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BEARINGLESS CENTRIFUGAL PUMP FOR HIGHLY PURE CHEMICALS

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ABSTRACT

In the semiconductor device manufacturing there are processes like etching, stripping, cleaning and polishing involving aggressive liquid chemicals. In these wet processes pumps are probably the most critical parts concerning the high requirements on purity, chemical resistance and reliability. The pump has to be a self-contained system to prevent any contamination of the highly pure liquids. Until today only pneumatically driven bellows or diaphragm pumps can fulfill these requirements. But this technology has some serious disadvantages.

A new bearingless pump system is introduced, which consists of a bearingless slice motor, a chemically resistant centrifugal pump and controller electronics. In a bearingless slice motor three spatial degrees of freedom can be stabilized passively. That reduces the complexity of the pump system. The slice-rotor levitates inside a hermetically closed pump housing. In order to prevent contamination of the liquids the slice-rotor is encapsulated with multiple polymer layers. Nevertheless, the permeation of aggressive chemicals through these polymer coatings has to be taken into account.

The benefits of a bearingless solution for a highly pure process pump are: As a rotary pump principle is applied, flow and pressure are continuous and can precisely be controlled. Absolutely no particles are generated inside the pump due to the contact-free bearing and the pump housing can be sealed hermetically. No maintenance is necessary because of the lack of mechanical wear. Compared to pneumatical solutions the pump system is small in size because of better efficiency.

MOTIVATION

As the density of transistors on the most powerful processors grows – now surpassing 200 million on a 1-cm^2 die – [1] the requirements for a clean environment raises. This also has to be considered for the chemicals used in wet processes, like etching, stripping or cleaning. In delivery and recirculation facilities pumps are probably the most critical parts referring to the high requirements on purity, chemical resistance and reliability.

Requirements

Depending on the process step, different mixtures of acids, oxidizers, organic solvents and bases are used at temperatures up to 160°C. So every liquid-contacting part of a process pump has to be chemically resistant to these aggressive chemicals.

Any contamination of the medium with metallic ions or particles must be prevented, because this results in failure or degradiation of chip performance. Therefore the medium may not be in contact with metallic parts inside a pump.

Because any operational failure entails enormous costs, process pumps have to be highly reliable and must operate with little maintenance to shorten facility down time as low as possible.

Today there exists no usable dynamic sealing, which fulfills these requirements and prevents any leakage of dangerous liquids. So only self-contained pump systems are applicable in wet process tools.

Todays Technology

Until today only pneumatically driven bellows or diaphragm pumps comply with the above requirements if they are made completely of a chemically resistant fluoropolymer, like PVDF, PTFE or PFA. But this technology has some serious disadvantages.

The diaphragm/bellows has to withstand a high mechanical stress. Even with special materials the diaphragm has to be changed every six months to two years. At higher temperatures the maximal usable performance (pressure) decreases. Furthermore, the moving valves and flexing diaphragms still generate small amounts of particles.

Bellows and diaphragm pumps deliver a pulsatile flow and pressure. Even with additional flow dampers the flow still has a noticeable ripple, which influences the process quality in an undesirable way. In addition, bellows and diaphragm pumps generate substantial noise and vibrations.

The whole pump system including the flow dampers and the air compressor has an energy efficiency of less than fifteen percent due to the pneumatic principle. Compared to the delivered hydraulic power the system also requires a lot of clean room space.

Sometimes rotary pumps like magnetically coupled systems with medium-lubricated slide bearings are used. This slide bearings generate particles during normal operation and will be immediately destroyed, if they operate without a medium.

Magnetic Bearing Technology

The ideal pump for wet process delivery and recirculation would be a magnetically coupled rotary pump with contact-free bearings, i.e. magnetic bearings which work without any wear. So process fluids are not contaminated by particles. As the pump principle is rotary, flow and pressure are continuous and can be controlled precisely without any valves.

In this paper a new bearingless pump system is introduced, which satisfy the requirements to a process pump for highly pure chemicals. The major problems for this application and possible solutions are described.

