A BULK-MICROMACHINED SOIL MOISTURE PROBE WITH A MIXED-SIGNAL INTERFACE

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Abstract: This paper presents a Multi-Chip-Module based (MCM) microsystem for irrigation management suitable for greenhouse environmental control. The proposed microsystem includes a soil moisture microsensor, analog interface and sigma-delta converter, and signal processing for digital filtering. A heat-pulse technique is used to determine the volumetric heat capacity and thus the water content of a porous media, such as the soil. This method is based on the Joule effect (heater probe) and on the Seebeck effect (temperature probe). By using CMOS standard processes (low-cost) and wireless capabilities, a wireless network architecture can be implemented for measuring the soil moisture at the plant root level.

Keywords: Soil Moisture, Microsystems, Micromachining, Smart Sensors, Sigma-Delta Modulation.

1. INTRODUCTION

In the field of environmental control applications such as irrigation management systems many sensors are needed for temperature, relative humidity, CO_2 concentration, solar radiation and soil moisture.

The economic factors and the desire to minimize resource over-consumption have increased the requirements for irrigation management systems to manage water more efficiently. This resulted on a wider spectrum of available equipment for measuring soil water status (Charlesworth, 2000).

Today a large number of sensors based on different methods — e.g., nuclear, electromagnetic, tensio-metric, and capacitive — are available for measuring soil moisture. Generally, these methods present several drawbacks in irrigation management systems: soil dependency, inaccuracy and high cost.

Time domain reflectometer (TDR) sensors, which are based on the influence of soil water content on the propagation of electromagnetic waves, are independent of soil texture, temperature and salt content, but their high cost restricts their applicability to these systems (Topp *et. al.*, 1980, Topp and Davis, 1985).

Advances in silicon micromachining in the last years have stimulated a wide demand for silicon-based microsensors. Integrated microsensors, with on-chip interface circuitry, are currently replacing discrete sensors due to their inherent advantages, namely, low cost, high reliability and on-chip processing. To achieve small, robust, and inexpensive microsystems, it is desirable to integrate the soil moisture sensor with digital signal processing and wireless front-end. Therefore, this microsystem when implemented close to the plants roots will be a breakthrough.

The same basic fabrication concepts and materials, which have made microelectronics successful, are now being adapted to make low-cost, small, and high-performance sensing devices. Additional advantages can be achieved if all electronic elements and sensor are contained in one chip, leading to a so-called smart sensor.

In this paper a silicon bulk-micromachined soil moisture sensor with mixed-signal interface is presented. The dual-probe heat-pulse (DPHP) sensor is 30 mm long, 6 mm wide and 0.8 mm high. The probe pitch is 3 mm, allowing small-scale spatial measurements of water fractions of the soil. This is important for inferring soil moisture at plant root level.

2. SOIL MOISTURE THEORY

The soil's heat capacity, ρc_p, is evaluated by adding the volumetric heat capacities of the soil constituents:

$$\rho c_p = 1.92 X_m + 2.51 X_o + 4.18 \theta_v \qquad (1)$$

where X_m, X_o, and θ_v are the mineral, organic, and water fractions of the soil, respectively. The leading coefficients represent the volumetric heat capacity ($MJm^{-3o}C^{-1}$) of each soil constituent. When a pulse of heat is applied during a fixed time interval to the heater probe, the maximum rise in temperature (ΔT_m) at some distance from the heater is measured. As mentioned by Campbell *et al.* (1991) the relationship between the ρc_p and ΔT_m is:

