A MEMS-based wireless multisensor module for environmental monitoring

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Abstract

In order to enable further developments in low cost wireless sensor networks (WSNs) for unobtrusive environmental monitoring, increased miniaturisation and integration of hardware is essential. This paper outlines the design concept and preliminary results for a multifunctional micromachined sensor unit, comprising CMOS-compatible temperature, humidity and gas sensors on a single silicon substrate.

1. Introduction

The distribution of embeddable, wireless, multisensor modules creates a network that can continually detect and record environmental stresses in the surrounding ambient. Such networks, generally referred to as wireless sensor networks (WSNs), are finding applications in areas that require deployments of a large number of sensor and actuator nodes [1–4]. These include precision farming, telecommunications reliability, environmental monitoring and building utilities control, where it is important to monitor environmental stresses in real time in order to detect potential failures and localised anomalies. In order to unobtrusively embed wireless sensors within everyday objects, it is important that WSN hardware becomes cheaper and further miniaturised.

Microelectromechanical systems (MEMS) are ideally placed to make a substantial contribution towards such miniaturisation of wireless sensor nodes because of their small size, multifunctional capability and low manufacturing costs. Through sensor integration, MEMS based devices enable deployment of multiple sensors on a single substrate, reducing the overall size and cost of the sensing platform. Furthermore, this technology enables the addition of low-cost sensor redundancy, thereby improving node reliability where needed [5,6].

This paper outlines the use of Tyndall’s 1.5 \( \mu \text{m} \) surface micromachining process to fabricate a multifunctional environmental monitoring chip for use with one such wireless platform (the Tyndall25 node [3,4]). Preliminary results from integrated temperature, humidity and gas sensor prototypes are presented; it is planned to incorporate additional sensing functionalities (such as corrosion and gas flow velocity) in later generations. The integration of these MEMS sensors with a communicative data-logging platform is also described in this paper.

2. Integrated MEMS sensors

2.1. Fabrication process

A low-temperature surface micromachining process has been developed for the manufacture of integrated sensors. The MEMS fabrication steps are part of an above-IC process; if needed, the underlying CMOS may contain Wheatstone bridges, voltage amplifiers and \( C–V \) converters for on-chip signal conditioning. The uppermost metal of the CMOS process (Metal2) also forms the bottom electrode of MEMS structures, allowing close integration of sensors and circuitry on one die.

To enable rapid and cost-effective sensor development, CMOS circuitry has been omitted from first sensor prototypes. The MEMS fabrication steps begin with the deposition of a layer of 0.5 \( \mu \text{m} \) thick insulating oxide on a 100 mm diameter silicon wafer. A layer of 0.5 \( \mu \text{m} \) thick aluminium/1\% silicon is then deposited to serve as a bottom electrode for a capacitive humidity sensor, bond pads and associated metallisation. This metal is also patterned to create a temperature sensor, and is passivated by a 130 nm thick PECVD silicon oxide layer to prevent unwanted corrosion. Since MEMS structures will ultimately sit on top of IC circuits, this oxide will also constitute the last layer of the CMOS process. Next, a polyimide layer serves both as the sacrificial layer for the gas sensor and a moisture-sensitive dielectric for the humidity sensor. A second aluminium layer is then sputtered and patterned (to form a resistive element for the gas sensor and a top electrode for the humidity sensor). Careful design of the relative geometries of the humidity...
and gas sensors then allows selective removal of the polyimide in oxygen plasma; the sacrificial layer is completely undercut from beneath the gas sensor whilst remaining between the electrodes of the humidity sensor. This allows thermal isolation of the gas sensor and retains a moisture-sensitive dielectric in the capacitive humidity sensor, Fig. 1.

The operation and characterisation of each sensor is described briefly below.

2.2. Humidity sensor characterisation

Capacitive relative humidity (RH) sensors consist of a moisture-sensitive dielectric material sandwiched between two metallic electrodes [7]. The relative permittivity of the dielectric is a function of the amount of moisture in the material, and at least one of the electrodes is perforated or patterned in such a way as to allow access to the polymer layer by the external ambient.

The relative humidity (RH) sensor under development here is based on a metal–polymer–metal capacitor. The capacitance, \( C \), of the structure is \( C = \varepsilon_r e_0 A/d \), where \( A \) is the common surface area of the electrodes and \( d \) is the thickness of the dielectric. The dielectric used in this case is a 2.4 \( \mu \text{m} \) thick layer of HD Microsystems PI2545 polyimide, spun and cured according to the manufacturer’s instructions [8]. The relative permittivity, \( \varepsilon_r \), of the polyimide has a nominal value of 3.5 at 50%RH according to the manufacturer’s material datasheet.

