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〈기술해설〉

Drypumping of Semiconductor Processes-Clean and Arduous Applications

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반도체 공정에서의 건식 펌프

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ABSTRACT－We review the dominant technologies used to pump semiconductor process tools in the pressure range to 10^{-9} Torr and attempt to address the question of technological direction for vacuum generation in this industry. In particular, the principles of operation of Roots, Claw, Roots/claw and magnetic levitation turbomolecular pumps are discussed.

요 약－10^{-9}Torr 정도의 압력에서 작동하는 반도체 공정 도구들을 펌프하기 위해 주로 사용되는 기술들을 살펴보고, 이 분야에서 진공을 만드는 기술적 방향에 대해 언급한다. 특히, Roots, Claw, Roots/claw 펌프의 작동원리와 자기 부양식 turbomolecular 펌프를 다루었다.

1. Introduction

In its normal context, the term "dry pump" is used to describe a positive displacement vacuum which discharges continuously to atmospheric pressure and in which the swept volume is free of lubricants or sealing fluids. Other types of pump, such as turbo-, cryo- and sorption pumps may also be dry but do not discharge continuously to atmosphere. The operating principles of various types of dry pump have been reviewed in recent literature [1, 2].

In this paper, it is recognised that many new applications require to be pumped by clean, oil-free pumping systems to pressures as low as 10^{-9} Torr. Using current technology, and with the additional requirement for durability and reliability, this can only be achieved by the use of more than one pump, typically and increasingly a magnetic levitation turbo pump (MLTP) backed by a positive displacement machine.

Driven mainly by the requirement for high reliability, the prevailing opinion is that MLTP's backed by dry primary pumps will come to dominate vacuum generation at the "Hi-Tech" end of the semicon market; this paper will therefore concentrate on these two technologies.

2. History of Dry Primary Pumps

Prior to 1984, a number of experimental and special purpose dry primary pumps had been devised. Most of these earlier machines were too expensive or required impractically small running clearances

Pumping Principle	Pult Torr	Japan	Row	Remarks
Multistage Roots	0.004	3	2	5 or 6 stages; intercoolers
Multistage Screw	0.005	5	–	High speed(10,000 rpm); small clearances(0.1 mm)
Multistage Piston	0.01	–	1	Very clean
Screw+Carbon Vane	0.0005	1	–	Carbon blades degrade
Orbital Scroll	0.001	3	1	Small clearances
Roots+Claw	0.007	–	1	1 Roots+2 or 3 Claw Stages
Claw	0.004	–	2	1 to 4 Claw Stages
Molecular Drag or Hybrid +Diaphragm	$10^{-5}\sim10^{-9}$	–	2	Low Throughput at High Pressure
Multi-principle, Single Shaft	0.001	1	–	High speed(30,000 rpm); high power
Membrane	5	Many	Many	Limited Corrosion Resistance and Life

Fig. 1. Dry pump principles, showing manufacturer's claimed ultimate pressures. Estimates of the number of manufacturers in Japan and the Rest of the World (ROW) are shown. "Hybrid" indicates turbo+molecular drag stages on a single shaft.

to be commercially viable.

The first practical industrial dry pump was introduced in 1984 in Japan and was based on the Roots principle with 6 stages in series. Following prolonged field trials in the semiconductor industry, the first of the Roots/claw machines was introduced in a 3-stage version in 1985. Since 1985, there has been a multitude of dry primary pumping mechanisms based on diverse principles such as screw compressors, orbital scroll compressors, piston pumps, axial compressors and diaphragm pumps. Some devices combine two or more pumping concepts in a single package (Fig. 1).

Initially, the high capital cost of dry mechanisms tended to limit their use to applications where conventional oil-sealed pumps were having serious problems of service life. Examples of difficult processes are aluminium-etch, low pressure CVD, low temperature oxide (LTO), tungsten and nitride deposition. In such processes, the problem for the pump group is one of coping with gross quantities of process byproduct in the form of dust, subliming solids, corrosive vapours or residual process chemistry within the pump mechanism.

With the use of perfluoropolyether (PFPE) fluids and comprehensive filtration accessories, oil-sealed rotary pumps were evolving to meet the challenge. However, the greatly increased time between major service intervals and the elimination of consumable items such as expensive lubricants or filters, made dry pumps attractive to end-users. Their operating costs are lower to the extent that, even with their high capital cost, they typically pay back within a year. For example, the cost of PFPE fluid and filter elements for an oil-sealed rotary pump used on an LTO process is typically \$6000/month, with pump replacement every 6 months[3].