SYSTEM OVERVIEW

Figure 1 shows the structure of a bearingless pump system, which consists of a motor, a centrifugal pump and a frequency converter with controller. In the realized pump system a bearingless slice motor drives the centrifugal pump. Radial position and angular speed of the slice-rotor are controlled by the frequency converter, which provides also interfaces to the process tool and service personnel.

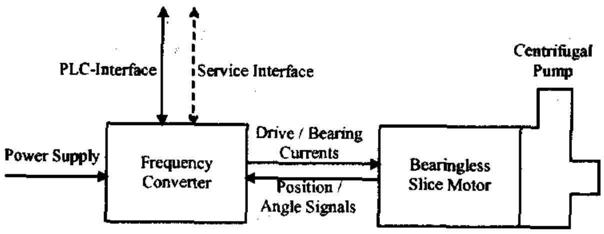

FIGURE 1 Structure of bearingless pump system

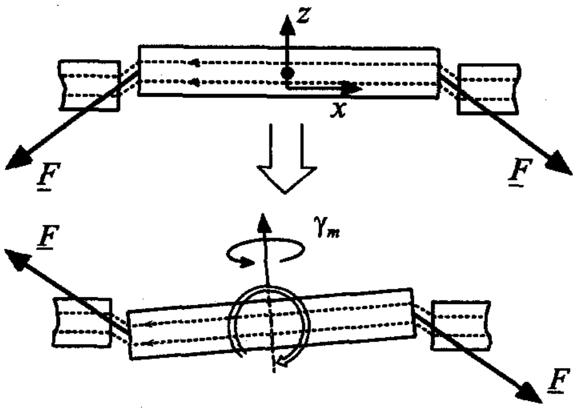

FIGURE 2 Passive stabilization of the slice-rotor

BEARINGLESS SLICE MOTOR

Recent developments in the fields of electrical drives and magnetic bearings have led to so-called 'Bearingless Motors' (see [2], [3], [4], and [5]). In contrast to conventionally mounted motors the 'bearingless motor' generates the magnetic bearing forces in the motor itself, so that the rotor levitates without touching the stator, i.e. 'bearingless'.

Normally, two radial bearings are needed for the full stabilisation of five spatial degrees of freedom of a rotor. Therefore in a bearingless motor design two motor/bearing parts are usually required. Such a motor construction becomes rather long.

In a joint project of the ETH and Levitronix GmbH the bearingless slice motor was developed (see [6], [7] and [8]). The idea of this motor is to choose the length of the rotor small compared to its diameter resulting in a slice-rotor. In this case it is possible to stabilize three spatial degrees of freedom passively.

The functional principle of the passive stabilization is shown in figure 2. The upper figure shows an axial displacement of the slice-rotor. The displacement results in attractive magnetic forces, which act against the displacement and therefore stabilize the axial position of the rotor.

The lower figure shows a tilting of the slice-rotor, which results in a torque against the displacement. This angular position is also controlled by passive magnetic forces, which turn the slice-rotor back to a horizontal position.

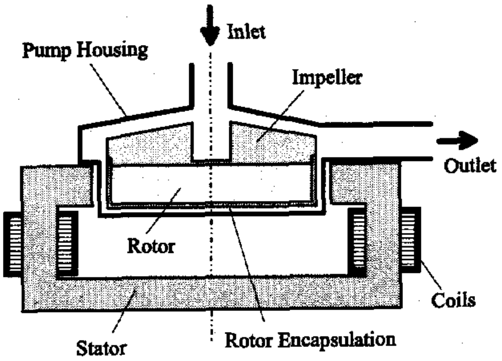

FIGURE 3 Principle of bearingless slice motor pump

With this concept, a simple and cost effective solution for a centrifugal pump becomes feasible. figure 3 shows the basic arrangement of such a 'Bearingless Slice Motor Pump'. By bending the stator teeth down and forming a so-called 'temple motor', the windings are not in the way of a radial outlet of the pump.

