3 The Design of Cleanrooms for the Microelectronics Industry

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INTRODUCTION

The technology of cleanroom design had its conception in medical/pharmaceutical facility development, and it was born in the rush to expand World War II's science of armament and warfare. Its adolescence paced the needs of the race into space and finally came into adulthood in time to meet the challenge of manufacturing in the Lilliputian world of microelectronics, where micrometre-sized particles are like automobile-sized rocks, and impurities of the order of parts per trillion can be crucial.

The demands of creating an environment which provides the near-perfect conditions required in the manufacturing processes of this world of microelectronics were, and are, stringent and include areas which are vital to the success of manufacturing. Maximizing product quality and yield requires strict control of, and co-ordination between, the manufacturing facility, tooling, process and operation, but all of these heavily depend upon the strict environmental control afforded by advanced cleanroom technology.

Contamination control engineering, along with its related equipment, materials, and skills, has become so advanced that the facility and its environmental control should no longer need be the limiting factor. If this is so, where is the challenge in designing cleanrooms for microelectronics manufacturing? Obviously, the goal of cleanroom environmental control is to provide contamination-free space in which to manufacture a contamination-free product. Following the approved procedures should produce the desired result, but contamination has a way of occurring unexpectedly, sometimes without any sign to indicate its origin. The cleanroom, the manufacturing process, equipment and method of operation are all equally possible sources of contamination. While the technology was yet in its youth, the immediate assumption was, and generally justifiably so, that the cleanroom itself had failed. Present-day cleanrooms are of a much higher standard and have controls and monitors by which the cleanroom's operating condition can be quickly evaluated. If it proves to be operating properly, the process, process equipment and operation can then be examined in turn.

The world of environmental control has truly expanded, because, to be recognized as a contamination-control engineer, one must now accept the challenge of including domain and responsibility. One must also be involved in evaluating handling equip-

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ment, and training personnel in contamination control, as well as all the other innu-merable facets of the total control problem.

MANUFACTURING SEMICONDUCTOR CIRCUITS

Manufacturers of semiconductor circuits have become very large users of cleanrooms. The reason is that the manufacturing operations take place at almost the molecular level and the physics of the operation of the device depend upon purity of materials in atomic percentages measured down to parts per trillion. These levels are unheard of in any other human endeavour.

First germanium and then silicon became the wonder elements of the twentieth century. This is because they are semiconductors of electricity. Semiconductors derive their name from their ability sometimes to conduct an electrical current and other times not. This is controlled by their internal structure on the atomic level and by the circuitry into which they are inserted. Certain atomic elements can be added to the structure during manufacturing which enables these effects to take place. While there are many described categories of devices (taken on a discrete device level), the basic functions performed are: voltage amplification, switching, resistivity and induction. Combined with diodes and transistors these form the basis of semiconductor circuits.

To give some perspective to those who are unfamiliar with the process, the following is a brief summary, together with levels of contamination control required, of the manufacturing steps used in making semiconductor circuits. The very-large-scale integration (VLSI) and the complementary-metal-oxide-semiconductor (CMOS) pro-cesses on silicon are used as an illustrative example.

Common practice divides the manufacturing of integrated circuits into three phases: materials, wafer fabrication and assembly and test.

Materials

Starting with silica sand, the process is as shown in Table 3.1.

During the sequence most of the operations take place in an ordinary factory en-vironment. Protection against contamination is provided, for the most part, by d the processing within sealed systems. Preparation of the charge for the Czochra puller, however, as well as clean-up of the crucible, must be done in a well-contro cleanroom (minimum standard ISO 5 (Class 100)). Any contamination introdu during that step will get into the ingot and will either cause a failure in the process make a single crystal or cause unacceptable electrical properties to develop.

The last part of the process also requires a clean environment (minimum standa ISO 5 (Class 100)) to allow the equipment to produce the required finish, thickness taper and flatness. Also, great care must be taken to avoid leaving any mobile ions or doping elements on the surface. Subsequent high temperature operations could then distribute these into the crystalline structure and destroy the desired electrical properties.

This is a vastly simplified description of the entire process, completely ignor many tests, cleaning steps and process adjustments required to produce ma required purity, crystalline size, orientation, uniformity and possess

TABLE 3.1

Start with	Into	Produces
a. Sand, coal, coke, wood chips	Submerged arc electric furnace @ 2000°C	Silicon metallurgical grade (MGS)—98% Si
b. MGS (powdered) HCl (gas) + catalyst	Reactor @ 300°C	$SiHCl_3$—impure (trichlorosilane)
c. $SiHCl_3$ (impure)	Distillation column	$SiHCl_3$—pure
d. $SiHCl_3 + H_2$	Reactor	Silicon, electronic grade (EGS) 99.99%+
e. EGS	Czochralski crystal grower—high temp. inert gas atmosphere	Single-crystal silicon ingot
f. Single crystal silicon ingot	Special grinder	Polished cylinder with flat(s)—full length—to define crystal orientation
g. Polished cylinder	Diamond saw	Round slices with one or two flat sides
h. Slices	Grind, lap and polish machines	Wafers ready to be made into integrated circuits

electrical properties. The description is also based on using only silicon as the semiconducting material. There are numerous other systems in use today, involving multi-metal semiconductors, silicon (or other semiconductors) deposited on glass, sapphire, diamond, etc. These systems do not negate any requirement for right control of contamination. On the contrary, such complications usually provide additional mechanisms for contamination to be detrimental to function and quality, the result usually being a requirement for more stringent control.

Wafer Fabrication

In this phase of the manufacturing, all the active and passive elements of the semiconductor circuits are built onto or into the polished silicon wafer. On the microscopic level one can observe a cross-section of pure silicon being changed by: the addition of atoms deep into the pure metal to a controlled depth and concentration; metal being etched away; layers of silicon oxide being deposited over everything then selectively etched away to be replaced by silicon with other impurities, or aluminium; then layers being selectively etched away and replaced by more oxide and metal. The process is repeated until many layers are applied, interconnected, stabilized, passivated, etc.

Processes include: heat up to 1100°C; attack by exceptionally aggressive chemicals; flooding with chemical vapours so toxic that the most rigorous controls are required to protect people; exposure to violent levels of ionizing radiation and superheated, ionized plasmas. All of these take place to create circuits and active devices whose dimensions range down to 0.01 μm for critical features. The active elements which are interconnected into one device can be in the millions. All of these are packed into a chip measuring about one centimetre square. As all the dimensions are controlled by photographic processes (photo-lithography), the success or failure of manufacturing is absolutely determined by the control (and elimination) of contamination. The minimum class required is ISO 5 (Class 100), with the most critical steps requiring ISO 3 (Class 1) or better.

The processes encountered in wafer fabrication are given in Table 3.2.

The above steps are not necessarily in sequence, or all-inclusive, but serve to illustrate the complexity and enormous number of steps required. It is recognized that this sequence, or parts of it, may be repeated many times for one device. The complexity is added to by the precise inspections, measurement and cleaning required at least once between steps.

TABLE 3.2

Start with	Into	Produces
a. Polished wafer	Diffusion furnace or epitaxial reactor (high temperature atm. with water vapour)	Wafer with SiO_2 layer on surface
b. Oxide covered wafer	Spinner-coater which applies photo resist (PR)	Wafer with oxide PR layers
c. Wafer with PR	Pattern application (exposure of PR to UV light or electrons through photomask)	Exposure of pattern on PR
d. Exposed wafer	Developer (wash out either exposed or non-exposed pattern depending on type of PR)	Wafer with PR pattern
e. Wafer/PR pattern	Etch (etchant removes oxide exposed by pattern development)	Metal exposed through oxide
f. Wafer with pattern	Diffusion furnace or ion implant (add impurities to exposed silicon)	Implanted or diffused pockets in Si
g. Diffused wafer	PR removal (either plasma or wet etch removal)	Cleaned surface ready for more processing
h. Clean wafer	Reactor (deposit silicon layer)	New layer of active silicon
i. Metallized wafer	Repeat steps b to g	Wafer with clean surface
j. Clean wafer	Sputter reactor (apply aluminium coating)	Conducting layer
k. Metallized wafer	Repeat steps b to g	Clean surface
l. Cleaned metallized wafer	Repeat steps a to g	Clean surface
and so on until:		
x. Cleaned wafer	Reactor (nitride overcoat application)	Surface protected wafer
y. Surface protected wafer	Back etch (for thinning)	Thinned wafer
z. Thinned wafer	Backside plating	Electrical contacts

In the wafer fabrication area the objective of contamination control is to protect the work-in-process from errors created by contamination. There is a rule of thumb which says that the maximum size of particle which can be tolerated is one tenth the dimension of the smallest critical feature. For example, an electrical gate whose smallest critical dimension is 1.0 μm, can be made defective by a particle 0.1 μm and larger. Other types and sources of contamination, such as dissolved contaminants in deionized water, can produce killer defects that may or may not be traceable.

For the above reasons, in the wafer fabrication area the utmost in contamination control must be extended to the work until the wafer is completely protected.

Assembly and Test

This third phase is where the individual devices are tested, separated from the others on the wafer, mounted onto a substrate or leadframe, electrically connected from the terminating pads on the silicon chip to the leads on the leadframe, encapsulated, finally tested and shipped. In general, cleanliness levels between ISO 7 (Class 10000) and ISO 5 (Class 100) are required.

The operation is as shown in Table 3.3.