It was success in the pumping of very harsh semiconductor applications which initially established the commercial viability of dry pumping. Throughout the late 80's, however, the technology thrust towards 16 and 64 Mbit DRAM chips and the increasing requirement for ultracleanliness in all aspects of wafer processing, has created a new application sector for dry pumps. As the benefit of extreme measures to avoid particulate generation and contamination become established in Japan in the form of improved yield, researchers and some end-users are setting extraordinarily demanding standards of cleanliness. There is also a strong trend for process engineers to require MLTP/dry pumps for pumping equipment such as load locks (an application which is not arduous and where commercial considerations have historically proscribed their

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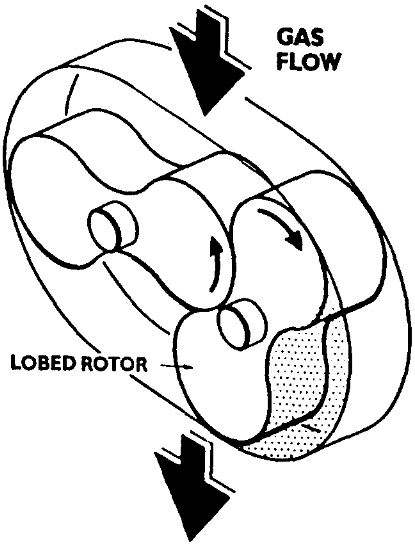

Fig. 2. A 2-lobe Roots stage showing the flow path and the displacement volume of the right impeller only.

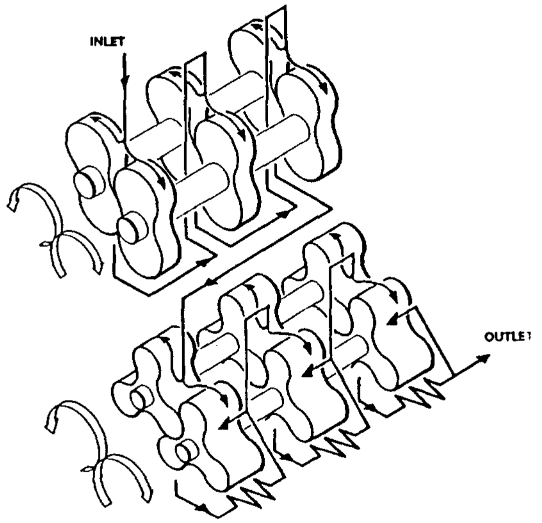

Fig. 3. An industrial 6-stage Roots dry pump, organised as two machines in series. The gas and recirculation paths are shown by arrows.

use), mainly in order to be certain that organic contamination cannot occur.

The utilisation of dry *primary pumps* in the semiconductor industry is now split into these two main application sectors, i.e. clean pumping and the reliable pumping of very harsh and difficult processes.

3. Principles of Operation

3.1. Dry primary pumps

At present, the dry primary pump market is dominated by devices which employ one of only two pump design concepts, namely (a) machines based entirely on Roots impellers, usually with 5 or 6 stages and interstage cooling; (b) machines based on a mixture of Roots and claw impellers, or based entirely on claw impellers, usually with 4 stages and no interstage cooling.

3.1.1. Roots machines

Figs. 2 and 3 illustrate the principle of a multistage Roots machine and Fig. 4 shows a single compression cycle for one stage. Roots stages are very efficient in compression at pressures below 10 Torr. Fig. 5 shows the ratio of outlet to inlet pressures as a function of outlet pressure for one size of Roots stage; it can be seen that the compression exhibits a steep maximum at 0.6 mbar (0.8 Torr), falling slowly on the low pressure side and more rapidly on the high pressure side. At atmospheric pressures, the ratio has decreased to a value in

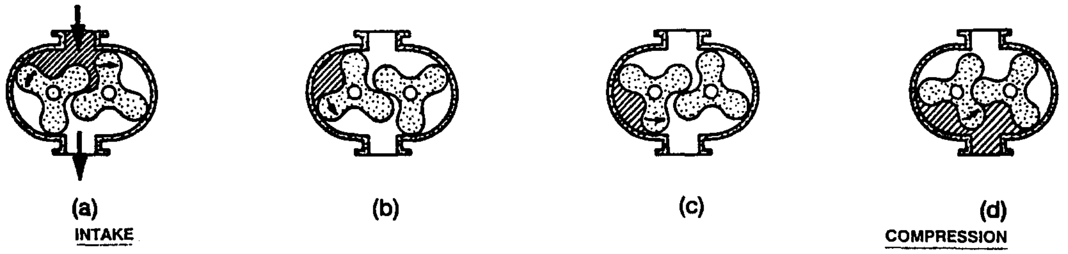

Fig. 4. (a)-(d) The volumetric transport of 1 of 6 discharges per revolution for a 3-lobe Roots stage. Note that the pumping action of the left impeller only is shown. For low inlet flows, considerable heating of the gas occurs due to repeated compression and re-expansion of the exhaust gas.

