Sensors and Actuators A, 25–27 (1991) 723–727

Resonating Microbridge Mass Flow Sensor with Low-temperature Glass-bonded Cap Wafer

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Abstract

A resonating microbridge mass flow sensor has been realized suspended inside a micro flow channel. Thin-film technologies and micromachining are used for the fabrication of the sensor wafer and a cap wafer with opposing V-grooves. A low-temperature glass-bonding technique is used to assemble the wafers allowing for feedthrough of the electrical connections. Measurements show sensitivities of the resonance frequency of several kHz per sccm nitrogen gas flows at average temperature elevations of the microbridge in the range 20 to 100 °C.

Introduction

A mass flow sensor based upon the frequency shift of a resonating structure has been developed. Thermal excitation and piezoresistive detection are used to induce and measure the vibrations. This is accompanied by a static temperature elevation of the structure, which induces a thermal compressive stress. Using the cooling effect of a passing gas stream (thermo-anemometry principle [1]), a temperature drop will induce thermal stresses in a heated structure which will strongly affect its natural resonance frequencies. Earlier we reported upon a thermally excited resonating membrane mass flow sensor [2], which showed the basic idea of operation. Modelling showed that the sensitivity of the sensor is highly dependent on the ratio between heat transfer by conduction to the clamped edges of the structure and the heat transfer by forced convection to the gas. Due to the large heat loss by conduction to the clamped edges of the membrane, as well as the small heat transfer by forced convection, the sensitivity was low. This called for the development of a microbridge prototype. The realization of the bottom wafer of this sensor with microbridges has been presented elsewhere [3]. The resonance frequency response as a function of the heat generation in the microbridge and testing of the uncapped sensor wafer in an air flow showed an increased sensitivity. In this paper we report upon the realization of the capped sensor structure and the response of the sensor as a function of the mass flow.

Realization

The mass flow sensor consists of two (110)-silicon wafers with anisotropically etched V-grooves, the microbridge being suspended at the centre of the flow channel (see Fig. 1). The realization of the sensor wafer has already been described [3]. The microbridge itself consists of a stress-reduced silicon nitride layer [4] with thin-film polysilicon resistors for excitation and detection [5] embedded in it. Several different resistor pattern designs were realized. Electrical connections with the resistors are made by Cr/Au metallizations. The fabrication of the cap wafer starts with a 2 inch (110)-oriented silicon wafer. Two-sided bulk micromachining using thermal oxide as the mask material yields a construction with V-grooves on the front side and contact openings, for bonding pad

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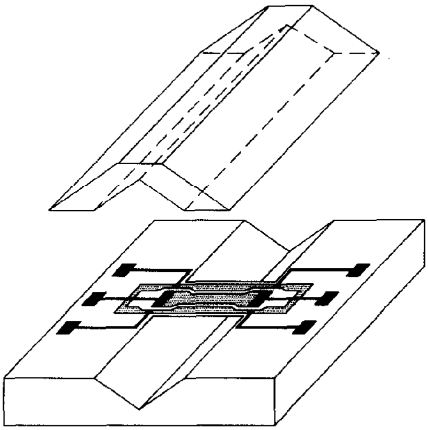

Fig. 1. Bird's eye view of the sensor assembly. Dimensions are 600 × 200 × 2.1 μm for the microbridge and 420 μm for the height of the flow channel.

access and for alignment marks through the wafer. After stripping the remaining silicon oxide in BHF, the wafer is cleaned and oxidized again. Because this wafer has to be bonded on a completely processed sensor wafer covered by a thick SiN layer, Cr/Au metallization patterns and etched V-grooves, a low-temperature glass-bonding technology was developed [6]. Low-temperature glass bonding occurs by means of melting an intermediate glass layer. This allows for feedthrough of the electrical connections. The glass layer deforms during melting, filling the surface roughness, covering steps (Cr/Au pattern) and enclosing possible dust particles. The cap wafer is coated with a 1.5 μm thick boron oxide film grown by APCVD in a horizontal hot-plate bell-jar reactor. The deposition rate is 33 nm/min for a N_2:O_2:B_2H_6 (2000 ppm) gas mixture of 6500:70:405 sccm at a temperature of 425 °C. Immediately after the boron oxide deposition, the oxide layers are stripped from the back of the cap wafer by RIE in a freon 13 plasma to prevent sticking at an applied load during bonding. Next, both wafers are aligned using a mask aligner, and fixed by exposure of a few drops of UV-hardening glue in openings in the cap wafer, etched for this purpose. Both wafers are placed in an oven under an applied load of approximately 5000 Pa, slowly heated up to 465 °C, and kept at that temperature for 10 min. After slowly cooling down to room temperature the bonding process is completed. Preliminary experiments show good bonding over the entire wafer area. The cross section of the complete sensor is shown in Fig. 2.