In the realized motor the rotor is a diametrically magnetized permanent magnet slice. The used high-energy magnet material (NdFeB) allows an air gap of over 3 mm. As shown in figure 4 the temple motor builts a compact body, where the magnetic circuit is closed by a stator back iron at the bottom of the motor. Active control of the radial position and the rotation of the slice-rotor is assured by the currents in the bearing and drive windings of the bearingless motor.

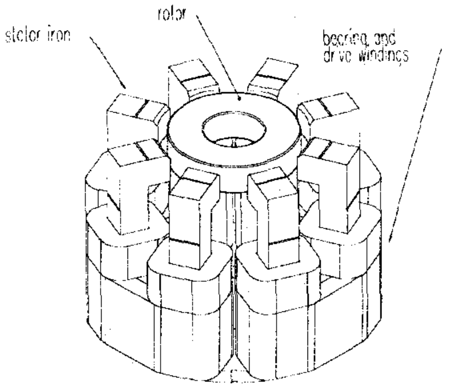

FIGURE 4 Bearingless slice motor of temple design

FREQUENCY CONVERTER

The reduction in degrees of freedom, which have to be controlled actively, reduces also the complexity of the frequency converter and the controller software. The realized pump system is controlled by a compact electronic unit, with a controller board realized as a sandwich PCB on a power board. Only four independent power channels with a maximal output current of 8 A are needed to supply the four motor phases (2 drive / 2 bearing). Each power channel consists of an H-bridge and is built with discrete MOSFETs.

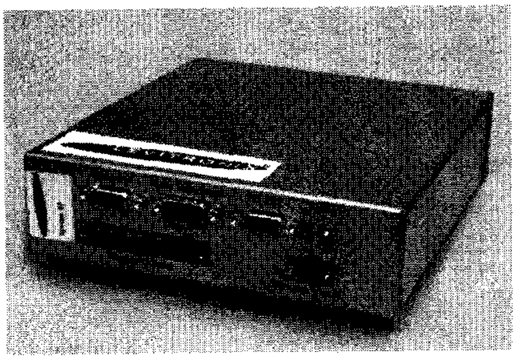

FIGURE 5 Frequency Converter

Position, speed and current control loops are realized fully by software in a digital signal processor TMS320F240 of Texas Instruments. The control scheme of the bearingless slice motor is based on vector control [9]. Furthermore there are a PLC-Interface (Programmable Logic Controller) to the process tool and a RS232 service interface included on the controller board. The control electronics is inserted in a compact casing (185x170x50 mm) including the radiator (see figure 5).

PUMP

A bearingless centrifugal pump (figure 6) consists of very few parts only. The slice-rotor can be directly integrated in the impeller, which levitates within the hermetically closed pump housing. The axial thrust is smaller than the passive reluctance forces, because it is compensated hydrodynamically by the design of the impeller. Because of the bearingless principle, it is also easy to remove the impeller from the motor.

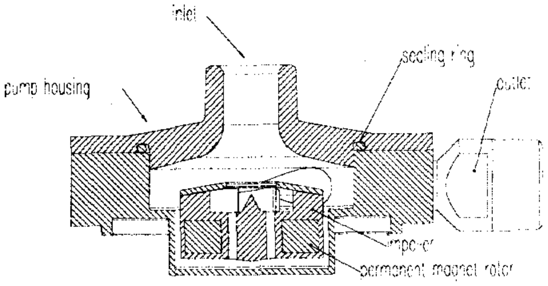

FIGURE 6 Pump housing and rotor with impeller

At rotational speeds up to 8000 rpm the hydraulic characteristic in figure 7 was measured. Over a wide flow range the differential pressure between outlet and inlet depends only on the rotational speed of the impeller. At flows over 45 litres per minute the pump generates a recognizable noise because of cavitation at the inlet. The maximal power is limited by the thermal limit of the power electronics and the motor. If higher pressures up to 5 bars are required, two pumps can be connected in series, which doubles the total differential pressure.