$$\rho c_p = \frac{q}{e \pi r^2 \Delta T_m} \qquad (2)$$

where q (Jm^{-1}) is the heat applied per unit length of the heater, e is the base of natural logarithms, and r (m) is the distance between the heat and temperature probes. Three assumptions are required for the proper use of this model: (i) that the finite heater can be approximated to an infinitely long heater, (ii) that the cylindrical heater can be approximated to a line source of heat, and (iii) that the short-duration heating can be approximated to an instant release of heat. Providing that (i) the ratio of heater half-length to temperature probe spacing is greater than to 2.5, we can assume (0.14 % error) that the probe heater is infinite. In addition, (ii) if the ratio of heater radius to temperature probe spacing is less than 0.06, and (iii) the heating duration is less than 8 s, Kluintenberg, *et al.* (1993) show that the errors are minimized and sustain the use of Campbell model (2) as a model for determining heat capacity. Substituting Eq. (1) into Eq. (2) and rearranging yields an expression that shows the relationship between θ_v and ΔT_m:

$$\Delta T_m = \frac{q}{e \pi r^2 \left(1.92 X_m + 2.50 X_o + 4.18 \theta_v\right)} \qquad (3)$$

or,

$$\theta_v = \frac{\dfrac{q}{e \pi r^2 \Delta T_m} - (1.92 X_m + 2.50 X_o)}{4.18} \qquad (4)$$

Although ΔT_m varies with ρc_p and θ_v, q can be selected to produce an adequate temperature signal for the expected range of θ_v on a typical agricultural soil (0.05 to 0.35 m^3m^{-3}). The partial derivative of ΔT_m with respect to θ_v yields the expression of temperature rise sensitivity with respect to the change in soil water content:

$$\frac{\partial \Delta Tm}{\partial \theta_v} = \frac{-4.18 q}{e \pi r^2 (1.92 X_m + 2.50 X_o + 4.18 \theta_v)^2} \qquad (5)$$

3. MACROSENSOR

A heat-pulse macro device, illustrated schematically in Figure 1, was used in this study to test the dual-probe heat-pulse method.

It consists of two needle probes assembled in parallel to provide a heater and a sensor probe, as reported by Tarara and Ham (1997) and Song *et. al.* (1998). The needles were made from stainless steel tubing, 0.912 mm in diameter, protruding 20 mm beyond the edge of the acrylic mounting. Spacing between the heater and the sensor probe is 3 mm wide.

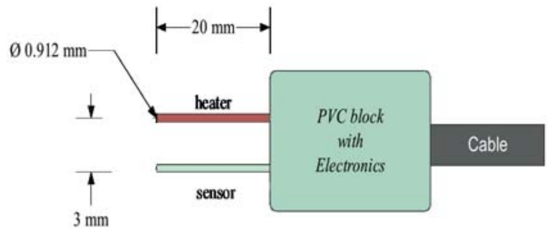

Fig. 1. Sketch of the soil moisture macrosensor

The heater was made from enameled Stablohm 800A wire (0.062 mm in diameter and 440.8 Ωm^{-1} of resistivity), which was inserted in the heater needle. The heater resistance is 68.5 Ω. A copper-constantan thermocouple was inserted and centered in the sensor needle. The needles were then filled with high thermal-conductivity epoxy glue to obtain water-resistant, electrically insulated probes.

The heat pulse was generated by applying a DC voltage of 11.5 V to the heater for a fixed period of 8 s. This gave a nominal value for q of 100 Jm^{-1} [$(10.5\ V/68.5\ \Omega)^2 \cdot 440.8\ \Omega m^{-1} \cdot 8\ s$]. A prototype data acquisition system based on a microcontroller and a sigma-delta ADC was developed for controlling the heat pulse, for monitoring the current through the heater and for measuring the thermocouple's temperature. Average power and the maximum temperature were recorded for later analysis.

4. SYSTEM OVERVIEW

Since the bulk-micromachined sensor and electronics are implemented in different technologies, at this point all system modules are being implemented in a multi-chip module. In a near future they will be implemented in one chip only using a standard CMOS process with post-processing micromachining techniques.

