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Resonating Microbridge Mass Flow Sensor

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Abstract

A resonating microbridge mass flow sensor with a frequency output is presented, based on standard IC and thin-film technologies, and on front-side anisotropic etching. The operation, realization, theory and experiments are described. The sensitivity is compared with that of a resonating membrane prototype. Preliminary results show a base resonance frequency of 85 kHz at a temperature elevation of the microbridge of 20 °C, with a shift of 0.8 kHz in the mass flow range from 0 to 10 sccm.

Introduction

Conventional mass flow controllers consist of a minute laminar flow sensor channel bypassed by a laminar flow restriction in the main flow channel, together with an electronic control unit and a control valve [1]. The actual mass flow sensor consists of two or three filaments *outside* the sensor channel pipe. These serve as resistive heaters and resistive temperature sensors. Although this configuration is robust and cheap, it leads to a poor sensitivity and a slow response of the sensor.

Micromachining provides the opportunity of suspending the heater and the temperature sensor *inside* the minute sensor channel. Several designs have already been reported [2–7], all with an analog temperature measurement. We are developing a mass flow sensor based on the frequency shift of a resonating microstructure, thus providing a high sensitivity, a high stability, a high resolution and a fast response. Also, the quasi-digital character of the output signal is highly compatible with digital circuitry. The basic idea was demonstrated with the thermally excited resonating membrane prototype [8]. In this paper we present its successor with an improved performance, the resonating microbridge mass flow sensor.

Operation

Figure 1 illustrates the operation of the sensor. The microbridge is suspended at the centre of the

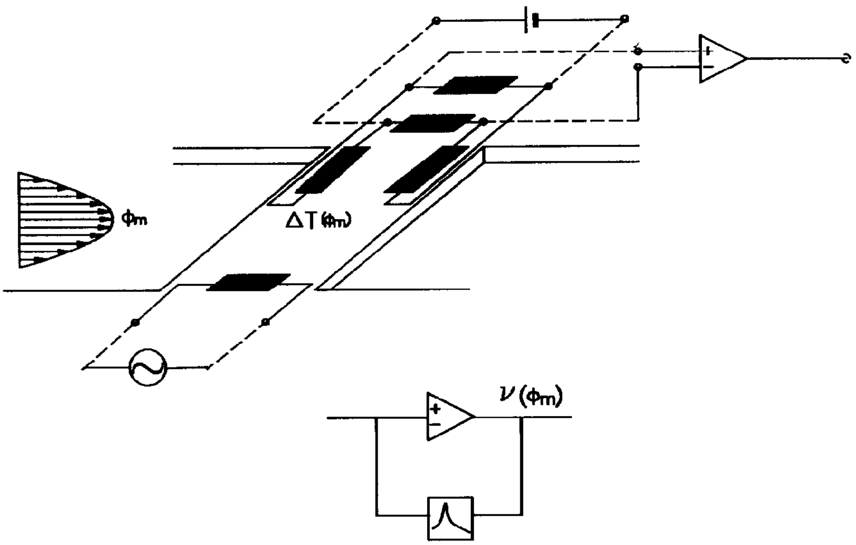

Fig. 1. Operation of the resonating microbridge mass flow sensor, suspended inside the flow channel, with resistors for thermal excitation and piezoresistive detection of the vibration; this electrical two-port forms an oscillator with off-chip drive circuitry; the oscillation frequency is dependent on the temperature elevation of the heated microbridge, which is a function of the mass flow.

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flow channel, i e at the centre of the velocity profile (left) Thin-film resistors are embedded within the microbridge for excitation and detection of forced vibrations, a d c and an a c voltage are superimposed and applied to the excitation resistor The generated dynamic heat forces the microbridge into a bending mode vibration by thermal expansion of its upper layers, the vibration is detected by thin-film strain gauges in a Wheatstone bridge arrangement A feedback loop amplifier off-chip completes the electrothermomechanical oscillator [9]

The static temperature elevation of the microbridge, caused by the dissipation in the resistors, is dependent on the heat transfer by conduction and forced convection, and strongly influences the natural frequencies of the structure [8] The oscillation frequency, which is now a function of the mass flow, is easily converted into a digital signal for further manipulation An additional advantage of the frequency-based measurement is that it imposes few requirements on the electromechanical transduction properties of the applied thin films and on the balance of the Wheatstone bridge

Realization

The starting material is a 2 in (110) silicon wafer The microbridge itself consists of three thin films, all with a thermal expansion match with the substrate 1 8 μm LPCVD silicon nitride as a carrier material, 0 16 μm LPCVD polysilicon for the resistors and a 0 15 μm LPCVD silicon nitride passivation layer (see Fig 2) The etching of the groove underneath the microbridge is accomplished at the end of the process sequence by front-side anisotropic etching This imposes severe requirements on the metallization

