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DEPOSITION

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4.6 Deposition



- Deposition has replaced lithography as the most important technology in semiconductor manufacturing.
- Deposition is segmented into CVD, PVD and Epitaxy.
- CVD has replaced PVD as the most important deposition technology.

Lithography has long been regarded as the queen of wafer fabrication in the drive towards submicron geometries. But, in recent years problems with depth-of-focus and materials have limited lithography's ability to drive the industry. Consequently, it has yielded its crown to thin film deposition.

Deposition is the process of laying down a thin film of material on the surface of a silicon wafer. The semiconductor manufacturing process uses many of these films, sandwiched together on a wafer. These layers form the wires and insulators that ultimately interconnect all the transistors of the device being produced. VLSI Research groups these films into four general categories. They are metals, silicides, polysilicon and dielectrics. The actual processes used to deposit these films and how they fit into the overall semiconductor manufacturing process are described in greater detail in Section 1.1 of Volume 1. This section shows how these categories define the market for equipment that deposits the films.

Each film has its own specific requirements that must be met during the manufacturing process. The demands that these criteria put on the deposition equipment is the primary reason for its rise in importance. One of the most important determinants of

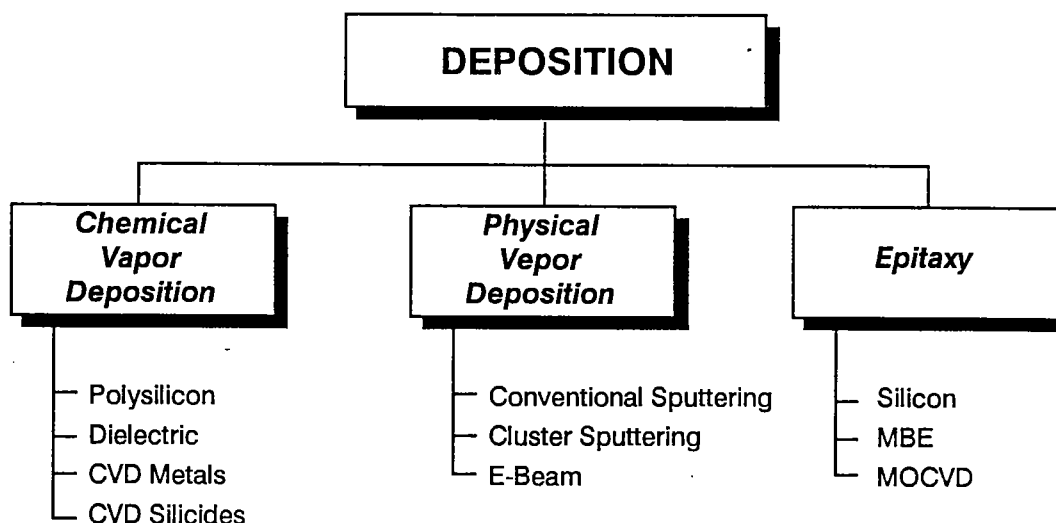
a reactor's capability is its ability to control film thickness. Film thickness is especially critical as device geometries continue to get smaller and films thinner. While there is no standard for measurement, surface planarization is often more important than thickness uniformity. The surface of deposited films must be flat and smooth in order to compensate for the shallow depth of focus of today's lithography systems.

In addition, good step coverage is critical. The deposited films must be continuous, free of key holes and pin holes in order to prevent cracking, the passage of contamination between the layers and the shorting of sandwiched layers. Other important criteria include the ability to maintain pure, stress free films of uniform stoichiometry and the ability to minimize subsurface reflections.

There are essentially three markets for depositing the thin films used in semiconductor manufacturing. They are chemical vapor deposition (CVD); physical vapor deposition (PVD); and epitaxy. These industry segments are depicted in Figure 4.6.0-1.

The growing importance of the deposition market, especially CVD, to semiconductor manufacturing is best illustrated in Figure 4.6.0-2. The figure shows that the deposi-

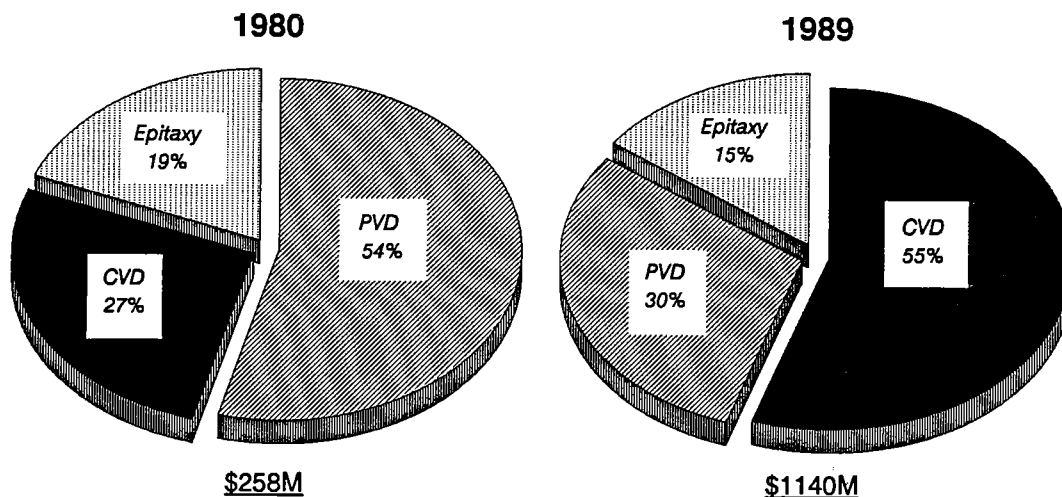
Figure 4.6.0-1



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Figure 4.6.0-2

The Deposition Market



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tion market grew nearly five fold in the eighties. In contrast, microlithography grew four fold. The figure also shows the growth in importance of CVD during the eighties. By the end of the eighties, CVD made up over 50% of the market. Much of this growth was at the expense of PVD, which saw its share of the deposition market decline from over 50% to 30% during the eighties. The epitaxy market maintained its share of the deposition market. Each of these three deposition markets have slightly different characteristics.

Chemical vapor deposition involves the use of chemical decomposition to deposit of thin films. This method is commonly used for depositing silicon-dioxide, polysilicon, phosphosilicate glass (PSG), borophosphosilicate glass (BPSG), silicon nitride, tungsten and many other films. CVD offers an inexpensive way to obtain uniform films with excellent step coverage. It can be used to blanket the wafer with a film, or to selectively deposit in certain areas. Its versatility and low cost have lead to widespread use of CVD systems. CVD systems are one of the most critical pieces of manufacturing equipment on the factory floor. The only limitation to CVD applications is that there must be a known chemical reaction in order to produce the desired film. VLSI Research segments the market for CVD equipment by the type of film since they are so important. These segments are polysilicon, dielectrics, CVD metals and CVD silicides.

PVD involves the physical removal of material from a target via ion bombardment. This is similar to sand blasting. Film material flies away from the target and adheres to the wafer, making the desired film. PVD can be used to deposit nearly any material on any substrate. This is because physical vapor deposition is physical in nature and does not rely on a chemical reaction. Sputtering is the most common PVD method used in semiconductor manufacturing. PVD films do not offer the step coverage of

CVD, nor are they as economical as CVD. Thus, PVD is generally used in only those cases where a viable film chemistry does not exist. Generally, PVD methods are limited to the deposition of aluminum, gold and their alloys.

There is a renaissance, of sorts, occurring in PVD as the industry enters the nineties. The importance of PVD has increased because of the dilemma between lack of step coverage in CVD and lack of depth of focus in lithography. This has lead to the need for tungsten plugs and titanium nitride barriers which, in turn, is making PVD the natural place for true integrated processing to emerge. Several new integrated systems have been introduced for this purpose and equipment vendors are frantically trying to qualify various multi-step processes on them. This trend has lead to a further segmentation of the PVD market to both conventional sputtering systems and these newer multi-process, cluster sputtering systems. The new cluster tools incorporate CVD, PVD and etch into the same system. Their central purpose is to put down aluminum. So they are directly competitive with conventional PVD systems.

Epitaxial deposition is a unique form of CVD. The purpose of epitaxial deposition is to grow additional single crystal silicon above the original wafer surface. This is the reason for the name 'Epitaxy'. It is a Greek term that means 'arranged upon'. The atoms are used literally as building blocks to extend the original crystal lattice. The market is segmented by the various methods used to deposit epitaxial layers. These segments are: Silicon, MBE and MOCVD.

Overall, epitaxy remains a niche market that serves predominately bipolar applications. Despite many promises, silicon epitaxy has only found limited use in MOS because it is an expensive solution to the problems encountered in MOS processing. Manufacturers have found less costly solutions to many

of these problems and so avoid using epitaxial layers in MOS. The use of epi may become more widespread in the nineties as BiCMOS becomes more popular. An epitaxial layer is required for the bipolar portion of BiCMOS. Moreover, the epitaxial layer needed for BiCMOS must be patterned

which will bring epitaxy reactors back into wafer fab. Nevertheless, the market will remain small. The other segments of epi, MBE and MOCVD, will continue to be characterized as niches within a niche. These methods will primarily be used in gallium arsenide applications.

CURRENT INDUSTRY CHARACTERISTICS

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4.6.1 Current Industry Characteristics



- The focus in CVD is on how the films are applied, rather than how the systems are configured.
- True integrated processing systems are emerging out of the PVD market.
- The epitaxy market is experiencing a resurgence because of the increased use of BiCMOS.

Today's advanced processes are dependent on depositing a variety of economical, high quality films. In general, today's MOS processes will use a minimum of six deposition steps. The number of deposition steps is driven by the process and integration scale of the device being manufactured. This trend to increase device integration is creating new demand for deposition equipment. For example, the industry moves from CMOS to high performance BiCMOS will cause mask layers and total process steps to increase by approximately 25%.

These trends can be further illustrated by comparing the film layers of an early bipolar device against the layers of a modern CMOS device. Figure 4.6.1-1 shows the early bipolar device. This device had only four deposition steps in the process: An epitaxial layer, an interlayer dielectric, a metal layer and a passivation layer. Contrast this with Figure 4.6.1-2 which shows a modern 256 Kbit CMOS SRAM. It has over fifteen deposited films. The figure also demonstrates that a much wider variety of films are needed to produce today's devices. Some of the more common films are shown in Table 4.6.1-3. The need for these high quality films has made deposition equipment, especially CVD equipment, increas-

ingly essential to integrated circuit manufacturing.

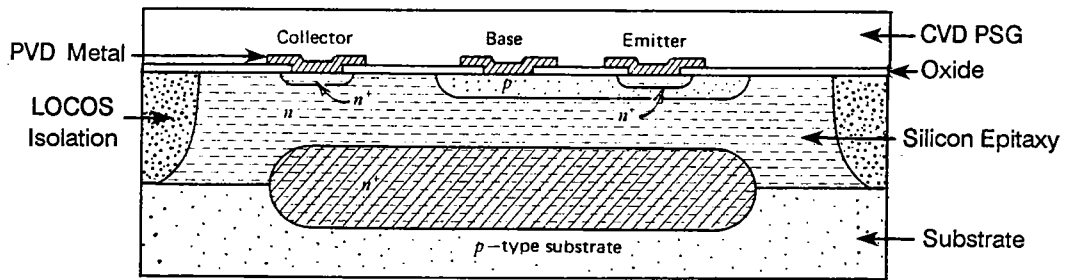
In fact, the demands placed on the equipment by the wide variety of films that must be deposited has caused the industry to begin to focus more on the films than system architecture. This new focus calls into question some of the segmentation that has been employed by the industry since the late seventies, especially in the CVD market. The concern over films has led many suppliers to view the CVD market in terms of ability to deposit certain types of films, rather than system design.

The general feeling is that the design of CVD equipment does not capture the true nature of the competitive environment. To better reflect this fundamental change in industry view, VLSI Research has begun segmenting CVD equipment by the type of films the system is capable of depositing. The CVD market will now be segmented by the following film categories: polysilicon, dielectrics, CVD metals and CVD silicides.

PVD equipment is also at a crossroads. The increased number of deposition steps, along with increases in device complexity, smaller geometries and lack of focus depth

Figure 4.6.1-1

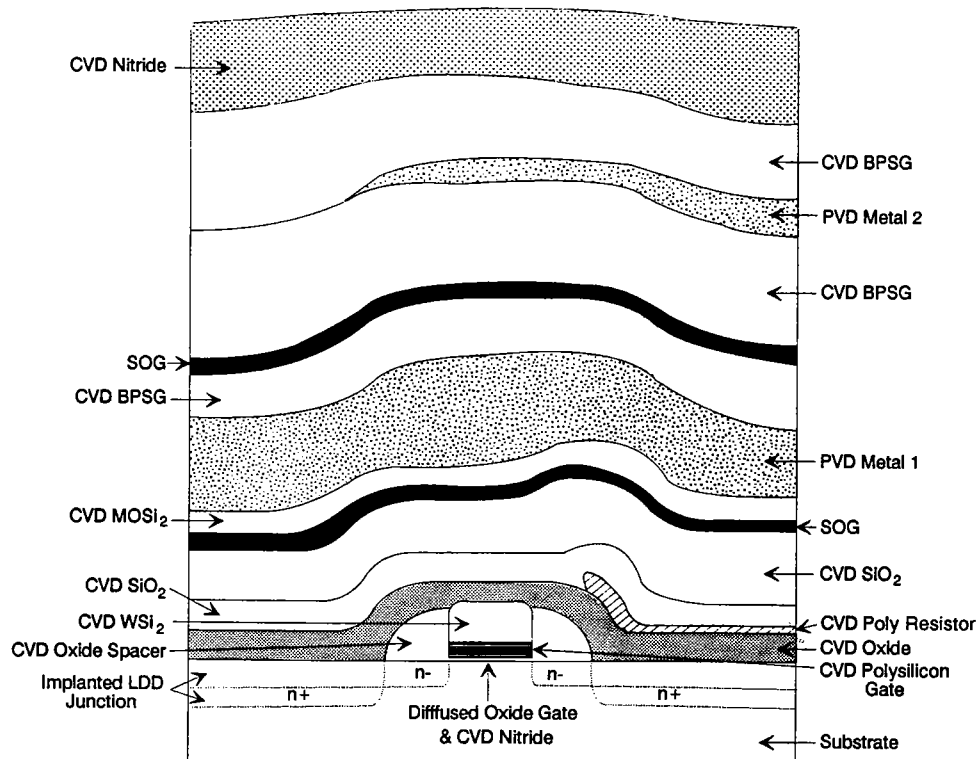
Film Layers of a Simple Bipolar Device



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Figure 4.6.1-2

Film Layers of a 256 KBit CMOS SRAM



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TABLE 4.6.1-3

Commonly Deposited Films

- Polysilicon
- Dielectric
 - Silicon Dioxide
 - Silicon Nitride
 - Phosphosilicate Glass
 - Borophosphosilicate Glass
- Metals
 - Aluminum Alloys
 - Tungsten
 - Titanium Nitride
- Silicides
 - Tungsten
 - Molybdenum
 - Titanium

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in lithography are creating new criteria for step coverage in PVD. The demands of sub-micron processing is moving the industry towards integrated processing which combines PVD, CVD, clean and RTP while maintaining a vacuum.

The first integrated processing systems evolved out of the CVD market. While, these first generation cluster tools were widely successful in the market, they were largely a technical failure. Thruputs were too low; costs too high; and better alternatives evolved. Consequently, most first generation cluster tools have been relegated to depositing single layer films.

Most people are now convinced, that a second generation cluster tool will be essential for depositing multi-layer PVD films. Consequently, true integrated processing in which multilayer films of different materials are deposited, is evolving out of the PVD market. To capture this emerging market, the PVD market will now be segmented between conventional sputtering systems and a new segment called cluster sputtering. Included in this new segment will be those cluster tools for which aluminum interconnect is the basic application for the system's architecture.

Although there is no need to alter the segmentation of the epitaxy market, the epitaxy industry is experiencing a change. The increasing use of BiCMOS processing is rejuvenating the epitaxy market. The trend toward BiCMOS will bring epitaxial reactors back onto the factory floor where lower utilization will increase overall demand for epitaxy systems. Thus, what was a low profile market in the eighties, will see renewed growth in the nineties.

