Space: the Ideal Place to Manufacture Microchips

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ABSTRACT

The electronics industry is dependent on the production of microchips; high value, low mass, devices well suited to production in orbit. Microchip fabrication procedures inherently involve what are, by earth standards, extreme cleanliness of facilities, processes that intrinsically require good vacuums, and substantial control over contaminates. In addition, on earth the exposure of materials to the atmosphere between processes steps creates complications that require additional procedures to remove thin oxide layers. The controlled environment, and common vacuum of extratressestrial facilities helps control the cleanliness, allows for simpler processing equipment, diminishes the contamination problem, and reduces the oxidation of materials between process steps. However, some complications are introduced by steps that currently work best with gravity. This paper surveys the advantages and problems for extraterrestrial processing of microchips.

INTRODUCTION

The long term viability of space manufacturing is dependent on finding products for which extraterrestrial facilities offer sufficient net advantage over earth based production to justify the large start up costs of moving into that new environment. For the near term this requires merchandise that has a high value per unite mass, consumes little in the way of resources that must be shipped from earth, and has a net processing advantage over planetary based fabrication facilities. Most material science related orbital considerations have concentrated on the microgravity environment of space and its ability to improve either the current processes (eg. the growth of higher quality crystals, or superior separation of materials) or create new ones (near perfect spheres). However, several earth based industries require excellent vacuums as an inherent part of their production procedures. This papers examines the advantages and disadvantages of space based manufacturing for one such substantial user of vacuum processing, the microchip manufacturing industry (know as semiconductor fabrication in the field). Research into the viability of ultra high vacuum processes in orbit that is currently planned

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both for the Japanese modules on the Freedom space station, and with the "Wakeshield" project, will not be considered. However, those results would clearly expand some of the considerations expressed here.

BACKGROUND

The electronics industry is growing rapidly and will soon be the largest manufacturing business on the planet. The technological force driving this advance is the production of ever more complex integrated circuits or microchips. Furthermore, the raw value relative to their mass of such chips is very high, about \$1 million per pound (\$2.2 million/Kg.) for the newest large microprocessor chips without their packages. For example Intel’s 80486 chips cost about \$400 each currently (in 1990), but the actual weight of the integrated circuit chip itself (exclusive of the packaging holding it) is only about 0.00008 pounds (0.0002 kg). That value/mass ratio is much higher than even current launch costs (about \$4000 per pound or \$9000 per Kg.), making such devices a definite candidate for space processing. The industry currently uses this high value/mass ration to manufacturing the integrated circuit itself in one location (eg California) then shipping it half way around the world for the final packaging (eg Singapore).

Now, consider the basic processes of semiconductor fabrication as currently practised on earth[1]. Starting material is a flat thin disk of silicon, called a wafer or a substrate, typically 6-8 inches (150-200 mm) in diameter by 0.02-0.024 inches (0.5-0.6 mm) thick. After intensive cleaning, a thin layer (typically 0.00004 in, or one micrometer - about 1/75th of a human hair’s diameter) of silicon oxide (glass) is grown on the surface by heating the wafers in furnaces in the presence of steam or oxygen. Then, in what is called photolithographic definition, a thin film of an organic light sensitive material called photoresist is laid down, and an image of the desired pattern optically projected onto the surface (see Figure 1). When developed the resist is left in the unexposed area, while the exposed region has the resist removed from it. The wafer is subject to an environment which then etches away the glass film in the areas where the resist was exposed (see Figure 2). Subsequent processing is used to alter the silicon by subjecting it to bombardment by other atoms such as Boron or Arsenic (called ion implantation) to adjust the resistance of the material (technically known as doping to adjust the conductivity type). Additional films of silicon, metals (typically of aluminum alloy) or insulators such as glass or silicon nitride are deposited, photolithographically patterned, and etched to produce the desired structures. The important points to note the combination of steps here: deposition or growth of a layer, photolithographic definition, and etching is repeated many times with many layers and patterns to make the final circuit. When done the large wafer is cut up to many small chips, typically 0.4 by 0.4 inch square (1 by 1 cm square), making the final chip that is then packaged.