The silicon nitride layers are silicon-rich for stress compensation This provides a thin film with suitable electrical and thermal as well as mechanical properties [10] The deposition parameters are a dichlorosilane to ammonia mass flow ratio of 240 40 sccm, at 0 29 mbar and 835 °C, and a growth rate of 5 nm/min The film properties are a silicon to nitrogen atomic ratio of 1 1, a refractive index $n = 2\ 3$ and a residual stress $\sigma = 3\ 7 \times 10^7$ N/m^2

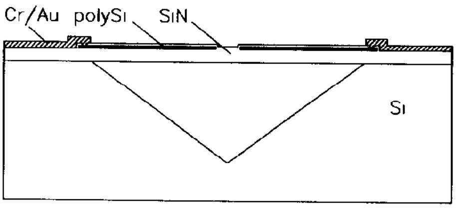

Fig 2 Schematic representation of the cross section of the sensor

The polysilicon film was doped *in situ* with phosphorus This provides a piezoresistive thin film with a uniform dopant concentration and with good thermal stability [11] The deposition parameters are a silane to phosphine (2000 ppm) to nitrogen mass flow ratio of 60 30 300 sccm, at 1 mbar and 620 °C, a growth rate of 4 5 nm/min and annealing at 850 °C for 30 min The film properties are a dopant concentration $N = 2 \times 10^{20}/\text{cm}^3$, a grain size of 20–30 nm, a sheet resistance $R = 410\ \Omega/\square$, a temperature coefficient of resistivity of −600 ppm/°C, a gauge factor $k = 20$ and with a temperature coefficient of −2500 ppm/°C The resistor pattern was etched in a HNA solution (250 85 4 ml)

After dry etching the microbridge pattern and subsequently the contact holes (both in a Freon 13/oxygen plasma, Freon/oxygen plasma post-etch treatment for the polysilicon hydrogen damage), a 0 2 μm chromium–0 5 μm gold double layer was sputtered and patterned by Ion Beam Milling (gold layer), and by wet chemical etching (chromium layer) This metallization film is inert to the anisotropic etchant Moreover, as it demonstrates a low pinhole density as well as a good step coverage, it protects the polysilicon against the etchant at the contact holes

Finally, the (110) substrate was anisotropically etched in a solution of potassium hydroxide/water (1 2 by weight) at 75 °C, resulting in shallow V-shaped grooves with inclined (111) side walls and with the microbridges positioned perpendicularly across Figure 3 shows a typical example

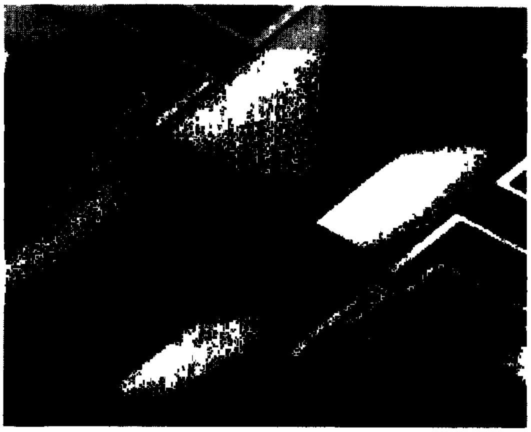

Fig 3 SEM photograph of the 600 × 200 × 2 1 μm stress-compensated silicon nitride microbridge with *in situ* phosphorus-doped polysilicon resistors and chromium–gold interconnection, suspended across the V-shaped groove in the (110) silicon substrate

with one centre resistor across the microbridge from one end to the other Wheatstone bridges are located on each end of the microbridge, both with two strain gauges on the microbridge on either side of the centre resistor, and two resistors on the substrate Bonding a cap wafer with a matching V-shaped groove on top completes the flow channel with the sensor suspended inside

Theoretical Results

The theory for the heat generation, the heat transfer, the resonance frequency, the frequency shift and the gain are published elsewhere [12, 13] These predict a resonance frequency of the unheated microbridge in Fig 3 of approximately 90 kHz, a frequency shift of 0 6 kHz/°C, a temperature elevation of the microbridge with this particular resistor pattern of 1 °C/mW without air flow, and at a mass flow of 10 sccm a cooling effect by forced convection of 10% of the total heat transfer At a temperature elevation of 20 °C this results in a base frequency of approximately 80 kHz, and a frequency shift of 1 kHz in the mass flow range from 0 to 10 sccm For d c supply voltages of 5 V applied to the excitation resistor of 2 8 kΩ and to the Wheatstone bridge, a gain of −100 dB is predicted Note that for the resistor pattern of the microbridge in Fig 3 the head generation is close to the clamped ends Although this leads to a relatively low sensitivity of the temperature elevation to mass flow, this location is favourable for a high gain of the excitation and the detection

Experiments

Figure 4 shows the experimental set-up Note that the sensor is tested without the cap wafer on A gain/phase analyser is used to measure the transfer function of the vibrating microbridge with thermal excitation and piezoresistive detection An example of resulting Bode plots for the sensor in Fig 3 for several combinations of the applied d c and a c voltages is shown in Fig 5 It shows the characteristic peak in the gain of the transfer function and phase shift of 180° at the resonance frequency of the microbridge, with the quality factor of this vibration mode of 130 Resonance modes of higher orders were also easily detected From these Bode plots, the resonance frequency as a function of the static heat generation P, and the gain as a function of d c supply voltages were determined (see Fig 6(a) and (b), respectively)

