 37	0 36
03/24/94	81	40 6	3163	P	CLEC		10	0 52	250	12 8
03/24/94	92	46 2	3152	P	CLECo		0 32	0 029	7 34	0 63
03/24/94	155	77 7	3136	P	LEC		0 24	0 029	3 84	0 37
03/24/94	73	36 6	3174	P	CLECo		0 27	0 029	7 90	0 79
03/24/94	60	30 1	3154	P	CLEC		34	1 5	1130	50
03/24/94	149	253 3	3114	A	LEC	L4	0 21	0 029	0 83	0 11
03/24/94	146	248 2	3138	A	LEC	L2	0 33	0 029	1 33	0 12
03/24/94	91	154 7	3167	A	CLEC	L2	0 37	0 029	2 39	0 19
03/24/94	94	159 8	3182	A	CLEC	L4	0 22	0 029	1 38	0 18
03/24/94	92	156 4	3156	A	CLEC	L2	0 34	0 22	2 17	1 41
03/24/94	84	142 8	3169	A	CLEC	L4	0 43	0 04	3 01	0 28
03/24/94	140	69 9	3108	A	LEC	L1	0 09	0 029	1 56	0 41
03/24/94	94	46 9	3155	A	CLEC	L1	0 5	0 03	12 37	0 64
03/24/94	98	48 9	3183	A	CLEC	L1	0 19	0 029	4 27	0 59
03/24/94	146	73 1	3118	A	LEC	L2	0 18	0 029	3 28	0 40
03/24/94	101	50 5	3157	A	CLEC	L2	0 12	0 029	2 75	0 57
03/24/94	93	46 5	3175	A	CLEC	L2	1 8	0 06	41 03	1 29

(Continued)

Appendix A - Table A-1 (Continued)

Date	Time (min)	Volume (liters)	Sample Number	Sample Type	Room	Location Code	Arsenic Mass (μg)	Gallium Mass (μg)	Arsenic Conc ($\mu g/m^3$)	Gallium Conc ($\mu g/m^3$)
03/24/87	317	538 9	3194	A	BCKGRDC	BREAK	0 1	0 03	0 19	0 06
03/24/87	455	773 5	3023	A	HB	HB3	1 4	0 46	1 81	0 59
03/24/87	456	775 2	3027	A	HB	HB1	2 6	1 9	3 35	2 45
03/24/87	303	150 9	3038	P	HB		0 46	0 31	4 40	2 05
03/24/87	436	216 3	3028	A	HB	HB4	0 38	0 09	2 52	0 42
03/24/87	266	26 6	3019	P	EPITAXY		0 15	0 06	<5 64	<2 26
03/24/87	404	40 4	3048	A	EPITAXY	E2	0 15	0 06	<3 71	<1 49
03/24/87	403	685 1	3037	A	EPITAXY	E2	0 15	0 06	<0 22	<0 09
03/24/87	375	37 5	3029	A	BCKGRDe	EPI	0 15	0 06	<4 0	<1 60
03/24/87	298	248 2	3032	P	LOAD RM		3 4	0 49	13 70	1 97
03/24/87	455	768 9	3003	A	LOAD RM	LR1	0 64	0 18	0 83	0 23
03/24/87	409	695 3	3002	A	POLISH	P2	0 029	0 029	<0 1	0 04
03/24/87	41	20 5	3189	P	CLECo		0 22	0 04	12 7	1 95
03/25/87	41	20 4	3200	P	CLEC		56	2	2750	98 04
03/25/87	54	27	3097	A	CLEC	L1	2 1	0 11	79 3	4 07
03/25/87	54	91 8	3081	A	BCKGRDC	DOOR	1	0 25	10 9	2 72
03/25/87	53	26 5	3070	A	CLFC	L4	2 1	0 09	80 9	3 40
03/25/87	59	100 3	3051	A	CLEC	L4	11	0 38	110	3 79
03/25/87	59	99 7	3059	A	CLEC	L2	2 8	0 15	28 1	1 50
03/25/87	237	118 7	3176	P	LEC		0 63	0 03	5 8	0 25
03/25/87	85	42 6	3190	P	CLEC		17	0 54	400	12 68
03/25/87	245	122	3160	P	LEC		0 17	0 06	1 70	0 49
03/25/87	101	50 3	3173	P	CLECo		0 74	0 08	15 09	1 59
03/25/87	229	114 6	3184	A	LEC	L1	0 21	0 019	2 98	0 17
03/25/87	106	53	3100	A	CLEC	L1	0 5	0 029	9 79	0 55
03/25/87	229	114 4	3169	A	LEC	L2	0 15	0 029	3 26	0 25
03/25/87	100	50	3191	A	CLEC	L4	0 69	0 029	14 70	0 58
03/25/87	232	394 4	3178	A	LEC	L4	0 33	0 04	0 84	0 10
03/25/87	234	395 5	3170	A	LEC	L2	0 4	0 029	1 01	0 07
03/25/87	107	182	3071	A	CLEC	L4	3 4	0 3	18 68	1 65
03/25/87	99	167 3	3198	A	CLEC	L2	0 77	0 04	4 60	0 24