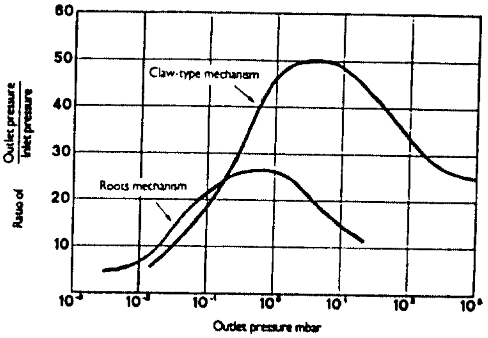

Fig. 5. Comparison between the pressure ratios developed across a Roots stage and a claw stage of differing displacements, as a function of stage outlet pressure.

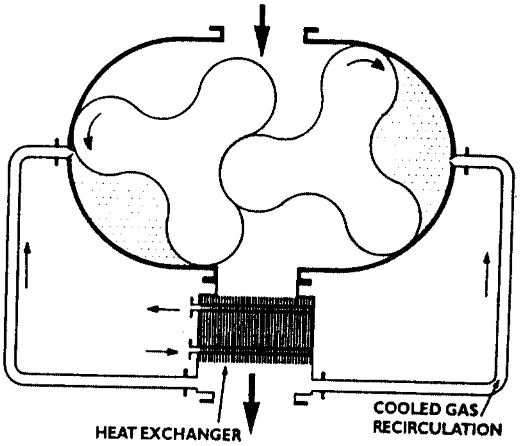

Fig. 6. Recirculation and heat exchanger configuration for a typical Roots working above 10 Torr but with low throughput. Recirculation creates a continuous flow through the heat exchanger and cools the exhaust gas.

the range 1.5-2.0.

It is common practice to use 2-lobe impellers at low pressures and 3-lobe impellers at high pressures. Series-connected Roots stages require a definite size progression of swept volume from stage to stage which is optimal for only one particular inlet pressure. The switch to 3-lobe impellers is a consequence of the need for size progression, and also permits the use of recirculation cooling, as described below. A 3-lobe Roots stage gives six compressions per revolution, since each lobe on each shaft transfers a quantity of gas to the outlet of the stage.

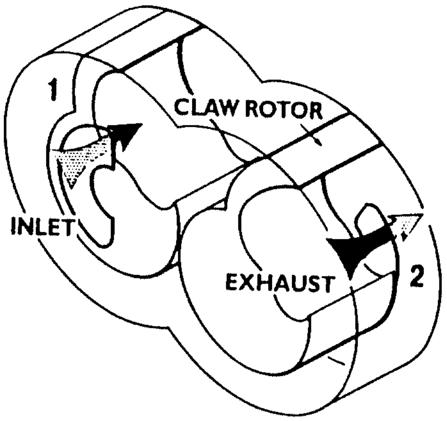

Fig. 7. A claw stage showing the location of the inlet and exhaust ports.

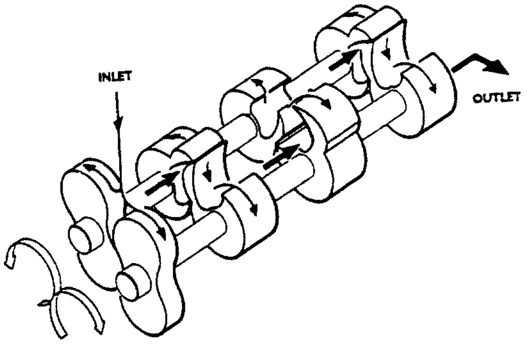

Fig. 8. An industrial Roots/claw pump showing the rotor configuration; the gas path is shown by arrows. Note the reverse orientation of the middle claw stage.

The stage pressure drop is applied across the rotor tips and the line of near contact of the rotors in the centre of the stage - ther clearance at this point is critical and it can easily become the point of greatest unwanted reverse flow in the mechanism.

At low gas flows, the high pressure stages generate considerable heat due to continuous reworking of the gas in the exhaust volume of each stage. To reduce heating of the impellers, multi-stage Roots machines usually require recirculation of cooled gas from the outlet of a stage back into its swept volume (Fig. 6). The technique is typically used on the three high pressure stages in a 5 or

