Ultra-Pure Fluid Flowmeter for Harsh Environments

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ABSTRACT

A new ultra pure fluid flowmeter for harsh environments is presented. The total sensor accuracy is 1% while the repeatability is 0.5% of full scale with a viscosity dependency of 1.5% from 1 to 30mPas.

The sensor is based on active magnetic levitation. All wetted surfaces are made of polytetrafluorethylene (PTFE), or perfluoralkoxy (PFA). Therefore it can be used in the very challenging field of semiconductor manufacturing and in the chemical industry.

KEYWORDS

Flowmeter, semiconductor manufacturing, high purity, harsh environment

INTRODUCTION

During semiconductor manufacturing, fluid flow measurement is used in cleaning, stripping, plating and etching processes, in chemical mechanical polishing (CMP) and in photolithography. It is considered an important process parameter in many semiconductor-manufacturing processes. The liquids used consist of acids, bases, oxidants, solvents and slurries and may therefore be corrosive or abrasive.

A requirement for flowmeters in semiconductor manufacturing is low particle generation (less than one particle smaller than 0.1µm per ml liquid). Furthermore, wetted sensor parts must not corrode, while contamination of chemicals with metals, anions and organic hydrocarbons must be limited to sub ppt level, to achieve high yield.

Various flowmeter principles are used in semiconductor manufacturing that suffer from different shortcomings. The four main flowmeters are turbine flowmeters, differential pressure flowmeters, ultrasonic flowmeters and vortex flowmeters. Low particle generation is mainly a problem for sensors with rotating parts, which are used in turbine flowmeters. Signal drift of differential pressure flowmeters makes recalibration necessary. Gas in the liquid can cause failure of ultrasonic flowmeters. The considerable prices of the current flow sensors prohibit a large-scale application of flow process measurement in semiconductor manufacturing.

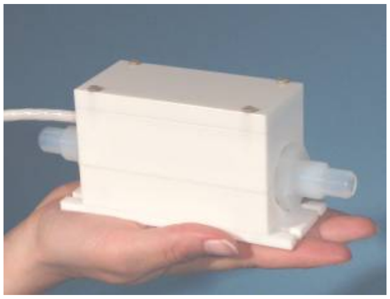

Figure 1: Flowmeter prototype

We have achieved a sensor design using a new principle to overcome the current problems with measuring liquid flow in harsh environments (Figure 1) [1]. Because there are no rotating parts, the particle generation is very small. A compensating measuring principle is used to minimize the sensor drift. Therefore recalibration is not necessary. The principle is resistant to gas or air bubbles in the liquid. The simple design allows a low-cost production of the flowmeter opening a broad field of new applications in harsh environment.

The main objective when designing a low-cost flowmeter with minimal drift independent of any fluid properties can be achieved using the magnetic bearing technology.

FLOWMETER PRINCIPLE

The flowmeter presented is based on an active axial magnetic bearing (Figure 2).

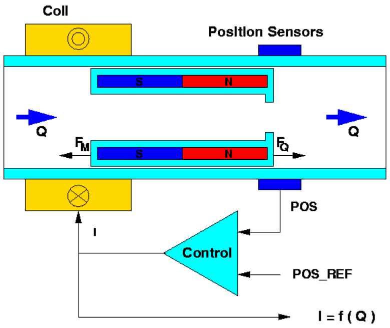

Figure 2: Flowmeter principle

A copper coil surrounding a Teflon tube magnetically controls the position of a Teflon-encapsulated permanent magnet inside the liquid, which exerts a force on the magnet. The electromagnetic force of the active magnetic bearing compensates the fluid force on the bearing. The resulting control current is a measure of the process liquid flow, in consideration of density and temperature. All wetted sensor parts are coated with either polytetrafluorethylene (PTFE), or perfluoralkoxy (PFA). These Teflon materials are known as the most resistant to both acids and bases.

FLOWMETER DESIGN

The sensor is based on the orifice flowmeter principle, where a reduction in the pipe diameter results in an increase in velocity, which causes a reduction in pressure downstream. The relationship between this pressure drop and the fluid flow rate can be calculated [2] using the Bernoulli and the continuity equation. Disregarding friction and expansion the volume flow

$$\dot{V} = \alpha A_2 \sqrt{\frac{2\Delta p}{\rho}}$$

Equation 1: Volume flow in restriction type instruments

is calculated, where $\dot{V}$ is the volume flow, Δp the differential pressure at the orifice, ρ the density of the fluid, A_2 the restricted pipe area and α a restriction and Reynolds number dependent coefficient.