(Continued)

Appendix A - Table A-1 (Continued)

Date	Time (min)	Volume (liters)	Sample Number	Sample Type	Room	Location Code	Arsenic Mass (μg)	Gallium Mass (μg)	Arsenic Conc ($\mu g/m^3$)	Gallium Conc ($\mu g/m^3$)
03/25/87	88	150	3162	A	BCKGRDC	DOOR	0 59	0 07	3 93	0 47
03/25/87	69	117 3	3061	A	LEC	L4	0 17	0 029	1 45	0 25
03/25/87	69	116 6	3192	A	LEC	L2	0 13	0 029	1 11	0 25
03/25/87	205	348 5	3187	P	CUT-OFF		190	190	550	550
03/25/87	211	358 7	3164	A	CUT-OFF	CO1	230	230	640	640
03/25/87	375	188 6	3188	P	GS		0 75	0 78	5 09	4 14
03/25/87	431	215 4	3158	A	GS	GS3	0 18	0 11	1 76	0 51
03/25/87	432	734 4	3185	A	GS	GS1	0 8	0 64	1 09	0 87
03/25/87	427	730	3172	A	GS	GS2	0 85	0 61	1 16	0 84
03/25/87	437	217	3186	A	BCKGRD	BREAK	0 22	0 1	2 06	0 46
03/25/87	432	734 4	3181A	A	BCKGRD	OFFICE	0 53	0 44	0 72	0 60
03/25/87	432	216 3	3165	A	BCKGRD	OFFICE	0 21	0 12	1 23	0 55
03/25/87	412	206 3	3181	A	COMP	CP1	0 25	0 04	3 21	0 19
03/25/87	387	194	3196	A	COMP	CP2	0 29	0 05	3 66	0 26
03/25/87	152	258 4	3033	P	LOAD RM		1 5	0 45	5 80	1 74
03/25/87	350	175	3009	P	HB		13	15	74 87	85 71
03/25/87	456	228	3010	A	HB	HB4	0 16	0 08	1 10	0 35
03/25/87	386	38 6	3004	A	EPITAXY	E2	0 15	0 06	<3 89	<1 55
03/25/87	382	38 2	3034	A	EPITAXY	E2	0 15	0 06	<3 93	<1 57
03/25/87	378	37 8	3050	A	BCKGRDe	EPI	0 15	0 06	<3 97	<1 59
03/25/87	358	35 8	3022	P	EPITAXY		0 15	0 06	<4 19	<1 68
03/25/87	428	728	3035	A	POLISH	P2	0 05	0 039	0 07	0 05
03/25/87	453	770 1	3012	A	HB	HB2	3 3	3 1	4 29	4 03
03/25/87	453	770 1	3046	A	HB	HB3	0 47	0 33	0 61	0 43
03/26/87	252	428	3072	A	LEC	L2	2 1	0 27	4 91	0 63
03/26/87	250	425	3053	A	LEC	L4	0 77	0 093	1 81	0 22
03/26/87	101	171 7	3066	A	CLEC	L2	5 5	0 38	32 03	2 21
03/26/87	102	173 4	3078	A	CLEC	L4	5 7	0 38	32 87	2 19
03/26/87	275	137 7	3076	P	LEC		1 1	0 22	8 26	1 60
03/26/87	88	44 1	3090	P	CLEC		36	2 2	820	49 89

(Continued)

Appendix A - Table A-1 (Continued)