From the point of view of understanding the advantages of orbital manufacturing it is important to note the major problems of semiconductor fabrication on earth. Making microchips is unlike most common production processes where much of what is manufactured operates properly, and only a small percentage should fail. The main point is that most fabricated microchips do not work, and only by testing after production are the operating devices known. The percentage of the chips that properly function, called the yield, varies from less than 1% when a product is initiated to about 50-80% for a mature, nearly obsolete device. Once the electrical circuit design is correct the biggest battle in fabrication is to increase those yields, and to simplify the process if possible. That determines the level of profit, the ability to deliver the product, and ultimately the price to the user.

ADVANTAGES OF ORBITAL MICROCHIP FABRICATION

The first advantage of the extraterrestrial is to note that more than anything else chip yield is controlled by the presences of dirt (particles) in processing and contamination of the chip with unwanted materials. For cleanliness requirements modern chip fabrication "clean rooms" must filter their air to contain per cubic foot less than 1 particle of a diameter smaller than 1/250 of a human hair (0.00001 inch or 0.3 micrometers). The rooms are positively pressurized to prevent outside air from leaking into them. Workers in those facilities already wear clothing that looks like space suits, preventing any contamination of the processing environment by their skin or hair. These clean suits have helmets that filters the air they exhale before allowing it to enter the room. Otherwise the very "dirty" human body products of hair, particulates and organic compounds would ruin any microchip. While gloves are worn for the hands, wafers are never even touched with these, but when single wafers must be held, a small set of tweezers (or more commonly now a vacuum suction pickup device to reduce contact even more). Even so as much as possible modern facilities try to have automated equipment handle the chips, rather than humans, as would be true in space manufacturing. As for contaminants the earthly environment is filled with substances that destroy the chip yields. For example one of the commonest earth substances, salt, contains sodium, an element that kills the operations of transistors. Many other ubiquitous organic and inorganic substances also will destroy the chip yields.

By comparison the vacuum of space is a very clean environment, free from most common contaminants. With an extraterrestrial facility the companies start with a clean slate, and only have to arrange things to prevent contaminates from being introduced to the facility, instead of fighting to remove them in the first place, as on earth. Furthermore, there is now the option of easily doing many operations in the free vacuum of space, something that would be prohibitive on earth. Many air born contaminates (organics, salt in water vapour etc.) are avoided by vacuum handling of the wafers as much as possible. Thus many earth based contamination problems can be reduced or eliminated and chip yields increased.

In addition maintaining this cleanliness on earth is tremendously costly in both energy and consumables. Huge amounts of power are consumed constantly moving the air in such production facilities through filters to remove the contaminants of the outside world. The clean room robes must be specially cleaned at least weekly, both to remove contaminants, and to prevent lint being attached to the outside. Workers typically go through several pairs of gloves per day. Care must be taken that nothing exposed to the wafers seldom touched by bare hands, and extensive cleaning of such items must be done when that does occur. By comparison brief exposure to the vacuum of space, the atomic oxygen in low earth orbit, and the hard ultraviolet from the sun would rapidly clean any equipment or space suits much better than the careful cleaning preparation of their early counterparts. Indeed, storage of materials in vacuum would not only keep them extremely clean and reduce the volume of pressurized room needed for such a production facility.

The second major advantage of space semiconductor fabrication comes from the fact that many of the processes performed on the chips require that a vacuum be obtained before starting. The native vacuum in even low orbit is about one billionth of one percent that of sea level (technically, 10 nanoTorr or 1.3 microPascals of pressure). This is about 5 to 10 times better than the standard operating pressures of most semiconductor processes, technically considered the very high vacuum range on earth. Such procedures are depositing thin films of materials, etching away those most of those films, and bombarding the chips with atoms of specific elements. Thus much of an earth based chip fabrication line consists of complex pumps to create small volumes of vacuum and even the pressure levels generated are relatively high by low earth orbit standards. Indeed, much of the capital costs, operating expenditures and even maintenance efforts of a fabrication line are devoted to keeping those vacuums present, or correcting problems caused by failures to obtain low enough pressures.

