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A high sensitivity CMOS gas flow sensor on a thin dielectric membrane

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Abstract

We report the first implementation of a double-polysilicon thermopile gas flow sensor in an industrial CMOS process The sensor uses the Seebeck effect between n-doped and p-doped polysilicon as provided by the CMOS process In order to prevent a pn-junction between the two materials the polysilicon lines are connected through aluminium contacts Thermal isolation is achieved by placing the thermopile on a thin silicon dioxide membrane Sensitivity with respect to nitrogen flow velocity and heating power is 0 36 mV/sccm/mW in the linear range, i e one order of magnitude better than our previous CMOS polysilicon/aluminium thermopile sensors (*Sensors and Actuators A*, *25–27* (1991) 577–581)

Introduction

Gas flow sensors are mainly used in automotive applications, air conditioning and process control systems Conventional hot wire anemometers are expensive and usually have a large response time On the contrary, integrated silicon gas flow sensors have many advantages First they are small and therefore have a fast response time Second they can be batch fabricated to reduce cost Third they can be combined with on-chip electronic circuitry for signal conditioning and power supply to enhance their performance

Like conventional sensors, most silicon gas flow sensors measure flow through heat transfer by the gas Exceptions are microresonators, where the gas flow changes the resonance frequency of a microbridge [1], and differential pressure sensors, which measure the upstream and downstream gas pressure in a tube Integrated hot wire anemometers measure the change in the resistance of thin film thermoresistors connected to a Wheatstone bridge [2, 3] Integrated thermopiles measure gas flow through the Seebeck effect A thermally isolated resistor is heated with a constant power Its temperature is measured by the thermopile A gas flow changes the resistor temperature and therefore the output voltage of the thermopile Integrated thermopiles usually consist of aluminium/p-doped silicon thermocouples in bipolar technology [4, 5] or of aluminium/polysilicon thermocouples in CMOS technology [5]

In this paper a silicon gas flow sensor based on a new type of integrated thermopile is presented For the first time the thermocouples are formed between n-doped and p-doped polysilicon Compared with aluminium/polysilicon thermopiles the sensitivity is increased by a factor of three due to the higher Seebeck coefficient and lower thermal conductance The thermopile is located on a closed membrane structure, in contrast to our previous devices, where the temperature sensitive structure was placed on a cantilever beam or a bridge [2, 5] The membrane structure has two advantages First, the closed structure is less sensitive to dust particles which could shorten the thermal isolation of an open cantilever beam or bridge structure Second, it is easier to obtain a laminar gas flow across a membrane than across a cantiliver beam A disadvantage of the membrane structure is its more involved fabrication process, which requires additional PECVD, lithography and RIE steps in addition to the CMOS IC process

Design and fabrication

Figure 1 shows an SEM photograph of the sensor The thermopile consists of two times fifteen n-polysilicon/p-polysilicon thermocouples connected in series with the ‘cold’ contacts on bulk silicon and the ‘hot’ contacts in the center of the membrane close to a 2 8 kΩ polysilicon heating resistor

Figure 2 shows a closer view of the center of the membrane with the heater and three thermocouple ‘hot’ contacts The parallel n-doped and p-doped polysilicon lines are connected through aluminium to prevent pn-junctions between the differently doped materials The membrane consists of a sandwich of field oxide and CVD oxides The size of the membrane is 400 μm by 400 μm, and the thickness about 3 μm The length of a thermocouple is 160 μm The device is designed for and fabricated by an industrial double polysilicon 3 μm CMOS process (provided by EM Microelectronic Marin), followed by an anisotropic etching step with one additional mask

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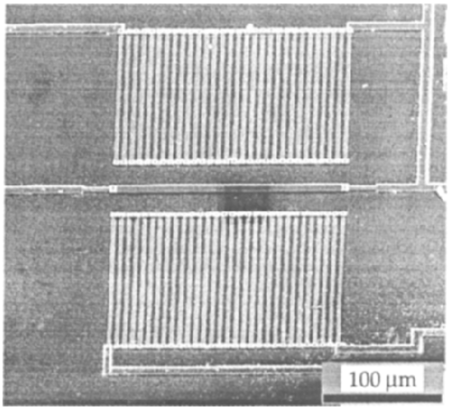

Fig 1 SEM picture of CMOS gas flow sensor

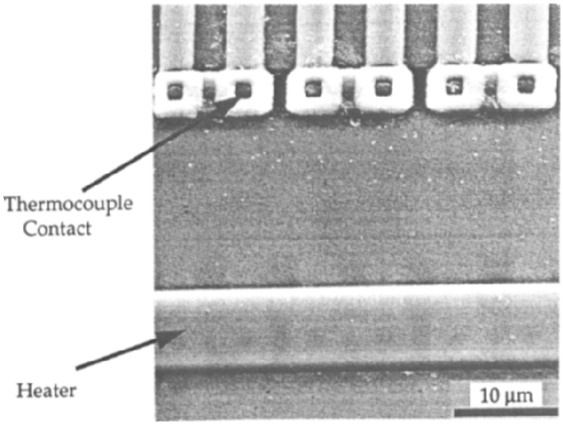

Fig 2 SEM picture of three thermocouple contacts together with the heating resistor

