Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurements,
IMEKO TC3, 17-21 Sept. 2001, Istanbul, Turkey

Micromechanical Silicon Microbalance

Kari Riski*, Aarne Oja**, Teuvo Sillanpää**, Hannu Sipola**, Heikki Seppä**
Jyrki Kiihamäki***, Pekka Seppälä*** and Jani Karttunen***

**Centre for Metrology and Accreditation,Helsinki, Finland*

***VTT Automation, Finland*

****VTT Electronics, Finland*

Abstract

A micromachined capacitive silicon microbalance has been designed and fabricated. It is intended for weighing masses of the order of 1 g with a resolution and accuracy of about 1 µg. The device consists of a micromachined SOI (silicon-on-insulator) chip which is anodically bonded to a glass plate. The capacitance is formed between two electrodes. The flexible electrode is the SOI layer. The other electrode is metal layer on the glass. The glass electrode is divided into three sections. The sections are used for detecting the tilting of the top electrode due to eccentric loading. The measuring circuit implements electrostatic force feedback which keeps the top electrode at a constant horizontal position irrespective of the mass of the load. First test measurements have demonstrated that an accuracy of about 2 to 3 µg at 1 g can be reached.

1. Introduction

The excellent mechanical properties of single-crystalline Silicon have been utilized in a variety of measuring sensors including pressure sensors and acceleration sensors. In these devices the mechanical deformation of silicon is often determined by measuring changes in the capacitance between the moving silicon part and a fixed electrode. With this technique repeatabilities of the order of 10 ppm have been reached in commercial pressure sensors.

Micromechanical silicon balances in which the weighing is based on the change of the capacitance between a thin silicon membrance and a ridgid capasitor have been described in the literature [1,2]. These devices could however not be easily modified to high precision mass measurements partly due to eccentric loading errors. Because of non-linear distance dependence of the measured capacitance such loading errors can cause severe problems. In the device presented here we have solved the problem due to eccentric loading by dividing the fixed electrode into three sectors [3,4,5]. We have also improved the dimensional accuracy by using structured SOI (silicon–on-insulator) wafer rather than bulk Si wafer [5].

In most mass comparators or precision balances the gravitational force due to the mass is measured by the method of electromagnetic force compensation [6]. With this method a linearity and repeatability better than 1 ppm can be reached. The construction of such device is complicated as compared with a balance which is manufactured from a single silicon chip. It is expected that a such Silicon balances would be especially favourable for the measurement of small masses (less than 10 g).

2. Mechanical Structure

The sensing element of the device is illustrated in Figure 1. It consists of a SOI (silicon-on-insulator) chip anodically bonded on a class chip. The overall dimensions of the sensing element are 10 mm x 10 mm x 0.9 mm. The fabrication of the device has been described elsewhere [5]. A cross section of the device is shown in Figure 2. It consists of an upper Si-layer which also forms a circular spring, an insulating SiO_2-layer, a lower Si-layer disc which is the rigid base for the weighing pan, air gap, a glass plate and the supporting frame for the spring. The thickness of the upper Si-layer (spring) is 8 µm and the thickness of the lower Si-disc is about 380 µm. The air gap between the disc and the glass plate is about 10 µm. The thickness of the glass plate is 0.5 mm. The diameter of the Si-disc is about 6.5 mm and the width of the spring is about 0.7 mm. The upper silicon surface is covered with an Aluminium layer except for the spring section. There is an electrical connection from the Al-layer through the SiO_2 layer to the lower Si disc. The disc forms the upper electrode of the capacitance. The electrical connection is through the Al-layer. The lower electrode is a metal layer