Date	Time (min)	Volume (liters)	Sample Number	Sample Type	Room	Location Code	Arsenic Mass (μg)	Gallium Mass (μg)	Arsenic Conc ($\mu g/m^3$)	Gallium Conc ($\mu g/m^3$)
03/26/87	223	111	3077	P	LEC		0 91	0 14	8 54	1 26
03/26/87	86	42 9	3092	P	CLECo		0 81	0 07	19 32	1 63
03/26/87	261	130 6	3055	A	LEC	L2	0 43	0 038	3 58	0 29
03/26/87	99	49 5	3067	A	CLEC	L2	1 6	0 1	32 71	2 02
03/26/87	263	132 3	3093	A	LEC	L1	0 42	0 05	3 46	0 38
03/26/87	93	46 8	3069	A	CLEC	L1	5 1	0 27	110	5 77
03/26/87	366	183 6	3098	P	GS		0 86	0 48	6 73	2 61
03/26/87	423	211 3	3062	A	GS	GS3	1 8	1 9	10 19	8 99
03/26/87	427	726	3054	A	GS	GS2	3 6	4	4 96	5 51
03/26/87	429	729	3052	A	GS	GS1	8 1	9 6	11 11	13 17
03/26/87	406	202 6	3056	A	BCKGRD	BREAK	0 21	0 07	1 69	0 35
03/26/87	407	692	3079	A	BCKGRD	OFFICE	0 58	0 37	0 84	0 53
03/26/87	406	203 6	3099	A	BCKGRD	OFFICE	0 14	0 66	1 17	3 24
03/26/87	407	202 8	3057	A	COMP	CP2	0 42	0 38	2 74	1 87
03/26/87	394	670	3024	A	HB	HB3	3 4	0 47	5 07	0 70
03/26/87	389	657 4	3000	A	HB	HB2	5 1	0 13	7 76	0 20
03/26/87	366	36 6	3006	A	EPITAXY	E2	0 15	0 06	<4 10	<1 64
03/26/87	375	638	3041	A	EPITAXY	E2	0 15	0 06	<0 24	<0 09
03/26/87	265	26 5	3025	P	EPITAXY		0 15	0 06	<5 66	<2 26
03/26/87	372	37 2	3039	A	BCKGRDe	EPI	0 15	0 06	<4 03	<1 61
03/26/87	436	741	3045	A	POLISH	P2	0 18	0 16	0 24	0 22
03/26/87	330	561	3031	P	LOAD RM		3 5	0 43	6 24	0 77
03/26/87	418	711	3040	A	LOAD RM	LR1	0 066	0 019	0 09	0 03
03/26/87	401	200 4	3017	A	HB	HB3	1 2	0 019	6 27	0 09
03/26/87	300	151 2	3042	P	HB		1 3	0 11	8 97	0 73

Appendix A - Table A-2 Acid Air Sample Results for Morgan Semiconductor

Date	Sample Number	Type	Room	Time (min)	Volume (liters)	HCL Mass (μg)	HCL Conc ($\mu g/m^3$)	HF Mass (μg)	HF Conc ($\mu g/m^3$)	Nitric Mass (μg)	Nitric Conc ($\mu g/m^3$)
03/24/87	804	Area	LOAD RM	278	134	70	520	1 0	7 5	11 0	82
03/24/87	802	Area	LOAD RM	157	76	18	230	0 5	6 6	2 0	26
03/25/87	807	Area	LOAD RM	320	160	37	230	3 8	24	6 0	38
03/26/87	805	Area	LOAD RM	217	105	75	710	0 7	6 7	8 0	76
03/26/87	806	Area	LOAD RM	211	102	1098	10700	1 0	9 8	180	1760

Appendix A - Table A-3 Silica Air Sample Results for Morgan Semiconductor

Date	Sample Number	Media	Type	Room	Time (min)	Volume (liters)	Quartz Mass (μg)	Quartz Conc (μg/m³)	Cristobalite Mass (μg)	Cristobalite Conc (μg/m³)	Tridymite Mass (μg)	Tridymite Conc (μg/m³)
03/24/87	3509	PVC	P	POLISH	282	479	<15	<31	<15	<31	<15	<31
03/24/87	3514	PVC	A	POLISH	379	644	20	31	<15	<23	<15	<23
03/25/87	3504	PVC	P	POLISH	358	609	<15	<25	20	33	<15	<25
03/25/87	3501	PVC	A	POLISH	423	719	<15	<21	<15	<21	<15	<21
03/26/87	3508	PVC	P	POLISH	380	646	<15	<23	<15	<23	<15	<23
03/26/87	3516	PVC	A	POLISH	440	748	<15	<20	<15	<20	<15	<20
03/23/87	3515	PVC	A	POLISH	288	490	<15	<31	20	41	<15	<31
03/23/87	3503	PVC	P	POLISH	168	286	<15	<53	<15	<53	<15	<53