High Resolution Capacitive Sensor Systems

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What's the size of a hydrogen atom?

1. Introduction

In the year 1791 scientists in France defined the length of one meter as a part of the circumference of the earth. Almost two hundred years later the meter was defined as a part of the speed of light. On the requirements of the industry and the developing of new technologies it is necessary again to see the world in a new scale. In a time, where you can buy computer chips, manufactured in micrometer technology, it is necessary to develop new processes for the future. The challenge is now the nanometre with the addiction to picometres. To fulfil the needs of the semiconductor industry, the developers of Micro-Epsilon are able to measure sub-nanometres only 25 years after the latest definition of the meter. The size of one nanometre is approximately the length of four neighboured atoms. In fact, it is possible to detect movements in a size of one hydrogen atom.

2. Technical principles

How is it possible to measure such small movements in reality? What will be measured? Only systems based on the capacitive principle are able to reach such resolutions. But what is capacity?

The distance between two conductors has an effect upon the electric field between, when a voltage is applied to one of them. Both conductors have an electrical charge and the difference between them results in an electrical field. Capacity is a factor for needed energy of the two conductors to hold this charge.

For the capacitive measuring principle, the sensor and measuring object function as an ideal plate capacitor. If an alternating current of constant frequency and constant amplitude flows through the sensor capacitor, the amplitude of the alternating voltage on the sensor is proportional to the distance to the target (ground electrode).

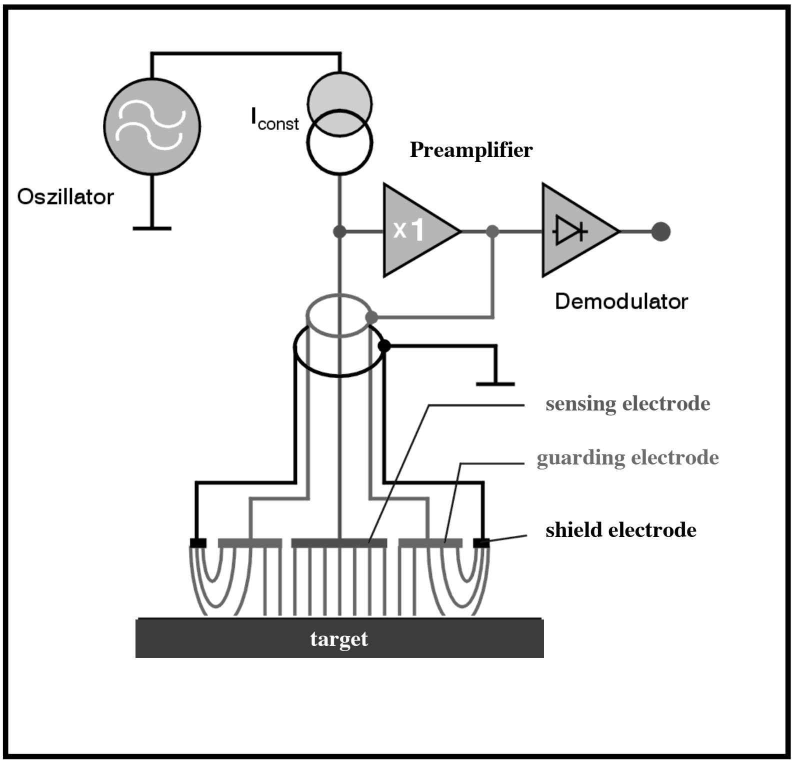

Abb. 1: schematic drawing of capacitive measurement principle

In practice, due to the design of the sensors as guard ring capacitors, almost i deal linear characteristics are achieved. However, a constant dielectric between sensor and target is required for a constant measurement; the system is very sensitive to dielectric changes in the measuring gap. Capacitive sensors also measure insulated materials, as these are acquired as a changed dielectric. An almost linear output signal for insulators is also achieved by using an electronic circuit. As an electromagnetic process, a capacitive measuring system measures on all metals with constant sensitivity and linearity as standard. The system evaluates the reactance of the plate capacitor which changes strictly in proportion to the distance.