4.6.1.1 Development of the Deposition Industry



- CVD continues to be the most economical and popular deposition method.
- PVD is feeling competitive pressures from improved CVD technologies.
- Epitaxy is experiencing increased use, but remains a niche technology.

The semiconductor industry has been developing deposition equipment for use in manufacturing since its inception. Two of the three primary deposition methods, chemical vapor deposition and epitaxy, evolved out of the needs of semiconductor manufacturing. Physical vapor deposition is a much older technology that was borrowed by the semiconductor industry. These methods are interrelated, but each has taken a different path within the semiconductor industry.

4.6.1.1.1 Development of the Chemical Vapor Deposition Industry

Chemical Vapor Deposition evolved from within the semiconductor industry during the 1950's. It was first used as a means of depositing silicon epitaxial layers for making bipolar transistors. Since that time, the semiconductor has become dependent on CVD equipment to deposit the wide variety of economical, high quality films needed for today's advanced MOS and BiCMOS processes. Not surprisingly, the growth in the number and type of deposited films has resulted in the development in a number of deposition techniques over the years. Historically, these techniques have been categorized into four major technologies based on

configuration of the equipment. These four equipment types are:

- Atmospheric Pressure Systems (APCVD)
- Low Pressure Systems (LPCVD)
- Plasma Enhanced Systems (PECVD)
- Photo Induced CVD Systems (PICVD)

APCVD became the first configuration used to manufacture semiconductors. These systems developed in the mid-fifties were used to deposit silicon epitaxial films for bipolar transistors. For the most part, APCVD systems were just modified diffusion furnaces. With the advent of the IC in the sixties, APCVD systems soon found new applications for depositing glass (silicon-dioxide) onto the surface of a semiconductor wafer. In fact, a popular term used for CVD at the time was 'glassivation'. The purpose of these early glass films was to insulate interconnect wiring and protect the die from the environment, i.e. to 'passivate' it. Today, these are called dielectrics and passivation films. The first dielectric film to be used was silicon dioxide.

As the seventies began, two things happened that placed new demands on manufacturers of CVD equipment. First, devices become more complex and geometries continued to decrease. This increased the need for improving the uniformity and step

coverage of the films. Second, there was a technology shift from PMOS transistors to NMOS. With this move came a shift from metal gates to the self-aligned silicon gate MOS structures, and the first use of polysilicon films to make the silicon gate electrodes, interconnects and capacitors for the transistor DRAM cell.

These trends resulted in a rapid shift to the use of PSG (and later BPSG) as a dielectric just prior to metallization and for passivation. These films came to be extensively used by the semiconductor industry because of their low temperature melting point. This gives them good planarization properties which eliminates pin holes and cracks. After reflow, PSG and BPSG films tend to be conformal on bottom and flat on top, thus smoothing device topography. This increases metalization yields significantly. The discovery of the reflow process by Intel was so important that it enabled them to dominate the RAM market in the first half of the seventies.

These dielectrics were originally deposited in diffusion furnaces. An oxide was first grown, then it was doped with phosphorus to form Phosphosilicate Glass. It was recognized fairly early that PSG films could also be deposited at lower temperatures by using APCVD. This allowed reaction temperatures to be lowered from the 800-900 °C range, to the more desirable ranges of 400-450 °C. Equipment was developed specifically for this application. This equipment is known by the proprietary terms Vapox, Pyrox or Silox. Vapox was coined by Fairchild engineers and stands for 'vapor deposited oxide'. Pyrox stands for 'pyrolitic oxide' and Silox (Silicon Oxide) is a registered trademark of Applied Materials. The Applied Materials ASM2100 Silox system is shown in Figure 4.6.1.1.1-1.

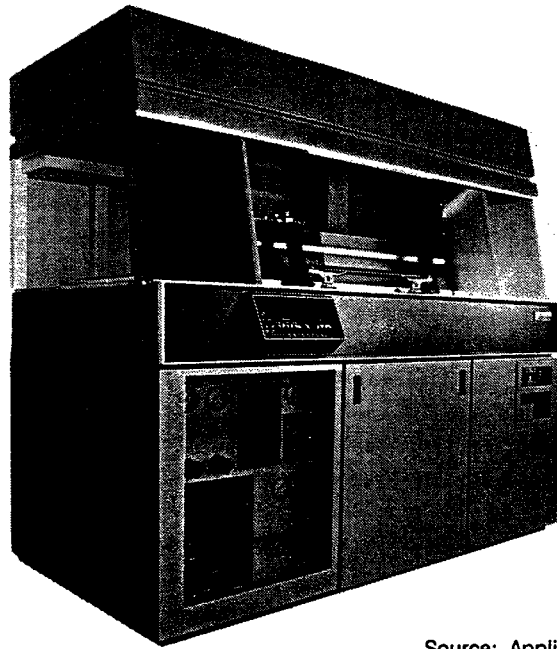
Today, APCVD systems have become quite sophisticated and compete effectively against other methods for the deposition of

a variety of films. A modern APCVD system, the BDF-41 from BTU International, is shown in Figure 4.6.1.1.1-2.

Initially, APCVD in diffusion tubes was also used to deposit polysilicon layers. However, lack of uniformity and low throughput led the industry on a search for better ways to deposit polysilicon. The result of this search was the invention of LPCVD systems.

The advantage of LPCVD is that low pressure allows reduced processing temperatures, improved step coverage, improved uniformity and decreased the importance of gas flow dynamics. Consequently, wafers could be stacked vertically in a quartz boat instead of being placed horizontally. This dramatically increased throughput thereby lowering cost. The first commercially available LPCVD system was developed by Unicorp under license to Motorola. The system was introduced in 1974. This initial system was nothing more than a diffusion furnace with a door and gas-injection plumbing added to one end and a vacuum pump on the other. LPCVD soon became the preferred method of depositing high quality polysilicon films.

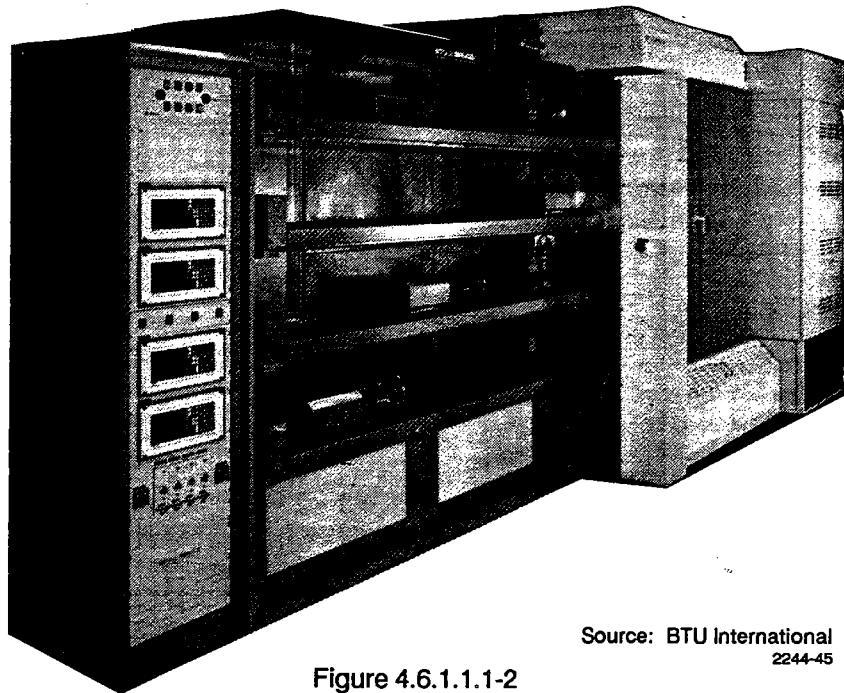
PECVD systems were developed in the late seventies as a response to a desire in the industry to lower processing temperatures for both silicon dioxide films and silicon nitride. End users especially wanted to use nitride as a passivation layer. LPCVD methods could not be used because the high temperature (660 °C) needed for the process caused too many problems the underlying aluminum layers. PECVD allowed these temperatures to be reduced to below 450 °C. The success of PECVD systems allowed the industry to compliment silicon dioxide with a nitride passivation film. ASM International came up with the first practical PECVD reactor for production, and this pushed it into the leadership position in CVD in the early eighties.



Source: Applied Materials
2244-38

Figure 4.6.1.1.1-1

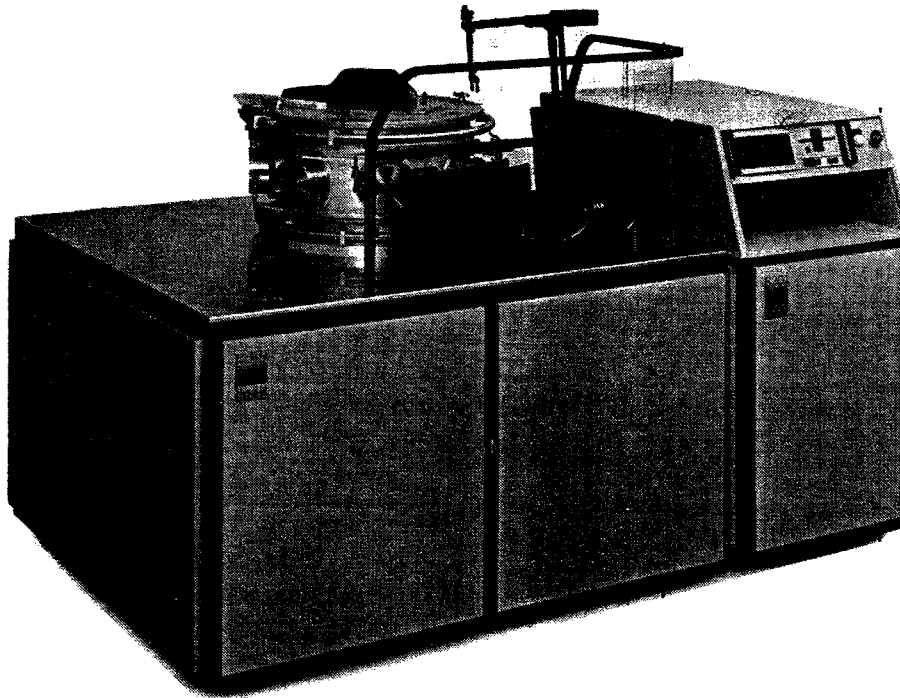
Applied Materials' AMS 2100 Silox System



Source: BTU International
2244-45

Figure 4.6.1.1.1-2

BTU International's BDF-41 APCVD System



Source: Genus
2244-44

Figure 4.6.1.1.1-3

The Genus 8301 Tungsten LPCVD System

As the industry entered the eighties, new problems emerged that had to be dealt with. Among these, increases in the electrical resistivity of the polysilicon films due to decreasing critical dimensions became the most critical. Resistivity increased because resistivity is inversely related to linewidth. Normally, line resistance increases linearly with a scaling factor K , when lines are scaled by $1/K$. But, it increases by K^2 at those points where two films make contact such as in gate windows. Consequently, the performance improvements that could intrinsically be made by scaling could not, in fact, be realized without a reduction in parasitic resistance. Or worse, device performance might actually deteriorate since parasitic contact resistance increases so rapidly. Thus, as linewidths continued to shrink, the resistivity of the films become an important consideration for the intercon-

nect. This problem led to new processes where films with lower resistivity could be deposited using CVD methods for the interconnect.

By the mid-eighties, the first metal films were being successfully deposited with commercial CVD systems. The first metal films were tungsten and the equipment was developed by Genus. The first company to successfully offer LPCVD systems for metallization was Genus. Genus' first product, the 8301, was shipped in 1983. This system is shown in Figure 4.6.1.1.1-3. At that time, other metals and their silicides were also being considered for metallization because of their lower resistivity. The resistivity and barriers to application of some of these metallic thin films are shown in Table 4.6.1.1.1-4. Among the pure refractory metals listed in the table, tungsten proved to be

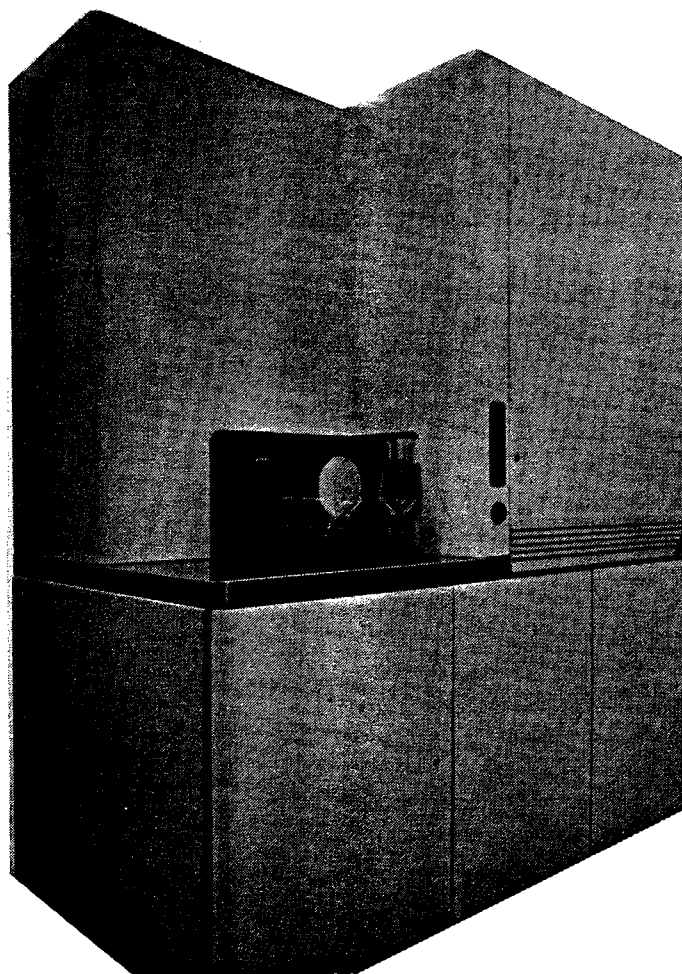
TABLE 4.6.1.1.1-4

Characteristics of Conductive Thin Films

Film	Deposition Method	Film Resistivity ($\mu\Omega$ cm)	Characteristics							
			Stability	Resistivity	Chemical Reaction	Oxidation	Temperature	Complexity	Step Coverage	Cost
Doped Poly silicon	CVD	500	○	●	○	○	●	○	○	○
Molybdenum Silicide (MoSi_2)	CVD	100	●	●	○	○	○	○	○	●
Tantalum Silicide (TaSi_2)	Sputtered	50	○	●	○	○	○	○	○	○
Tungsten Silicide (WSi_2)	CVD	50	●	○	○	○	○	○	○	○
Titanium Silicide (TiSi_2)	Sputtered	25	○	○	○	○	○	○	○	○
Molybdenum (Mo)	CVD	8	○	○	○	○	○	○	○	○
Tungsten (W)	CVD	9	○	○	○	○	○	○	○	○
Aluminum (Al)	Sputtered	4	○	○	○	○	○	○	○	○

○ Good ○ Fair ● Poor

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Source: Anicon/SVG
2244-48

Figure 4.6.1.1.1-5

The Anicon Full Spectrum CVD System

the most popular. It was inexpensive, highly conformal and provides good diffusion barriers, good step coverage and ability to withstand high temperatures. Tungsten won out in the marketplace carrying Genus to the market leadership position.