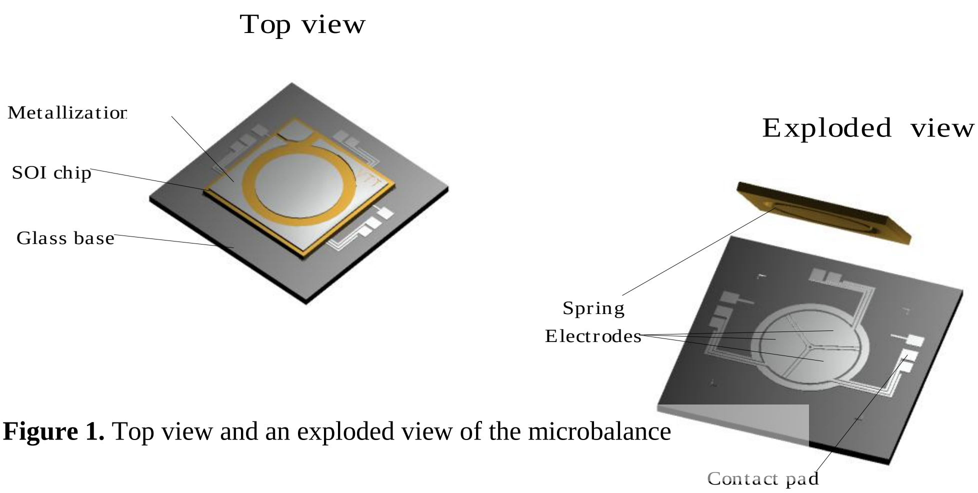

Figure 1. Top view and an exploded view of the microbalance

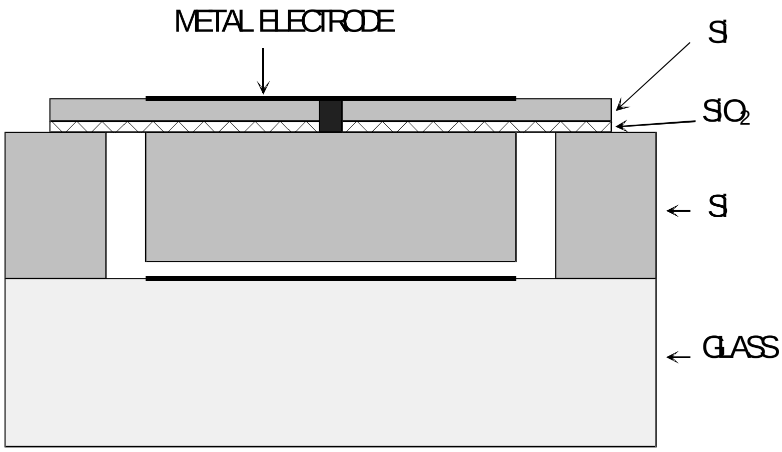

Figure 2. Cross section of the microbalance

evaporated on glass surface. It is divided into three segments. The capacitance between the disc and each segment can be measured separately.

The mass to be weighed is placed in the middle of the upper electrode. The force due to gravity pushes the upper electrode towards the lower electrode. The circular spring resists this movement. The resisting force F is approximately proportional to the vertical movement z of the weight.

The spring constant $k = F/z$ has the formula:

$$k = \frac{4\pi E t^3}{3(1-v^2)}\left[a^2 - b^2 - \frac{4a^2b^2}{a^2-b^2}(\ln\frac{a}{b})^2\right]^{-1} \qquad (1)$$

where E is the Young's modulus of silicon, v is Poisson's ratio of silicon, t is the thickness of the spring, a is the outer radius of the spring and b is the inner radius. With a=4 mm, b=3.25 mm, t=8 µm, E=170 GPa and v=0,3 we find $k\approx5200$ N/m. For a 1 g weight the displacement is $z \approx 2$ µm.

3. Principle of Operation

The idea of operation is to keep the distance between the capacitor plates constant independent of the load. In such a case the nonlinearity of the spring constant does not affect the linearity of the device. The separation of the capacitor plates is controlled by a DC-voltage. The voltage pulls the plates closer to each other. The voltage dependence is quadratic. If the voltage is too high the spring can not resist the pulling force and the plates will be pulled together. This is an undesired situation. The sensitivity of the balance is however at maximum close to this pull-in-voltage.

When the balance is empty the voltage U_{m0} is introduced between the capacitor plates. The spring is bent and the separation between the capacitor plates is d-z_b , where d is the initial separation without any load or voltage and z_b is nominal bending of the spring. If a mass m is placed on the balance the voltage is reduced to