The needs for contamination control in this phase are very different from the other two previously described manufacturing processes. Here the device is already protected from atomic and ionic pollutants, but must still be protected against large conductive particles shorting between leads. Also they must be protected against

TABLE 3.3

Start with	Into	Produces
a. Completed wafer	Multi-point prober (function test of each device)	Tested wafer. Failed devices identified with ink dot
b. Tested wafer	Mounting fixture (wafer mounted on plastic mounted on metal ring)	Wafer ready for dicing saw
c. Mounted wafer	Dicing saw (diamond saw precisely cuts through wafer to separate dies)	Separate die, adhesively held to plastic
d. Separated die	Die attach (vacuum probe picks off good dies and attaches them to leadframe)	Device to leadframe
e. Device on leadframe	Lead bonder (gold wire attachment of device to leads)	Device electrically attached to leads
f. Electrically completed device	Encapsulating (either plastic moulding or hermetically sealed 'can')	Completed device ready for final test
g. Completed device	Burn-in test (prolonged test under operating conditions and environmental extremes)	Device ready for shipment

electrostatic charge build-up and discharge (in this region the devices are very vulnerable, a 12 V discharge can destroy a circuit). Any oil or other material on surfaces may prevent sealing or adhesion of plastic or ink. Films or particles on a surface may also interfere with obtaining a good electrical contact and cause false readings on test. The principal difference is in the size or quantity of contaminants. In the wafer fabrication area contaminants that are too small to be seen in an inspection microscope may be fatal. The opposite is true in assembly and test; the fatal particles or other contaminants may be too large to be readily picked up in microscopic or other inspections.

Thus we have a brief description of the semiconductor manufacturing process and why contamination is a problem. It has been simplified to illustrate how important the problem is. We must now consider how to design clean areas suitable for the manufacture of semiconductors.

DESIGN GUIDELINES

Wafer fabrication facilities are among the most expensive to build and operate. To make matters even worse, the expensive state-of-the-art equipment can be superseded within two years and the average wafer fabrication area can have a maximum useful life of five years. These observations demonstrate that wafer fabrication must produce enough profits to amortize the cost of construction in the first two years, or the probability of success is small. It is important therefore to keep the goal of reducing these high construction and operating costs firmly in mind as one plans the design for the cleanroom.

The following guidelines are given to aid in reducing these costs:

Do not overdesign. A full vertical-flow, through-the-floor air return, ISO 3 (Class 1) cleanroom undoubtedly provides the cleanest, most versatile, easiest to use (most forgiving) facility. It can also be guaranteed to be prohibitively expensive to build and operate. If you can limit the strictest control to the area in which the work-in-process is most vulnerable to damage from contamination, and isolate that zone by a fixed barrier (such as a glass or plastic wall) then you may reduce the most costly area to 5% of the total.

Design for flexibility. Whatever the system may be, strive to make it possible to rearrange equipment, walls, filters, air returns, utilities, etc. easily. This should be at the least expense in the long term and, most importantly, cause the least disturbance to production when changes are made. You can be sure that equipment and processes will change and it is also axiomatic that the new equipment or process will not fit in the old space and will require a change in utilities, so there must be sufficient room for expansion.

Provice bulkhead-mounting of the process equipment, wherever possible, in critical contamination-sensitive areas. This allows separation of the product-flow from the process equipment and operation, maintenance and engineering personnel. The product movement area (highest level of cleanliness control) can hence be very small compared to the operations and equipment area (lower level of control). Major savings may be made here. Ideally, material handlers, properly trained and clothed, should be the only persons exposed to the same environment as the product. Then, should economic studies prove feasibility, it should be easy to replace those material handlers with an automated system. Currently, it makes little difference to contamination levels whether properly garbed and trained people or robotic systems are used and it is doubtful that this will change.

Provide a cleanroom environment only where it is needed, and only to the level needed. To do this successfully, it must be remembered that a 'clean zone' is like a vacuum—nature abhors it! The cleaner the zone, the more consequential are small leaks and pressure differentials. Therefore, a buffer zone of clean air of a lesser degree of control, surrounding the clean zone, is always appropriate, as is a slightly lower pressure. Even entry and exit from an uncontrolled area through an air lock creates an opportunity of contamination to enter.

Always examine process equipment. The process equipment should be cleaned thoroughly, and tested for residual contamination as well as contamination generation or retention, before introducing it into the cleanroom. Obtain a certificate from the manufacturer guaranteeing the maximum level of contamination dispersed from his equipment in terms of particles per wafer per pass, or other significant measurement appropriate to the equipment. This manufacturer's guarantee should be regarded as an extremely significant condition for purchase, as these contamination sources have enormous yield consequence.

Design utility distribution systems to:

1. Provide ready access for attachment equipment without the necessity for shutting down the system or cleanroom.
2. Provide adequate flow rates to prevent stagnation and impurity pick-up.
3. Prevent pressure fluctuation during operating 'runs'. Even slight variations can have disastrous effects on the product. It is true not only on the supply, but on the extract (exhaust) as well. It pertains to all systems of process utilities supply and return such as:
   - gases supply and extract (exhaust)
   - liquids supply and drain
   - electrical supply and earth-ground.
4. Periodically provide attachment points and blanked-off valves for all gases and liquids (except deionized water) so that a connection can be made without the danger of contaminating active process lines; they are virtually impossible to clean once contaminated. Deionized water systems should be provided with isolation valves and sterilization connections to:
   - make a new connection
   - perform sterilization
   - test to assure sterility and purity specifications
   - open the system.

5. Always design for the ultimate filtration of gases and liquids to be after the last valve or flow measurement device, so that the filter is the last thing before the product. This is so important that process equipment must be modified before installation if the situation is otherwise than required. There is no valve available at present whose operation does not produce particles in the fluid it is controlling, to a yield or function-damaging level.

Design for freedom from vibration and electromagnetic interference. These have become very critical. Both have some of the same origins and the design for the control of these should start, very early, with site selection. Before any site is adopted, thorough testing and analysis should be made of: seismic activity, soil conditions, proximity to railroads, highways, airport landing and take-off paths, adjacent industry, adjacent bodies of water where waves beating on shores can create earth impulses very difficult to attenuate and at a very damaging frequency. Large rotating electrical machinery in the vicinity produces both vibrational excitation of the ground and an electromagnetic field, the strength of which varies as the square of its power. High tension power lines in the vicinity not only produce electromagnetic fields but may excite some structural elements to mechanically vibrate at some multiple (or fraction) of the base frequency. All of these, and others, should be evaluated carefully by experts familiar with the microelectronics industry's needs before a decision is made to proceed. The time and money spent doing this may prevent the expenditure of correspondingly larger amounts of both, should a wrong choice be made. Certainly it is needful to establish parameters for the design of foundations, columns, spacing of structural elements, etc.

Define how the cleanroom is to be built. The success of a cleanroom project depends to a large extent on what is put on paper and how it is constructed. One feature, often ignored, but certainly within the purview of the designer, is the designation of when and how cleanliness controls are to be enforced during the construction phase. It is possibly the most important instruction the designer can give, for it determines in large measure the amount of built-in dirt that can greatly prejudice future operations. Dirt, built in during construction, will come into the process during operation and can determine success or failure of the cleanroom. My recommendation is to require cleanroom procedures to be applied as soon as the building is 'dried in', i.e. before any facility or utility systems or equipment are installed. From that point on, continuous cleaning is required, so that no dirt is trapped during construction to cause trouble later. Such cleaning should include: vacuum cleaning (with a brush) every surface, damp wash with free-rinsing, non-ionic detergent, rinsing with deionized water and a final wipe-down with 'tack-cloth' prior to turning the facility on. Following such a procedure should allow the specified conditions to be met within seconds of system turn-on and with few subsequent excursions.

DESIGN FEATURES

Layout

The design of semiconductor cleanrooms has evolved over several years. The design of a cleanroom which has been popular for a number of years is shown in Figure 3.1. The

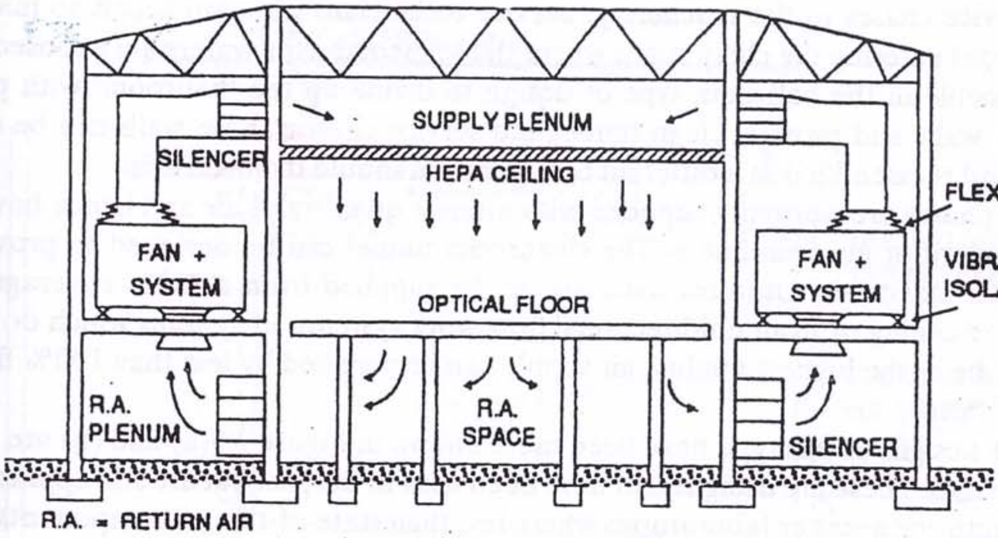

FIGURE 3.1. Vertical flow cleanroom often used in semiconductor manufacturing.

air flows in a unidirectional way from a complete ceiling of high efficiency filters down through the floor of the cleanroom. Some designs return the air through a plenum just below the floor, while other designs (similar to the type shown in Figure 3.1) have a large basement beneath the plenum, that basement being used for services. The design shown in Figure 3.1 is often called the 'ballroom' type because there is one large cleanroom. Typically it is over 1000 m^2 in floor area. It is expensive to run but it is very adaptable.