Orifice flowmeters are specified in DIN 1952 for tube diameters D>50mm and Reynolds numbers $\mathrm{Re}_D = \frac{\overline{w} \cdot D}{\nu} \geq 5000$.

$\overline{w}$ is the fluid velocity in m/s, D the tube diameter and ν the kinematic viscosity.

To reduce the pressure drop of the sensor, a Reynolds number range $0 \leq \mathrm{Re}_D \leq 10000$ for a flow rate of up to 10l and a dynamic viscosity between one and 50mPas was chosen. In this range the standard orifice norm has a higher viscosity dependency, causing a higher viscosity dependent measurement error than specified in DIN 1952.

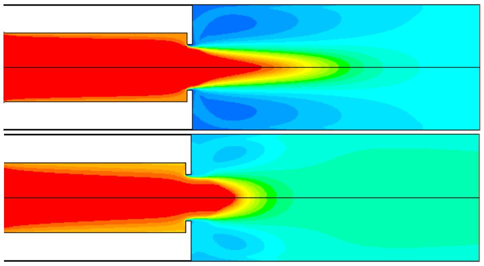

Figure 3: Total pressure in flowmeter at 10mPas (top) and 50mPas (bottom). The color visualizes the different pressure allocations.

Figure 3 shows the total pressure in the sensor at a viscosity of 10mPas and 50mPas with different resulting forces on the floating body. The color symbolizes the total pressure at the outlet of the floating body. The simulations show a lower pressure at the orifice outlet at 10mPas than at 50mPas. The resulting force on the floating body is therefore higher at 10mPas than at 50mPas, because the main force on the floating body is caused by the pressure drop (Figure 4). This force change is also measured on the prototype resulting in a full-scale error of 6%.

Optimization of the Floating Body

To minimize the viscosity dependency and hence to make it applicable for semiconductor processes where the viscosity changes caused by aging and solvent evaporation, the floating body was optimized with the fluid simulation program FLUENT [3], using the $k-\varepsilon$ turbulence model with enhanced wall treatment and a 0.2mm and smaller mesh grid.

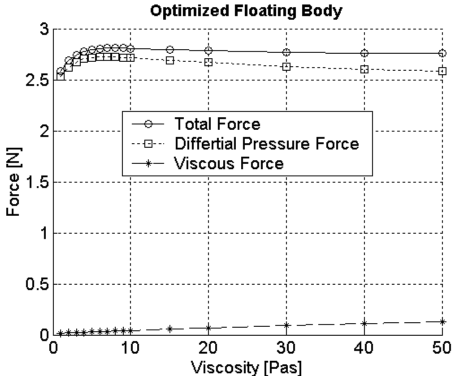

Figure 4: Simulated force on the floating body

The simulation results in an optimal floating body shape with an almost constant fluid force for viscosities between 5 and 50mPas. The simulated force below 5mPas is reduced because of the fluid flow through the gap between the floating body and the sensor tube, which is viscosity dependent.

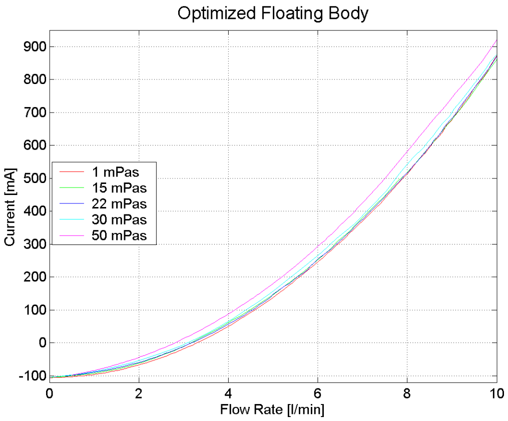

Figure 5: Coil current in function of flow rate

The measurement on the prototype (Figure 5) shows that the fluid flow through the gap does not influence the total force on the floating body as much as simulated but that the total force is bigger for higher viscosities. Figure 5 shows the compensating coil current for the liquid flow range up to 10 l/min for different viscosities from 1mPas up to 50mPas. The optimized shape has a measured viscosity dependency of 1.5% in a viscosity range from 1mPas to 30mPas (Figure 5).