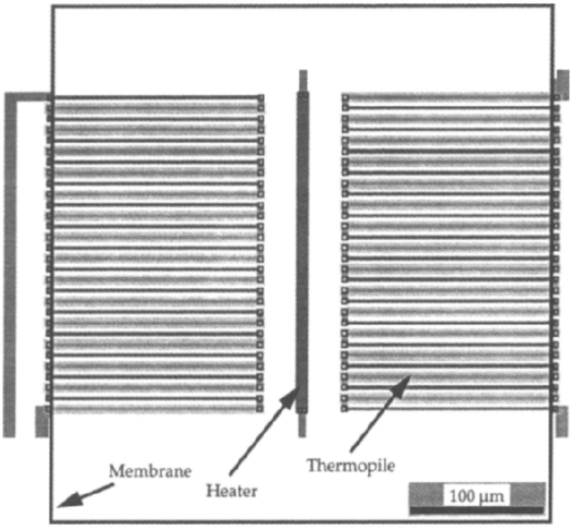

Fig 3 Layout design of double-polysilicon gas flow sensor The frame corresponds to the membrane size after the final etching step

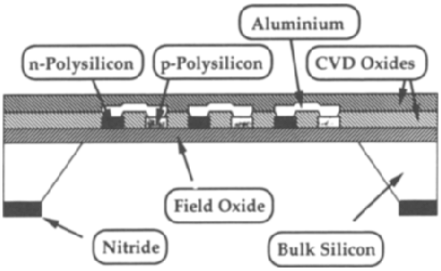

Fig 4 Cross section through sensor after CMOS process and anisotropic etching step

Figure 3 shows the sensor design layout The frame around the thermopile corresponds to the membrane size after the final etching step After designing the layout data was submitted to a CMOS foundry There the complete CMOS IC processing was performed without any changes The post-processing anisotropic etching was done in our laboratory using KOH A 0 6 µm thick PECVD nitride was deposited and patterned on the back of the wafer to define the membrame During the etching step the front side of the wafer was mechanically protected from the etchant Finally, the sensors were bonded on standard ceramic substrates Figure 4 shows a cross section of the fully processed sensor

The portability of the double polysilicon thermopile principle to other CMOS processes has been demonstrated by fabricating similar structures using the 1 2 µm CMOS process provided by Austria Mikro Systeme (AMS) Unterpremstatten

Thermopile characterization

Figure 5 shows the two thermopile output voltages and their sum versus the heating power The two thermopiles are not identical due to a slight misalignment

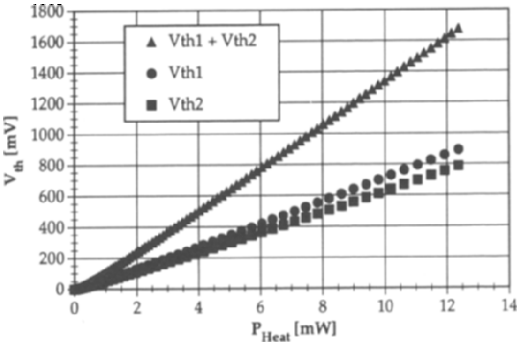

Fig 5 Thermopile output voltage vs heating power

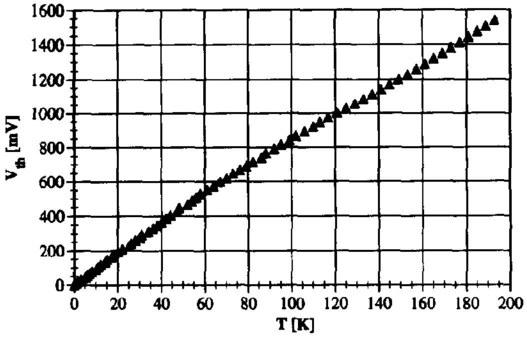

Fig 6 Thermopile output voltage vs temperature difference between hot and cold junction

of the membrane mask The sum of the thermopile output voltage rises linearly with a slope of 135 mV/mW Since the thermopile consists of thirty thermocouples, one single couple produces 4 5 mV/mW The maximum allowed heating power is about 20 mW The beam temperature as a function of the heating power was calculated by measuring the resistance of the heater and using its known temperature coefficient The polysilicon temperature coefficient is 500 ppm/K and was previously determined on a heated chuck