In the 'ballroom' type of cleanroom a ceiling of high efficiency filters provides clean air throughout the whole room irrespective of need. It is clear that the best quality air is necessary where the product is exposed to airborne contamination, but that lesser quality would be acceptable in other areas. Using this concept, less expensive cleanrooms have been designed in which service chases with lower environmental cleanliness standards are inter-dispersed with cleanroom tunnels (see Figure 3.2).

The production machinery is bulkhead-fitted so that the piped services can be run

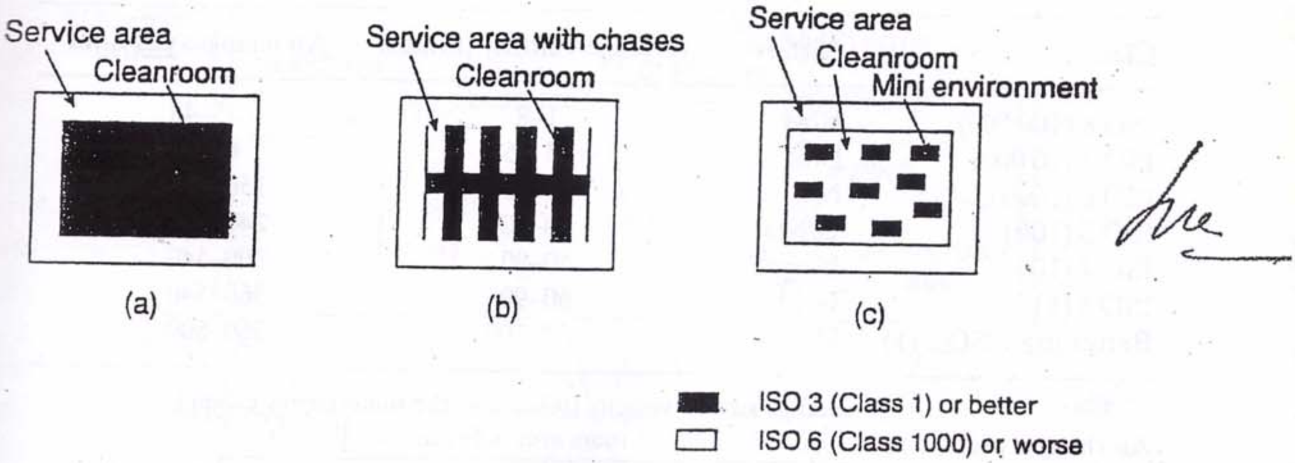

FIGURE 3.2. Plan views of three types of cleanrooms: a) ballroom type; b) service chase type; c) minienvironment type.

within service chases to the machinery. Service technicians can gain access to machinery without entering the clean space where the semiconductor wafers are exposed. It is also possible in the ballroom type of design to divide up the 'ballroom' with prefabricated walls and provide clean tunnel and service chases; these walls can be dismantled and reassembled in a different configuration should the need arise.

Service chases are normally supplied with a lesser quantity of air and hence have a lower standard of air cleanliness. The cleanroom tunnel can be designed to provide different air standards. Unidirectional air can be supplied from a 100% coverage of filters in the ceiling or from unidirectional flow work systems; in systems which do not require to be of the highest quality, air supply can be supplied by less than 100% filter ceiling coverage.

Various designs of this type have been used. Shown in Figure 3.3(a) and (b) are two typical designs. These are designs that have been used in the past but are still applicable in manufacturing areas or laboratories where less than state-of-the-art components are produced.

To achieve lower standards appropriate to less stringent contamination control areas in both sub-divided 'ballroom' and tunnel designs, the air supply volumes can be lowered by reducing the ceiling filter coverage from less than 100%. This method is shown diagrammatically in Figure 3.4.

If this method is to be employed, use may be made of Table 3.4. Table 3.4 is published in the Recommended Practice 012 of the IEST although the nomenclature of the room classification has been changed to that used in this book. Please note that the values used in this table are only a guide and are considered by some authorities to be *inappropriate for cleanrooms used in manufacturing industries other than semiconductor.*

If the cleanroom design uses an air supply plenum, then the unfiltered air in the plenum will be at a higher pressure than the air in the cleanroom. Unfiltered air can therefore leak from the supply plenum into the cleanroom through badly sealed, or unsealed, joints in the structure (Figure 3.5). Particular care must therefore be taken to ensure that the joints are correctly sealed. Such leak problems can be overcome if the area above the ceiling is below the pressure of the cleanroom. This can be achieved by

TABLE 3.4. Air velocities in cleanrooms.

Class	Airflow	Average velocity (ft/min)	Air changes per hour
ISO 8 (100 000)	N/M	1–8	5–48
ISO 7 (10 000)	N/M	10–15	60–90
ISO 6 (1000)	N/M	25–40	150–240
ISO 5 (100)	U/N/M	40–80	240–480
ISO 4 (10)	U	50–90	300–540
ISO 3 (1)	U	60–90	360–540
Better than ISO 3 (1)	U	60–100	360–600

$$\text{Air changes per hour} = \frac{\text{average air flow velocity (taken over the whole supply ceiling)} \times \text{room area} \times 60\ \text{min/hr.}}{\text{room volume}}$$

N = non-unidirectional; M = mixed flow room; U = unidirectional flow.

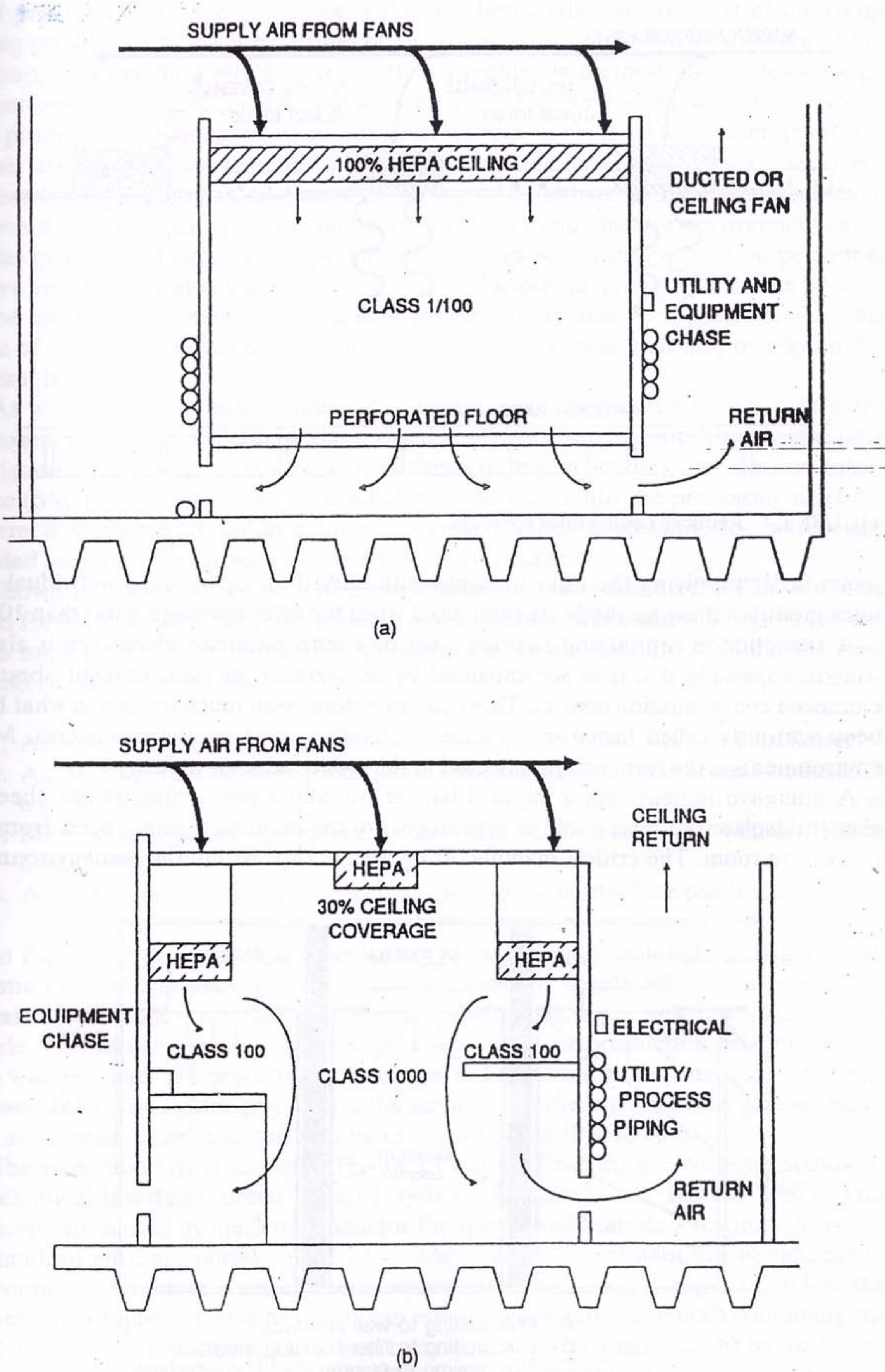

FIGURE 3.3. Two types of tunnel and service chase designs.