Flow Calculation

Figure 5 shows, that the relation between flow rate and force or coil current is a quadratic function depending on the floating body:

$$I = A\dot{V}^2 + B\dot{V} + C$$

Equation 2: Coil current in function of volume flow rate through the flowmeter

I is the coil current, $\dot{V}$ the flow rate passing the sensor and A, B and C the parameters of the quadratic sensing function.

In a calibration step the quadratic function is measured and inverted. The inverted function results in:

$$\dot{V} = R + \sqrt{S + T \bullet I}$$

Equation 3: Volume flow in function of coil current

R, S and T are constants resulting from the inverted equation.

The calculation of the actual fluid flow is done in the signal processor, based on this inverted function, the temperature of the magnet and the density of the liquid. The rare earth magnet used has a reversible temperature coefficient of -0.12 %/°C and therefore a compensation of the magnet field is necessary. The actual temperature of the liquid, thus of the magnet, is measured with two temperature sensors, one along the Teflon tube and one on the electronics circuit. The measured fluid temperature signal has an accuracy of ±2°C, and can be externally used to monitor the process temperature.

CONTROL AND SIGNAL PROCESSING

A signal processor is used for active position control of the permanent magnet floating body, as well as for the computation of the actual flow. It can be seen (Figure 6) that the controlled system is stable because of the damping *d* of the liquid medium to measure.

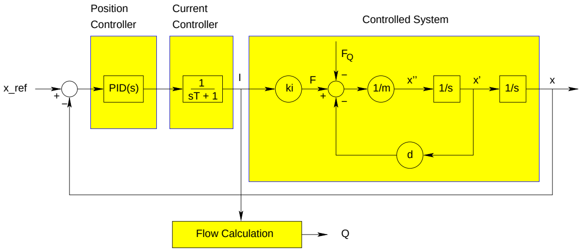

Figure 6: Control structure of the sensor

The position controller of the sensor system consists of a cascaded digital controller based on a current and a position regulation. The current cascaded structure reduces the time lag compared to a single position controller, which was tested with a simple non-cascaded structure. The cascaded version used allows higher dynamics of the flow rate measurement. A first order low pass filter in figure 6 symbolizes this fast current controller.

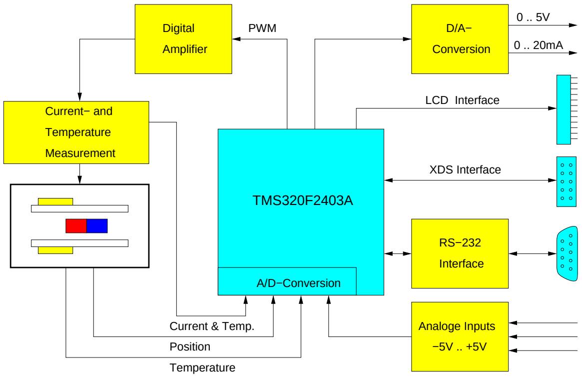

Figure 7: Hardware structure

The resulting hardware structure (Figure 7) is based on a signal processor with integrated 10-bit A/D converter. External electronics provide control current amplification for the electromagnet. To reduce power consumption and heating, which causes nonlinear sensor behavior, the coil current is amplified with a digital full bridge circuit. Analog signal electronics amplifies and filters the actual coil current, the position of the floating body and the temperature of the permanent magnet to be read by the signal processor.
The signal processor provides a digital serial RS232 interface via a level converter while analog interfaces provide a 4-20mA-current and a 0-10V-voltage output of the sensor measurement. The sensor is flash programmable via RS-232- and XDS interface.