In the basic function of a capacitive sensor, the field also emanates sideways from the electrode, whereby incorrect distance information could be obtained. A guard ring that confines the field and produces a homogenous measurement data is mounted around the electrode for the reduction of this edge effect. This principle is responsible for the linear characteristic curve. Although the guard is essentially needed for high linearity and resolution, the field lines emanating from the guard ring do not interfere with the measurements. However, the field also penetrates plastics. If there is a plastic object in the measuring gap, the thickness of the insulating material between the two capacitor plates (electrode and opposing surface) can be determined. Thereby, the change of the signal is evaluated which is dependent on the permittivity and the thickness of the insulator. The permittivity must be constant for a reliable thickness measurement.

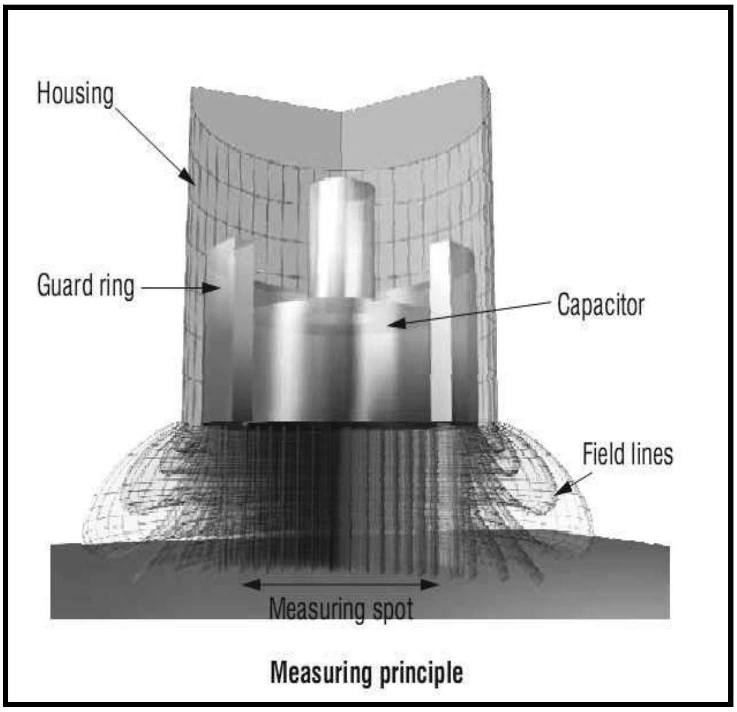

Abb. 2: schematic drawing of capacitive measurement principle sensor head

Capacitive systems are amongst the most precise. The challenge is that extremely small distances cause an equally small change in the signal. In most of the applications it´s not possible to create a sensor with a measurement range down to some µm to detect sub-nanometres, so a very high resolution is necessary. This means there are on average only a few electrons between sensor and controller for an indicated change in distance.

If additionally only very small leakage currents or parasitic currents flow on the path from sensor to the controller, the distance information is no longer correct. Therefore, the complete sensor chain has some difficult requirements. For example, very complex triaxial cables are needed. This unique, hermetically sealed RF cable provides high signal quality. In combination with the guard ring technology used by the manufacturer, very precise measurements are possible.

Capacitive sensors are amongst the most precise in the world. Resolutions of well under one nanometre are achieved. A clean and dry environment is required as changes of the material between sensor and measuring object can affect the signal. Low and constant humidity is useful.

A great advantage of capacitive sensors is the averaging over the sensing area. It´s easy to imagine, that a resolution of distances smaller than the diameter of some atoms can only work with a great amount of atoms and their averaged surface. Of course, the target should be constant.

To get a high resolution, a relatively short cable length between sensor and controller is recommended at all times.

To get a high resolution, also the electronic components have to be designed with high accuracy. Starting at the current source, over the preamplifier up to the demodulation and conversion units, a lot of experience is necessary to fulfill the requirements.