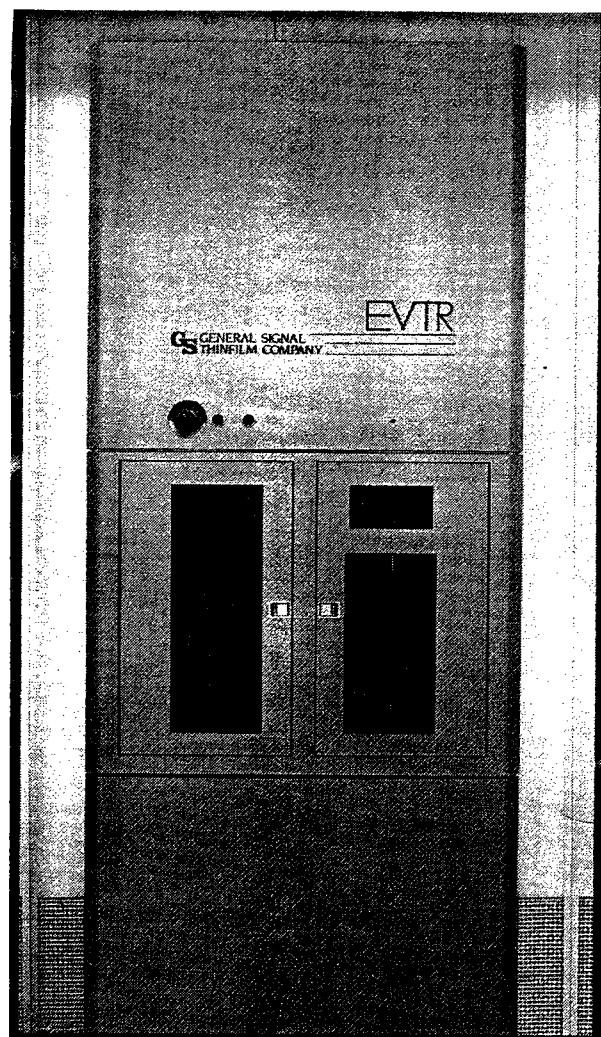
Gas flow dynamics continued to play an important role as geometries shrunk. To solve some of the problems brought on by these dynamics, Anicon (now part of Silicon Valley Group) introduced a novel approach

to LPCVD in the mid-eighties. This system was named the Full Spectrum CVD System and is shown in Figure 4.6.1.1.1-5. The unique feature of this system was the use of a bell jar chamber and its exotic quartz ware. The gases were injected separately into the chamber and mixed above the wafers so that there was no downstream dilution of gases. The system improved uniformity and wafer cleanliness because the gas flowing over each wafer was fresh.

The mid-eighties also saw the return of interest in diffusion furnaces for LPCVD applications. However, it was not the same configuration as the old horizontal system. In these new furnaces, the tube has been placed on its end in a vertical configuration. These systems, called vertical LPCVD furnaces, became very popular in Japan because of their small footprint, low particulate generation and improved film uniformity over conventional horizontal LPCVD systems. Moreover, it was much more economical to use than a cluster tool. The General Signal Thin Film EVTR verticle LPCVD furance is shown in Figure 4.6.1.1.1-6.

Planarization reared its head in the mid-eighties as depth of focus on G-line fell below 1.5 microns. Applied Materials was the first to respond with what would be one of the most successful semiconductor equipment systems of all time, its Precision 5000 CVD. This single wafer, multi-chamber cluster system was introduced in 1987 and it was immediately clear that it would revolutionize the industry. Applied was production worthy because it was the first to offer a successful planarized ILD (Interlayer Dielectric). It soon became the standard by which other systems were judged. The system is shown in Figure 4.6.1.1.1-7. Another popular system was introduced about a year later by Novellus. Novellus' Concept One is a batch system that showed an ability to compete effectively against Applied Materials' system by offering lower processing costs. The Concept One is shown in Figure 4.6.1.1.1-8.

Photo-induced CVD was one technology that never came to fruition. It was first introduced in the early eighties. Hughes Aircraft and Tylan were the first to commercialize it, since that time several companies have entered the market. The first PICVD system was introduced by Tylan. The Tylan PVD-5000 system is shown in Figure 4.6.1.1-9. The system utilizes a UV



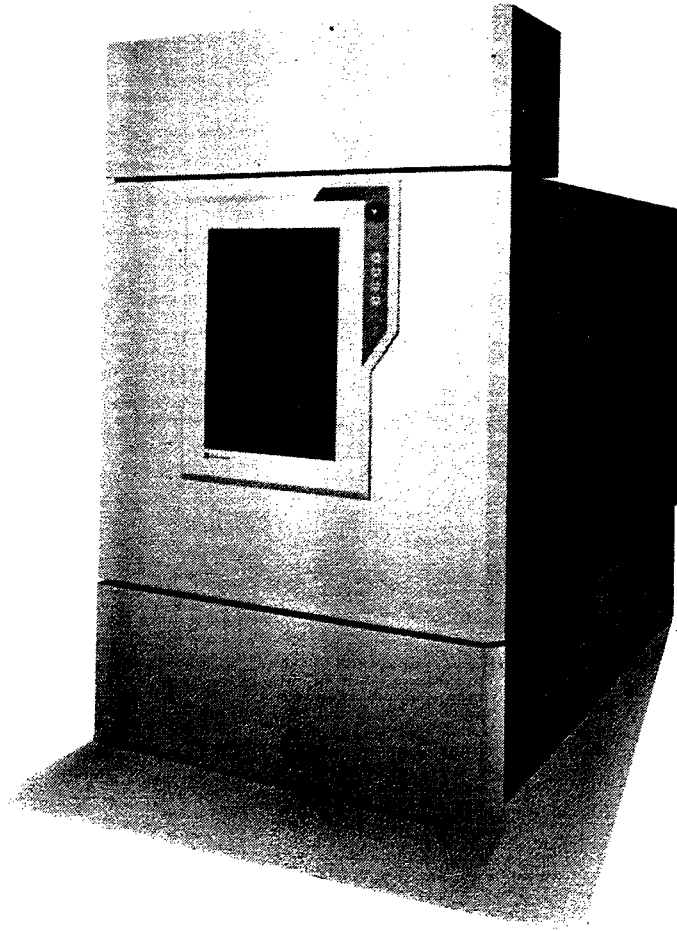
Source: General Signal
2244-49

Figure 4.6.1.1.1-6

General Signal Thin Film's EVTR Vertical CVD Furnace

light source and mercury vapor at low pressure to excite the gas reaction. There are several advantages to PICVD. The systems could deposit films at temperatures between 50-250 °C. There was no radiation damage and no film stress. The films were of very high quality with relatively few pin holes. However, the safety issues involved in the use of mercury in the process doomed its future.

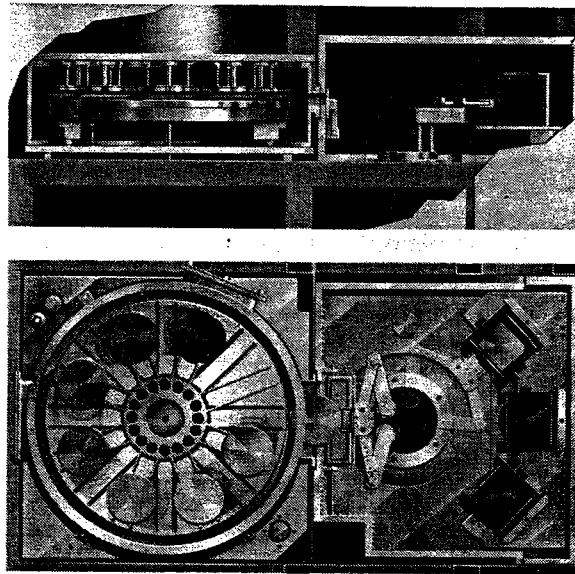
The fears about safety led to a new PICVD methods which utilizes excimer laser as the light source and eliminated mercury. Met-



Source: Applied Materials
2244-50

Figure 4.6.1.1.1-7

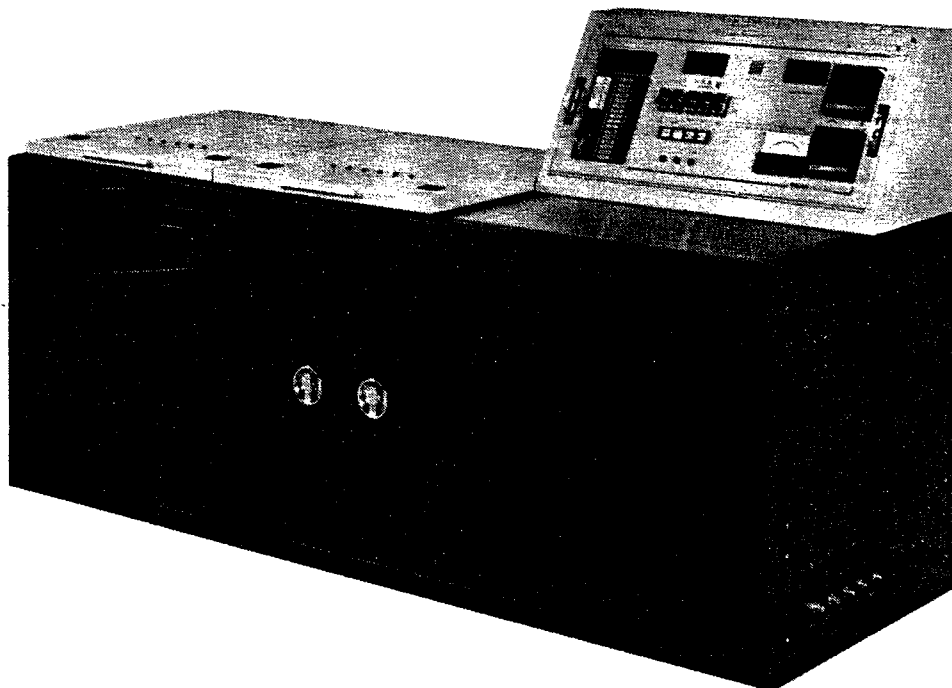
The Precision 5000 CVD from Applied Materials



Source: Novellus
2244-41

Figure 4.6.1.1.1-8

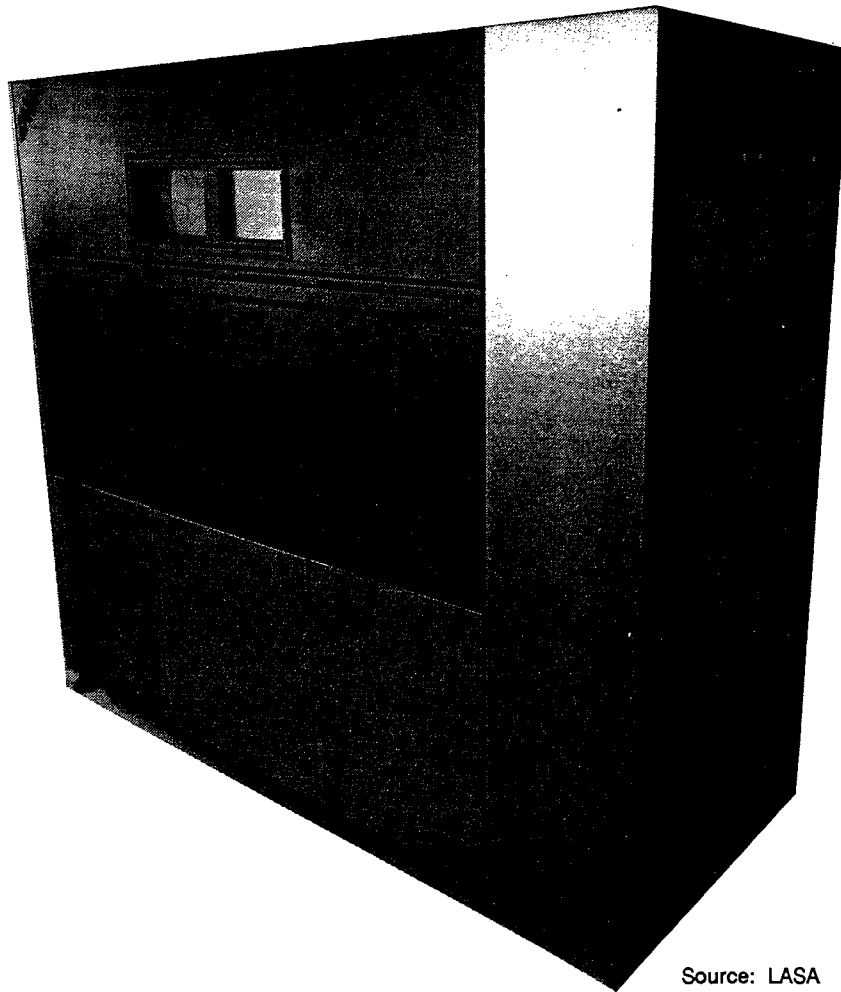
Novellus' Concept One CVD System



Source: Tylan
2244-42

Figure 4.6.1.1.1-9

Tylan's PICVD System



Source: LASA
2244-43

Figure 4.6.1.1.1-10

The LASA's Excimer Laser PICVD System

als have been deposited in this manner since 1972 in the laboratory. However, it was not until the mid-eighties that firm began to work on commercializing the process. By the end of the eighties, LASA and Elron had working systems. These systems have the advantage of not being limited to oxides. They can deposit all semiconductor related materials, including silicides and refractory metals. The laser

induces a CVD process that can be used to deposit tungsten interconnects and silicon dioxide. Further, the system can be used to deposit or etch, and can even be used as a direct writing system. The primary use to date, has been limited to quick turnaround prototyping. These systems have not found widespread use. The LASA system is depicted in Figure 4.6.1.1.1-10.

4.6.1.1.2 *Development of the Physical Vapor Deposition Industry*

Physical Vapor Deposition is an old process that long predates the semiconductor industry. PVD refers to a process that can generally deposit any material on any substrate. It is widely used in a variety of industries to perform such functions as putting optical coating on lenses and glasses, and coating jewelry. The process is physical in the sense that the material is vaporized from the target and is deposited on the wafer. This terminology is usually limited to those processes which do not incorporate a chemically reactive deposition as in CVD. In PVD, the material is literally evaporated and subsequently condenses onto the surface of the substrate.

Today, physical vapor deposition includes all vapor metallization and deposition processes which are accomplished under a very high vacuum. Although semiconductor manufacturers use CVD whenever possible because it is more economical, all manufacturers make use of PVD at least once during the process of manufacturing semiconductors. Generally, this is to deposit aluminum which can not be deposited using CVD methods.

PVD for semiconductor applications can be thought of as consisting of three distinct methods. The oldest consists of resistive heating. In this method, a metal is heated in a crucible until it vaporizes. Resistive heating is an obsolete method and will not be discussed further. The second method consists of electron beam bombardment—or E-beam evaporation as it is called—to achieve vaporization of the metal source. The E-beam, or E-gun, was a technique introduced by Temescal. Figure 4.6.1.1.2-1 shows Temescal's model FCE-3200 E-beam evaporation system. In E-beam deposition, an intense electron beam is directed at the metal. The beam melts a small puddle, which then vaporizes and deposits on the

wafers which are held at the top of the chamber.

E-beam was the method of choice for many years because it worked well for depositing pure metals. But, the trend towards smaller geometries increased the use of alloys and less pure metal which began to limit the usefulness of E-beam. The move to alloys was necessary because the smaller geometries meant shallower diffused junctions. When pure aluminum is deposited onto silicon, it will often penetrate these shallow junctions and short circuit the device. In order to prevent this reaction, manufacturers began to alloy aluminum with silicon. Copper is then added to increase the grain size in order to improve the conductivity of aluminum-silicon and prevent metal migration. This AlCuSi alloy allowed for even smaller linewidths and improved step coverage.

E-beam equipment manufacturers tried to meet the demand for alloys by offering multiple gun systems. As a result, a surge in the use of dual gun E-beam systems appeared in the mid-seventies. In this equipment, one material is evaporated from one gun while the other is evaporated from the second gun. Three guns are needed to deposit AlCuSi. In any case, however, the resulting film is more of a mixture than it is an alloy. Moreover, the mechanical mechanisms that feed the material to the E-beam gun have proven to be quite difficult to control. The systems do not maintain uniform feed rates, so the stoichiometry and thickness of the films vary. Further, good results are tricky to achieve on a day-in-day-out basis. The difficulty of using E-beam for alloys caused it to lose popularity except in those cases where pure aluminum is used and for lift-off techniques. Today, E-beam finds little use outside of these uncommon applications.