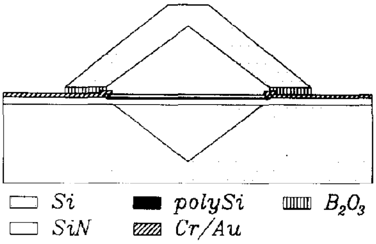

Fig. 2. Cross section of the complete sensor.

Experiments

Figure 3 shows the experimental set-up for testing the sensor. The nitrogen gas supply (Fig. 3(a)) is controlled using a commercially available mass flow controller, which was calibrated using the soap pellicle method for mass flows up to 30 sccm. Inlet and outlet nipples were glued on top of the cap wafer to lead the mass flow through the micro channel. A HP 4194A gain/phase analyser (Fig. 3(b)) was used to measure the transfer function of the mass flow sensor regarded as an electrical two-port. The sinusoidal output signal of the source channel was amplified and superimposed on a d.c. voltage, which was then applied to the excitation resistor [7]. The output signal of the Wheatstone bridge is amplified by a differential amplifier and applied to the test channel of the gain/phase analyser. Electrical contact to the bonding pads is made by probe pens. The contact force of the probe pens on the chip is kept as low as possible, still ensuring good contact. This contact force deforms the chip and leads to additional stress in the microbridge. As the microbridge is close to the neutral plane of the cross section of the bottom and cap assembly, it is relatively insensitive to bending of the assembly. All measurements were done

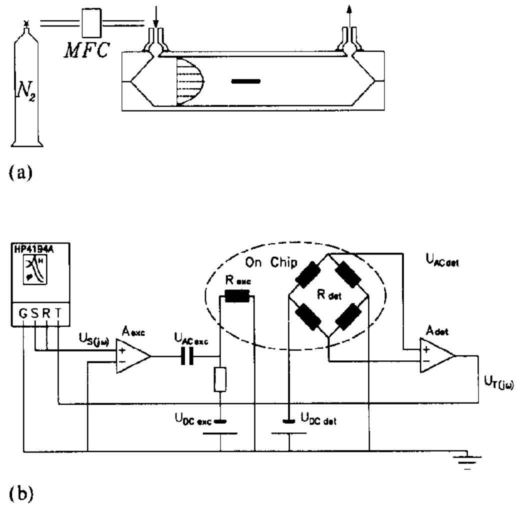

Fig. 3. (a) Experimental set-up: gas supply and flow path, showing nitrogen gas cylinder, mass flow controller and the cap and bottom wafer assembly with inlet and outlet nipples. The suspended microbridge is also shown. (b) Experimental set-up: electrical operation.

at the first-order resonance frequency of the microbridges.

First a series of resonance frequency measurements was conducted as a function of the excitation and detection voltages. Depending on the resistor patterns, different minimum voltages were required for detectable resonance peaks with sufficient signal-to-noise ratios. These measurements are shown in Fig. 4(a)–(d) for four different resistor patterns. The curves show a decrease of the resonance frequency with increasing heat dissipation until buckling of the microbridge occurs. After buckling the resonance frequency rises with further increasing heat dissipation. Assuming no additional stress in the microbridge is introduced by bonding and contacting the chip, other than the residual tensile stress of the SiN, the average temperature elevation of the microbridge can be determined. Using the theoretical buckling temperature ($T_b = 64$ °C) [8] and the heat generation at which buckling occurred, the thermal conductivity (χ_λ) of the microbridge can be calculated and used to determine the average temperature elevation at other heat dissipations. This is also shown in Fig. 4(a)–(d).

Next, measurements were performed for the first-order resonance frequency as a function of the mass flow for different temperature settings of the microbridges. The results for the different resistor types are shown in Fig. 4(e)–(h). The resonance frequency increases with increasing mass flow for temperature elevations below T_b; for buckled microbridges (temperature elevation higher than T_b) the resonance frequency decreases with increasing mass flow. It can be seen that microbridges with a heat generation concentrated at the centre (types A and B) exhibit a larger resonance frequency dependence of the mass flow. This is due to a smaller heat loss by conduction, which gives a relatively larger influence of the heat transfer by convection of the mass flow. Microbridges with resistor type D, i.e., with the excitation and detection resistors adjacent to the clamped edges, can be operated more easily at lower temperature elevations because of the higher conductivity to the clamped edges and a more efficient excitation and detection of the vibration. Sensitivities of the resonance frequencies to temperature variations are highest near the buckling temperature. The sensitivities for the different types, within a temperature range 20–100 °C, range from +4 kHz/sccm below the buckling temperature to −7 kHz/sccm above T_b for mass flows up to 30 sccm. A more complete analysis of the measurement results in comparison with theoretical modelling will be presented elsewhere [9].