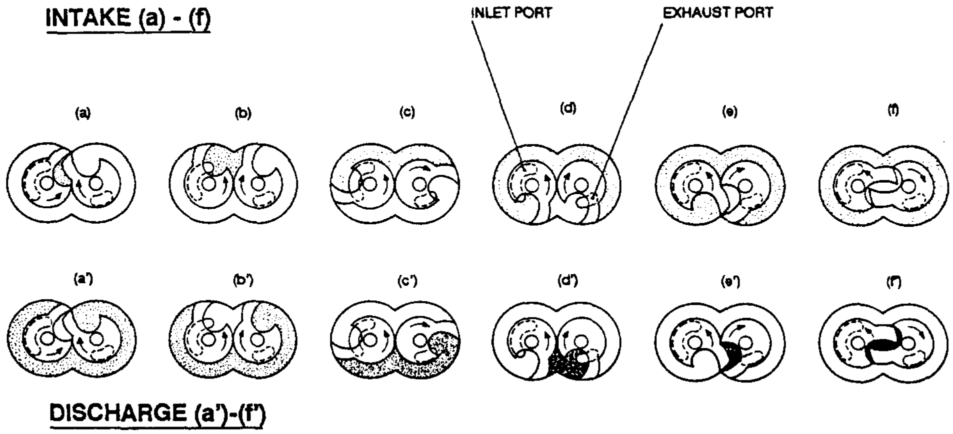

Fig. 9. Compression sequence for 1 revolution of a claw stage. (a)-(f) show the intake sequence with the inlet port open from (b)-(d). The compression and exhaust sequence is shown in (a')-(f') with the exhaust port open from (c')-(d'). The carry-over volume, which limits the maximum obtainable compression, is shown in (f').

6-stage machine. The heat generation is an unavoidable consequence of the pumping principle and intercoolers must be used, particularly if heat load (e.g. to clean rooms) must be minimised.

3.1.2. Claw and roots/claw machines

Figs. 7 and 8 illustrate the principle of a claw-impeller pump and Fig. 9 shows a single compression cycle for one stage. It should be noted that each claw pair is self-valving both at the stage inlet and outlet, such that when all outlets are open, all inlets are also open. At such times, the stage pressure drop is applied across both rotor tips and the line of near contact of the rotors in the centre of the stage - the clearance at this point is critical and it can easily become the point of greatest unwanted reverse flow in the mechanism. In order to achieve compression, it is desirble to ensure that the total backflow per revolution through all clearances is small in comparison to the carryover volume. Under these conditions, the stage pressure ratio at zero flow is proportional to the square of the raio of the swept volume to the carryover volume [4]. This condition is most readily approached by increasing the rotational speed; since noise, vibration and power consumption also increase rapidly with rotational speed, there is clearly an optimum running speed which depends on the physical size of the mechanism.

By reversing the orientation of alternate rotor pairs, each stage can communicate with the next via a very short gas path. This is important in minimising dead volumes and cold spots in the interstage gas paths. Local gas temperature can have a profound effect on the tendency for some process gases to deposit solid material in the pump.

Series-connected claw stages give good compression even without stage size progression. The ratio of outlet to inlet pressure as a function of outlet pressure is also shown in Fig. 5, where it can be seen that the ratio exhibits a pronounced maximum at 3 mbar (4 Torr), falling slowly to the high pressure side and more rapidly to the low pressure side - this behaviour is the reverse of that of a Roots stage. At atmospheric pressure, the ratio tends asymptotically to a value typically in the range 12-25 depending on impeller size i.e. the impeller is still efficient at high pressures. It is for this reason that the design of a highly efficient multi-stage pump should employ Roots impellers for the low pressure stage(s) and claw impellers for all of the high pressure stages.

Roots impellers exhibit the undesirable property of requiring to be angularly synchronised to a small fraction of a degree of rotation, thereby greatly complicating the engineering design of small-capa-

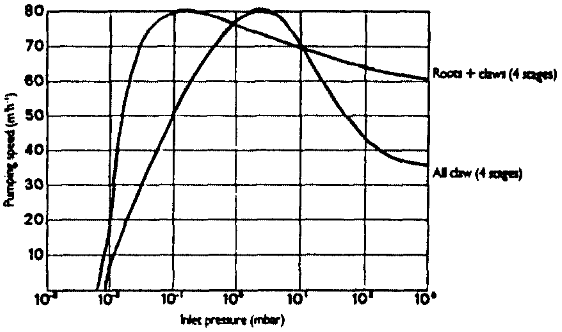

Fig. 10. A comparison of the pumping speeds for two 80 m³/hr dry pumps, one with a Roots/claw configuration and the other with claws only.

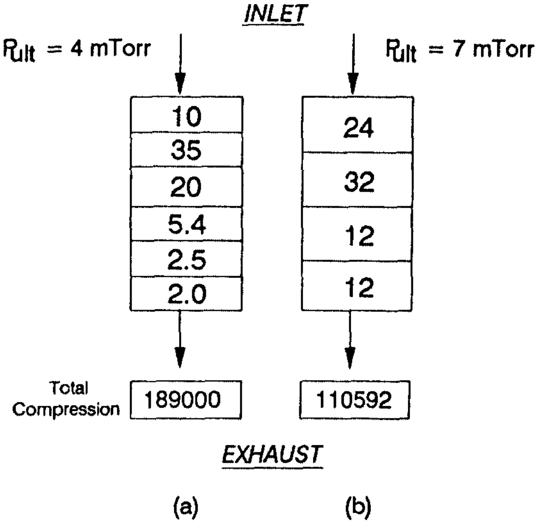

Fig. 11. Comparison of the stage pressure ratios for typical examples of (a) 6-stage Roots pump (b) 4-stage Roots/claw pump of comparable displacement. The measured values apply at ultimate pressure with no gas ballast or purges.

city (i.e. 25 m³/hr or less) mechanisms, due to the risk of rotor collisions. Because the timing requirements of claw impellers are much less critical, they are better suited to the engineering task of designing multi-stage small dry pumps.