The relative Seebeck coefficient α_{np} of the two polysilicon materials is found by plotting the thermopile output voltage versus the temperature difference between the 'hot' contacts in the membrane center and the 'cold' contacts on the bulk (Fig 6) In view of the high thermal conductivity of the bulk silicon, room temperature is assumed for the 'cold' contacts This is in agreement with qualitative temperature measurements using an IR camera From the slope of the curve in Fig 6, the value of the relative Seebeck coefficient α_{np} of 270 μV/K is obtained for a thermocouple between n-doped and p-doped polysilicon This value is verified by measuring separately the Seebeck coefficients α_n of n-polysilicon (−200 μV/K) and α_p of p-polysilicon (+70 μV/K), respectively

Although the Seebeck coefficient of 270 μV/K is four times higher than that obtained with an aluminium/polysilicon thermopile, it is still much smaller than Seebeck coefficients obtained for monocrystalline silicon versus aluminium [4, 5] But the lower Seebeck coefficient is more than compensated by the excellent thermal isolation of the thin oxide membrane Monocrystalline silicon membranes usually have a thickness around 10 μm Therefore a large amount of the generated heat is dissipated to the substrate through the membrane by heat conductance and a large power is required to heat the sensor significantly [5] Also aluminium/polysilicon thermopiles suffer from heat conductance to the substrate through the aluminium lines

In contrast to the above the new double-polysilicon thermopile on the thin oxide membrane has an excellent thermal isolation The polysilicon thickness is below 0 5 μm and the polysilicon thermal conductivity κ is about 30 W/m/K [6] A small heating power results in a high temperature difference between beam tip and silicon substrate and therefore produces a high sensitivity The thermopile figure of merit z is defined [4] as

$$z = \frac{(\alpha_n - \alpha_p)^2}{[(\rho_n \kappa_n)^{1/2} + (\rho_p \kappa_p)^{1/2}]^2} \tag{1}$$

where $\alpha_{n\ p}$ is the Seebeck coefficient, $\rho_{n,p}$ the electrical resistivity and $\kappa_{n\ p}$ the thermal conductivity for the two materials

A value of $z = 1\ 3 \times 10^{-5}\ K^{-1}$ is obtained for the n-polysilicon/p-polysilicon thermopile with the polysilicon values for the electrical resistivity ρ (50, 44 μΩm) and the thermal conductivity κ (30 W/m/K) This value for z has the same order of magnitude as that of monocrystalline thermopiles [4, 5]

The signal-to-noise ratio SNR is mainly determined by the thermal noise of the internal resistance R of the integrated thermopile [4] Considering a bandwidth from 0 to 1 Hz, the thermal noise U_{noise} is given by

$$U_{noise} = \sqrt{4kTR} \tag{2}$$

where R is the internal resistance of the thermopile, T is the temperature and k is the Boltzmann constant With $R = 380$ kΩ and $T = 300$ K the signal-to-noise ratio SNR is about $1\ 7 \times 10^9$ per Watt heating power Compared to our previous aluminium/polysilicon thermopiles [5] this value is not increased because of the higher internal resistance of the double-polysilicon thermopile However, the goal is to amplify the thermopile output voltage with on-chip integrated standard amplifiers, which have a higher equivalent input noise level than the thermopile Therefore the higher signal of the double-polysilicon thermopile compared with the aluminium/polysilicon thermopile results in a higher

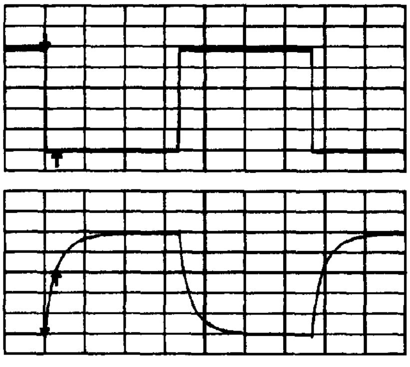

Fig 7 Thermopile response (lower plot) to a heating voltage step (upper plot) Time/div = 5 ms

overall performance The *SNR* corresponds to a noise-equivalent-power *NEP* of 600 pW and a noise-equivalent-temperature-difference *NETD* of 10 μK

Figure 7 shows the thermopile response to a heating square wave voltage with an amplitude of 1 V The time constant of the heater/thermopile system is 1 45 ms in both directions

Flow measurement results

All flow measurements were made with pure nitrogen gas at room temperature The gas flow was controlled with an MKS mass flow controller in the mass flow range of 0 to 1000 sccm, which corresponds to a flow velocity v of 0 to 85 m/s in our measurement setup The sensor chip was mounted under a PMMA substrate containing a flow channel of 0 5 mm diameter