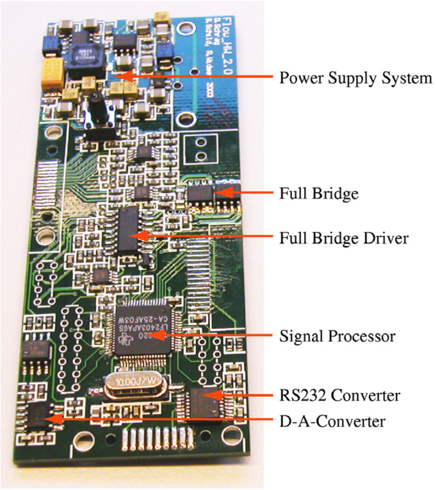

Figure 8: Signal-processor-based electronics

For a compact sensor system, a small electronics (Figure 8) of 40mm times 100mm with analog electronics, signal processing and power electronics was necessary.
A four-layer printed circuit board design with different ground and supply levels was used for analog, digital and signal processing to reduce signal interference.
The sensor is supplied with a voltage of 24VDC, which is the common supply voltage in semiconductor manufacturing tools.
A power supply system generates the necessary voltages for the analog and digital subsystems. The 16-bit signal processor TMS320LF2403A with a clock frequency of 40MHz controls the digital full bridge amplifier, computes the current liquid flow and controls the sensor interfaces RS232, current and voltage outputs.

RESULTS

This flowmeter has been designed for a flow range of up to 10 l/min. By changing the orifice diameter of the floating body, the flow range can be extended freely within a certain range. Floating bodies have also been designed for a range 0-5l/min.
The total accuracy of 1% and the repeatability of 0.5% of full scale are comparable to con-

ventional flowmeters in semiconductor manufacturing.

As can be seen in Figure 5, the viscosity dependency is 1.5% over a viscosity range from 1mPas to 30mPas.

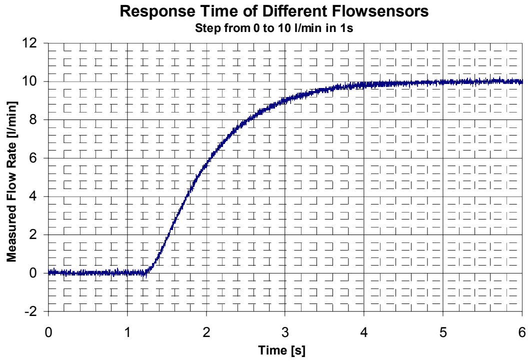

Figure 9: Sensor response to flow rate change. The measurements were performed at a constant fluid temperature of 30°C.

The flow sensor reacts to a flow change from 0 l/min to 10l/min according to Figure 9. This response time can be reduced, resulting in a higher noise level.

The sensor is hardly disturbed by large-scale gas bubbles as can be seen in Figure 10. The flowmeter signal changes when gas bubbles pass though the sensor but the signal before and after the disturbance is the same. This is an advantage compared to ultrasonic flowmeters where gas in the measurement path can cause failure.

The current prototype shows a maximal pressure drop of less than 45mbar of the full range. This corresponds to 4% of the pressure drop of the most often used differential pressure flowmeter [2], resulting in a more efficient delivery cycle.

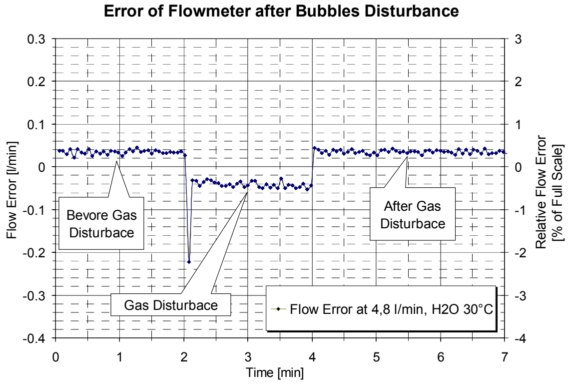

Figure 10: Bubble test with a gas disturbances

By avoiding mechanical friction, the sensor presented generates virtually no particles. Furthermore, the sensor has no fluid-filled cavities and no wetted metal parts. The design is compact and simple, making a low cost product possible.

As the electromagnetic force of the active magnetic bearing compensates for the fluid force on the bearing, there is inherently minimal drift, being considered one of the main advantages, because this reduces maintenance.

A signal of the liquid temperature is provided with an accuracy of ± 2°C. This signal is used internally to compensate for fluid temperature change and can be used externally to monitor the process temperature.

DISCUSSION

Based on the magnetic bearing technology, this sensor shows many advantages compared to conventional flowmeters.

The developed flowmeter meets the requested accuracy and shows a good viscosity dependency. The simple design results in cost reduction, which allows a wide application in process flow measurement. This improves process control and leads to a better yield in semiconductor manufacturing. Because the liquids that are used, like slurries, are expensive, better process control can lower the costs when less process media is needed.

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