Consider now some specific processes in detail. In the case of thin film depositions some common processes involve evaporating the material (metals such as aluminum alloy or other inorganics) via thermal or electron beam heating methods. More commonly now sputtering of the material is done by bombarding surface of a target of the desired material with accelerated argon ions, which knock off the atoms of the material and deposit them onto the wafer surface some distance away. In either case the quality of the deposited film is critically dependent on any oxygen or contaminants present in the chamber that may interact with the depositing atoms or the surface of the wafer while the film is being formed. Etching of thin films are typically done with what are called dry processes these days, due to the superior control over the resulting films obtained from the older wet chemical acid etches. Dry etching all involve good vacuums that are modified for the etching process. Common methods are sputtering (where atoms of argon bombard the film and knock of the surface atoms a few at a time), reactive ion etching (where specific ions react chemically with the film to remove it), and plasma etching (where a cloud of ionized gas reacts chemically with the film). In add cases the presence of small contaminants can significantly affect the uniformity of the etching processes and the quality of the surface left behind. The high quality of space vacuum, combined with the ability to move the chips from one manufacturing step to another without entering an oxygen containing environment, would drastically increase chip yields in these deposition and etching processes. Present day systems involve air locks that move the wafers into the vacuum chambers, then out again to minimize contaminants. Even so it takes considerable time to pump down the chamber to the desired pressure. When exposed to higher pressures any surface absorbs gases on it that are only slowly release to the vacuum (called outgassing). This involves considerable delays in processing of the wafers at each vacuum step just to pump the systems down to the desired pressure. In addition, on earth the exposure of wafers to air when shifting them between operations, plus contamination from other sources in the vacuum systems, grows small layers of materials that require special procedures to remove before the desired structures can be created. Thus it is common to require a small etching step (typically sputtering of the surface) to remove these thin layers before depositing critical films like metal layers that make electrical contacts to other layers. In space where an atmosphere is needed inert gas chambers can be used easily, something expensive to maintain on terra.

Extraterrestrial operations also reduce the supply requirements of semiconductor facilities. The actual mass of the gases and solid targets needed for the thin film depositions are quite small. By comparison with the substrate the mass of the layers being deposited in process are insignificant, totaling only 1% of the original wafer mass in a typical chip. However, on earth significant amounts of expensive clean gas must be run through many pieces of equipment when they are in the standby or preparation condition to prevent contamination from the outside world. In orbit the clean vacuum of space actually offers a superior way of keeping non operating systems uncontaminated. In addition often extra gases, such a hydrogen, must be added to the desired gas flow in a process to lock up any oxygen that seeps into the system from the outside world. Here again removing the surrounding atmosphere reduces the problem.

The advantage of space from the equipment construction point of view is illustrated by the third major vacuum process, ion implantation, where atoms of specific materials are accelerated to a good fraction of the speed of light to force them to penetrate and modify the silicon composition with small quantities of desired impurities. Much of the operating expense of these implanters (small versions of scientific accelerators) is maintaining the vacuum in the chamber. Indeed, for all the deposition, dry etching, and implantation processes the major portion of the equipment mass and expense is the large effort to obtain those vacuums. The utility sections of most semiconductor fabrication facilities are filled with the different pumps that must run day and night maintaining the vacuums. The oils spewed out by the pumps must be carefully removed from the clean areas, and special equipment prevents them from entering the vacuum chambers. Space based equipment would be smaller, simpler, use less power, are cheaper to operate, require less supplies and less susceptible to failures that would ruin the wafers than their earth based equivalents.