In the operating mode the heating resistor is driven with constant power This leads to a thermopile output voltage of 135 mV/mW caused by the thermal gradient between membrane and bulk silicon A gas flow across the chip modulates the temperature distribution on the membrane and reduces the thermopile output voltage Figure 8 shows the thermopile output voltage versus the nitrogen flow for a heating power of 13 mW In the range from 10 to 100 sccm the signal decreases linearly For higher flow the sensor ouptut saturates In the linear range we measure a voltage decrease of 4 6 mV/sccm, yielding a sensitivity per heating power of 0 36 mV/sccm/mW Figure 9 shows the sensor signal in the linear range from 10 to 100 sccm flow The non-linearity in this range is less than 1%

Due to the temperature coefficient of the polysilicon the 2 8 kΩ heating resistor changes its resistance with increasing flow Hence a constant heating voltage or a constant heater current does not automatically provide a constant heating power By connecting another 2 8 kΩ resistor in series to the heater, the power is kept constant over the whole flow range within better than 0 05% This additional resistor does not change its resistance because it is not thermally isolated on a membrane A polysilicon resistor on the bulk silicon or an external resistor can be used Figure 10 shows the stabilized and the non-stabilized heating power versus the gas flow Without the additional resistor the change in power is 1 6% over the flow range from 0 to 1000 sccm

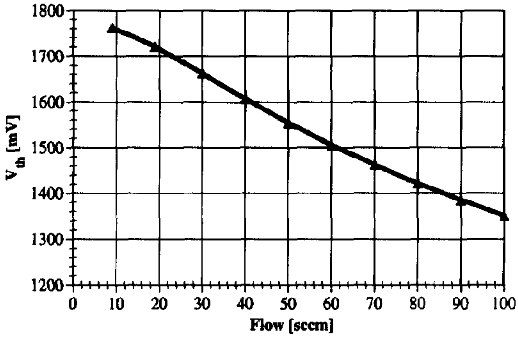

Fig 9 Linear range of sensor signal vs gas flow (sensor of Fig 8)

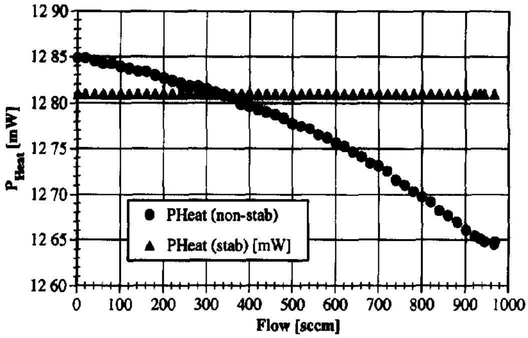

Fig 10 Stabilized and non-stabilized heating power vs gas flow

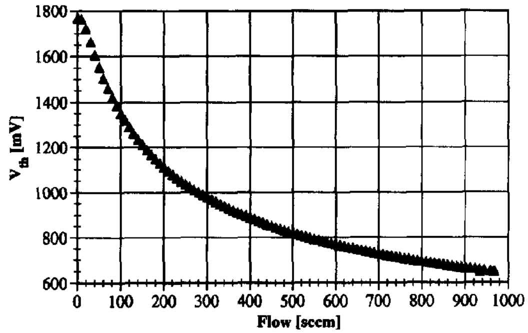

Fig 8 Sensor signal vs gas flow (3 μm CMOS IC process, EM Microelectronic)

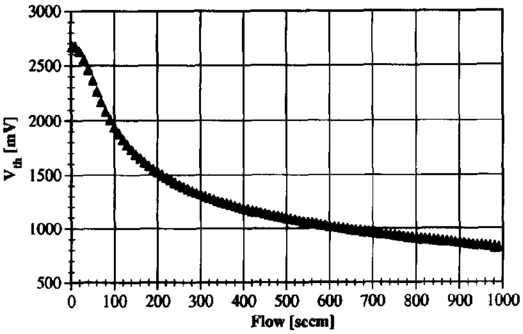

Fig 11 Sensor signal vs gas flow for thermopile based sensor fabricated using the 1 2 μm CMOS process provided by Austria Mikro Systeme (AMS)

Figure 11 shows the thermopile output voltage versus the gas flow of a sensor which was fabricated using the 1 2 µm CMOS process of AMS The sensor is heated with a power of 16 4 mW The very high voltage is mainly achieved because of the higher integration The sensor consists of 21 thermocouples located on a 200 µm by 120 µm cantilever beam The sensitivity in the linear range is 8 1 mV/sccm This corresponds to a sensitivity per heating power of 0 50 mV/sccm/mW

Conclusions

A new CMOS integrated gas flow sensor based on an n-doped/p-doped polysilicon thermopile has been presented The sensor was fabricated in an industrial 3 µm CMOS process, combined with a post-processing etching step The sensor is highly sensitive due to the high relative Seebeck coefficient between the different doped polysilicons and the low thermal conductivity of the oxide membrane The portability of the used method is demonstrated by integrating similar devices in an industrial 1 2 µm process provided by another chip foundry

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