With the increasing use of aluminum alloys and the inability of E-beam to provide films

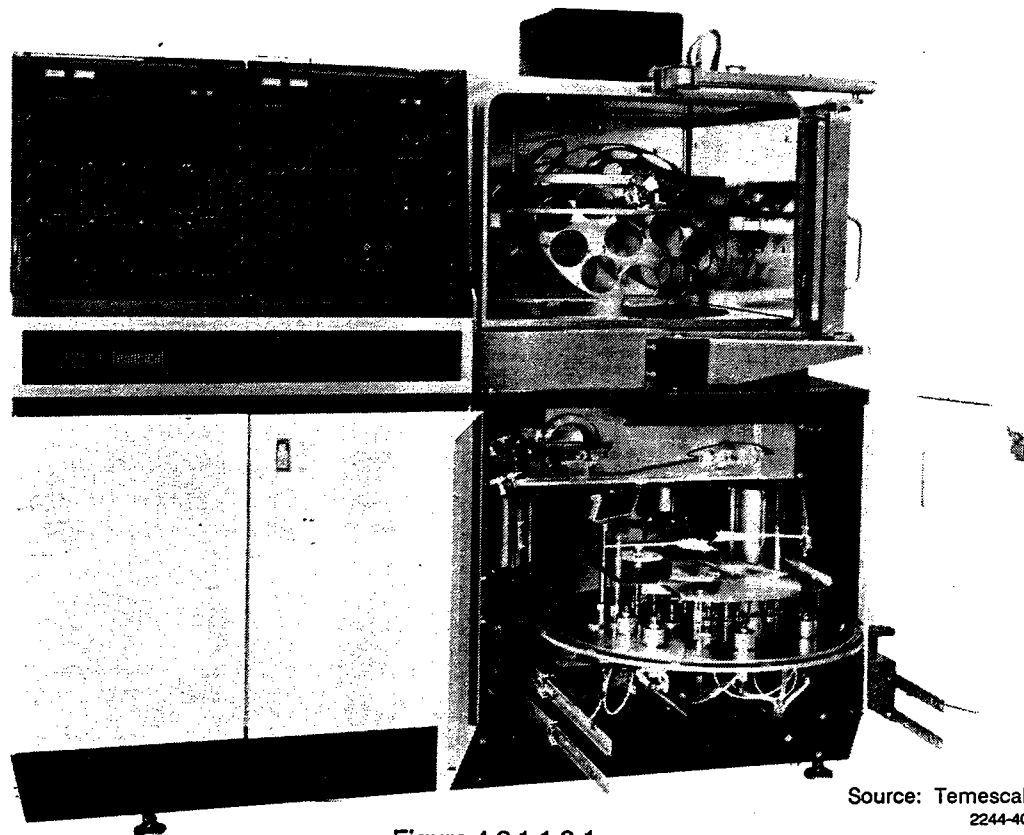


Figure 4.6.1.1.2-1

Source: Temescal
2244-40

The Airco Temescal FCE-3200 E-Beam Deposition System

of the needed quality, manufacturers began to turn to sputtering as the favored PVD method. In sputter deposition, the material to be deposited, i.e.—the target—is electrically grounded and bombarded by ions rather than by electrons. These ions knock off the target atoms. The atoms that have been removed are then directed onto the substrate by electric and magnetic fields. Sputtering is preferred by semiconductor manufacturers because of the improved step coverage and adhesion it provides over other PVD methods. Sputtering also allows for better control of the film characteristics by balancing the pressure, deposition rates and target material of the sputter system.

Sputtering is actually an old process. It was first formulated in 1852 by Sir William Robert Grove, who referred to the process as 'cathode disintegration.' It did not find widespread use within the semiconductor industry until about 20 years following the inception of the industry. Today, sputtering is used by nearly all semiconductor manufacturers. The highest technical development in the sputtering industry occurred in the eighties. Generally there are four methods of sputtering used for semiconductor applications. They are direct current (DC) diode, radio frequency (RF) diode, triode and magnetron. The first three methods are generally simple referred to as diode sputtering.

Diode sputtering was the first sputter process developed for depositing semiconductor thin films. It involves two electrodes: the cathode and the anode. The substrate, a silicon wafer, rests on the anode and the target on the cathode. When a high voltage is supplied to the system and the argon pressure is correct, electrons flow from the cathode to the anode and material is sputtered from the target onto the wafer. In diode sputtering, the plasma resides between the target and the wafer. Not only does that target material condense on the wafer, but fast electrons and ions from the plasma also bombard the wafer which causes contamination. Further the heating produced by diode sputtering causes problems with the deposition of aluminum. The process leaves behind residual oxygen in the chamber which combines with the aluminum to form aluminum oxide which can compromise the conductive property of the aluminum. Further, diode sputtering wastes a lot of material.

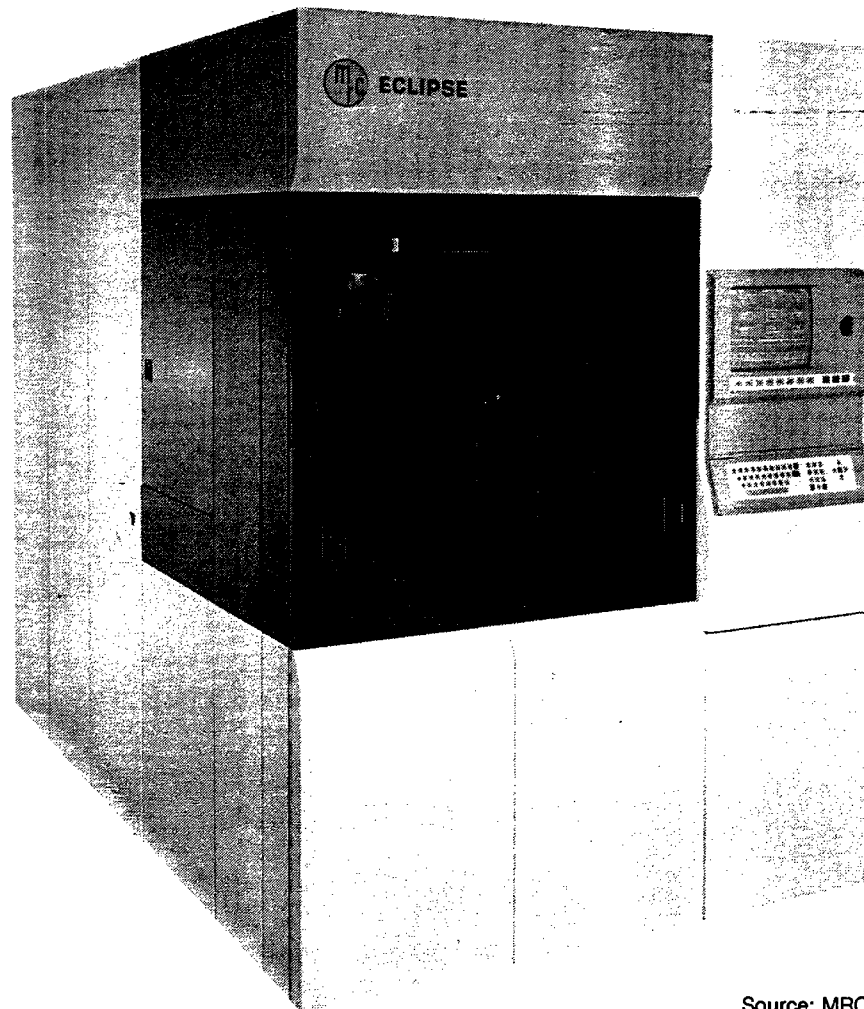
In an effort to reduce the problems brought on by diode sputtering, MRC introduced magnetron sputtering. Magnetron sputtering enables higher deposition rates, lower substrate temperatures and reduced voltages. It is similar to diode sputtering except the cathode incorporates magnets that hold the electrons to the region around the target. This helps sustain the plasma better and enables the wafer to remain outside the plasma and be protected from contamination. The system acts like a gun. The sputtered species is shot out from the target toward the wafer. This method proved to be very successful and soon replaced diode sputtering. As is the case with diode sputtering, magnetron can use RF or DC power. RF is used when sputtering from an insulating target, and DC is used when sputtering from a conductive target.

Many companies lost tremendous market share when they missed the switch from E-

beam to sputtering in the early seventies. MRC emerged from that battle as the largest PVD supplier and the boost given to MRC during that period allowed the firm to maintain its position as a strong competitor throughout the eighties and into the nineties. MRC's latest system, The Eclipse, is shown in Figure 4.6.1.1.2-2.

The advent of VLSI at the later half of the seventies brought new demands on the suppliers of sputter equipment. Users were demanding a single wafer, side-sputtered, cassette operated system with load locks. Varian met the challenge by introducing the 3180. This system took the industry by storm and allowed Varian to take away the market leadership from MRC, Balzers, Temescal and Perkin-Elmer. The 3180 is shown in Figure 4.6.1.1.2-3.

As the eighties began, new challenges were faced by PVD suppliers. CVD systems were improving and manufacturers were switching over to this less expensive deposition methods. Further, layer-to-layer interconnect was becoming a major issue that began to impact PVD in the eighties. As device complexity increased, interconnection requirements caused die size to increase over and above what would otherwise be needed to fit extra elements into the die. This increase resulted in yield losses. About two-thirds of an IC's die area is taken up by metal and polysilicon interconnects. This placed tremendous pressure on semiconductor suppliers to either reduce interconnect linewidths or to add buried conducting layers. Historically, this has had little impact on PVD suppliers. Reducing linewidths did not add new PVD steps. The additional layers put down were usually polysilicon; and polysilicon is deposited by CVD, not by PVD. However, these historical trends were altered by new developments in manufacturing technology. Manufacturers began adding more mask layers and the number of process steps doubled.



Source: MRC
2244-51

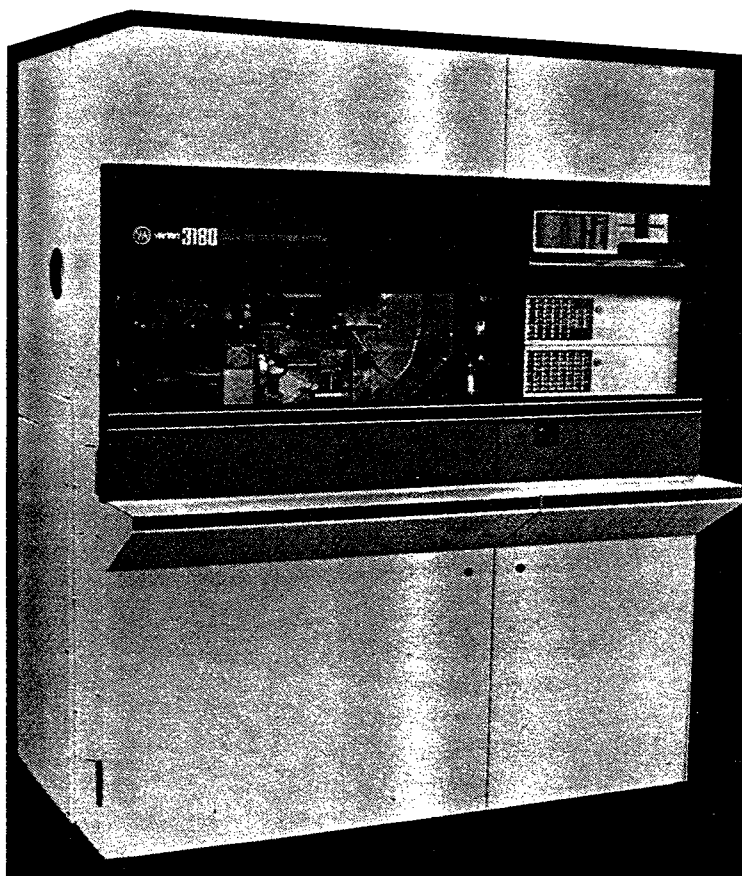
Figure 4.6.1.1.2-2

The MRC Eclipse Sputtering System

Double polysilicon layers became a commonplace multiple layer approach in the early eighties to form capacitors for DRAM cells and for the first level of interconnection. At one time, National Semiconductor planned to manufacture its 64K dynamic RAM by using as many as three polysilicon interconnect layers. However, each polysilicon layer adds several high temperature diffusion and annealing steps. This compounds wafer distortion and yield problems. The technology was simply not ready in the

early eighties. National was unable to solve these problems and had to go back to a conventional process. Thus, the use polysilicon for interconnect peaked in the mid-eighties with two layers. In its place, manufacturers began using double and triple metal layers.

The mid-eighties also saw some manufacturers experiment ion cluster beam deposition in an effort to displace some CVD, sputtering and epitaxial applications. This was



Source: Varian
2244-39

Figure 4.6.1.1.2-3

Varian's 3180 Sputtering System

considered advantageous because ICB deposition allows low temperature film growth. Temperatures could be reduced from current ranges of 1200-1300 °C to about 620 °C for silicon. Such a reduction would prove vital in further reduction of bipolar junctions, as well as for GaAs junctions. However, ion cluster beam technology proved to be exceedingly difficult to commercialize and never made it into widespread use. This may change as Mitsubishi and Nissin Electric have developed new generation systems.

PVD was also challenged in the early eighties by PECVD of aluminum which promised to replace some other PVD applications. ASM International was the chief proponent

of this method. The primary advantage offered by PECVD is that it provides 100% conformal step coverage. It also has a high throughput, is more economical and the film properties are excellent. Moreover, no electrical charges are injected into layers during deposition. Its disadvantage is that it only works with pure aluminum or with aluminum alloyed with 0.8% silicon. This severely limits its application since silicon and copper alloys of well over 1% are the most common in use today. Additionally, the PECVD process is difficult to control and can become unstable. Thus, manufacturers lost interest for a few years. As the nineties began, however, there was renewed interest in PECVD of aluminum. In addition, CVD aluminum remains a threat to sputter-

Figure 4.6.1.1.2-4

Likely Submicron Double-Level Deposition Cycles
(From 1st Level Metal)

Option 1 (TiN Barrier, Al Fill)		Option 2 (Ti:W Plugs)		Option 3 (W Plugs)	
EQPT	ACTIVITY	EQPT	ACTIVITY	EQPT	ACTIVITY
↓ CVD	BPSG Deposition	↓ CVD	PSG Deposition	↓ CVD	BPSG Deposition
RTP	BPSG Reflow	RTP	PSG Reflow	RTP	BPSG Reflow
	Contact mask & etch		Contact mask & etch		Contact mask & etch
RTP	Reflow	RTP	Reflow	RTP	Reflow
PVD	TiN Barrier Deposition	PVD	Ti:W Plug	CVD	Selective W plug
PVD	Al Deposition	CVD	Blanket W		Resist planarization
RTP	Anneal		Resist planarization	PVD	Ti:N deposition
	Metal-1 mask	PVD	Ti:W, Al/Cu deposition	PVD	Al/Cu deposition
CVD	Interlevel PECVD		Pillar mask	RTP	Anneal
Spinner	Spin-on-glass	Etch	Multi process etch	CVD	Interlevel CVD
Etch	Etchback	CVD	Interlevel PECVD	CVD	Spin-on-glass
	Metal-2 mask		Blanket resist	Etch	Etchback
Etch	Etch		Mask		Metal-2 mask
CVD	Passivation PECVD		Planarize	Etch	Etch
			2nd level deposit	CVD	Passivation PECVD

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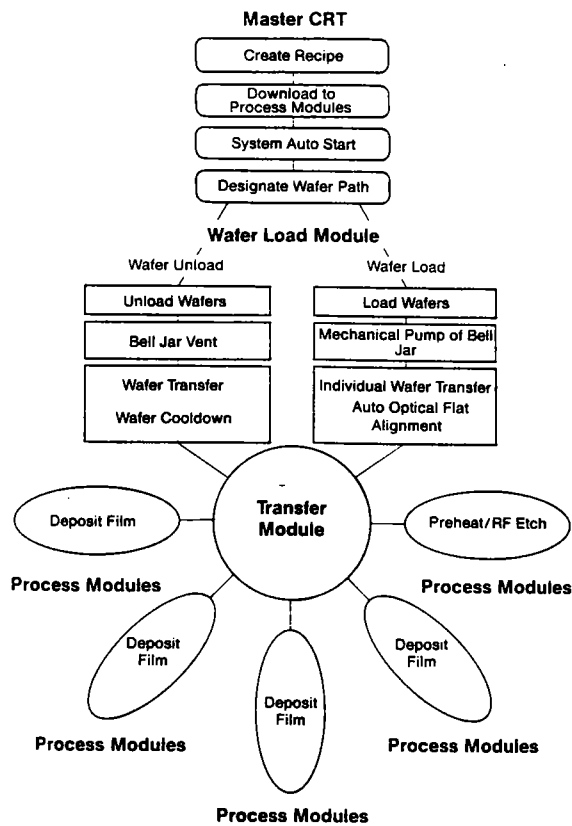
ing. Should such a CVD system become feasible, it would lower the cost of depositing aluminum, raise yields and eliminate the need for most PVD applications.