In order to facilitate rapid moisture diffusion into and out of the film, and a correspondingly fast response time, the sensor is split into 23 fingers, each 40 \( \mu \text{m} \) wide and 1150 \( \mu \text{m} \) long. The total area of the sensor is 1.2 mm \( \times \) 1.2 mm. Underneath each finger is a 20 \( \mu \text{m} \) wide bottom electrode which defines the common surface area of the capacitor. The discrepancy in the widths of the top and bottom electrodes allows the polyimide layer to be cleared from beneath the gas sensor using isotropic etching in oxygen plasma, whilst allowing the active area of the humidity sensor to remain unaffected; the undercut after 40 min in a 300 W barrel ashcer was 4.5 \( \mu \text{m} \). The capacitance of the sensor has been simulated using Coventorware [9] and is 7.6 pF at 50%RH (see Fig. 2).

Characterisation has been carried out in a benchtop climatic chamber using wire-bonded die in open ceramic packages. Measurements were carried out using an Agilent 4284A LCR meter and were performed at 100 kHz and 50 mV. A plot of the response of the sensor to variations in humidity at 25 \( ^\circ\text{C} \) is shown in Fig. 3; sensitivity of 23 fF/%RH is achieved and the sensor shows a hysteresis value of 3.5% at 50%RH.

2.3. Temperature sensor characterisation

Since the resistance of most metals is an approximately linear function of temperature, a simple and accurate temperature sensor can be made from a metallic thin film resistor. A change in ambient temperature alters the resistance of the metal, which is sensed in a balanced circuit. The temperature dependent resistance is usually written as

\[
R = R_0 (1 + \alpha \Delta T),
\]

where \( R_0 \) is the resistance of the sensor at some reference temperature, \( \Delta T \) is the deviation from that temperature, and \( \alpha \) is a physical property of the sensor material known as the thermal coefficient of resistance (TCR) at the reference temperature [10].

In this case, the sensor is fabricated from a 2 \( \mu \text{m} \) wide, 0.5 \( \mu \text{m} \) thick line of aluminium/1% silicon, chosen because of its CMOS compatibility and relatively high TCR. The line is drawn in a meander configuration to save space and increase sensitivity per unit area; in this manner the line is 0.143 m long and the sensor consumes an area of 1 mm \( \times \) 1 mm. The sensor is passivated with a thin oxide in order to increase corrosion resistance and lifetime, Fig. 4.
Measurements were carried out using an Agilent 34411A multimeter on a cascade temperature-controlled wafer probing station. The sensor has a sensitivity of 20.1 $\Omega$/°C as shown in Fig. 5, and $\alpha$ has been measured as 0.0039/°C.

2.4. Gas sensor

Thermally isolated microstructures may be used in a variety of sensing applications, such as infra-red, flow velocity, pressure and gas detection, by measuring the variation in thermal conductance of the structure in response to changes in the surrounding ambient. This paper demonstrates one such structure and illustrates its operation as a gas detector. The sensor consists of a suspended aluminium wire, 100 $\mu$m long and of cross-sectional area 1 $\mu$m $\times$ 5 $\mu$m, Fig. 6.

In the steady state, the temperature dependence of a current-carrying resistive element is given by

$$G \cdot \Delta T = I^2 R,$$

where $G$ is its thermal conductance and $I^2 R$ is the input electrical power (i.e. Joule heating power). Since $R$ is also temperature dependent and varies according to Eq. (1), then the resistance of the element may be expressed as

$$\frac{1}{R} = \frac{1}{R_0} - \frac{\alpha}{G} T^2,$$

and by measuring $R$ we may evaluate $G$ [10]. The thermal conductance of the device is a strong function of the surrounding ambient and is dependent on the pressure and properties of the surrounding gas. The sensor may therefore be configured as either a gas sensor or pressure sensor. In still ambient (assuming negligible heat loss due to convection), the total thermal conductance, $G$, may be expressed as

$$G = G_{\text{sensor}} + G_{\text{gas}} + G_{\text{rad}}.$$  

(4)

$G_{\text{rad}}$ (thermal conductance due to radiation) is usually neglected, and the structural thermal conductance of the sensor, $G_{\text{sensor}}$, is dependent on the material properties and geometrical structure of the device; it may be analytically estimated and is minimised by thermally isolating the sensor from the substrate. A full treatment is available in [10]. At atmospheric pressures, $G_{\text{gas}}$ is approximated by

$$G_{\text{gas}} = \kappa \frac{A}{d}.$$  

(5)

where $\kappa$ is the thermal conductivity of the gas, $A$ is the surface area of the sensor and $d$ is the substrate-to-sensor spacing (set by the polyimide sacrificial layer thickness). By assessing the difference in the thermal conductivity of the structure when measured at low pressure (when $G_{\text{gas}}$ is negligible) and at atmospheric pressure, $G_{\text{gas}}$ may be calculated.

Measurements were carried out using a Keithley 4200 semiconductor parameter analyser and a custom-built pressure chamber into which air and argon were introduced. The change in thermal conductance of the sensor is shown in Fig. 7; the pressure-dependent nature of the thermal conductance is outside the scope of this paper but is fully analysed in [11].