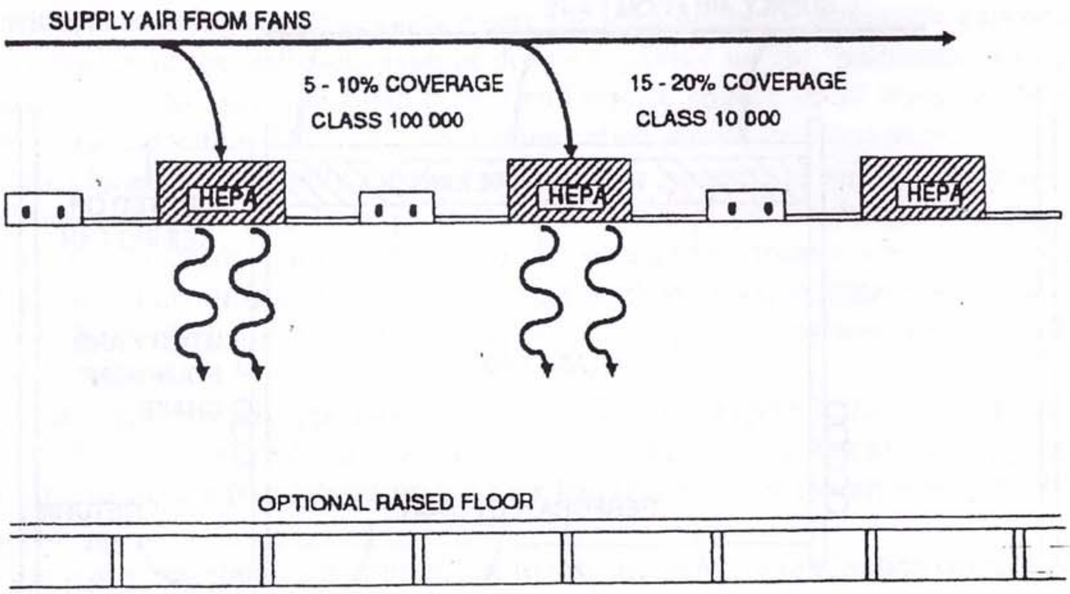

FIGURE 3.4. Reduced ceiling filter coverage.

individually supplying the filter housings with ducted air or by using individual fan/filter modules; these methods are often used when the filter coverage is less than 100%.

A reduction in capital and running costs of a semiconductor cleanroom is always sought, especially if this is accompanied by an increase in yield brought about by enhanced contamination control. There has therefore been much interest in what have been variously called 'isolators', 'barrier technology' and 'minienvironments. Minienvironments is the term commonly used in the semiconductor industry.

A minienvironment uses a physical barrier (usually a plastic film, plastic sheet or glass) to isolate the susceptible or critical part of the manufacturing process from the rest of the room. The critical manufacturing area is kept within the minienvironment

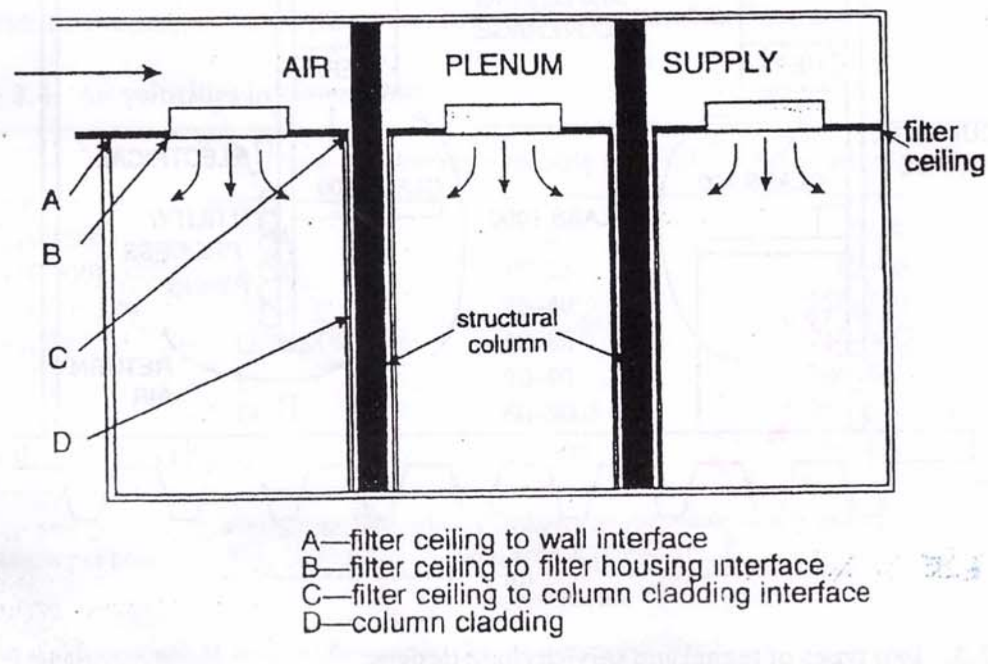

FIGURE 3.5. Infiltration of contaminated air into the cleanroom from an air plenum supply.

and provided with large quantities of the very best quality air, the rest of the room being provided with lower quantities of air. Shown in Figure 3.6(a) is a diagram of the air supply design used with a more traditional ventilation method. In this design large quantities of a unidirectional flow of air are provided to those parts of the room where the production personnel move wafers from machine-to-machine and lesser quantities of air are provided for the chases where the bulkhead-fitted machines are serviced. Shown in Figure 3.6(b) is a diagram of the air supply design used with mini environments, where the highest quality of environment is provided within the minienvironment and a lesser quality of environment is provided in the area where the production personnel move about as well as within the service chases. The total air supply volume can be seen to be much less when minienvironments are used. It can also be appreciated that this type of system lends itself to automation and the use of robots: that may or may not be desirable.

As well as using minienvironment to isolate the area where the silicon wafers are exposed, the wafers can also be transported between processing machines in specially designed carriers which interface with machines through a Standard Mechanical Interface (SMIF). The wafers are then laded by a SMIF arm into the processing machine where it is contained within a minienvironment. After processing, the wafers are loaded back into the carrier and taken to the next machine.

Shown in Figure 3.7 is a plan of a semiconductor production area which would be used for VLSI-CMOS or more critical product manufacturing and is designed for use with minienvironments. Typical requirements for the air cleanliness within the area would be similar to the following:

1. An environment where the wafers are fully exposed—ISO 3 (Class 1) or better.
2. An area where wafers are protected in cassettes and enclosed boxes—about ISO 6 (Class 1000).
3. Machine–technicians–engineering chase area—ISO 6 to ISO 7 (Class 1000 to Class 10 000).
4. Adjacent areas outside the cleanroom envelope—standard air conditioning.

In Figure 3.7 the areas where the wafers are exposed are isolated by rigid walls of plastic or glass and provided with a unidirectional air supply which will give ISO 3 (Class 1), or better, conditions. These minienvironments are shown in the darkest shade. The darker grey area represents the area where the production personnel move the wafers which are protected in cassettes and enclosed boxes; this may be ISO 6 (Class 1000). The lighter grey area is the service area where technicians gain access to the services and machines; this may be ISO 6 to 7 (Class 1000 to 10 000).

The particular layout shown in Figure 3.7 was designed for use with the Standard-Mechanical-Interface-Format (SMIF) system (Workman and Kaven, 1987). This concept, supported by the Semiconductor Equipment and Materials Institute, provides a standard entrance portal, thereby allowing a single type of handling equipment to introduce and remove a set of silicon wafers into the process equipment. When the process is complete, people or robots can remove the sealed SMIF pods containing the wafer cassettes from one machine and transfer it to another machine to be loaded by the SMIF arms (see Figure 3.6 (b)). The SMIF equipment is designed to optimize production yields and permit high-volume throughput, but the same layout concept