The nineties has also seen the beginning of a trend that may prove even more important for the PVD equipment vendor. The step coverage limitations of PVD and materials problems with aluminum has led to increasing use of tungsten plugs, titanium nitride and aluminum-copper-silicon sandwiches. This is leading to a merging of CVD, PVD and etch into one cluster tool. The need for PVD as an integral capability in an integrated processing system is illustrated in Table 4.6.1.1.2-4. The table shows that PVD is a critical processing step in most of the double layer deposition cycles. As a result, most of the latest PVD equipment introduction in offer an integrated processing architecture. Companies such as

Anelva, Balzers, Applied Materials, Ulvac and Varian offer cluster tool architectures built for a PVD purpose. The flow of wafers through such a system is shown in Figure 4.6.1.1.2-5. The Applied Materials Endura 5500 is shown in Figure 4.6.1.1.2-6.

4.6.1.1.3 Development of the Epitaxy Industry

Technically epitaxy belongs to the CVD equipment market, but because its application is so different from other CVD applications it is covered separately here. Epitaxial deposition is primarily a high-temperature process. It takes place at 900 °C to 1250 °C. By contrast, other CVD processes occur between 20 °C and 850 °C. Epitaxy is used to deposit a single crystalline layer of silicon that orients itself to the crystal arrangement of the bare silicon wafer surface. Epitaxial



Source: Varian
2244-81

Figure 4.6.1.1.2-5

The Wafer Flow Within the Varian M2000

layers are necessary for bipolar and Bi-CMOS applications, but have found limited use in MOS applications. Additionally, certain types of epitaxial reactors have found widespread use in GaAs applications.

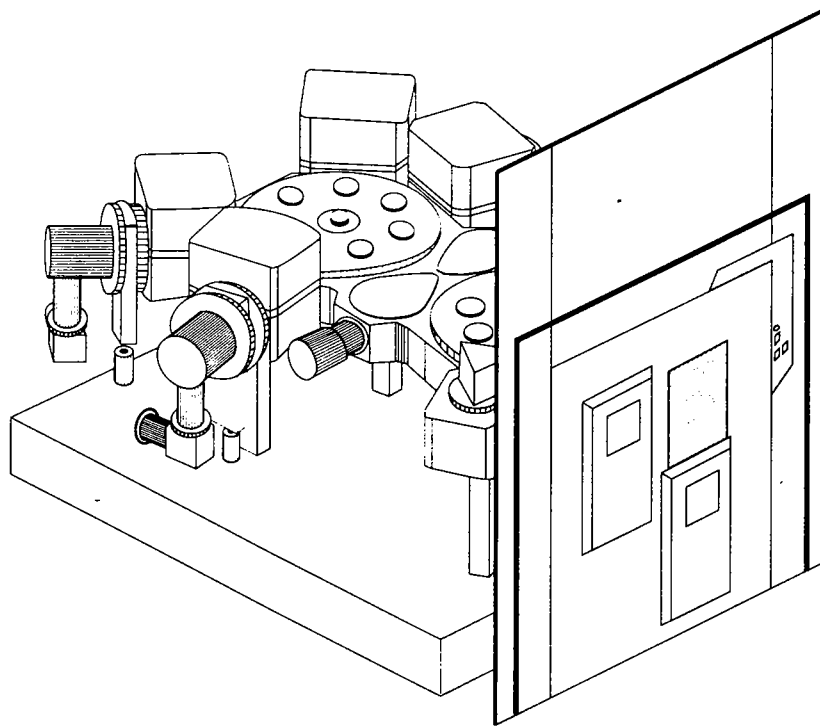
Four basic epitaxial processes have developed. They are liquid-phase epitaxy, vapor-phase epitaxy, molecular beam epitaxy (MBE) and metalorganic CVD (MOCVD). Liquid-phase is used for crystal growing and will not be discussed further. Vapor-phase is the primary method used in silicon processing. Older vapor-phase epitaxy equipment consists of two types. One is called the pancake reactor. The other uses a horizontal tube and is called the horizontal induction reactor. In both, the wafers lie horizontally on a susceptor. Both are 'cold wall'

reactors that utilize R.F. or induction heating rather than filament heating. The energy radiates through the walls and the wafer remain cool. In the pancake reactor, the vapor has a vertical flow, while the vapor flows horizontally in the horizontal induction reactor.

Molecular beam epitaxy is dominantly used for III-V material applications in the area of microwave, optoelectronic, lasers and high speed circuitry. The MBE process affords finer thickness control and lower temperatures. Thickness can be controlled to within five angstroms. Temperature of operation is between 650 °C and 1000 °C. Conventional epitaxy thickness control is ± 100 -125 angstroms while the temperature range is between 950 °C to 1250 °C. MBE has not proven to be competitive with conventional epitaxial techniques for the deposition of silicon. There are several reasons for this. First, the throughput of MBE systems is too low, at 3 to 6 wafers per hour. Second, large wafers cause considerable outgassing problems. Finally, the fine thickness control is generally not needed for silicon applications. Figure 4.6.1.1.3-1 shows a typical MBE system.

MOCVD is a method that uses metalorganic and hydride sources to deposit III-V materials. Today it is used to produce tunnel diodes, gun effect devices, electroluminescent diodes, GaAs FET's, photo cathodes, lasers and GaAs Schottky diodes. MOCVD has several advantages in producing these films. The main advantage of MOCVD systems is that they offer fine control over growth parameters, moderate temperatures (800 °C), excellent interface properties, good uniformity and indirect substrate heating. Figure 4.6.1.1.3-2 shows a typical MOCVD system.

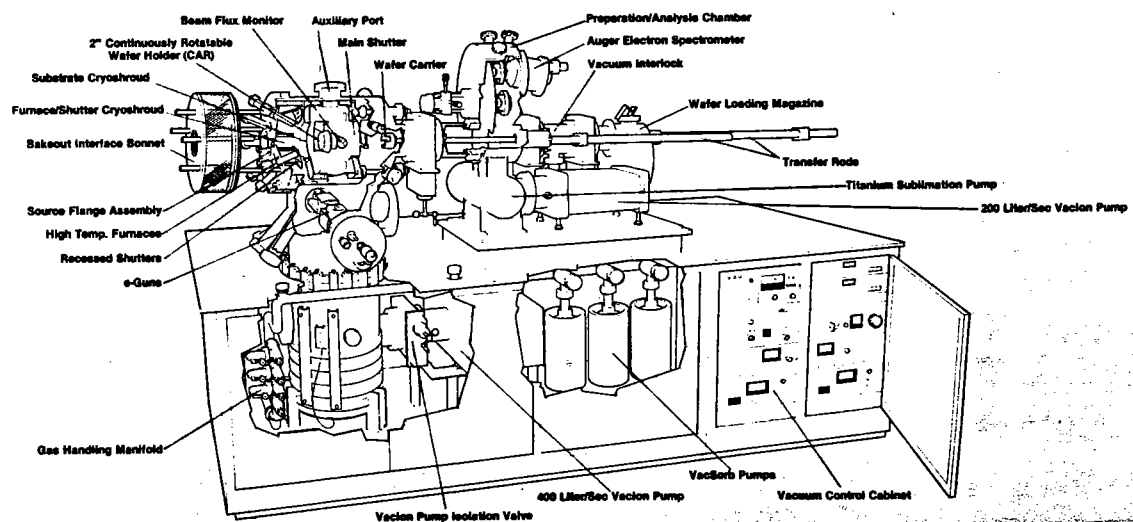
These three methods for depositing epitaxial layers all grew out of the demand for epitaxial films in the mid-fifties. For the first ten years, the technology was just being



Source: Applied Materials
2244-82

Figure 4.6.1.1.2-6

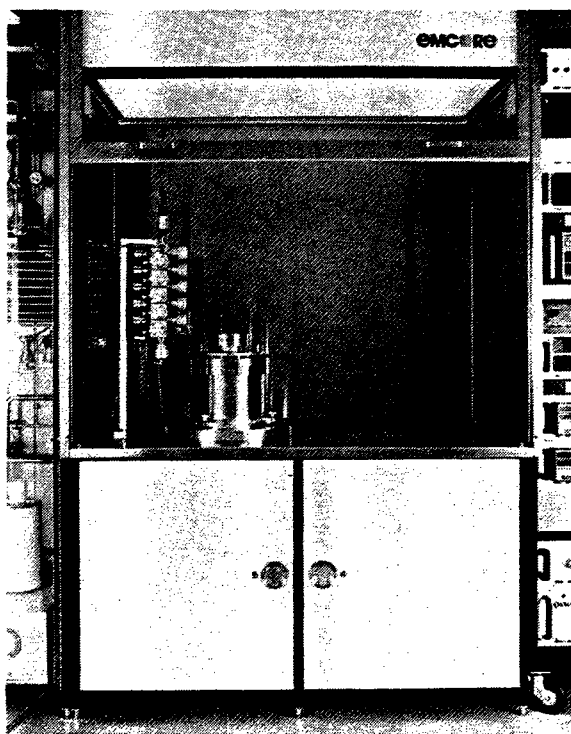
The Applied Materials Endura 5500



Source: Varian
2244-83

Figure 4.6.1.1.3-1

The MBE GEN II from Varian



Source: EMCORE
2244-84

Figure 4.6.1.1.3-2

The EMCORE MOCVD System

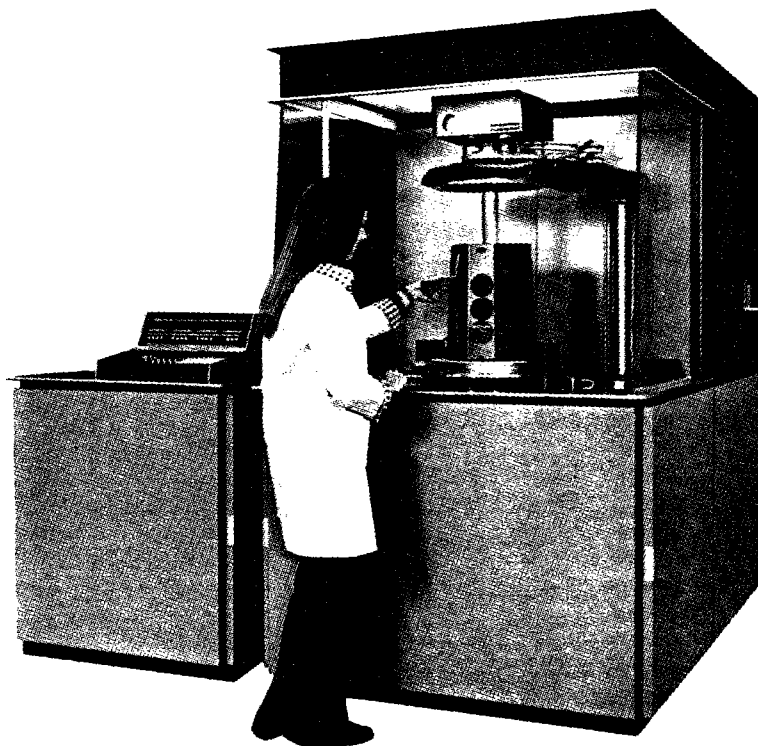
defined. It was still not clear what would work and what was required for semiconductor manufacturing. The first real reactors developed by commercial vendors for silicon deposition did not become available until 1965. However, most systems at the time were still being developed internally. The period between 1964 and 1980 was a time when equipment vendors began to exploit the market and develop new processes. MOCVD was developed in 1966 and MBE was developed in 1968, but these methods took a back seat to conventional vapor phase epitaxial methods.

Prior to 1973, horizontal reactors held the majority of the market because they offered high throughput, albeit at the expense of uniformity. Companies such as Tempress, Hugle and Unicorp were dominant vapor phase epitaxial markets at the time. Then

in 1973, Applied Materials introduced the 7000 series radiant heated, hot-wall vapor phase epitaxial reactor. This system was based on work of Walter Benzing, a pioneer in the field of epitaxial deposition, and Michael McNielly. This method of epitaxial growth and this equipment soon proved superior to the older epitaxial deposition methods. It was not only capable of high volume production but also maintained highly uniformed films. These reactors soon captured a major portion of the epitaxy market and brought Applied Materials from a small unknown company into a dominant place in the market. The series 7600 epitaxy reactor from Applied Materials is shown in Figure 4.6.1.1.3-3.

By the mid-seventies, there was a trend towards vertical reactors as LSI moved into production and required more uniform films. The low throughput of vertical systems hampered their ability to compete against Applied Materials in the production environment. Then, Epitaxy Inc. introduced the Gemini-1 vertical reactor in 1979. It was the first vertical reactor to have a wafer capacity and throughput that was comparable to that of a cylinder reactor. Several other vendors subsequently introduced similar equipment. By 1981, these vendors had revived the dying vertical reactor market. The Gemini-1 is shown in Figure 4.6.1.1.3-4.

Despite the technological advances being made, the seventies and eighties proved to be difficult decades for the epitaxy market. The increased use of MOS processing technology hurt the epitaxy market. Unlike bipolar devices where the use of buried collectors made epitaxial films essential, MOS devices do not have buried collectors. Their source and drain elements are deposited from the upper surface. Therefore, epitaxial layers are not needed in MOS devices. This sent the equipment industry on a search for reasons to use epitaxial layers for MOS devices.



Source: Applied Materials
2244-54

Figure 4.6.1.1.3-3

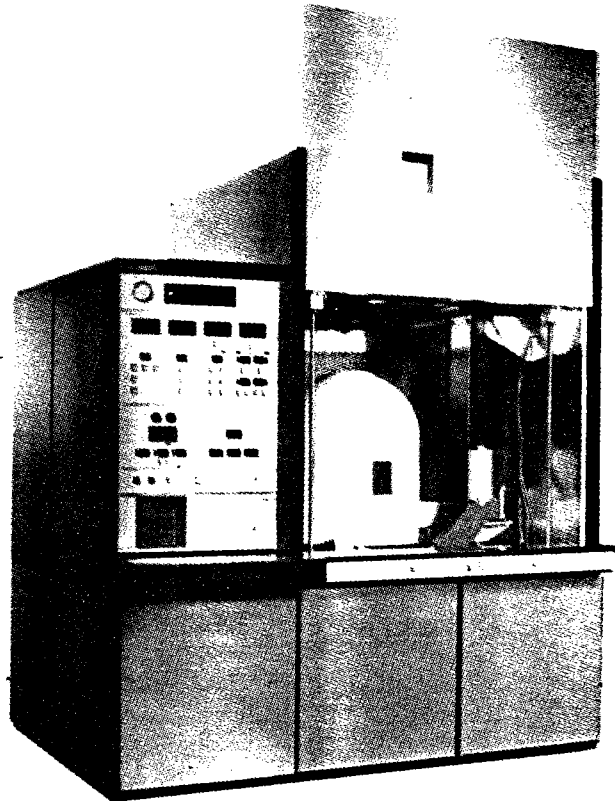
The Series 7600 Epitaxial Reactor from Applied Materials

This equipment industry felt that epitaxial films could hold several benefits for MOS processes. It was found that yields could be increased because undesirable impurities such as oxygen, heavy metals, and carbon tend to migrate to the epi-substrate interface. This is due to the difference in dopant concentrations between the two layers. Consequently these impurities can be swept away from active regions of the device, thereby enhancing yield.

Further, it was also found that several advantages could be gained by using a lightly doped epi layer above a heavily doped wafer. This offered the advantages of improved immunity from latchup, ability to bias the substrate, improved immunity to

column-disturb sensitivity, better control of dogtailing and increased resistance to alpha particles. These advantages generated some new demand for epitaxial furnaces in the eighties. However, epitaxy proved to be an expensive way to realize these benefits with MOS processing.