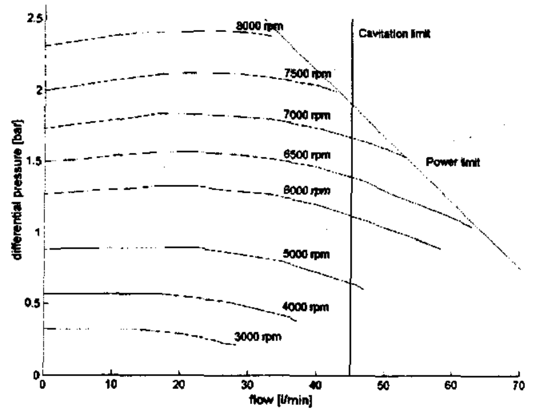

FIGURE 7 Hydraulic pump characteristic for water

At the working point of a differential pressure of 2.3 bar and a flow of 25 litres per minute the power consumption was measured and divided into the different losses in the pump system. At this working point, which corresponds to a hydraulic power of 96 W, the total system input power is 353 W. Just one percent (3 W) of the total power delivered to the motor is lost in the magnetic bearing. Copper and iron losses in the Motor amount to 40 W. Most of the power is lost in the pump because of the hydraulic pump efficiency of 37 percent. This results in a total system efficiency of 27 percent.

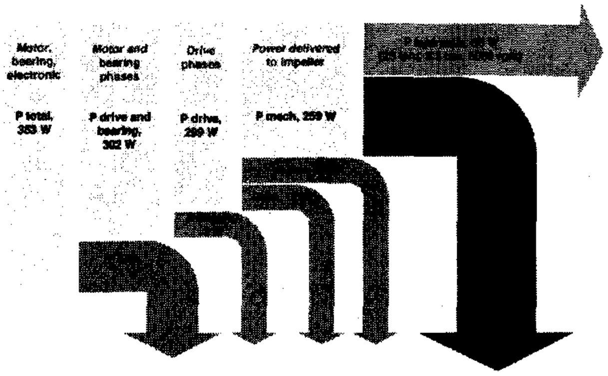

FIGURE 8 Power consumption and losses at 2.3 bar / 25 litres per minute

ROTOR ENCAPSULATION

In order to prevent contamination of the liquids the slice-rotor is encapsulated within multiple layers. To improve the resistance of the rotor surface it is possible to coat it with aluminium, which forms a thin aluminium oxide layer. A coating with diamond like carbon (DLC) or parylene protects it from aggressive chemicals. Finally, the rotor is encapsulated in PVDF, PFA or PTFE to reach a high purity and the required chemical resistance.

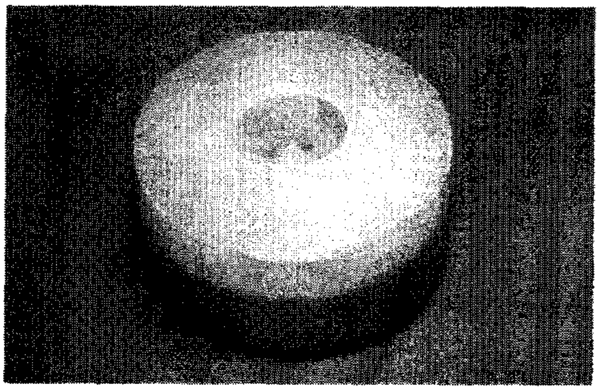

FIGURE 9 Encapsulated rotor with impeller

Nevertheless a small amount of chemicals diffuse through the polymer layers and reacts with the rotor surface, building salts and gases. In time the rotor encapsulation starts to swell and finally cracks, which will be disastrous in a wet process tool. To manage this problem, the interval for a rotor exchange has to be determined.

Diffusion processes can be expressed by Fick's laws of diffusion:

$$J = -D\frac{\partial c}{\partial x} \tag{1}$$

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \tag{2}$$

Where J is the rate of diffusion across a unit area, c is the concentration at a position x, t is the time, and D is a diffusion coefficient. Every penetrant-polymer system has its own diffusion coefficient D, which furthermor depends on temperature and penetrant concentration c. As practically no data over the in wet process used penetrant-polymer systems exist, this mathematical models only can be used to extrapolate the exchange interval out of experimental results achieved.