As will be discussed below, the discharge pressure of compound MLTP's is desirably in the range of a few Torr to enable reduced diameter forelines between the turbopump and its backing pump, which is typically some distance away. As can be

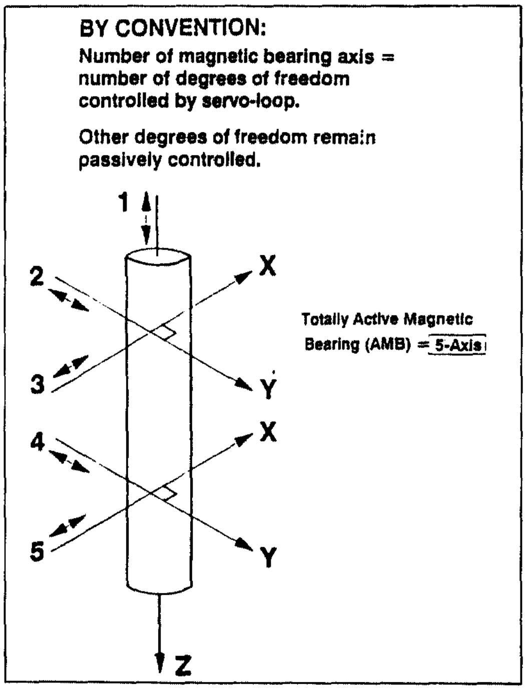

Fig. 12. Definition of the geometry of the bearing control axes in a magnetic levitation turbo pump.

in pumping speed at low pressure due to an all-claw construction is a significant disadvantage.

As discussed above, the mechanism is engineered such that the most significant backflow is due to the carryover effect, the volume of which can be made small in the design of the claw profile. Since each stage is acting as a self-valving, pure compressor and therefore requires minimum power from the motor at low flow-rates, the main consequence of this small backflow of hot gas is that only mini-seen from Fig. 10, the pumping performance of an all-claw machine is well matched to this requirement. For larger semicon pumps operating in a stand-alone mode or with a Roots booster, the loss mum cooling needs to be employed, resulting in low heat load to the cooling system. The stage compression ratios (defined as the ratio of outlet pressure to inlet pressure for each stage) for a modern 6-stage Roots machine are compared with a 4-stage Roots/claw pump of similar displacement in Fig. 11.

3.2. Magnetic levitation turbopumps

In conventional turbopumps, there are normally

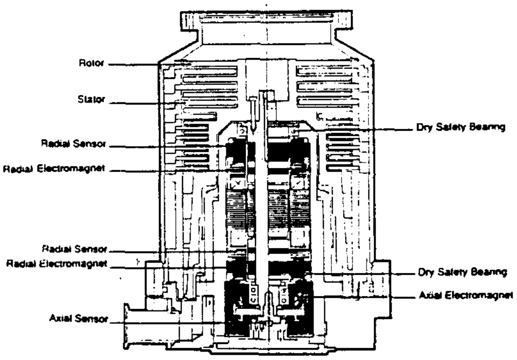

Fig. 13. A cross-sectional schematic of a 5-axis magnetic levitation turbo pump showing the main components of the bearing system.

two rolling element bearings which support the rotor. Such bearings invariably have a finite life which is dependent on preventive maintenance - especially relubrication - and the mechanical perfection of the bearing itself. In the MLTP, one or both of these bearings is replaced with a non-contacting magnetic suspension. Fig. 12 defines the nomenclature of magnetic bearing axes.

Megnetic bearings fall into two classes - avtive axis bearings and permanent magnet bearings. An active bearing contains a position sensor and a feedback loop which continuously corrects the position of the rotor element. Both active axis and permanent magnet bearings are primarily designed to generate high radial stiffness but, as a direct consequence of their principle of operation, they also generate significant axial forces. Earnshaw's Theorem [5] shows that it is impossible to construct a stable suspension system using only passive magnetic suspension. It is, therefore, necessary to have at least one active axis on a fully levitated rotor. For big pumps (500 *l*/sec or more), the large forces required to stabilise the rotor are more consistent with the use of electromagnets, resulting in pumps with 5 active axes. Fig. 13 shows an example of a 5-axis pump. For smaller pumps, it is practical and economical to use 2 permanent magnet radial bearings and a single axial, electromagnetic positioning system. There are applications for almost every possible combination of magnetic and rolling element bearings.