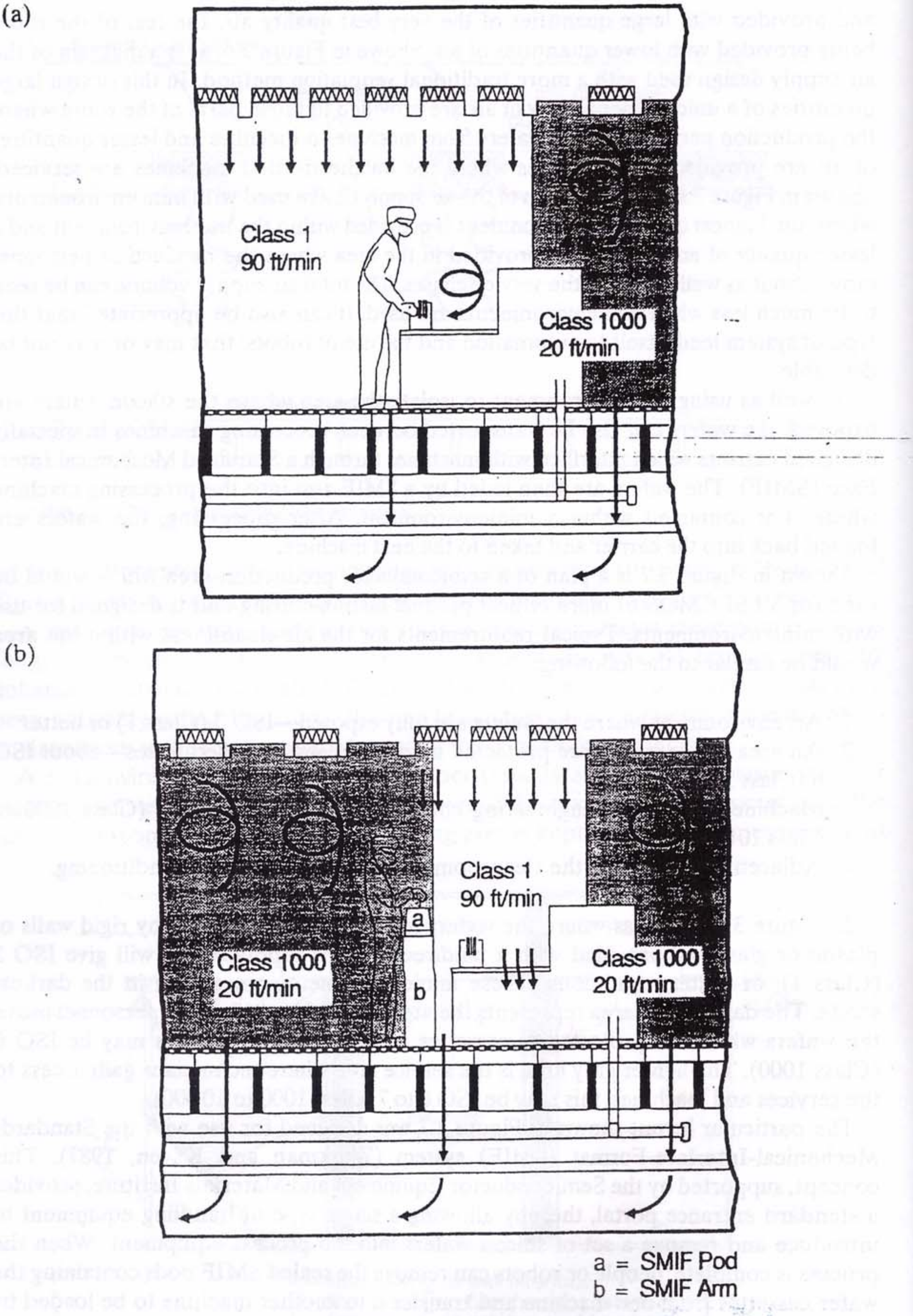

FIGURE 3.6. A comparison of the SMIF isolation and the more traditional approach. (a) Traditional type of ventilation. (b) Minienvironment using SMIF technology.

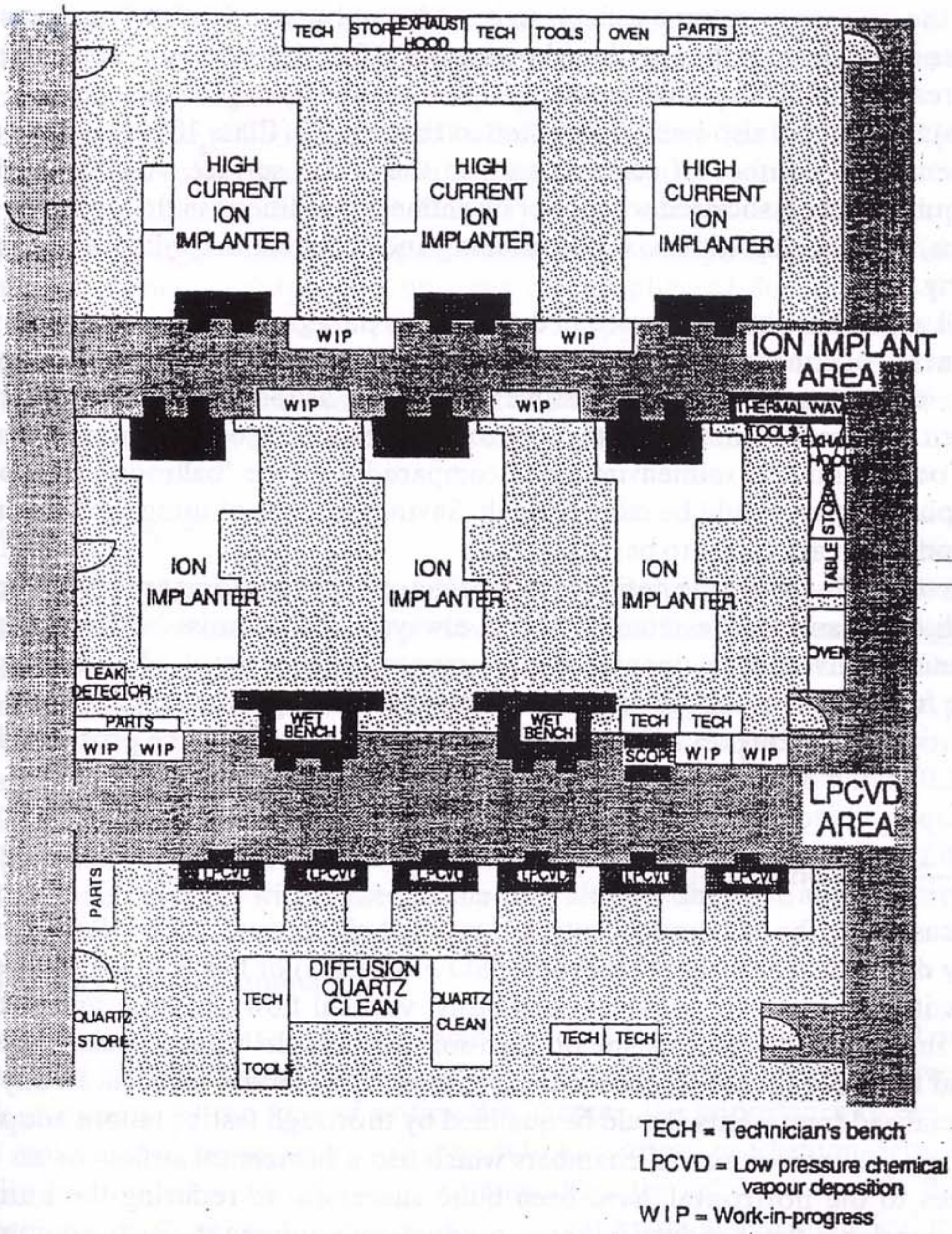

FIGURE 3.7. Wafer fabrication area designed for a SMIF/minienvironment system.

shown in Figure 3.6 (b) can be used with other systems. Other minienvironments, with different methods of accessing the wafers into the production machines, have been developed and as long as these are well designed, particularly with respect to the container for the wafer cassettes and the port which allows the transfer of the wafers into the minienvironment, they will work well.

Airborne conditions and surface particle contamination of the wafers produced in minienvironments are normally better than those achieved in the ballroom or tunnel/service chase cleanrooms. Wafer yields have been reported to have improved; the greater the density and size, the greater the benefit. A reduction in the costs of building a semiconductor fabrication area using minienvironments has been quoted to be less than 10%. However, in terms of the cost of such facilities, this can still be a significant amount of money. More important is the considerable savings to be made on running costs, as the air supply volume is likely to be reduced by about 50%. The cost savings will depend on the conditions thought necessary for the operator movement and service areas. ISO 6 (Class 1000) conditions have been suggested for he operator movement areas, but it has also been demonstrated that ISO 7 (Class 10 000) conditions do not influence the number of contaminants on the wafer surface. A downgrading of other requirements associated with lower cleanliness conditions in the operator movement area, e.g. clothing, gloves, wipes, cleaning and certification, will give a significant cost saving.

As well as the advantages quoted in the previous paragraph, there is also the potential advantage of a more economic start-up of a new cleanroom. Instead of opening up the whole cleanroom at once, it is possible to phase in, as required, the introduction of equipment. The contamination of the semiconductors during equipment installation is likely to be small in the minienvironment compared with the 'ballroom' type of area, where a phased plan would be more difficult. Savings in costs of using such a 'ramp up' of the production are likely to be large.

The factors influencing the design of microelectronic cleanrooms are often in conflict with each other and the resultant facility is always a compromise between cost, perceived need, convenience, individual preferences, highest level of technology and available funding. It is almost never of a single style or type, but of a multiple design configuration; this being an attempt to supply all of the needs of the process with one facility.

Air Flow—Direction

In most cases, for the maximum control of product cleanliness, the air flow should be vertically downward and should meet the ISO 3 (Class 1) or better cleanliness specification as it flows onto the product. Obviously, vertical flow onto the product is not possible in an evaporator, reactor or diffusion furnace. In those special cases, supplemental filter-blower units, scavenging air vanes, etc., should be tried. In any event, such specialized treatments should be qualified by thorough testing before adoption.

Some special environmental chambers which use a horizontal airflow or an airflow 45 degrees to the horizontal, have been quite successful in reducing the number of particles reaching the product in some production equipment. Such equipment, if available, may be worth investigating.

ULPA filters 99.9995% efficient when tested at manufacture against 0.1 micrometre-sized particles, and tested and certified at installation with a suitable particle challenge, must be used for ISO 3 (Class 1), or better. To permit ultimate flexibility and minimal record keeping of what kind of filter goes where, and because the differential cost between 99.00% and 99.9995% efficient filters is small for the convenience given, it is recommended that the same higher grade type of filters be used throughout the cleanroom. These can be used without any protective or ornamental screen or 'eggcrate' on the down-stream side of the filter. Internal or inlet dampers should be used to regulate air quantity.

The air should exit the room through perforated panel floors with integral air dampers to regulate the air flow. The floor covering should be made from a conductive, high pressure laminate and the system must be grounded (see Chapter 9). ISO Classes 3–5 (Classes 1–100) areas will require 100% coverage by perforated panels, while ISO

Classes 6 and 7 (Classes 1000 and 10 000) require only 50% or less coverage by perforated panels. Some solid panels will be required for use under equipment which has a closed base (it is easier to cut utility piping holes in solid panels).