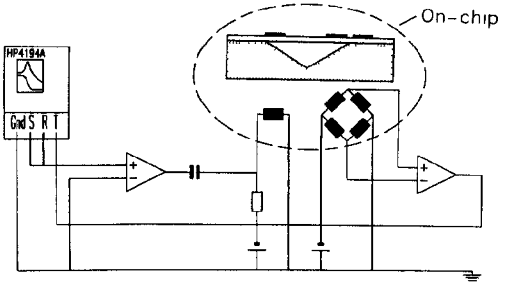

Fig 4 Experimental set-up with a gain/phase analyser for measuring the transfer function of the sensor

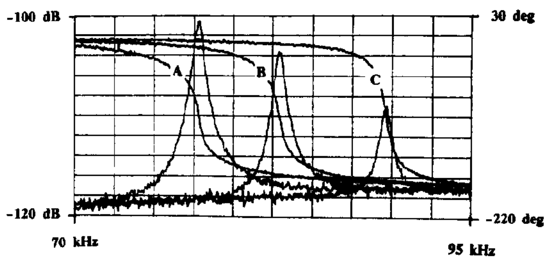

Fig 5 Bode plots of the transfer function of the sensor (A) $U_{DC1} = U_{DC0} = 4\,7$ V, $P = 20\,5$ mW, (B) $U_{DC1} = U_{DC0} = 3\,8$ V, $P = 12\,8$ mW, (C) $U_{DC1} = U_{DC0} = 2\,8$ V, $P = 2\,8$ mW

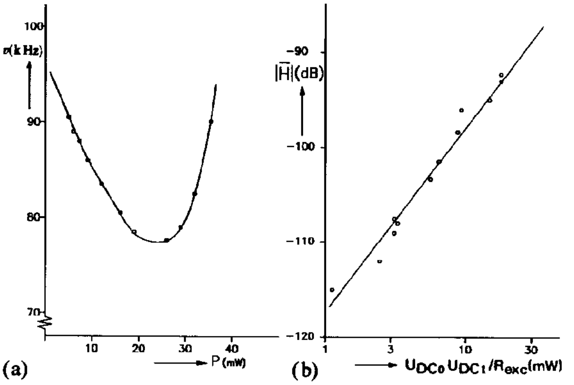

Fig 6 Experimental results (a) resonance frequency vs static heat P, (b) gain at resonance frequency vs d c voltages

The resonance frequency of the unheated microbridge is found from extrapolation to be 96 kHz The resonance frequency shows an initial decrease with increasing static power dissipation due to the induced compressive thermal stress This part of the graph, up to 20 mW, is in agreement with simple models describing the temperature elevation due to heat generation and the frequency shift of a pulled beam due to thermal stress [12, 13], with a shift of 1 kHz/mW, i e 0 5 kHz/°C

For higher power dissipations, however, the resonance frequency increases This is attributed to the effect of both the static and dynamic components of the heat generation to deform the microbridge to a shell, which has a larger flexural rigidity than a flat microbridge [8]

Finally, the sensitivity of the resonance frequency to mass flow was tested under air flow conditions with an estimated undisturbed air velocity of 3 m/s, which is approximately equivalent to a mass flow of 10 sccm in mass flow measurement At a base frequency of 85 kHz, indicating a temperature elevation of 20 °C, a shift of 0 8 kHz was measured This indicates an effective heat transfer by forced convection of 7% of the heat loss by conduction

To investigate the influence of the resistor patterns on the gain of the transfer function and on the sensitivity of the frequency shift to power dissipation and to air flow, excitation and detection resistors with various shapes and locations were tested The results will be published elsewhere [12]

Conclusions

A microbridge positioned perpendicularly across a V-shaped groove was realized using a (110) silicon substrate and KOH front-side anisotropic etching Stress-compensated silicon nitride encapsulating *in situ* phosphorus-doped polysilicon piezoresistors shows the required passivity to the anisotropic etching agent, as well as suitable electrical, thermal and mechanical properties Sputtered chromium–gold metallization meets the requirements for protecting the polysilicon against the KOH solution at the contact holes

Thermal excitation and piezoresistive detection of the vibration have proved to be feasible for these thin and long structures under tensile stress The gain of the transfer function at the first bending mode resonance frequency is sufficient for off-chip feedback amplification The sensitivity of the temperature elevation to mass flow is much higher than for the membrane prototype, at a base frequency of 85 kHz and a temperature elevation of 20 °C, a preliminary frequency shift was measured for the microbridge prototype of 0 8 kHz in the mass flow range from 0 to 10 sccm, whereas for the membrane prototype this shift was 13 Hz at 5 kHz and 8 °C The experimental results agree well with the theory

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