4. Clean Pumping

Much of the technology trend toward the use of dry pumps for clean applications has been driven by fundamental work in Japan. Ohmi's group has concluded [6] that contamination of wafer surfaces and films by the residual atmosphere must be eliminated if the fabrication of ULSI circuitry is to achieve acceptable yield. For instance, the growth of ultra-thin gate oxide was shown to benefit from the use of ultraclean, UHV equipment [7]. The requirement to achieve ultraclean and lightweight chambers for the next generation of cluster tools has created a new aluminium processing technology, resulting in surfaces with static outgassing rates which, at less than 10^{-13} Torr·*l*/sec·cm^2 [8], are more than 10 times lower than for stainless steel. The continuous pumping of such machines requires that the pumps themselves should not be capable of introducing contamination into the system. There are the additional requirements for very high reliability and long major service intervals. For UHV process tools, the technology of choice for high speed, high vacuum pumping is rapidly becoming the magnetic levitation turbopump.

For turbopumps running at full speed, the risk of backmigration of contaminants from the exhaust side of the pump is insignificant due to the very large compression ratio ($>10^9$) for most gases and vapours. Problems arise from two sources - one when the pump has been stopped, thereby allowing backmigration of contaminants to the inlet side of the pump; the other from the relatively modest compression ratio for hydrogen, ranging from 10^3 to 10^5.

The need for efficient pumping of hydrogen and the drive towards UHV has resulted in evaluation in Japan of a "tandem" turbopump, in which one MLTP is mounted at the inlet (and is backed by) a second MLTP, which is itself backed by a dry primary pump [9]. Such a combination, with the upper pump body and rotor electropolished and ultraclean, achieved a system base pressure of 5×10^{-11} Torr after a 29 hour light bakeout at less than 100℃. The compression ratio for hydrogen, measured at an outlet pressure of 0.1 Torr, was

5×10^8.

To minimise organic contamination, MLTP's are now commonly used (there are over 700 installations in semicon applications); these pumps obviously contain no lubricants and are very reliable, offering over 2 years of maintenance-free operation even on metal etch and LPCVD applications. They must, however, be backed by a dry, contamination-free primary pump.

The cleanliness of an industrial primary pump is ultimately determined by the concentration of residues from the manufacturing process, since all precision components are machined using cutting oils, etc and must then be cleaned with solvents. Standard solvent cleaning and vapour degreasing techniques are effective in removing hydrocarbon contamination. When analysed using a mass spectrometer, the residual atmosphere above a typical dry primary pump with an ultimate pressure of approximately 6×10^{-3} Torr shows hydrocarbon lines which are individually less than 10^{-6} Torr (nitrogen equivalent pressure) [10]. To suppress backmigration arising from hydrocarbons or PFPE from seals and bearing below measurable limits, continuous-flow gas barriers and/or inlet purging schemes are used. These provide the important additional benefit of establishing a known residual atmosphere (usually dry nitrogen) at the inlet of the pump (since the pump is a pure compressor, the atmospheric composition at the inlet would mirror the exhaust if no purges were added). It has been shown that, for dry pumps, the inlet flow required to suppress backmigration below measurable limits is small in comparison to that required for oil-sealed rotary pumps and increases the ultimate pressure by less than 5×10^{-3} Torr [10].

There has been a trend recently towards compound turbopumps with molecular drag outlet stages which raise the permissible discharge pressure above 10 Torr, allowing the use of clean diaphragm pumps as primary backing pumps. While such combinations can achieve UHV, they are limited by the low speed of the diaphragm pump - this can be very significant for applications where rapid pumpdown or cycling is required - and only one manufacturer offers an MLTP version (most machines use a rolling element bearing in their design). Diaphragm reliability continues to be a major issue, as fatigue failure causes a sudden (and sometimes catastrophic) venting to atmosphere. Such pumps are totally inappropriate for harsh and difficult processes.

In summary, based on recent work in Japan, it seems likely that clean and ultraclean pumping in the semiconductor industry will be dominated by MLTP's backed by dry, positive displacement, rotating machines.

4.1. Pumping of harsh and difficult processes

The main objective is to maximise uptime for the total pumping system, including the exhaust management system with the goal currently being set at 2 years for all processes.

To achieve this, pump system designs must achieve straight-through pumping for harsh, difficult processes. The use of inlet traps or post-process reactors creates an unavoidable requirement to stop the process and break vacuum in order to maintain them, thereby limiting the uptime.

Having created a situation where the process by-products can be dealt with at atmospheric pressure in the exhaust system, there is a parallel requirement to design the exhaust management system such that uptime is not limited by scrubber and exhaust line maintenance.

As application experience is gained from all over the world, the two year goal is coming within our grasp.

Very few pump principles can cope with the conditions generated by some semiconductor processes, where the primary pump may have to deal with copious quantities of dust, subliming solids, aggressive acids or continuing reactions within the mechanism. It is possible to keep pumps running for extended periods under such conditions, but the balance between reliable operation and rapid failure can be very delicate. Given the desirable condition that the rate of removal of pump contaminants must equal or exceed the rate of ingestion, there are clearly thresholds which must be achieved for reliable operation.