An alternative, acceptable solution to the design of air flow for ISO 6 and 7 (Classes 1000 and 10 000) is to use classical turbulent ventilation, the return air vents being in walls or islands and close to floor level. This may or may not pose a problem for ducting the return air back to the recirculating air systems, depending on over-all design. With this system one does, perhaps, give up some of the inherent flexibility of the total vertical flow, through-the-floor return system. Upgrading of such random-flow (turbulent) systems to ISO Classes 3–5 (Classes 1–100) or above would involve a prolonged shut-down and complete revision of the entire area; with the vertical unidirectional flow it is more easily and quickly accomplished.

Air Flow—Quantity

ISO Classes 3–5 (Classes 1–100) should be designed to between 0.3 and 0.5 m/s depending on the flow through the respective clean zones. It is important to observe the effect of air flow through critical production-equipment interface-locations. There are occasions when a reduction of airflow can result in a significant lowering of the particle level or reduction in the machine interference (cooling). Classes ISO 6, ISO 7 and ISO 8 (Classes 1000, 10 000 and 100 000) should be designed for 50, 30 and 18 ft/min (0.25, 0.15 and 0.09 m/s) flow through them. Primary control is achieved by providing equivalent filter/solid panels in the floor. After installation and start-up, adjustment of filter and perforated-panel dampers will be used to fine-tune air flow direction and quantity.

Airborne Molecular Contamination

It has been demonstrated that airborne molecular contamination has an effect on semiconductor yield. As the size of device geometry reduces, this is likely to be viewed with increasing concern. At the time of writing this chapter, the importance of the various types of molecular contamination, with respect to the various production steps, has not been fully determined and hence the requirements for the different areas in the semiconductor facility is not clear. Another problem that exists is that analytical methods for measuring airborne molecular contamination are insufficiently accurate, or available, to give users or designers a clear insight into the problems and solutions.

A standard for molecular contamination has been produced by SEMI and is known as SEMI Standard F21-95. This considers molecular contamination in four groups. These are A(cids), B(ases), C(ondensables) and D(opants). The classification is given an 'M' nomenclature followed by the type of molecular contamination being considered (A, B, C or D) and then the concentration in parts per trillion (molar). Thus, a classification of MA-100 would set a limit of 100 ppt of gaseous acid.

The most common airborne molecular contamination in the cleanroom is hydrocarbon in nature but can also include acids, bases and other process chemicals. The molecular contamination found within a cleanroom will come from:

- The fabric used in the construction of the cleanroom;
- The machinery within the room;

- Uncontrolled chemical releases;
- The people within the room;
- The outside make-up air;
- The air conditioning system.

The architectural and structural components of the cleanroom can be a major contributor to airborne molecular contamination. Many of the conventionally-used components and materials will be a source, including items such as gels, caulks, sealing compounds and common protective coatings such as primers and paints. Some plastic pipes and ducts can outgas and will therefore be a source. Flooring can be of special concern. The area of floor will be large and, depending on the materials used, could outgas considerable amounts of airborne molecular contamination. It will therefore be prudent to minimise molecular diffusion from the building fabric by use of materials that have a minimum of out-gassing. Air extract systems should be designed to effectively control the dispersion of contaminants from machinery, as well as minimise the dispersion of process chemicals both under normal working conditions and where an accidental spillage may occur.

As molecular contamination is in a gas phase, it will be recirculated round the air conditioning system. Air filters packed with activated carbon, or activated alumina, will reduce the levels of contamination. Activated filters are not very efficient, being about 99%. This efficiency is much less than that available from airborne particles filters but appears to be adequate for the present requirements. As knowledge is gained on this topic and more effective methods are devised to measure molecular contamination, then it is likely that more effective removal methods will be available in the future.

At the time of writing, the control of airborne molecular contamination is not an established measure for all new semiconductor facilities. However, where it has been decided that control of molecular contamination is not necessary, it would be prudent to include the flexibility and space to include control measures in the future. If mini-environments are used in the facility design, then control of molecular contaminants can be built into their air handling units. This is a more economic solution than controlling the recirculated and make-up air of the whole facility.

Filter suspension system

Regardless of whether a pressurized plenum system, or a ducted filter system is used, the incorporation of filters, solid panels and lights into a stable, non-leaking, unified system is dependent on the integrity of the sealing system. The one which has been found to be the most reliable has been the fluid- or gel-seal system of which there are several varieties. Properly installed and tested, they should not be a source of trouble. The suspension system should contain the fluid (or gel) while the filter has the knife-edge which mates into the fluid (or gel). (See Figure 8.18 in Chapter 8.)

Recirculation Air Moving System

Shown in Figure 3.8 is a drawing of a typical air movement system used to recirculate the air passing through the floor grilles to the high efficiency air filters. This system should have the following characteristics and requirements:

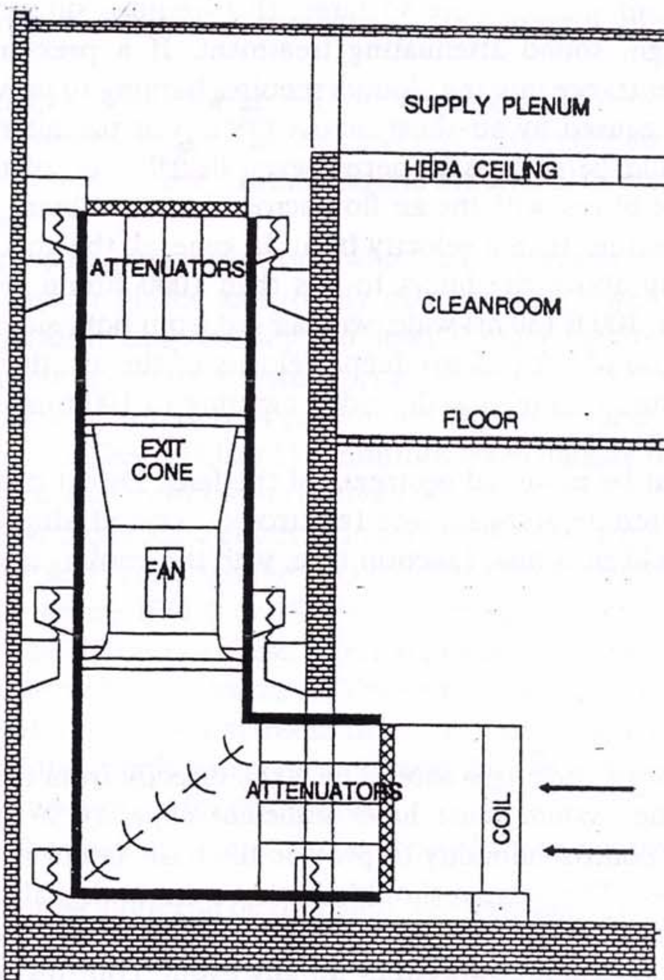

FIGURE 3.8. Recirculation air system.

1. Fan type: This should be an axial vane type with an optimum transition type of attenuator on both the inlet cone and exit. The motor should be external to the air stream.
2. Structural support for fans should be out-board of the wafer fabrication area with separate foundations, detuned column support and maximum isolator design, so that transmitted (structural) vibrations are kept to a minimum and not within the 0–200 Hz range.
3. The fan chamber should be lined with perforated stainless steel (type 304) sound attenuators stuffed with high density polypropylene-bagged fibreglass batting. This attentuation should be carried past the fan chamber so that at least one 90 degree bend of the air path on the upstream and downstream side is so treated.
4. The fan–coil–ductwork–perforated-floor–filter–prefilter system should be designed to produce a system pressure drop of not more than 2.0 inches pressure (500 Pa) with clean filters fitted.
5. The fans and motors should be remote from the wafer fabrication area so that EMI from the motors does not interfere with the sensitive fabrication process and inspection equipment. The allowable proximity varies directly as the square of the horsepower.

6. Because all of the air passages are so large, they require turning vanes and, depending on design, sound attenuating treatment. If a pressurized plenum system is used, the entrance into the plenum requires baffling to prevent backflow through the filters, caused by air-shear across the top of the filters. The depth of the plenum should be such as to permit even distribution of the air to the upstream side of the filters, with the air flow across the filters being in the nature of a pressure front rather than a velocity front. In general, the goal is to hold air velocity horizontally above the filters to less than 1000 ft/min (5 m/s). As an example, for a room 100 ft (30 m) wide, with air fed from both sides, the plenum should be a minimum of 5 ft (1.5 m) deep. Velocity of the air, then, would be a maximum of 1000 ft/min (5 m/s) at the sides, tapering to 100 ft/min (0.5 m/s), in the centre.
7. Cooling coils should be mounted upstream of the fans. Direct digital control is preferred with the temperature sensors (electronic) located after the fans. The cooling system should be a dual-function type, with the cooling coils controlling only sensible heat.

Fresh Air System

Fresh air for the wafer fabrication area should be taken directly from the outside, and conditioned for use. The system must have sufficient capacity to purify (filters, absorbers, washers) and control humidity to provide the basic latent heat control for the entire fabrication area. This system should also have direct digital control, which may be by either a face-and-bypass system, treating only a fraction of the air supplied by the fresh air system, or a full-flow system. In any event, controls measuring the relative humidity of the cleanroom should be used by the microcomputer to call for moisture (usually electrically generated steam) or lower temperature (refrigerated or absorption drying) to adjust the total latent heat. The fresh air requires to be distributed evenly to the intake of all the recirculating air fans. One of the easiest means to accomplish this is to run a distribution duct the full length under the floor so that the fresh air can flow evenly toward the recirculating fans mixing with the recirculating air as it goes. This is possible, of course, only if enough space exists under the floor to do this.