By the end of the eighties, these advantages began to evaporate as manufacturing processes improved. Manufacturers used guard rings, spacing and device isolation instead of epitaxial films. Wafer manufacturers improved their processing techniques and began eliminating impurities and providing high quality polished wafers. This further reduced the need for epitaxial wafers. Semiconductor manufacturers found that



Source: Epitaxy Equipment, Inc.
2244-55

Figure 4.6.1.1.3-4

The Gemini-1 Epitaxial Reactor

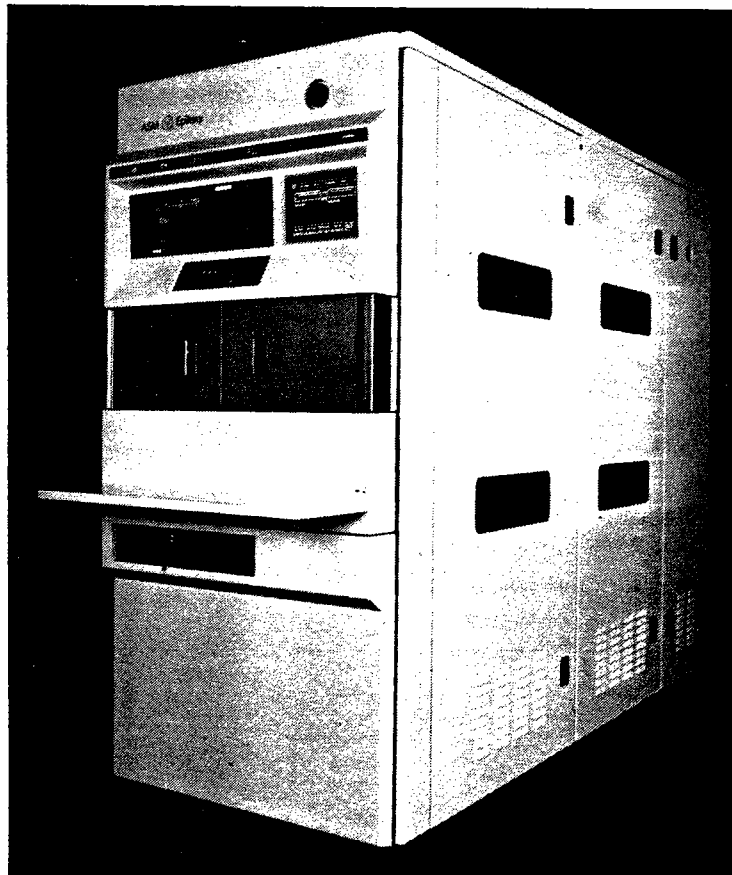
they could use more cost effective methods to prevent problems such as latch-up. The net result is that MOS epitaxy became a niche technology that was dying as the nineties began.

Fortunately, in the late eighties the industry saw the advent of BiCMOS processing. Since part of the device is bipolar, epitaxy became a critical technology again that was essential for manufacturing BiCMOS devices. This switch over to BiCMOS has given renewed hope for growth in the epitaxy market. This is because BiCMOS calls for

patterned epitaxial layers, forcing manufacturers to bring epitaxial reactors back into the factories. This will have a positive effect on the market for epitaxy equipment. Previously, the buyers of epitaxy equipment were the manufacturers of silicon wafers. These potential users are few and they are generally very efficient. With the increased use of BiCMOS, semiconductor manufacturers themselves must use modern epitaxy reactors such as the ones offered by ASM International (See Figure 4.6.1.1.3-5). This is a much bigger market of potential users than there was with the silicon wafer manu-

facturers. Therefore, there will be a need for more reactors. However, this does not mean that the epitaxy market will explode.

Epitaxy will remain a niche technology, and MBE and MOCVD remain niches inside a niche.



Source: ASM
2244-85

Figure 4.6.1.1.3-5

A Modern Epitaxy System from ASM

4.6.1.2 Technology



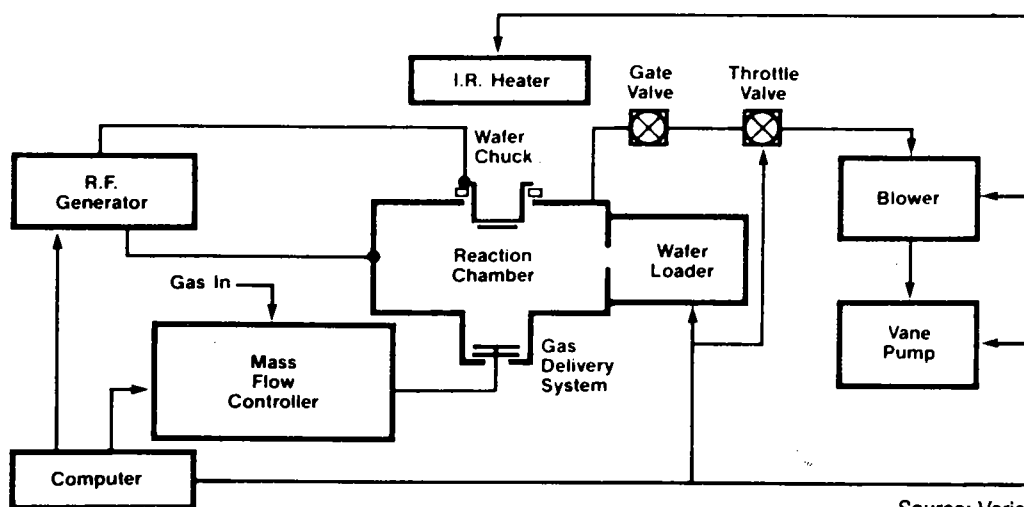
- CVD application require a known chemical reaction to deposit the desired film.
- Epitaxy is a CVD method so a chemical reaction is also required.
- The dominant PVD method is sputtering which can be used to deposit nearly any material on any substrate.

This section contains descriptions of the applications and the technologies used by chemical vapor deposition equipment, physical vapor deposition equipment and epitaxy equipment.

4.6.1.2.1 Chemical Vapor Deposition Technology

In semiconductor manufacturing, chemical vapor deposition is used to deposit silicon, dielectric, metal and silicide films. While the chemical reaction needed to deposit each type of film differs, the reactions take

place in similar CVD reaction chambers. A schematic of typical CVD system is shown in Figure 4.6.1.2.1-1. The mechanism of the system is fairly simple. First, chemicals containing the atoms required in the final film are injected into the deposition chamber and mixed. Then, the chemicals react with each other to form the proper film molecules in a vapor state. These molecules then adhere to the wafer's surface to form the required film. Generally, CVD reactions require the addition of energy, usually in the form of heat, to make the reaction occur.



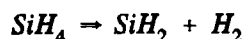
Source: Varian
2244-56

Figure 4.6.1.2.1-1

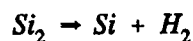
Typical CVD Schematic Diagram

The chemical reactions used to deposit the required films fall into one of four categories. The categories are pyrolysis, reduction, oxidation and nitridation. Pyrolysis occurs when heat alone is used to cause the chemical reaction. Reduction uses a molecule of hydrogen to cause the chemical reaction. Oxidation uses an oxygen molecule. Finally, nitridation is the chemical process of forming nitrides of silicon or titanium. The reaction within a CVD chamber may be purely thermal, it may be plasma assisted or it may be photo-induced, depending on the type of reactor being used and the type of film being deposition. For some films, each of these processes might be used.

The deposition of silicon uses a pyrolysis process. The reaction starts with the following chemistry:



The silane (SiH_4) is dissociated in Hydrogen gas plus a radical SiH_2 which is absorbed into the substrate. Hydrogen is subsequently released from the surface, leaving behind a film of silicon:



The production of silicon dioxide films use the oxidation process. This reaction is:



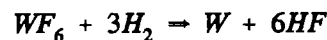
Other dielectrics such as PSG and BPSG can be deposited using a similar chemical reaction by doping the reactant gases with phosphine and or diborane. The unique feature of these reactions is that they can

proceed at temperatures as low as 450°C . This allows for silicon dioxide to be deposited over aluminum without damaging it.

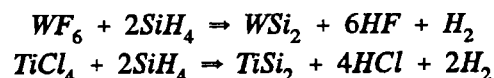
Silicon nitride films are achieved by using a nitridation process. This reaction occurs as follows:



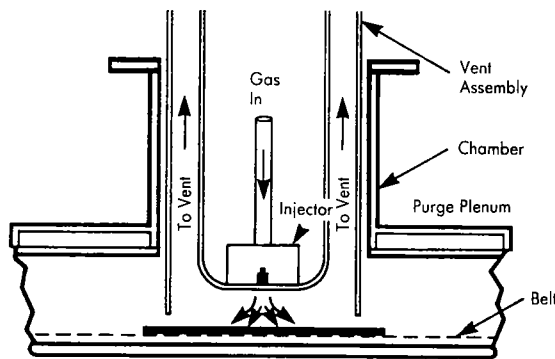
Among the metals and the silicides, the most popular metal in use today is tungsten. Tungsten is typically deposited from WF_6 by hydrogen reduction. The chemistry for this reaction is:



The process takes place at about 300°C which makes the process compatible with aluminum films. Similar reactions can be used to deposit Molybdenum, Tantalum, Titanium. Further, the silicides of these metals can also be deposited using CVD techniques. The deposition of tungsten silicide and titanium silicide proceed by the following reactions.



As mentioned earlier, there are several different reactors for depositing CVD films. The first available systems operated at atmospheric pressure. There are several different APCVD methods for depositing films. The typical system today can be seen in Figure 4.6.1.2.1-2. This schematic shows that the wafer moves along a conveyor belt that is heated from below by a hot plate. The belt moves the wafers under the nozzle which dispenses a vapor of the desired material. The reaction takes place in the



Source: Watkins-Johnson
2244-57

Figure 4.6.1.2.1-2

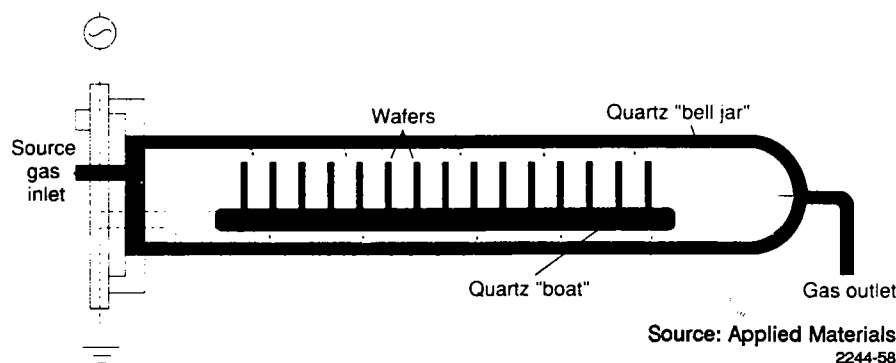
Typical Continuous APCVD Reactor

injection chamber just above the nozzle. There are other configurations of APCVD systems. These include horizontal tube, barrel and pancake systems. All of these configurations run under the same basic principle. The main difference is the chamber and method of moving the wafer.

LPCVD systems also come in many forms. The most common configuration is the use of a horizontal furnace tube. These systems are standard horizontal furnaces that have

had a vacuum pump connected to one end to reduce the pressure in the tube. A schematic of this type of system is shown in Figure 4.6.1.2.1-3. Within these horizontal LPCVD systems, wafers are placed into a quartz boat, then inserted in the tube. The wafers are heated to approximately 900 °C under reduced pressure. Gases are injected into the tube, which then react with each other causing a vapor of the desired material to form. From this vapor, the required film is deposited onto the wafers. This LPCVD method of depositing films was the standard until the mid-eighties when Anicon introduced the vertical isothermal reactor chamber (see Figure 4.6.1.2.1-4). Since then, many different chamber architectures have emerged.

As devices got more complicated, device manufacturers began to demand more sophisticated equipment. Users were looking for a system that achieved very low pressure and provided the ability to isolate the wafers from atmosphere. Many vendors such as Genus, Novellus and Applied Materials began to offer systems that met these demands. Figure 4.6.1.2.1-5 shows that the isolation of the wafers from atmosphere occurs through the use of load locks which isolate the process chamber from the clean-



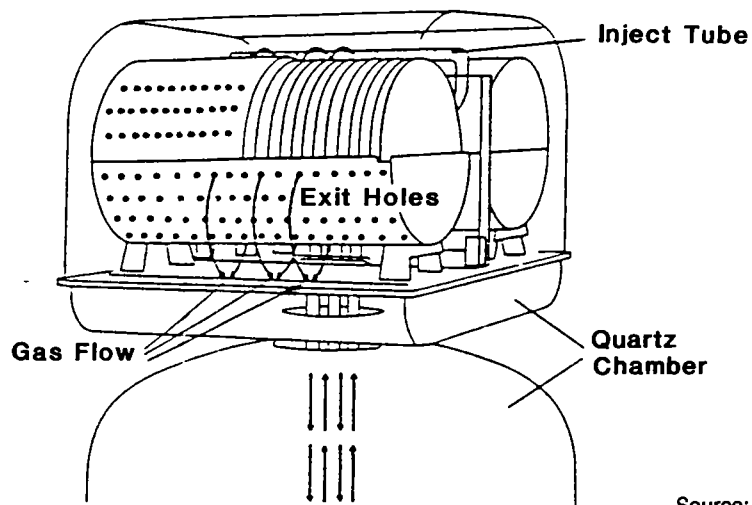
Source: Applied Materials
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Figure 4.6.1.2.1-3

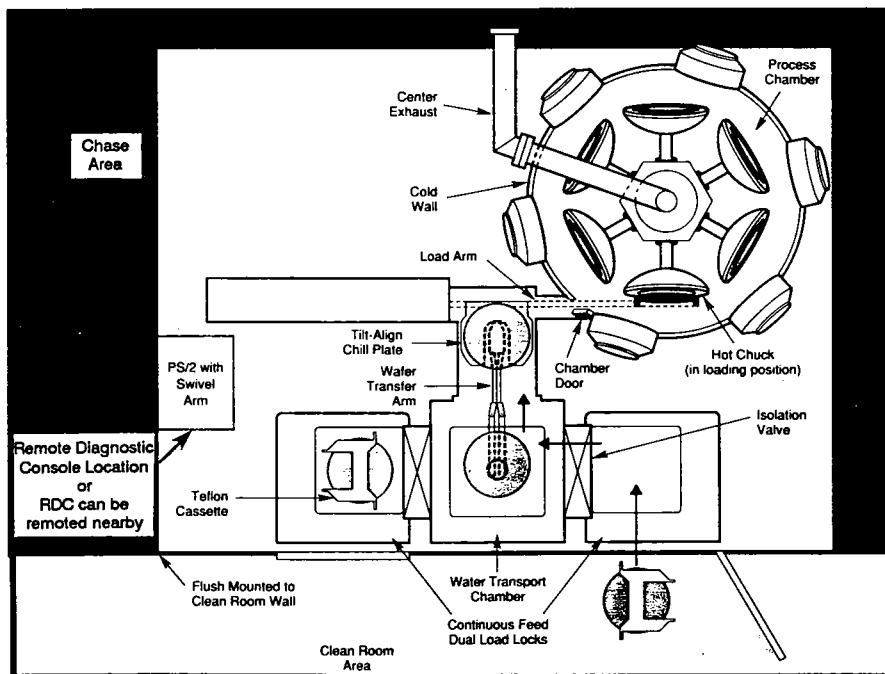
Typical LPCVD Horizontal Tube

Figure 4.6.1.2.1-4

The Anicon Vertical-Flow Bell Jar



Source: Anicon
2244-46



Source: Genus
2244-60

Figure 4.6.1.2.1-5

Load-Lock Isolation System of the Genus 8720

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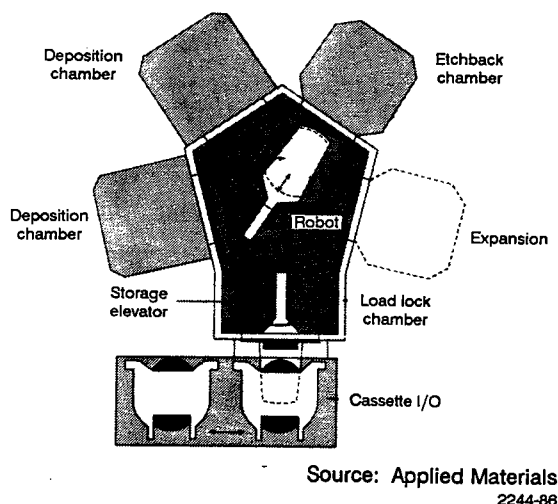


Figure 4.6.1.2.1-6

Schematic of the Precision 5000 CVD System

room and atmosphere. The advantage of these systems is that they help minimize contamination and allow for continuous processing. Applied Materials has taken the most radical departure from the tube concept by providing a single wafer multicham-

ber system, the Precision 5000 CVD. This system can have up to four CVD chambers. This system is shown in Figure 4.6.1.2.1-6.

In response to these new chamber designs, the diffusion furnace manufacturers developed vertical reactors. These systems are, in essence, standard horizontal furnaces that have been turned on their end and wafers are loaded horizontally in the tube. The benefits of the system are better contamination control, a smaller footprint and more uniform processing by maintaining good laminar flow. Figure 4.6.1.2.1-7 shows a schematic of a typical handling and elevator portion of a vertical furnace.