For any particular process, the variables available to the application engineer or the end-user are:

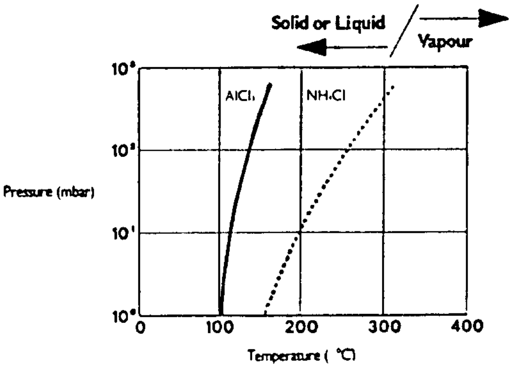

Fig. 14. Vapour pressure versus temperature for two commonly encountered sublimates.

(1) inert gas dilution and purging
(2) pump and inert gas temperature
(3) mechanical power.

1) Inert gas pressurisation of critical components of the mechanism serves to prevent ingress of contaminants to shaft seals, bearings, gauges, etc and the resulting flow in the exhaust system prevents backmigration of air or other contaminants (from other processes, for instance) into the pump. Nitrogen is also injected into strategic points throughout the swept volumes of dry pumps in order that process gases may be diluted to a level where they are no longer spontaneously reactive. Apart from dilution and hindrance of chemistry, these purges help to generate turbulence in the high pressure stages of the mechanism, thereby aiding the transport of particulates.

2) For condensible sublimates such as aluminium chloride, ammonium chloride and for acidic vapours, the maintenance of elevated temperature throughout the pump and exhaust system substantially reduces deposition. Fig. 14 shows vapour pressure as a function of temperature for two commonly-encountered sublimates. For each process, the best operating temperature must be found.

3) For situations where the mechanism may suddenly be confronted with a flake of dislodged deposit or a slow accumulation of dust within a stage, reserve motor power and a high-inertia mechanism can prevent the pump from seizure by pulverising and ejecting the debris quickly, or by maintaining rotation at increased power until the process step is completed.

For the most demanding processes such as LP-CVD and LTO - where ten to twenty grams of dusty silica byproduct are generated per run - the dynamic balance achieved by attention to (1) and (2) is very critical to reliable operation. On well-tuned systems, major service intervals of up to 18 months have been consistently achieved using Roots/claw pumps. Conversely, poorly tuned pumpsets can fail within days and give very disappointing results.

In the case of nitride deposition, it is the unwanted condensation of ammonium chloride from the vapour phase which presents a risk to the pump. As shown in Fig. 14, condensation will occur for temperatures less than 200℃ at 10 mbar (13 Torr) but the *rate* of condensation depends strongly on other factors such as the excess concentration of ammonia (or hydrogen chloride) and the gas velocity through the mechanism. For the nitride process, the tuning conditions involve the use of preheated purge gas, high pump operating temperatures and post-process hot gas purging; here, use is made of the fact that, if the concentration of free ammonia is reduced to a low level, rapid resublimation of condensed ammonium chloride occurs throughout the mechanism.

One technique of reducing the criticality of very dusty processes is the use of a high pressure exhaust recirculator [11, 12] which was introduced as a concept in 1988 and has since been successfully incorporated into a number of LTO reactors. Recirculation works by automatically valving the pump exhaust back to the pump inlet through a dust filter, while bleeding a modest flow of dry nitrogen (25 l/min) into the inlet. By this means, the inlet pressure stabilises at several hundred Torr and the pump runs at maximum power and throughput. The high gas velocities and turbulence within all stages of the mechanism serve to dislodge and eject deposits and dust from the pump, to be collected in the dust filter. Recirculation prevents overload of exhaust facilities such as dry scrubbers and prevents excessive consumption of nitrogen gas.

The main features of a difficult LTO process are described in Fig. 15. Prior to the use of recircula-

PROCESS: Low Temperature Oxide (LTO)
−BPSG, PSG

CONDITIONS: 100mTorr, 400℃

LAYER: 1 micron of doped SiO_2

LENGTH OF CYCLE: 2 hours

DEPOSITION TIME: 45 mins
(Oxygen purge before and after deposition)

RUNS PER DAY: 3 to 7

DUST GENERATED PER RUN: 15-20 gm

PUMP GROUP(typ): 1200 m^3/hr Roots blower
+80 m^3/hr Primary pump

Fig. 15. Main features of a dust-generating LTO process. The dust originates from the continuing chemical reaction of process gases within the pump. Wafer size=5".

tion, a 4-stage, 80 m^3/hr dry pump survived for as little as 7 days (oil-sealed rotary pumps failed in 2-3 days). With the introduction of 2 cycles of recirculation per run, the pump has operated for 24 months without requiring a major service, even though the average number of runs per day has nearly doubled. During this time, in excess of 12 kg of abrasive silica dust have passed through the pump. An alternative philosophy for dealing with byproducts is to design the pump such theat it may easily be opened for cleaning. A number of mechanisms are now available which offer this feature and these machines, when used to pump dusty processes, must be cleaned frequently. Conceptually, however, this philosophy bears comparison with the principle of up-stream trapping, where the regular venting and handling of toxic or dusty contaminants is labour-intensive, expensive and even hazardous. Most of the industry has resisted the use of foreline trapping, in favour of straight-through pumping, combined with process byproduct management at atmospheric pressure.