The control system which provides the finest control is that which uses heat to make the final adjustment of both temperature and relative humidity rather than cooling because the incremental change is easier to control.

For ISO 5 (Class 100) areas or better, it is imperative that the final filter should be at least an HEPA filter (99.995% efficiency). It has been shown that if this is not done, the majority of particles smaller than 0.5 μm diameter in the cleanroom, come directly from the outside through the fresh air system.

Air Return

The most versatile and easily controlled air return system is through-the-floor. If enough space can be provided under the raised floor, it is ideal to install all of the utility distribution there, bringing it to the process equipment from below.

The advantages to be gained from through-the-floor air return are:

1. It is difficult to block the air return. With side-wall return the production equipment and furniture almost always severely restrict the air flow.
2. It is easy to segregate and totally isolate the critical operations, but still have them accessible.
3. The most vulnerable operations, where silicon wafers are fully exposed, are best behind glass or plastic and totally protected by a well controlled flow of unidirectional air from the ceiling and down through the floor.
4. The simplest automation system presently available (SMIF) is readily adaptable and available on a variety of production equipment and offers total protection of wafers in ISO Class 3 (Class 1) conditions when outside the production chambers.
5. With the newest, most cost-effective layouts, the side-wall return is very difficult to use. It would require either a double-wall air return plenum between the ISO Class 3 (Class 1) zone and the ISO 6 or ISO 7 (Classes 1000/10 000) zones, or the use of the entire ISO 6 or ISO 7 (Classes 1000/10 000) zones as an air return plenum. The second of these alternatives is not attractive because of the non-controllable air flow in that zone. The same problems are also inherent with utility supply and return. All systems that one can conceive are awkward in some measure if the supply and return of gases, liquids and electrical systems have not the under-floor space for distribution.
6. Through-the-floor air return can be achieved in one of two ways:
   (a) The under-floor can be designed as a basement giving full structural support to the perforated floor.
   While it is expensive, it is not generally as costly as adding space laterally. In addition, many of the utility supply and disposal systems may be housed in this space. Should this alternative be adopted, consideration should be given to providing a good clearance—say 18 ft (5.5 m) between basement floor and the fabrication floor. In this amount of space there is room to do all of the desirable things such as relegation of most of the process equipment maintenance and supply functions to that area. Also, most of the maintenance work involved in adding or moving process equipment may be carried out without affecting production,
   (b) Install a raised access floor on top of the building floor.
   This is a satisfactory solution provided enough thought is given to the additional usages planned for the under-floor space. It should be deep enough to accommodate the air flow without significant increase in air resistance (it should be no greater than the pressure drop through the floor), while at the same time allowing placement of necessary process equipment support items such as filters, regulators, transformers, and the required utility supply and distribution system.
   The raised floor system needs to be of a heavy-duty design (350 lb/ft^2, i.e. 16.8 kN/m^2 minimum) with

   - full stringer support
   - four bolts to the pedestal
   - locking levelling nuts

- alternate row Z-bar bracing both ways
- either epoxy-cemented or bolted pedestal attachment to the floor.

The concrete floor under the raised floor should be coated, after pedestals are installed, to provide acid-resistant, water-proof protection to the concrete. In addition, sensing systems must be installed to detect and provide an alarm when any liquid leaks occur.

The total raised floor system must not create any amplification of the basic floor and structure vibration. Indeed, installed correctly, it should dampen the basic vibration significantly, since the structure being tied to the floor converts it from a vibrating membrane to a box-beam.

Fire Protection

Because of the use of solvents, gases, and other flammable materials which are often used at the high temperatures and pressures inherent in wafer fabrication facilities, the usual fire risk category is 'extra-hazard'. This requires a maximum-control sprinkler system (minimum spacing), both above and below filters, and also below the floor if flammable gases or liquids are piped through that zone. The alternative is a carbon dioxide or 'Halon' system, generally considered too expensive for large non-confined areas. These are usually reserved for under-the-floor high risk areas.

Sensing of fires requires line-of-sight coverage of the entire wafer fabrication area with both infra-red and ultra-violet detectors, and the under-floor area as well. The control system must be set to permit detection of, and alarm for, both smoke and fire with a time delay to make certain the emergency is not a false alarm, prior to triggering action, The delay permits evacuation of personnel from the affected zone before the suppressive action is taken. Also of significant importance is the fact that any interruption in production is extremely costly. A deluge of water on operating equipment, its microprocessor controls and electronic sensors; the shock of super-cold carbon dioxide impinging on heated process equipment; even the instantaneous shut-down of high thermal-inertia equipment like diffusion furnaces, CVD reactors, etc. can cause enormous damage.

Walls

Those used in a wafer fabrication are basically divided into two types:

1. *External walls*. These range from vault-type construction to standard architectural structures. Either may be appropriate depending on the type of product to be manufactured. Included in this category are those which are used for security purposes and provide the ultimate in radio frequency shielding (Figure 3.9). They provide up to 100 dB attenuation of internally transmitted signals or inadvertent transmissions over telephone lines, power lines, plumbing systems, extract systems, and radios, etc. Also to be considered is protection of computer controlled equipment against electromagnetic noise (Figure 3.10). The internal finish of peripheral walls should be a baked enamel or porcelain surface on metal. Metal panels must be sealed at all joints.
2. *Internal walls*. In the wafer fabrication area it has been found desirable, wherever

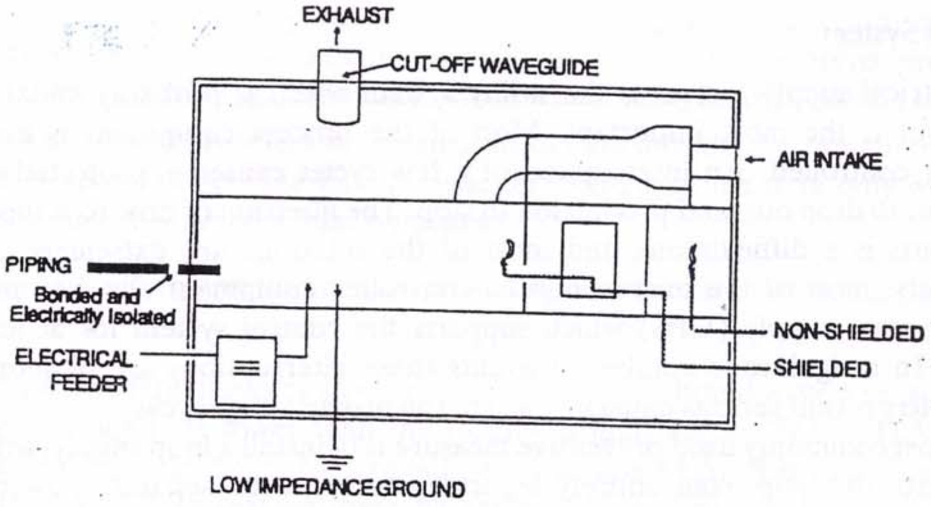

FIGURE 3.9. RF shielding.

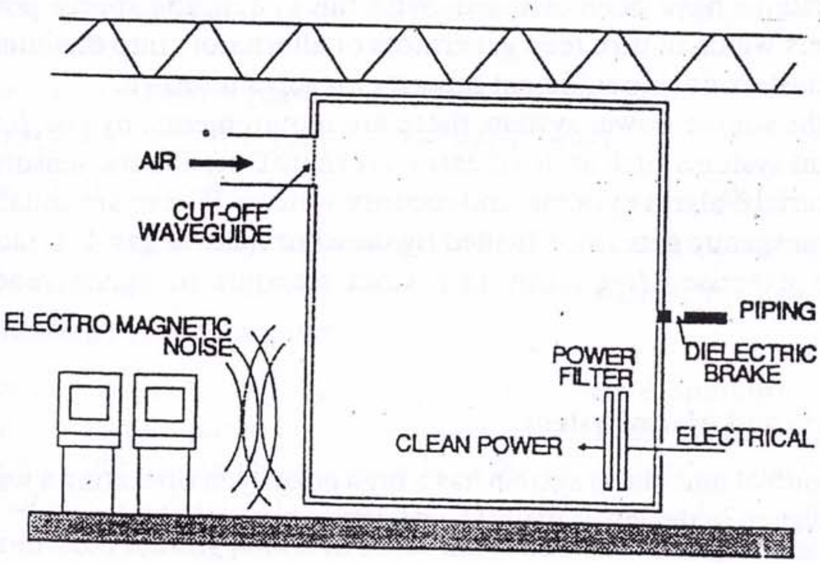

FIGURE 3.10. EMF shielding.

possible, to provide 'store front' walls composed of anodized aluminium structural members with glass or polycarbonate panels (which have been given a hardening treatment to reduce surface abrasion). The glass or polycarbonate panels may be replaced by metal panels where equipment penetrations are necessary. This type of structure permits see-through to all operating and maintenance areas and stimulates the required continual cleaning necessary for proper operation.

Lighting

In the wafer fabrication area lighting is best handled by fluorescent tubes mounted on the filter face as an integral part of the filter. Ballasts must be mounted remotely, out of the cleanroom. To preclude problems of deciding where the yellow and white lights should be, and to allow for future revision of layout, it is best to make all of the lights yellow. A guarantee should be required from the supplier stating that the yellow tubes meet the requirements for semiconductor manufacturing.