PECVD offers an alternative to use of thermal energy to cause the reaction in CVD. PECVD uses radio frequency-induced glow discharge to deposit the required material. The advantages of PECVD over other CVD methods, is that PECVD is a low temperature and pressure process which provides high quality, uniform films with reasonable throughput. Like the

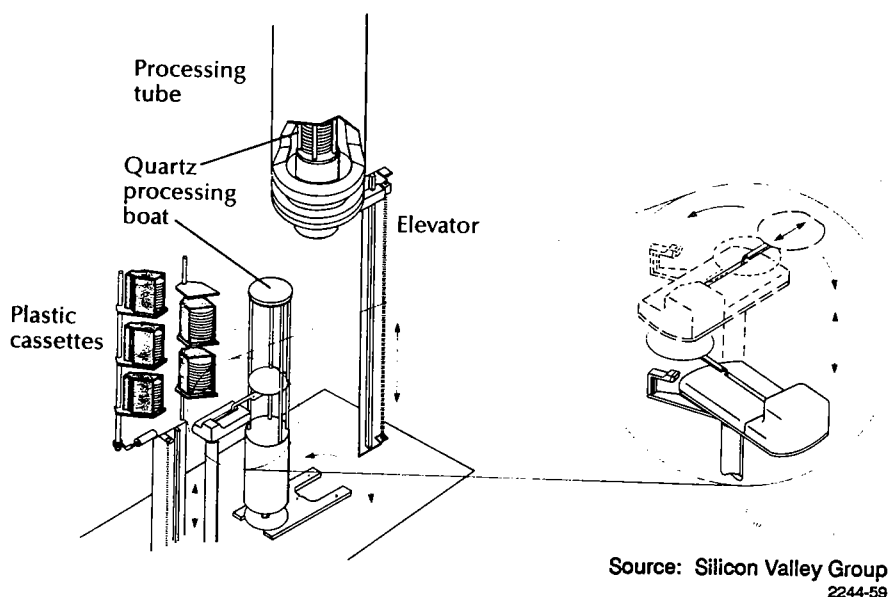
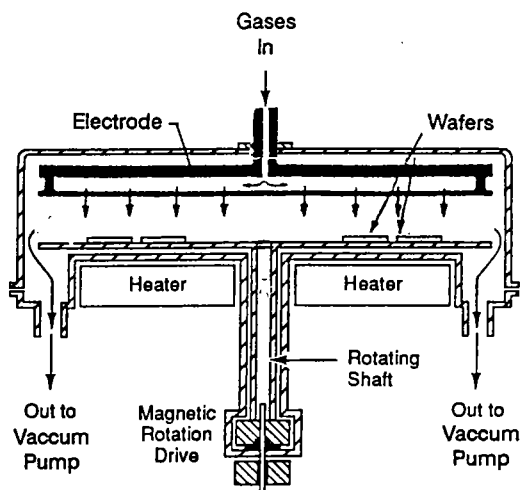


Figure 4.6.1.2.1-7

Handling Mechanism and Elevator System of a Vertical CVD Furnace

Figure 4.6.1.2.1-8

Schematic of a Vertical Flow Pancake PECVD Chamber



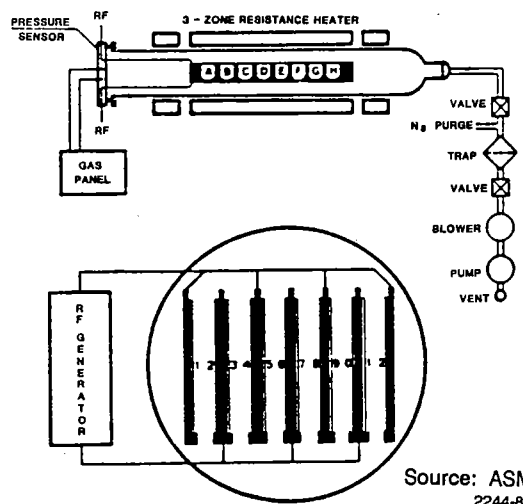
Source: VLSI RESEARCH INC
2244-69

other CVD methods, PECVD systems come in several configurations. The first configurations of PECVD were bottom-heated, pancake vertical-flow PECVD (see Figure 4.6.1.2.1-8). The schematic shows that the gases enter from the top and the electrode creates the plasma which is deposited onto the wafers. A more popular configuration was the adaptation of horizontal diffusion furnaces first developed by ASM International. A schematic of such a system is shown in Figure 4.6.1.2.1-9.

The first PICVD systems provided deposition of nitride and oxide at low tempera-

Figure 4.6.1.2.1-9

The ASM Plasma Assisted Furnace



Source: ASM
2244-87

tures (50 to 250 °C). These systems used ultraviolet light and mercury in a low pressure chamber to produce a photosensitive gas phase chemical reaction. The reaction in turn, deposited nitrides or oxides onto the substrates. There are several advantages to PICVD. The use of a UV source negates the possibility of radiation damage caused by high energy particles and there is no thermally induced film stress. Further, the films were of very high quality and contained relatively few pinholes. To date, however, the mercury process has had very little impact on the CVD market because of safety fears associated with using mercury.

These fears have led to a new PICVD method which utilizes excimer lasers to excite the process and does not use mercury vapor in the process. In contrast with ultra-violet light, photo-dissociation via a laser may prove to be a more fundamental advance in semiconductor technology. This is because laser induced CVD is not limited to oxides. It can deposit all semiconductor related materials, including silicides and refractory metals. Metals have been deposited in this manner since 1972 in the laboratory.

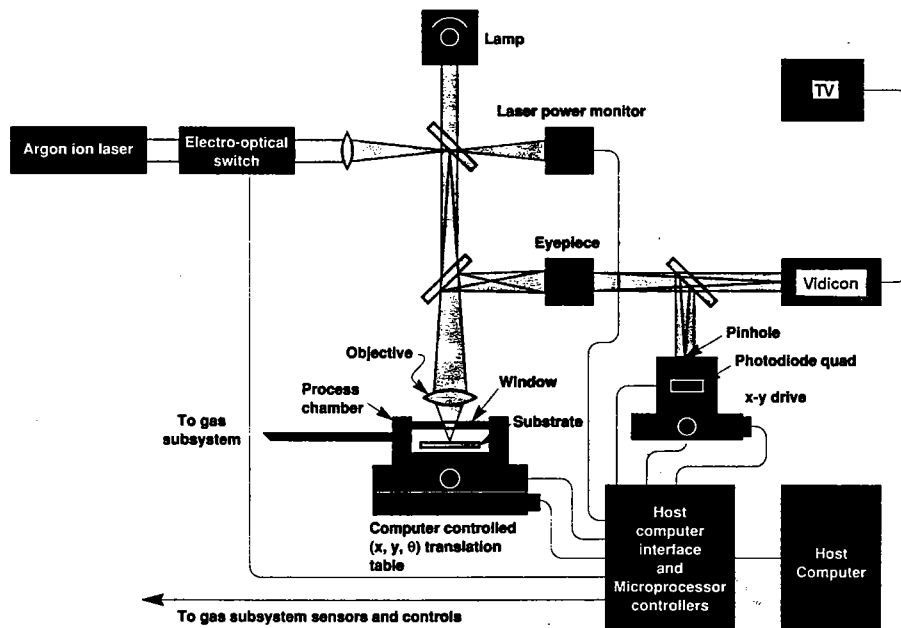
The schematic in Figure 4.6.1.2.1-10 shows how the LASA laser based PICVD system works. The benefits of a laser based PICVD system includes its ability to deposit and etch. It can even be used as a direct writing system. Hence, it has the potential to eliminate the need for microlithography, etching and deposition equipment. However, these systems will not become such a wide scale replacement tool in the near fu-

ture, they are being used for quick turn-around prototyping of device designs.

4.6.1.2.2 Physical Vapor Deposition Technology

Although there are many physical vapor deposition techniques, the focus here will be on sputtering, the dominant method used in semiconductor manufacturing today. Sputtering can deposit almost any film. But its use in semiconductor manufacturing is limited to a few layers. The primary reason for this is that PVD is about three times more expensive than CVD. This limits the use of PVD to those applications that can not be performed with CVD methods. This is usually the deposition of aluminum of aluminum alloys, which are most often sputtered.

The first sputtering systems were diode sputtering systems. This method is shown

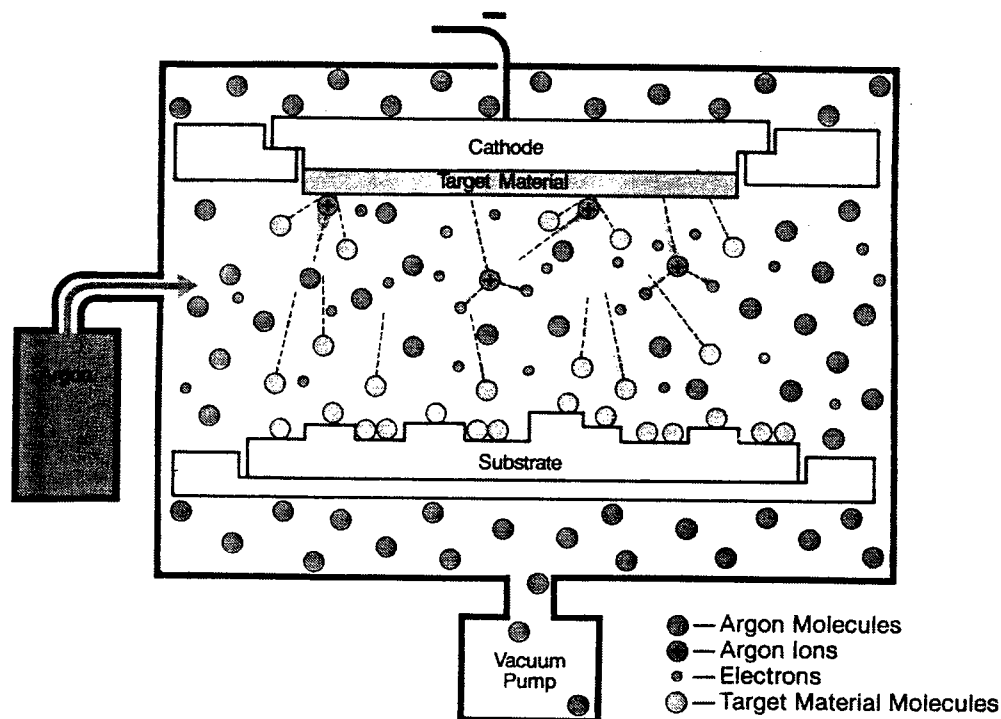


Source: LASA
2244-66

Figure 4.6.1.2.1-10

LASA's Laser Based PICVD System

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Source: CPA
2244-67

Figure 4.6.1.2.2-1

The Diode Sputtering Process

in Figure 4.6.1.2.2-1. The process is performed in a vacuum system in which there is a trace pressure of an inert gas, usually argon. The sources of the coating material, called the target, is connected to the cathode (the negative terminal). Electrons emitted from the cathode strike argon atoms, stripping away electrons to make positively charged ions in a plasma. The positive ions then accelerate towards the target, striking the target with enough force to knock molecules off of the target material. The molecules scatter towards the wafer, thereby forming a film.

Diode sputtering turned out to be a relatively energy inefficient process. Only about 2% of the energy applied to the discharge resulted in a deposition of a film. In addition, the heat developed during the process

lead to uneven film deposition and oxidized the aluminum. Finally, out gassing from the atoms that deposit on the sides of the chamber introduced contamination into the process.

Magnetron sputtering was developed to solve these problems and has become the method of choice within the semiconductor industry. Its advantage is that it keeps the wafers cooler and it focuses the molecules direction towards the target thereby achieving ten times the deposition rate of a diode target. Figure 4.6.1.2.2-2 shows a schematic of magnetron sputtering system. The primary difference between diode and magnetron sputtering is that magnetron sputtering uses a strong magnet set, usually located behind the target, to confine the electrons to the front of the wafer. These

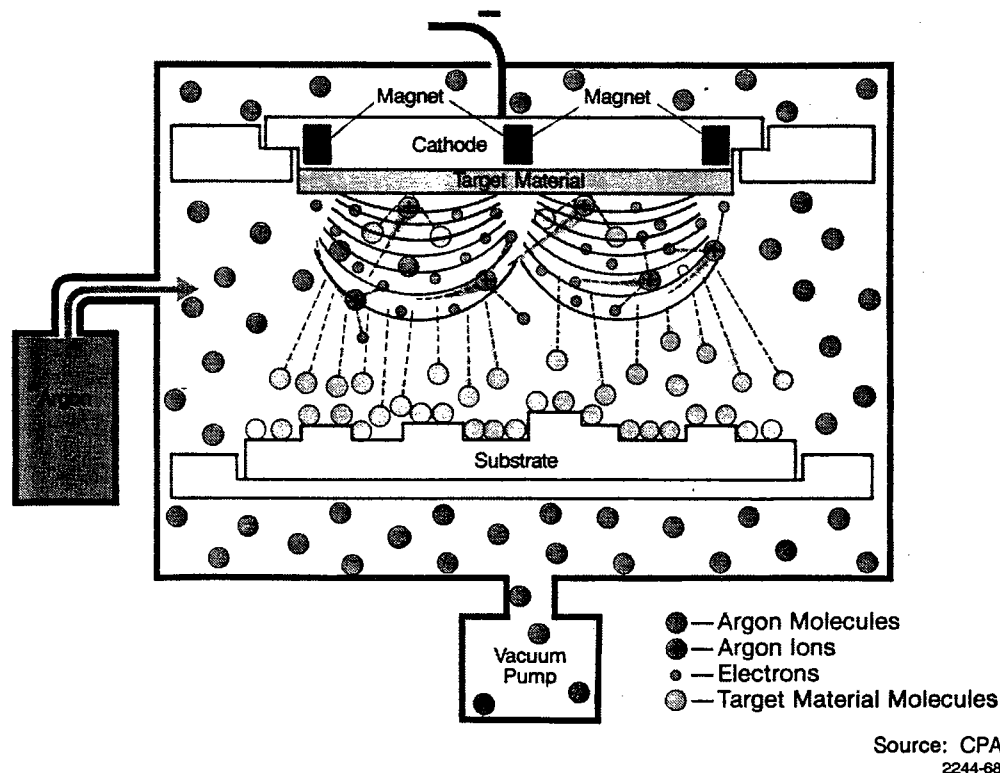


Figure 4.6.1.2.2-2

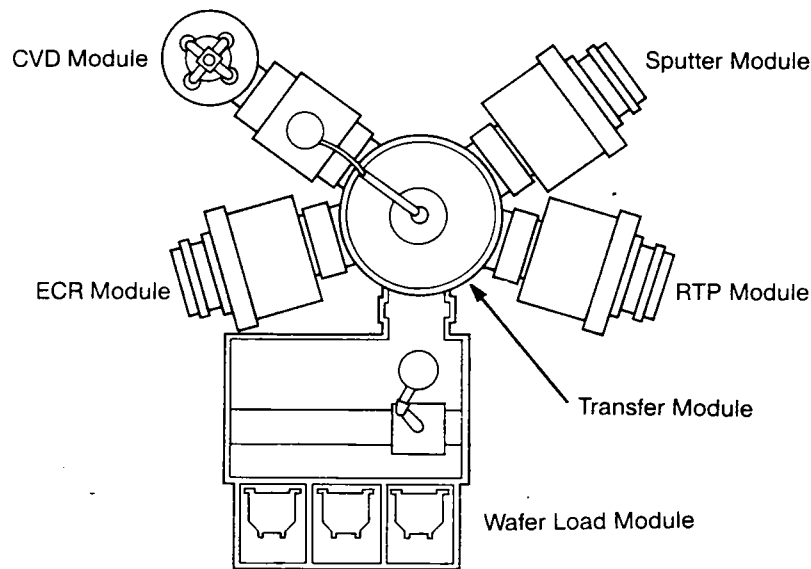
The Magnatron Sputtering Process

trapped electrons strike a greater number of gas molecules which increases the ion density in the plasma. This has the effect of increasing the sputtering rate. In addition, the cathodes are often configured with a separate anode that is positively charged and can collect the thermalized electrons. This allows the wafers to be almost completely removed from the electrical circuit.