Capacitive sensors are used in applications where precise results are required. They are used for measuring vibrations, oscillation, elongation, displacement, deflection, deformation and much more. In doing so, capacitive sensors are frequently used for in-process quality assurance, as a clean environment exists here for the sensors.

With the latest capacitive displacement measurement systems, resolutions of up to 0.038nm with a 0.05mm measuring range are achieved. Due to excellent temperature stability, applications in which high temperatures occur and where strong temperature drift of the signal is present, are ideal for this measuring method. Optical principles also do not provide a clean solution here as, for example, annealing metals do not allow any clean reflection of a laser spot, which would result in false measurement results.

As thermally induced conductivity changes of the measuring object have no influence on measurements, the principle is also reliable even with fluctuations in temperature. The measurement electrode is very flexible in its geometric design. As a plate electrode, it can be installed in different geometric forms depending on customer requirements

3. Applications

Travel displacement of a nano positioning unit at 4 K

In this application surfaces are inspected with nanometre resolution for Atomic Force Microscopy (AFM). The test item must be able to be moved in the nanometre range for a surface topography. To realize this efforts a positioning unit with piezo ceramics, movement in the x, y and z-axes was used. The positioning range, which is measured by the sensors, is 1.2mm x 1.2mm. The complete microscope head is cooled with liquid helium to 4K above the absolute zero point of -273℃ (corresponds to 0K). The traversing units operate at 4K ambient temperature in an ultra-high vacuum and under high magnetic fields. In order to measure the x and y movement, the manufacturer uses two capacitive sensors from Micro-Epsilon on the nano positioning unit. With a measuring range of 1mm, the sensors have a precision of less than 5nm and operate completely without contact. The extreme ambient conditions are a particular challenge. The sensors must provide identical results at 4K as at room temperature. This is possible due to the use of special materials for the sensor and cable, which provide stable measurements due to low thermal expansion. The sensors are not influenced by extreme ambient conditions. This application can only be solved using capacitive measurement technology. No precise statements about the measurement results were possible using eddy current sensors, as the temperature gradient of the target at 4K is very low and the specific current flow characteristics change.

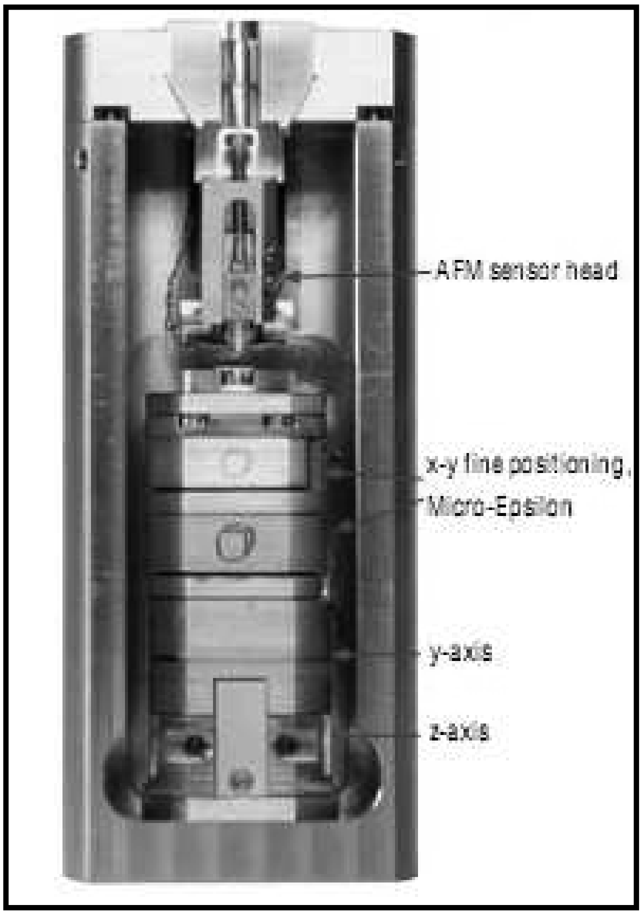

Abb. 3: two sensors of micro Epsilon in positioning unit

Measuring the thermal expansion on materials

Every material has its own characteristic thermal expansion. This parameter is at least constant within a certain temperature range.
To detect this sometimes very small expansion over temperature, different ways are possible. Either you can measure very long probes or you need to measure over a wide temperature range. For

example, to define an expansion factor of 1,5ppm, you have a probe length of 1 meter and a homogeneous temperature range of 100K. In this case, you get a travel range between the two ends of 150µm.