In summary, the time between major services has continued to increase as fine-tuning of the pump protection schemes has evolved. The use of recirculation has dramatically improved the reliability of pumps used for very dusty processes.

4.2. General issues for dry pumps

4.2.1. Noise and viration

The reduction in feature size for the new 16 and 64 Mbit DRAM chips brings with it the need to reduce noise and vibration throughout the entire facility to unprecedented low levels. Mechanical noise and vibration from all sources is now of serious concern to facility designers. For instance, sound levels may have to be reduced to 60dBA in the equipment spaces. By the use of special motors and by advances in the design of the mechanism, noise levels are being pushed down into the range 64-68dBA (depending on pump size) and there is potential for some further reduction. It seems unlikely, however, that noise levels from exposed pumps will fall adequately below 60dBA in the near future and the continued use of clean-room-compatible enclosures (probably Class 1000) is indicated.

As regards pump vibration, there is nothing to choose between the intrinsic vibration characteristics of either Roots or claw mechanisms, as vibration is due entirely to residual out-of-balance forces in the motor/mechanism and is under the control of the designer.

In practice, vibration issues arising within a semicon fabrication facility are predominantly due to the resonant excitation of poorly designed or poorly restrained metal forelines and other facilities connections than to the pumps themselves.

4.2.2. Water cooling

It is common for advanced wafer fabrication sites to provide pure, de-ionised water for cooling. Such water is very aggressive and can attack pump cooling jackets vigorously, with the formation of corrosion byproducts; when a large array of pumps is connected, this can severely contaminate the recirculating water supply. To resolve this, it has proved necessary to incorporate non-corrodible heat exchangers into dry pumps.

4.2.3. Shaft seals

All dry rotary pumps suffer from the fact that, somewhere in the mechanism, the impeller shafts must pass from the dry, clean swept volume into

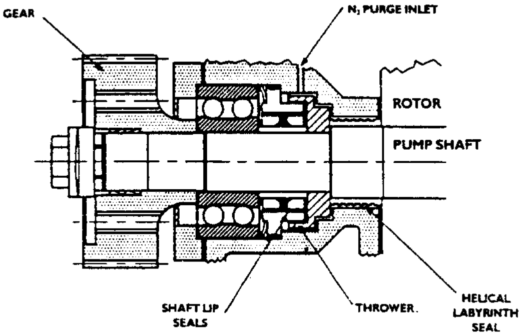

Fig. 16. The mechanical arrangement of an inner shaft seal for a dry pump, showing the nitrogen "gas-packing" scheme and the two flow restriction elements.

an oil-lubricated environment containing bearings or gears. The integrity of the shaft seals separating these two environments is of paramount impor- thereby creating an efficient barrier to migration.

5. Conclusions

What lies in the future? By 1993, the global semiconductor industry is predicted to be worth $ 112 billion, with Japan expected to account for 43% and North America for 36%. It is already one of the largest and most rapidly changing markets for vacuum procuts. The pace of change in fundamental vacuum technology is currently being driven by Japan and the absolute requirement for reliablility and, most recently, for cleanliness is forcing the most rapid and radical pump development for many years; interestingly, the number of known pumping principles has remained constant for decades.

It is clear that there is scope for considerable evolutionary development in claw-based dry pumps and it is our view that this technology has the most to offer of all the pumping principles discovered thus far. The alternative approaches are already close to their technological limits.

There does not seem to be any strong trend towards computer compatibility although all of the necessary technology exists and has been on offer for some years. The trend for many applications has been towards simplification of control equipment. In the case of harsh, difficult processes, there has indeed been a move towards monitoring of key parameters to enable preventive maintenance; as tance to the clealiness of the pump. Although many ingenious mechanical arrangements have been implemented, none is as effective in creating a high-integrity barrier to oil migration as the "gas-packed" seal. This works by injecting a supply of clean, dry nitrogen gas between two restrictions to flow (normallly lip seals or small annular clearances) as in Fig. 16. The pressure of the gas is higher than the pressures on either side of the restrictions, a result, the use of PLC's (Programmable Logic Controller), to control the operation of pump groups, is becoming common.

The most probable evolutionary path for dry pumps will be for them to become lighter, quieter and more compact, implying material changes, higher rotational speeds and better ultimate performance. They will also become cleaner, both internally and externally, where absence of particle generation will be an important requirement for both the process and the pumping environment.

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