There are many variations of the magnetron sputtering. Co-sputtering can be accomplished by placing two or more targets in the systems. This expensive technique can be used to create an alloy. The magnetic field can be induced by either electromagnets or permanent magnets. An electron cyclotron resonance source can also be used

to create a plasma. Further, the systems can be single wafer or batch. In essence, a sputtering method has been created to fit the need of nearly any production environment that a semiconductor manufacturer might require.

The most recent technological advancement in sputtering is the cluster tool. Typically, these systems are single wafer which use a central handler to distribute the wafer to the proper processing chamber. The similarity of the architectures being used by these vendors can be seen in Figure 4.6.1.2.2-3 which shows the Varian M-2000 and Figure 4.6.1.2.2-4 which shows the Applied Materials 5500.



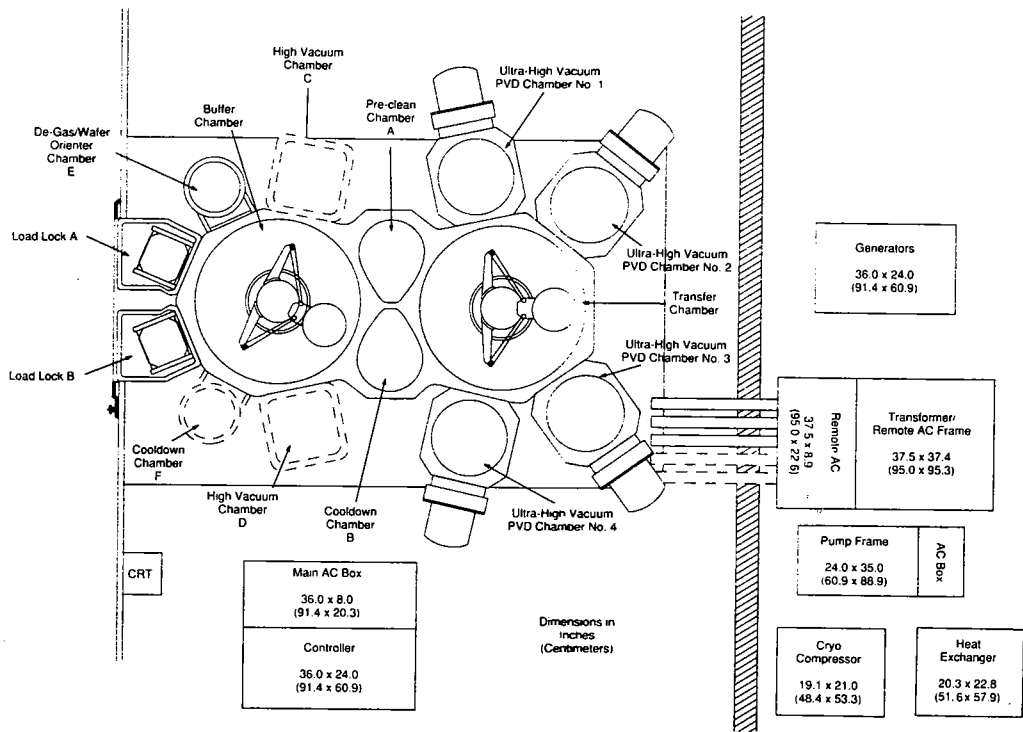
Source: Varian
2244-53

Figure 4.6.1.2.2-3

Conceptual View of the Varian M2000 Cluster Tool

Figure 4.6.1.2.2-4

Schematic of the Endura 5500 Cluster Tool From Applied Materials



Source: Applied Materials
2244-52

4.6.1.2.3 Epitaxy Technology

Epitaxial equipment is used primarily to deposit silicon. There are a number of different sources that can be used to deposit epitaxial silicon. The most common sources are found in Table 4.6.1.2.3-1.

TABLE 4.6.1.2.3-1

Chemical Sources of Epitaxial Silicon

Silicon Tetrachloride $\text{SiCl}_4 + 2\text{H}_2 \rightleftharpoons \text{Si} + 4\text{HCl}$

Silicon Tetrahydride $\text{SiH}_4 + \text{heat} \rightarrow \text{Si} + 2\text{H}_2$

Dichlorosilane $\text{SiH}_2\text{Cl}_2 \rightleftharpoons \text{Si} + 2\text{HCl}$

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The choice of a silicon source is dependent on the quality required, the temperature of the deposition chamber being used and the compatibility of the source with the equipment. Silicon tetrachloride (SiCl_4) was the first high-volume production silicon source for epitaxy. This was primarily due to its availability and high purity. SiCl_4 does not decompose thermally as do the other silicon halides and hydrides. Thus, a relatively high

temperature and H_2 are required for the reduction of SiCl_4 .

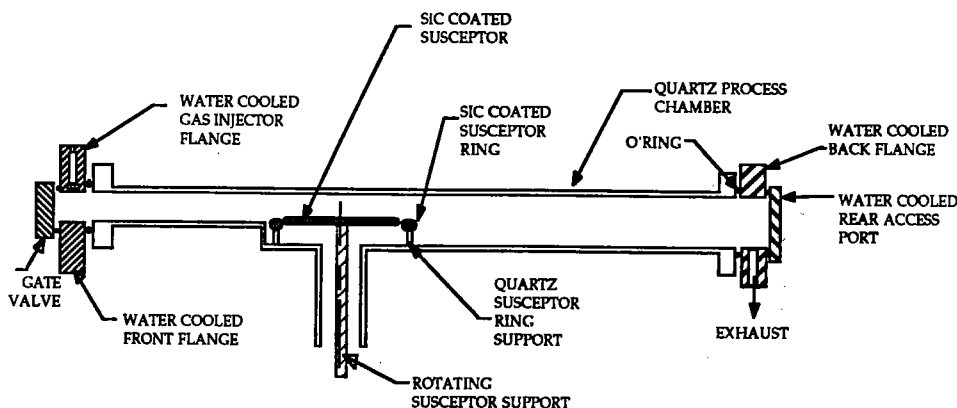
The requirement for low temperature processing has made dichlorosilane (SiH_2Cl_2) the most popular epitaxial source in production today. The lower temperature needed to perform the chemical reaction reduces autodoping and solid-state diffusion from previously diffused burned layers and provides a more uniform crystal structure.

Silicon Tetrahydride (SiH_4) can be used for silicon epitaxial layers. This chemical can be deposited at even a lower temperature than SiH_2Cl_2 and it presents even fewer problems with autodoping due to the lack of a halide by-product. But, the use of SiH_4 presents problem when it is used to deposit films thicker than a few microns. This is due to thermal decomposition in the gas phase as well as at the growing silicon surface. The gas phase decomposition results in silicon particles forming in the vapor phase, which may deposit on the silicon surface. These particles give spurious nucleation sites that cause defects in the epitaxial film.

There are several types of epitaxy reactors. Figure 4.6.1.2.3-2 shows a schematic of a

Figure 4.6.1.2.3-2

Reactor Chamber of the Epsilon One™ Single Wafer Epitaxy System



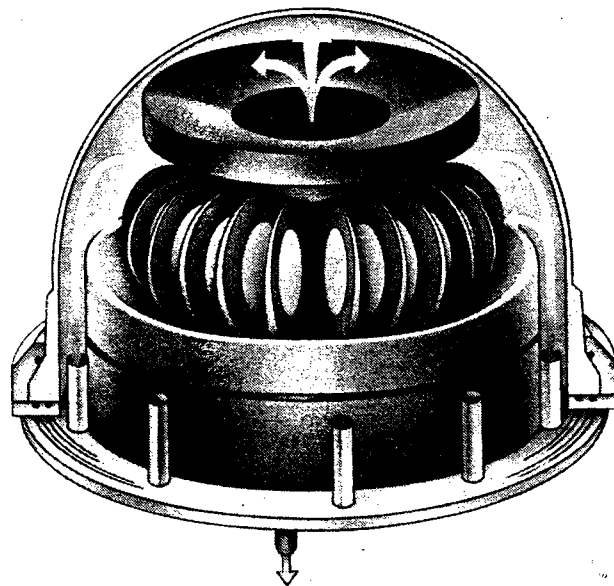
Source: ASM
2244-62

single wafer reactor. This reactor is a radiantly heated, low profile horizontal deposition chamber. The process gas flow enters from the left in the figure, and makes one pass over the rotating wafer and susceptor. This chamber can grow epitaxial silicon at the rate of five microns per minute. Another type of reactor chamber is shown in 4.6.1.2.3-3. This is a batch system. Each wafer resides in its own isothermal cavity that assures slip free heating, maintains wafer flatness and eliminates degradation of the wafer's back surface.

Molecular beam epitaxy is niche technology that is used primarily for materials from the III-V category. Typically, it is used for GaAs applications. The basic MBE chamber is shown in Figure 4.6.1.2.3-4. The growth of single crystal or compound films is accomplished by directing an electron beam at the source of material, which heats it to a liquid state. In this state, atoms evaporate out of the material, exit the cell

through an opening and deposit on the wafers. In most applications, the wafer is heated to give additional energy to the arriving atoms. The flex of the beam and the substrate determine the growth rate. One of the most critical components of the MBE system is the source of the molecular beams. These sources can be either thermal evaporators, cracking sources, e-beam sources or gas sources. Within an MBE system, each different material to be grown requires a separate source. For example, the growth of doped Al GaAs requires five different sources: One each for the Al, Ga, As and the P and N-type dopants. Most commercially available systems allow the installation of up to eight sources.

The main disadvantage of MBE is the slow rate of deposition, 60 to 600 angstroms per minute. The advantages of MBE are the ability to control the process the ability for low temperature (400 to 800 °C) processing and the ability to form multiple layers and

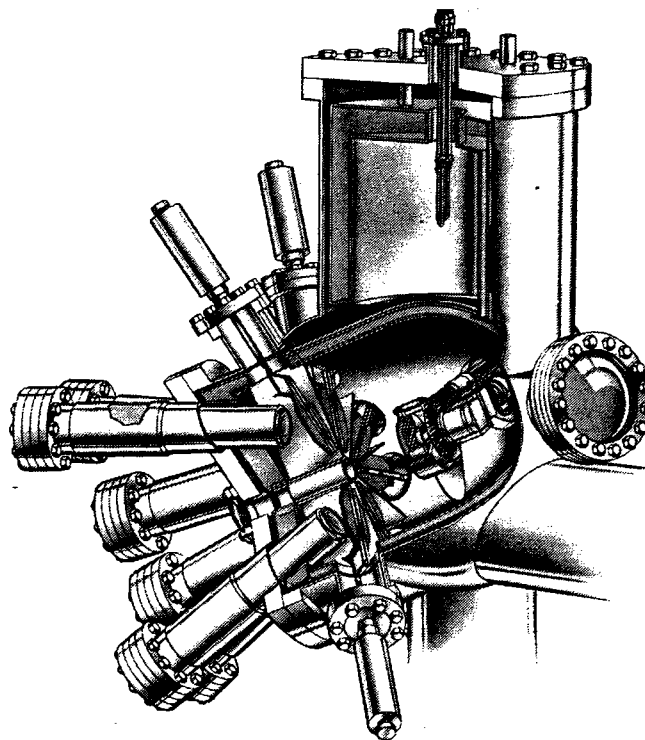


Source: Gemini/Lam
2244-63

Figure 4.6.1.2.3-3

Reactor Chamber of the Tetron One Epitaxy System

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Source: VG Semicon
2244-64

Figure 4.6.1.2.3-4

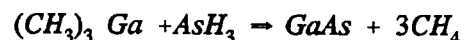
Growth Chamber of the V80H MBE System

the wafer during one process step. However, most semiconductor applications do not require the benefits that MBE provides. The inability of MBE to add anything to the manufacturing process, along with the system's low throughput and high cost, has relegated it to niche applications.

The same has happened to MOCVD. MOCVD is a vapor phase epitaxy method and that compete against MBE for GaAs applications. MOCVD is best known for its ability to deposit single crystal GaAs and GaAlAs. MOCVD systems use two different chemistries, halides and metalorganic. Halide MOCVD is a hot-to-cold reaction in which, for example, a group III halide is produced in a hot zone via reaction to a

group III element with HCl. The group-III halide then diffuses to a cold zone and reacts with a group-V species to form a III-V compound.

In the metalorganic reactions, GaAs is grown by metering trimethylgallium (a group III alkyl) and arsine (a group V hydride) into reactor. The reaction is as follows:

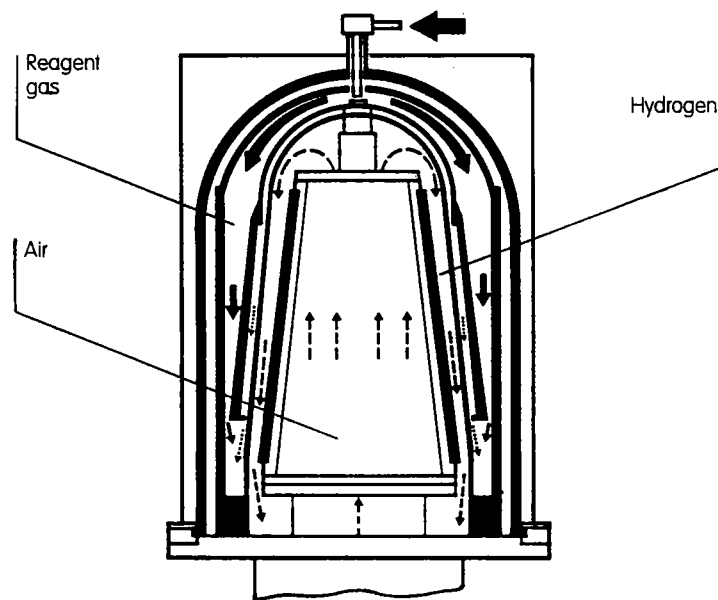


This reaction is a pyrolysis of the vapor phase mixture of the reactants in the temperature range of 600 °C to 800 °C. The

reactants crack and the gallium and arsenic elements diffuse through the boundary layer in the reaction chamber to combine on the hot wafer surface.

Up until the eighties, most reactors were semi-custom systems that were designed to meet the needs of the individual user. Since that time several commercially available systems have appeared. Typically, these systems use a barrel chamber like the one shown in Figure 4.6.1.2.3-5. Vertical configurations are also available. The figure shows a barrel configuration. The typical MOCVD reactors are configured for several sources to enable the deposition of multi-

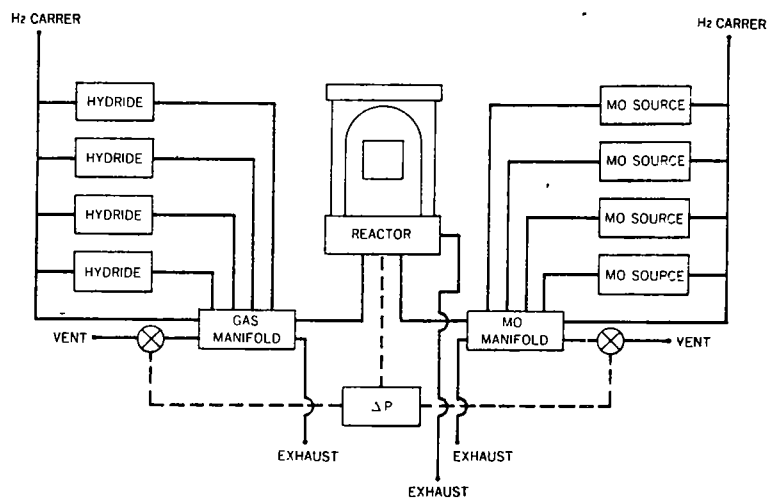
layer and multi-element thin films in a single growth sequence. Figure 4.6.1.2.3-6 provides a schematic of a MOCVD system where this is accomplished by having several sources available. The way the gases are metered into the chamber determines the layers and elements that are deposited during the growth sequence. As was the case with MBE, the throughput of MOCVD systems is low and the costs are high. Thus, these systems have not made it in mainstream silicon applications and has limited their use to niche technologies such as photovoltaics, photocathods and microwave circuits.



Source: Cambridge Instruments
2244-65

Figure 4.6.1.2.3-5

Typical MOCVD Reactor Chamber



Source: SAMCO
2244-88

Figure 4.6.1.2.3-6

Schematic of a Typical MOCVD Reactor