At atmospheric pressure, the ratio of the increase in thermal conductance of the sensor when placed in air to the increase when placed in argon is 1.37:1. This is in good agreement with the ratio of the thermal conductivity of air (0.024 W/Km) to that of argon (0.017 W/Km), indicating that the structure is capable of operating as a gas sensor at atmospheric pressure [12].

2.5. CMOS integration

For development purposes, an initial approach combining MEMS and off-chip signal conditioning has been explored for process refinement, device verification and system test. An integrated CMOS + MEMS chip has also been designed in order to have both sensors and signal conditioning on a single die, reducing space consumption while obtaining easily usable outputs. Wheatstone bridges have been designed for use with the temperature sensor.
and gas sensor, while a non-inverting capacitance-to-voltage converter (C–V) has been associated with the humidity sensor. The schematic of the C–V converter is shown on Fig. 8. The CMOS technology used is a 1.5 μm gate length compatible with the Tyndall Institute’s Central Fabrication Facility manufacturing process.

During the design phase of this C–V converter, analog simulations were developed using Accusim with a clock functioning at a 500 Hz rate for low power consumption, with a switch capacitor of 0.1 pF and $V_T = 1.5$ V. In order to attain sensitivity greater than 5%RH, it is necessary to be able to detect at least a 100 fF change in capacitance. That precision has been attained according to the simulation results, where four more clock cycles were counted every time the transducers capacitance was increased by 100 fF. This requires a 1.6 s measurement, but this is not a major drawback for our application. Future work will try to increase this sensitivity to a better value than 5%RH by reducing the parasitic capacitances around the switches together with working on the amplifiers and reference voltages. This yields a C–V converter capable of measuring variations in humidity with a precision of better than 5%.

3. Data-logging unit with a multiple sensors layer

3.1. Tyndall25 platform: a wireless host for integrated sensors

The multifunctional sensor described above includes temperature, humidity and gas sensors on a single chip and has been designed for use with the Tyndall25 cube, to demonstrate the capabilities of such MEMS based multisensor system. This modular 25 mm host has been designed as a wireless sensor network (WSN) developmental platform by the Ambient Electronics Systems group in Tyndall, and is in use in a wide variety of configurations and deployments in research institutes in Ireland. It incorporates a high degree of modularity from both a hardware and software perspective [13]. The node currently comprises a microcontroller layer, an RF communication layer based on Nordic or Zigbee technology, a memory layer and a power layer. On top of them will sit the MEMS based multisensor system which has been developed and described above, and which is the focus of this paper. The latter will integrate sensor bare dies on a 25 mm × 25 mm PCB layer, together with the necessary signal conditioning to enable processing of the sensor output by the microcontroller layer ADCs. A wide variety of applications can therefore be targeted by using site-specific node design. The platform is described in more detail in [3,4,13].

Fig. 9 illustrates a first iteration of this sensor layer. The sensors integrated on the platform are bare die MEMS sensors, attached and wire-bonded to a printed circuit board (PCB) layer, together with the required circuitry. In future iterations, a fully integrated CMOS + MEMS process on the same substrate will comprise both sensor and signal conditioning on-chip, reducing space consumption and enabling increased sensing redundancy.

The sensing unit is capable of collecting and processing data from multiple sensors. It is possible to collect up to four different
sensor responses using four different ADCs, at a given sampling rate, in either 8 or 16 bits, depending on the precision required. For characterisation purposes, both wireless and serial communication have been implemented [3], [4], and a readout has been developed to interpret data sent from the module in real time. Since monitoring environmental changes does not require a high sampling rate, power consumption can also be minimised by appropriate task scheduling. Cross-calibration is also made possible with multi-sensing, as the influence of other parameters is taken into account by correlating all sensor responses. Hence, for example, a correction for the influence of temperature on humidity sensors can be implemented after characterisation.

3.2. Interfacing of a serial memory for data-logging

The modularity of the platform also provides for the integration of a serial EEPROM for data-logging and storage. An Atmel AT25HP512 and a programmed SPI bus are used for this purpose. High flexibility for further development is available at this stage, as task scheduling is user defined. Environmental events monitored by the sensors on the highest layer will then be assessed by the microcontrollers and data will be processed, compressed, transmitted and/or stored as necessary.

4. Conclusions

A wireless multisensor platform for environmental monitoring is being developed.

To date, humidity, temperature and gas sensors gave been fabricated. The polyimide-based capacitive relative humidity (RH) sensors show a sensitivity of 22 fF/%RH, while the aluminium/silicon temperature sensors have a response of 20.1 Ω/°C. Preliminary measurements have verified that a suspended, thermally isolated aluminium structure is capable of operating as a gas sensor.

They have then been integrated on the highly modular programmable Tyndall25 mote, where the “plug and play” stackable layers include RF communication, power, and on-board data processing. A serial memory layer is also incorporated, completing a multifunctional environmental monitoring unit that is capable of data mining, cross-calibration, compression, storage and transmission.

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References