Furthermore, there is a safety issue that is advantageous to space processing. The common gases used in many of the etching, or deposition processes read like some witch's brew of World War I gas warfare: Chlorine, Silane, Phosphine, Arsine, Diborane. While relatively small quantities of these needed for the processes, they are often extremely deadly with life treating exposures at levels ranging from 400 parts per million (ppm) for Phosphine to 6 ppm Arsine[2]. Hydrogen, a common carrier gas for many procedures, along with Silane are also fire hazards. As a result, semiconductor fabrication facilities are filled with gas sensors, watching for the slightest leak of these materials. On earth substantial quantities of air are always being vented to the outside world to remove the inevitable small leakages before they build up to dangerous levels.

That exhausted air must be replaced with expensively filtered fresh air. In space, any such leaks are not life threatening because all such gases would be stored and used outside the pressurized areas. The fire threat is eliminated by the lack of oxygen. The small amount of leakage around the facility would rapidly disperse into the vacuum of space. The quantities involved are too small to contaminate the nearly environment to any extent so that other local processes would not be affected.

One future trend favouring space processing is the exposure systems for photolithography. To obtain smaller structures on wafers (reducing the size of transistors, lines etc.) this equipment is being driven toward the use of shorter wavelength illuminations; hard ultraviolet (vacuum UV) and soft x-rays. At these wavelength the atmosphere itself absorbs and interferes with the illumination. Some consider that large synchrotrons will be needed to generate the x-rays sources needed for these facilities. Synchrotrons need large volumes of vacuum lines around which electrons are accelerated to near light speed. Another candidate is using electron beams to write directly the patterns on the resist rather than exposing it with light (generating a very fine image). Again this needs a large vacuum volume for operation.

Analysis instruments are also needing vacuums for operations. For example as the devices become smaller than visible light wavelengths the regular optical microscopes cannot see the images. This requires scanning electron microscopes, again requiring large vacuum chambers. The elimination of the time needed to pump down wafers to a low pressure in such instruments will expand the points in the fabrication process where they will be employed. More complex analysis, such as Augue spectroscopy and Secondary Ion Mass Spectroscopy, all require very good vacuums, and hence in orbit it may be economically possible to regularly monitor the processes with those procedures. Currently they tend to be used to try and understand what has occurred after processes are complete.

Finally, there is the advantage of microgravity itself. This allows relatively delicate handling of the wafers, whereby in many processes they need not be brought into physical contact with the surface of other objects. Such methods as ultrasound levitation of the wafer rather than standard conveyer belts (in pressurized sections) could minimize the damage to the wafer from handling. In vacuum sections the microgravity would require only the slightest physical touch to move the wafers from point to point. In addition, if the original silicon wafers are crystallized in orbit (which may produce better crystal quality), the wafers would not be subjected to the accelerations of a gravity field (or a rocket launch). Especially in the case of larger wafers (8 inch or more) this could reduce the bowing and other distortions from the flat of the wafers when subjected to such stresses. It may allow the wafers to be made thinner, thus increasing the number of wafers obtainable from a given volume of crystal.

The consideration just discussed also ignores the "Wakeshield" effect where the orbital velocity of the space station creates even higher vacuums in the shadow behind a shield facing the direction of motion. Covered better in other papers at this conference, suffice it to say that such shielding would improve these vacuum based advantages, and allows additional processes to be more easily done in orbit.

DISADVANTAGES OF ORBITAL FACILITIES

Orbital facilities are not without their problems for semiconductor processing. First the existence of any nearby air containing systems will lead to leakage and outgassing of contaminants. This can be minimized by having the main production points away from the inhabited areas. However, it must be noted that the levels of these contaminates are low compared to their earthly counterparts. This is more of an issue for ultra high vacuum related processes than the more common needs of chip fabrication.

Secondly there are a number of processes that require gravity for better operations. For example organic films, such as the photoresists, are typically obtained by placing a puddle of the liquid in the center of the wafer, then spinning the wafer rapidly until the centrifugal force cause the fluid to be thrown off the wafer with only a thin film being connected to the surface by surface tension effects. This would require more complex rotating systems to obtain in orbit. The importance of keeping those films uniform for proper photolithographic definition means considerable care must be made in the design of these coaters.