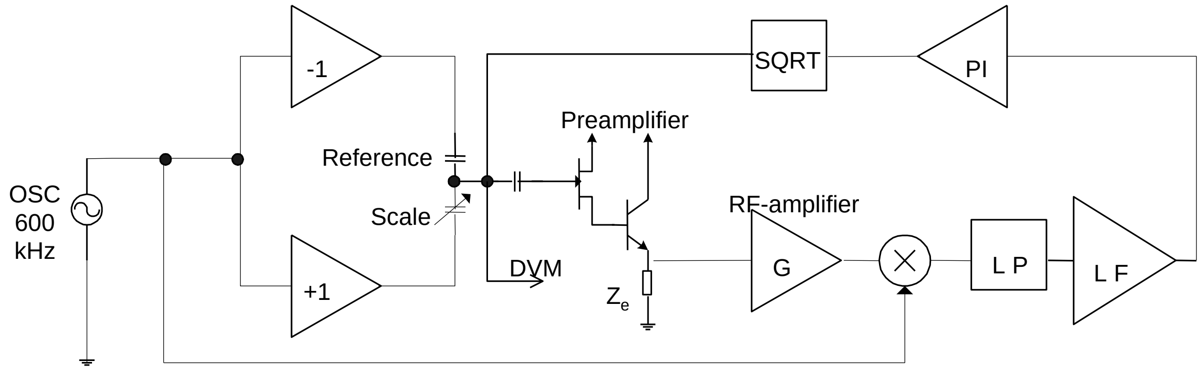

Figure 3. Block diagram of the measuring circuit

value U_m until the separation d-z_b between the capacitor plates is reached. The mass cannot be higher than the nominal mass $m_{nom} = k\ z_b\ /g$ because a higher mass would bend the spring more than the nominal value z_b. Here g is the acceleration of free fall. The following formula can be derived for the system in equilibrium:

$$mg + \frac{\varepsilon A}{2(d-z_b)^2}(U^2 + U_{ac}^2) - m_{nom}g = 0 \qquad (2)$$

where A is the area of the capacitor plate, ε is the permittivity of air, U is the dc-voltage between the capacitor plates and U_{ac} is the ac-voltage used for capacitance readout. It can be seen from Equation (2) that if the mass m is increased the dc-voltage U has to be decreased to maintain the equilibrium. The mass m can be expressed in terms of voltages U_m and U_{m0} in the following way:

$$m = \frac{\varepsilon A}{2g(d-z_b)^2}(U_{m0}^2 - U_m^2) \qquad (3)$$

In our design the distance d-z_b is kept constant by voltage feedback.

4. Electronics and Noise Characteristics

A schematic diagram of the controlling electronics is shown in Fig. 3. The capacitance of the balance is compared with a reference capacitor by an ac-capacitance bridge. An ac voltage with an amplitude of U_{ac} = 0.7 V and a frequency of 600 kHz is fed to both capacitors. Because the signal to the reference capacitor is inverted as compared with the signal to the balance capacitor the output current of the bridge is zero if the two capacitance are equal. The output of the bridge is fed to a PI-controller and from there through a square root circuit to the balance capacitor. The square root circuit keeps the feedback linear. The voltage across the balance capacitor is measured. Since the force is proportional to the square of voltage the mean square voltage is calculated by summing the squares of individual readings. If this is not done the voltage noise will lead to a systematic error.

The resolution of the ac-bridge is limited by the noise of the inverter, preamplifier and the AC voltage. It can be estimated that the relative noise of the capacitance $\Delta C/C$ due to the ac-

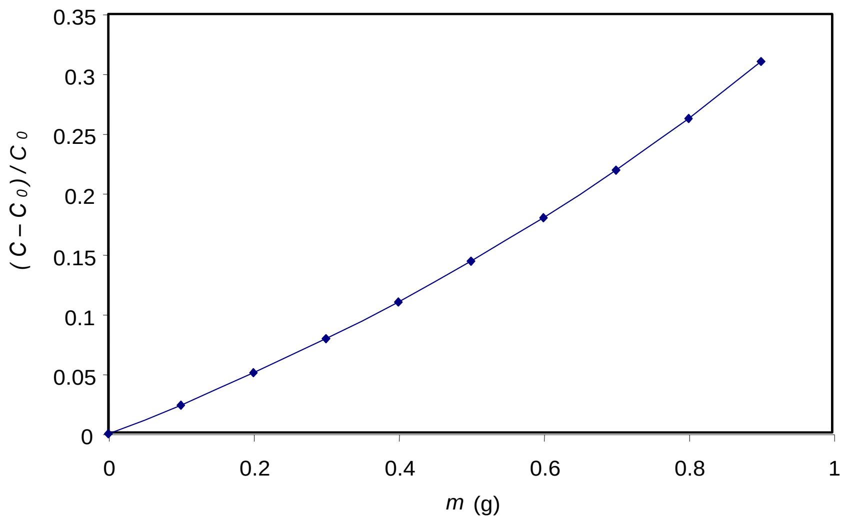

Figure 4. C F).

bridge is less than 0.1 ppm/ √Hz. It is possible that Silicon dioxide layers can cause additional low frequency (1/*f*) noise. It has been estimated

that the relative uncertainty of the mass $\Delta m/m \approx 4\cdot10^{-7}$ can be reached if the relative uncertainty of the feedback voltage $\Delta U_m/U_m$ and capacitance $\Delta C/C$ are 0.1 ppm.