Electrical System

The electrical supply system is the utility system which is probably under the least control yet is the most important. Most of the process equipment is now microcomputer controlled. An interruption of a few cycles causes unprotected computer equipment to drop out, and production to stop. The question of how to protect against such events is a difficult one and most of the solutions are extremely expensive. Fortunately, most of the microcomputer-controlled equipment also has an uninterruptible power supply (UPS) which supports the control system for at least a few minutes. In a significant number of events these interruptions are of short enough duration to prevent serious damage, even to the product-in-process.

The most commonly used preventive measure is to install a loop supply, with feeders coming into the loop from entirely separate sources; even separate power plants if possible. The effectiveness of this is problematic, since the 'Grid-System' ties all of the sources together. Some have felt so strongly about the problem of power interruption that huge UPS systems have been installed. With this system the source power is fed into battery clusters which in turn feed generators or alternators into the internal loop, with the battery clusters having sufficient capacity for soft shutdown.

Regardless of the source power system, there are requirements, by law, for back-up power to important systems such as: toxic extract (exhaust) scrubbers, sensors for toxic or hazardous materials, alarm systems, and security systems. These are usually accommodated by an emergency generator fuelled by diesel or natural gas. It is most important that they be exercised frequently to a strict schedule to assure readiness for emergency use.

Monitoring Control and Alarm System

The monitoring control and alarm system has a high priority in operating a wafer fab so it has great significance in design as well. The designer must consider:

- purity and physical condition of liquids, process gases and environmental air
- safety of personnel, plant and process equipment
- product yields and quality
- community relations with regard to effluent, toxicity or odours
- governmental agencies' requirements for control, measurement and reporting
- facility and utility system's condition and operating characteristics security.

It is obvious that no one system will do all of those things at once. The design of that system could be as complex as the devices being manufactured, or more so,

To make sure the system does not become excessively complicated, the following steps should be considered:

- Develop systems as simple and direct as possible to take care of one type of function (preferably microprocessor controlled).
- Use the same system architecture and components (such as sensors, microprocessors, output signals, etc.) so far as is possible for each system.

- Use a simple multiplexer function to tie them all together in a central computer system which will deal with alarm, display, recording, trend analysis, preventive maintenance scheduling, mean time before failure analysis, forecasting, etc.
- Do not provide for resolution and analysis of data outside the computer system. It will never be done. Likewise, provide for printing of the data only when it is necessary for mailing or similar purposes.

The following alarm and control systems should be considered as the minimum required:

1. Toxic gas and liquid sensing in room air. The sensors should have a sensitivity an order of magnitude lower than the threshold limit value (TLV). TLV is that concentration judged safe for normal persons exposed for 8 hours. The sensors should process the signal real-time. No sensitized tape systems should be used. An alarm signal should:
   - Provide unmistakable, loud audible alarm in the facility as well as security headquarters
   - Provide visual alarm (flashing light)
   - Notify safety; security; facilities, fire department
   - Record all particulars on the facility's computer data bank
   - Shut off automatically the toxic gases and liquids at their storage area
   - Perform other automatic corrective functions such as turning on water sprays on leaking pyrophoric gases.
2. Cleanroom air monitoring for temperature, relative humidity, acid fumes, and solvent fumes is required in relatively few places in the cleanroom. Particle monitoring should be done very frequently in the air stream approaching the product, as close as it is practical. The average wafer fabrication area should have several hundred fixed sensing points to cover the product at its most critical stages.

   Very careful advance planning is needed to decide

   - what and when data are to be taken,
   - where and how they should be stored and for how long, and the reporting format and frequency.

   The computer should be programmed to provide a view of current conditions, a synopsis of recent data (especially excursions or failures) and a limit placed on how long data are to be stored before automatic erasure.
3. Gas impurity analyses from the continuous gas monitor system. These should analyse plant gases (including clean dry air), stored liquid gas sources, or cylinder gases. All may be fed into the computer and analysed by the same method as air monitoring data, i.e. immediate notification of excursions out of specifications or failures: on call current conditions; synopses of historical data; cut-off point for erasure.
4. Automated measurements of toxic or other specified harmful content of extracts (exhausts) and liquid wastes being discharged from the plant may be required by law. Such data collection, analysis, reporting, storage, etc., are usually specified

by the appropriate authorities. These may be fed to be processed, stored, and reported by the computer. The difference from the previously described systems is that legal requirements will dictate the length of retention of records and whether hard copy is required.

5. Deionized water has higher standards than it had very few years ago. Where once 18 megohms was considered the ultimate standard of water purity, now parts per trillion of iron, silica, hydrocarbons and chlorine are known to be yield-killers and their effect on resistivity of water is minuscule. Bacteria can have a profound effect on the quality of epitaxial layers, even their remains can reduce yields. These and other problems are discussed in Chapter 11.
   Tighter specifications for deionized water are required and more stringent manufacturing controls are required. Unfortunately, to date, some of these requirements cannot be assessed by in-line automatic equipment but must be analysed in the laboratory. As engineering advances, equipment will become available.
6. Fire detection system. This will be as detailed previously.
7. Security system. This system will depend on the type of product. In all cases, however, it is essential to couple the major monitoring, control and alarm systems into security headquarters. The purpose is to permit them to make an informed response to any emergency and communication with responsible parties.

Remainder of System

The remaining systems required for a wafer fabrication area deserve much more space than will be given here. Two out of three of the systems are treated in depth elsewhere in the book, i.e.

1. Deionized water generation and distribution, Chapter 11.

2. Gases, storage and distribution, Chapter 12.

3. Liquid chemicals supply, storage and distribution.

In the automated or semi-automated factory of modern design, all possible fluids are piped to the point of use and the spent fluid piped off for recovery or disposal. Since most of these fluids are hazardous to people, and most are as pure as it is possible to produce and determine by test, it makes good sense to do all of the handling, transporting, use and disposal in a closed system.

There are numerous firms, including the principal suppliers of the chemicals, whose speciality is the design, supply, installation and operation of such systems. Because the systems, chemicals and piping materials are in a constant state of development it is best to let those closest to the problem and solutions do the design for you.

4. Extract (exhaust) systems.
This is a common mechanical engineering design problem with uncommon requirements.

Generally speaking, the solvent and heat extract (exhaust) systems are straightforward, as long as the toxic gas systems are kept separate, and the solvent levels remain under control. Some of the materials used in the processes are carcinogenic and must be collected in the scrubber effluent and disposed of properly.

The acid extract (exhaust) system is also comparatively easy to design except for NOx which is very difficult to remove from the gas stream and HF where the scrubber liquid effluent must be collected and disposed of as a toxic waste material. Great care must be taken to prevent scrubber liquid effluent from the toxic gas systems mixing with the acid gas systems or the toxic gas will be regenerated. Arsine, diborane, stibine, phosphene, etc. can never be safely ignored. Toxic extracts (exhausts) are always handled one system to one system; they are therefore small. The extract (exhaust) should be passed through a high temperature oxidizing unit, or a strongly oxidizing liquid reactor. It should then pass into a high efficiency water scrubber and then to atmosphere through an externally mounted centrifugal fan. The liquid effluent of the reactor and the scrubber must be disposed of as a toxic material.

Some encouraging results have been obtained recently by use of pelletized-bed absorber-reactors through which the toxic extract (exhaust) is passed. The effluent is composed of carbon dioxide and water vapour. When instrumentation is reliable enough to provide confidence in prediction of break-through (escape of toxic gas), such devices will be a welcome addition.

5. Cooling water systems.

There are enormous quantities of cooling water required for a wafer fab.

At least four types are required:

- Chilled water—normal, treated water (no chromates).
- Tower water 85°F (29°C) maximum) used in large quantities for process equipment cooling.
- 58°F (14°C) chilled water for cleanroom temperature control coils (dry).
- High resistivity cooling water for process equipment, especially that heated by RF induction. The temperatures and pressures vary from equipment to equipment so the size-requirement of these systems tends to be rather small.

Some suggestions may aid the design of cooling water systems:

1. Some production equipment cannot stand high internal cooling water pressure. Should the system differential pressure exceed the limiting pressure, install a properly sized pump and control valve between the equipment water outlet and the return line of the cooling system. This will permit the desired internal pressure, while allowing the differential pressure to do its work.
2. The 58°F (14°C) water for the dry coil cooling may be produced by using a recirculating (through the coils) system. This will require just enough of the 58°F (14°C) water continuously bled back to the return of the chilled water system to permit (40°F (4°C) chilled water to enter the loop to keep the temperatures constant. The load will vary slowly so that it is easy to hold the loop constant within 1°F (0.5°C). To install a water-to-water heat exchanger to handle this capacity would be difficult because of the large sizes required.
3. In northern climates it is often possible to use ground or surface water for cooling purposes. One factory in Germany was able to avoid spending over one million US dollars for chillers and saved a half million dollars a year in electrical power

reduction by using available ground water to replace all chilled water (except that used for dehumidification). It is important to note that risk of contamination of the source water is eliminated by installing a heat exchanger between it and the water used for cooling.

6. The material used for piping systems in wafer fabrication areas is discussed in Chapter 13 of this book.

CONCLUDING REMARKS

This chapter has presented the latest in design concepts for a wafer fabrication cleanroom and other systems required to make a successful facility. Other concepts have been alluded to, but, for lack of space, not detailed. There are many concepts and many variations of each. Clear thinking and sound judgement are the only way to choose between them.

It is quite true that enough is now known about control of contamination in environments that any conceivable requirement for such can be met, providing that instrumentation and methodology for test and measurement exist.

ACKNOWLEDGEMENT

Figure 3.6 is reproduced by permission of Asyst Technologies.

REFERENCE

Workman, W. and Kavan, L. (1987). 'VTC's submicron CMOS factory', *Microcontamination*, 5(10), 23–26.