Thirdly, many of the processes requiring organics or wet chemical etchings generate outgassings byproducts that must be carefully controlled in the enclosed environment of a small pressurized volume. This would tend to drive the systems toward totally dry processes that could be done in a vacuum. For example dry deposited photoresists may be desirable. Such changes in the actual materials used have occurred many times before in the history of semiconductor fabrication when new process capabilities become cheaply available.

Fourthly, much wafer handling equipment currently uses air pressure and gravity to hold wafers in place. This would need to be replaced by more mechanical type clasping actions.

Fifthly, as with all orbital facilities, heat rejection does become a problem. However, the simplification of the equipment caused by the vacuum reduces the power requirements, and hence size of the heating problem relative to the earth based facility.

Finally, some processes, especially wet chemical ones, currently use convection currents to keep the reaction uniform. Since convection does not occur in the microgravity environment such mixing must be generated by external driven methods when in orbit.

Actually, the gravity driven processes problems may suggest that one ideal place for microfabrication may actually be the Moon. There an excellent vacuum (by earth standards) is combined with a moderate gravity field. However, contamination problems from the lunar dust may provide some difficulty.

CONCLUSION

As noted in this paper most of the effort expended in an earth based semiconductor fabrication plant is spent in fighting the contamination that the environment and atmosphere present. In spite of some additional problems it is apparent the presence of a cheaply available vacuum makes outer space the natural place to manufacture microchips.

REFERENCES

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[2] R.C. Jaeger, "Introduction to Microelectronic Fabrication", Addison- Wesley, New York (1988), pg. 81.

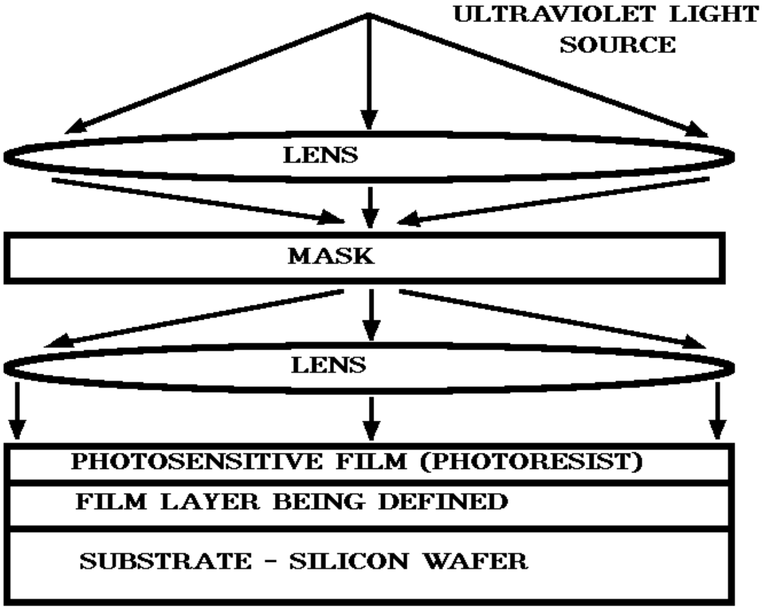

Figure 1: Photolithographic Defination of a layer by exposure of photoresist to the image of a mask.

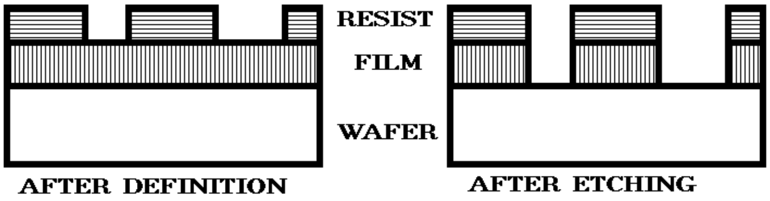

Figure 2: (left) Photoresist after development and (right) film after etching.