Conclusions

A resonating microbridge mass flow sensor has been successfully realized. Low-temperature glass bonding was used to assemble a wafer with thin-film microbridges suspended over V-grooves to a wafer with opposing V-grooves. This yields a micro flow channel with the microbridge suspended inside. No special requirements are necessary for feedthrough of the electrical connections. Measurements of the resonance frequency

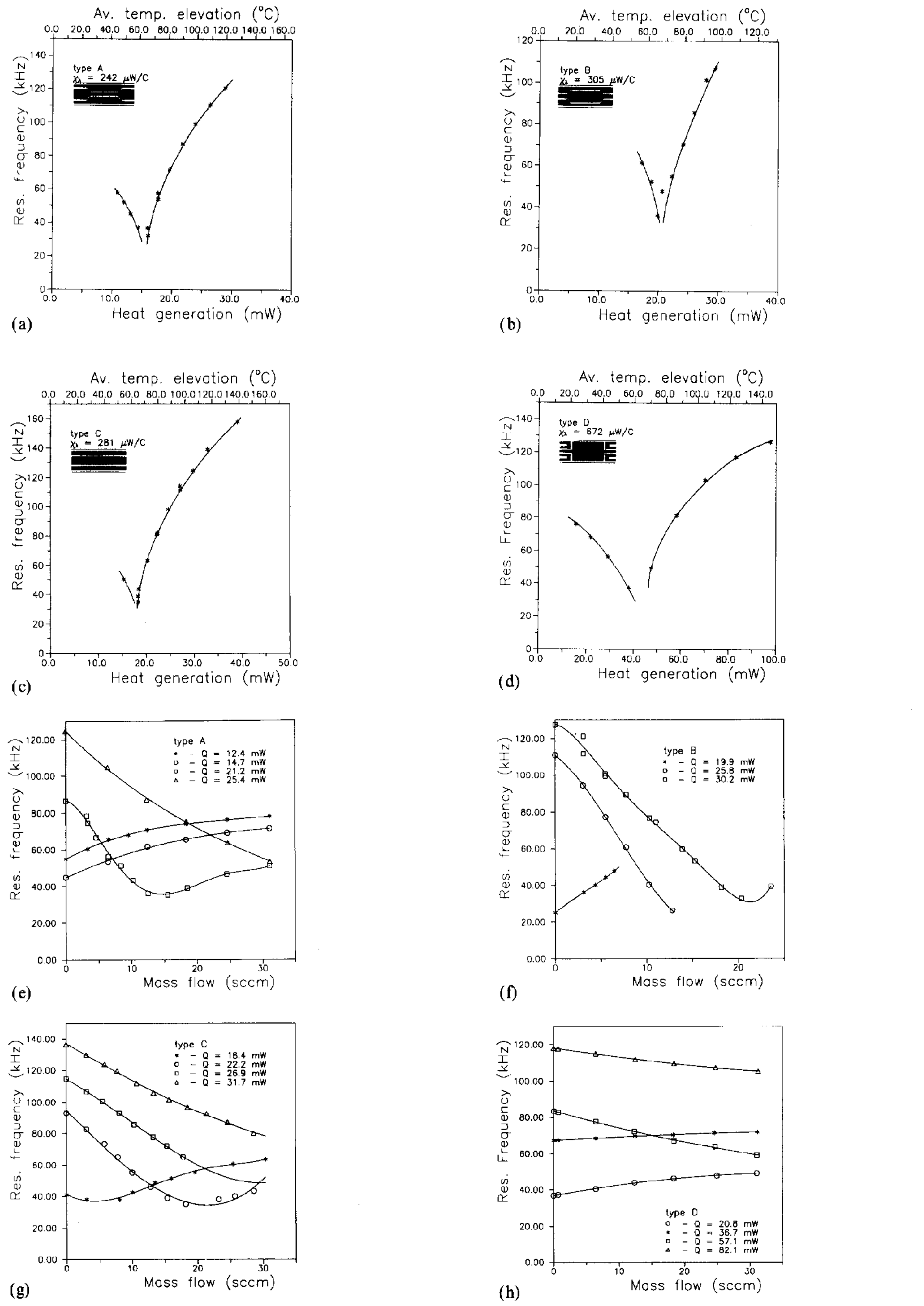

Fig. 4. (a)–(d) Resonance frequency vs. static heat generation/static average temperature elevation and (e)–(h) resonance frequency vs. mass flow for different heat generations for four resistor pattern designs (types A, B, C, D).

behaviour as a function of the static heat generation in the excitation and detection resistors on the microbridge show a decrease of the resonance frequency for increasing heat generation and an increase after buckling of the microbridge for larger heat generations. Mass flow measurements show a complex resonance frequency behaviour with sensitivities varying from +4 kHz per sccm below the buckling temperature to −7 kHz per sccm above the buckling temperature, with average static temperature elevations of the microbridges ranging from 20 to 100 °C.

Acknowledgements

This project is part of the Dutch I.O.P. scheme (Innovative Research Programme) 'Semiconductor Technology', and is co-financed by the Department of Applied Physics of the University of Twente. The research was carried out within the Micromechanical Transducers Research Group of Professor T. J. A. Popma, Professor J. H. J. Fluitman and Dr. M. Elwenspoek, and is in cooperation with ASM International/AMTC, Bilthoven, The Netherlands. We would also like to thank John Baxter and Katrina Emmett for carefully reading the manuscript.

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