This effect can be used also to measure temperature. The combination of two different materials with known temperature coefficient makes it possible to detect the difference in expansion over temperature. This difference can be measured with a high resolution capacitive system..

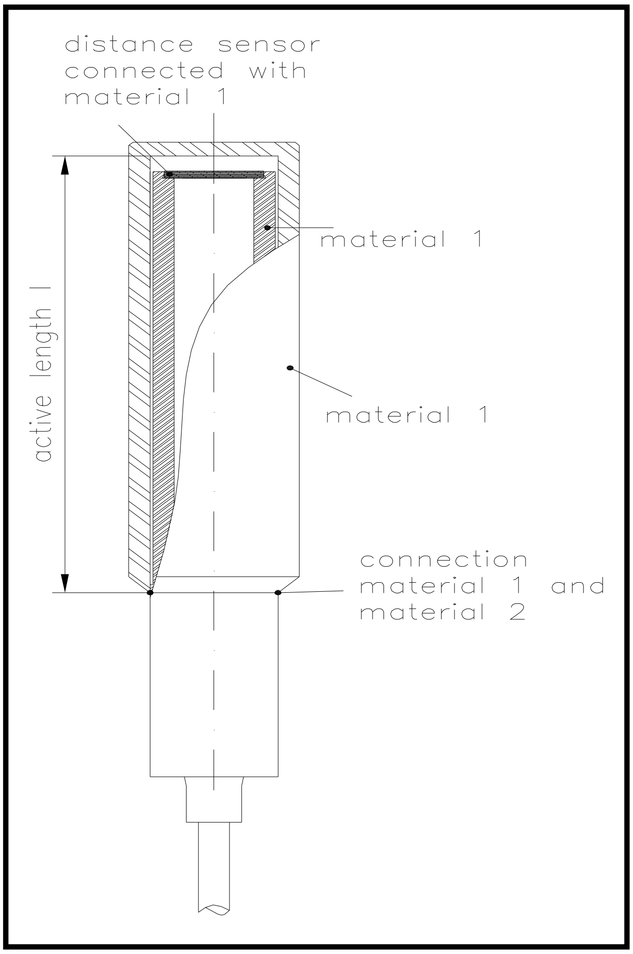

Abb. 4: ext. Micro Epsilon patent for capacitive temperature measurement

The achievable resolution in Temperature is defined by the measuring range (temperature or distance), the temperature coefficient and the electronic. If the materials are defined in a way that for a temperature range of $\Delta T = 50°C$ a change in length of $\Delta x = 50µm$ appears, this movement can be measured by a special capacitive sensor with a resolution of $\delta x = 0{,}15nm$. The resulting resolution in temperature is defined by the equation:

$$\frac{\delta T}{\delta x} = \frac{\Delta T}{\Delta x}$$

By conversion the temperature resolution is:

$$\delta T = \frac{\Delta T}{\Delta x} \cdot \delta x = \frac{50K}{50\mu m} \cdot 0{,}15nm = 0{,}15mK$$

In this application 150µK can be measured without any change caused by aging like e.g. in PTC´s. there's an improved long time stability.

4. The future

The challenge for further developments will be on one side to improve the resolution and stability for new demands in the semi- conductor industry (e. g. Pico-Meter- Resolution for EUV- lithography machines), on the other side, to open new possibilities, also new markets and new applications. Things get possible, which were not thinkable in the past.