Systematic errors such as eccentric loading, stability of reference capacitor and the measurement of the output voltage increase uncertainty. These components are expected to lead to a relative uncertainty of mass $\Delta m/m$ which is of the order of few ppm.

In addition to the uncertainty sources described above environmental conditions such as air pressure variations, temperature gradients and vibrations increase measurement uncertainty. Their effect have not yet been systematically analysed.

The spectral density of the output noise voltage was measured when the electronics was connected to a stable ordinary capacitor. Of particular significance in the planned application is the low-frequency noise. It was observed that over time periods from 10 s to 1000 s and above $\Delta C/C$ (Allan variance) was about 0.4 ppm. The noise is somewhat larger than expected from a theoretical calculation.

Next the output noise was measured when the unloaded balance was connected to the read-out electronics. There was a strong temperature dependence of the output voltage, of the order of 100 ppm/°C. When this drift was removed the Allan variance over time periods 10 s to 1000 s was less than 2 ppm. The reason for the strong temperature drift is still unclear. The effect of loading on the noise characteristics has not yet been investigated.

5. Measurements

The capacitance between the top and bottom electrodes as a function of DC bias voltage was measured. At small voltages the dependence is parabolic $(C\text{-}C_0)/C_0 = (U/U_0)^2$ as expected. Here C_0 is the capacitance without any voltage. When the pull-in point $z=d/3$ is approached the capacitance increases sharply. The behaviour is described by the formula:

$$\frac{z}{d}=\frac{2}{3}\left\{1-\cos\left[\frac{1}{3}\cos^{-1}(1-\frac{2U^2}{U_{pi}^2})\right]\right\}. \qquad (4)$$

The measured data can be described with C_0=37 pF and U_{pi}=45 V.

Data from a preliminary weighing experiment is presented in Fig. 4 where capacitance between the top and bottom electrodes is shown as a function of mass. The capacitance was fitted to the formula:

$$\frac{C-C_0}{C_0}=(1-\frac{mg}{dk})^{-1}-1 \quad . \qquad (5)$$

At small masses the dependence is linear. The solid line in Fig. 4 represents a fit to the data with $g/(dk)$ = 0.26 g^{-1} . The sensitivity of the device is 9.9 aF/µg for small masses.

7. Conclusion

We have designed and fabricated a micro-machined capacitive silicon microbalance which can be used for weighing masses of the order of 1 g at a resolution of about 1 µg. The device consists of a SOI chip which is bonded to a glass plate. The whole system is very compact. Changes of capacitance between the flexible top electrode and three fixed glass electrodes are measured. The measuring circuit implements electrostatic force feedback and keeps the top electrode at a constant position irrespective of mass loading.

8.References

[1] .Zimmermann H., Graf von Wengersky A., and Kraus J., German patent DE 3426165 A1, 1985

[2]. Holm-Kennedy J.W. and Umemoto D.K., U.S. patent 4969177, 1990

[3]. Sillanpää T., Oja A.S., and H. Seppä, Conference on Precision Electromagnetic Measurements, Conference Digest, 1990, p.23-24

[4]. Oja A., Seppä H., and Sillanpää T., Finnish patent FI 105237, PCT WO 99/67605, 1999

[5]. Oja A., Sillanpää T., Seppä H., Kiihamäki J., Seppälä P., Karttunen J., and Riski K., *Micromechanical Silicon Precision Scale*, in *Proceedings of the Symposium on Design, Test, Integration and Packing of MEMS/MEOMS, Eds. by Bernard Courtois et al.*, Proceedings of SPIE, 2000, 4019, p. 498 – 505.

[6]. Kochiek M. And Gläser M. (eds.), *Comprehensive Mass Metrology* , WILEY-VCH Verlag Berlin, 2000

Contact Person for Paper :

Dr. Kari Riski

Address

Centre for Metrology and Accreditation, P.O.Box 239, FIN-00181 Helsinki Finland

Tel: +358 9 6167 452

E-mail: kari.riski@mikes.fi