Due to the wide air-gap clearance in the bearingless slice motor it is possible to build a thick diffusion barrier against aggressive chemicals. To determine an exchange interval an encapsulated rotor is put in the used chemical mixture and its behaviour is observed. This experiment is done at elevated temperature to get faster results. For lower temperatures the diffusion coefficient D, i.e. the exchange intervall can be calculated in most cases with equation (3).

$$D = D_0 \cdot \exp\left(-\frac{E_D}{RT}\right) \tag{3}$$

An exchange time of more than 6 months has been evaluated for different chemical mixtures (DHF, HF/ethyl glycol, HCl). This time is an acceptable service interval, besides a rotor exchange is easy done in some minutes.

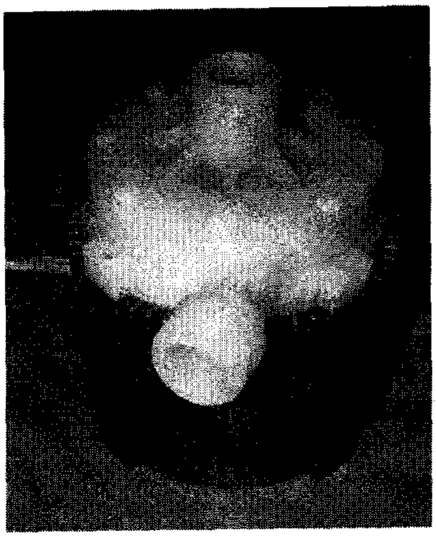

FIGURE 10 Bearingless slice motor

BEARINGLESS PUMP SYSTEM

Figure 10 shows the realized motor and centrifugal pump, which are 150 mm high and 130 mm in diameter. Because the motor is placed in a chemically aggressive environment the aluminium housing is protected by an ETFE-Coating. The frequency converter is placed outside this fire sensitive environment. The bearingless pump system meets the safty guidelines for semiconductor equipment, which include among other things fire and chemical protection standards.

SUMMARY

The bearingless pump system shown in figure 11 is designed for applications in the semiconductor industry, where a high purity and chemical resistance is required. Because of the contact-free bearing there is absolutely no generation of particles inside the pump. As the pump principle is rotary, flow and pressure are continuous and can be controlled precisely. Motor, pump and control unit are small in size compared to the maximal hydraulic power of 100 W.

By using the bearingless slice motor as drive a cost effective design of the pump becomes feasible. The simplified complexitiy compared to conventional magnetic bearings yield to a high reliability, because less parts are used not only for the motor, but also for the pump and the frequency converter.

OUTLOOK

In order to increase the benefits of the bearingless centrifugal pump, the internal controller values like speed, phase current, motor flux and rotor position can be used to calculate and monitor interesting pump parameters, like flow, pressure and medium viscosity [10]. An Implementation of these features requires additional effort in algorithm and software design.

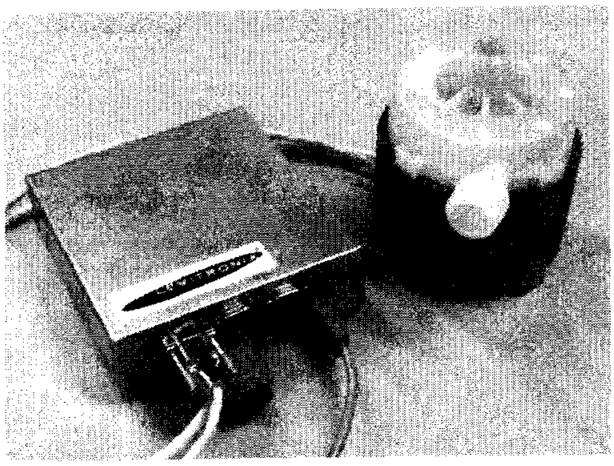

FIGURE 11 Bearingless pump system

As similar pump requirements exist in other areas then the semiconductor industry there are applications for the magnetic bearing technology in biotechnology, pharmaceutical industries and liquid food transportation for example. For each new application the specific requirements to the system has to be adapted and improved.

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