The multi-chip module is basically made of three blocks, schematically represented in Figure 2: a micromachined sensor, a mixed-signal interface, and a wireless front-end. The microsensor includes a needle-based heater and a thermopile based on diode p-n junction for sensing soil temperature before and after the application of a heat pulse. The mixed-signal block includes an instrumentation amplifier, a first order sigma-delta (Σ-Δ) modulator and a first order digital filtering block.

Soil moisture readouts are transmitted every 2 minutes. The RF interface is based on a commercially available transmitter operating at 433MHz.

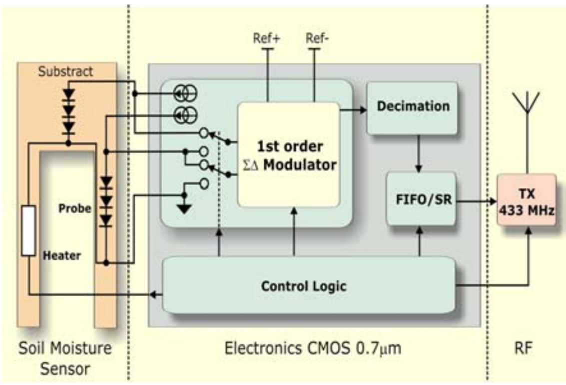

Fig. 2. Schematic representation of the system

4.1 Micromachined sensor module

Silicon has a high thermal conductivity (about 156 $Wm^{-1}K^{-1}$), which results on a thermal short-circuit between the heater-probe and the temperature-probe (Valente, *et al.*, 2001). To reduce heat transfer to the substrate, silicon dioxide growth (low thermal conductivity, 2 to 3 $Wm^{-1}K^{-1}$) is used, as depicted in Fig. 3. The temperature sensors are made from micromachined p-n junctions.

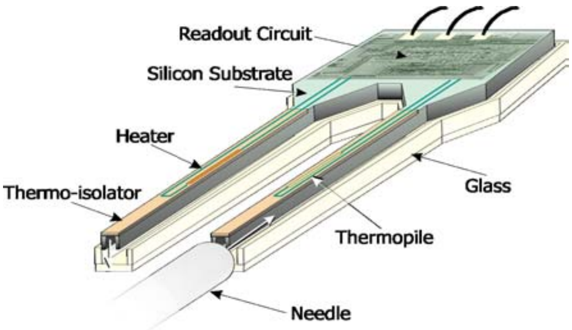

Fig. 3. Soil moisture sensor with readout electronics.

The sensor is about 30 mm long, 6 mm wide, and 0.8 mm high; the probe pitch is 3 mm, allowing small-scale spatial measurements of θ_v, which can be made near the soil surface where larger root densities are found.

Considering the expected range of water content (0 % to 40 %), and that common sensitivity of integrated junction-based thermal sensors is approximately -2.2 mV/ºC, then a 1 % change in soil water contents (θ_v) would cause a change in the p-n junction direct voltage drop of about 55 μV. Another p-n junction is used for measuring substrate temperature. A constant current generated in the mixed-signal interface biases these p-n junctions. ΔT_m decreases as less energy is applied to the probe (q), so a low-power design will require an A/D converter with higher resolution and better signal-to-noise ratio to maintain accuracy. Previous studies show that a minimum of 0.5 ºC for ΔT_m is a good choice (Bilskie, 1994).

4.2 Mixed-signal interface.

The maximum rise in temperature, ΔT_m, is measured by subtracting the soil temperature signal from the substrate temperature (reference signal). This results in a very small signal with a full-scale of about 3 mV. Input signal could be as low as 55 μV. Also, signal bandwidth is typically of the order of few Hz. In this way we have exchanged resolution for speed of conversion.

Sigma-Delta (Σ-Δ) converters have proven to be very suitable in low-frequency, high-performance applications. In our case, having a very low-frequency signal (<10 Hz) and medium accuracy (12 bit) a first order Σ-Δ converter has been chosen because of the lower complexity, die area and power consumption, compared to higher order Σ-Δ converters.

This architecture has severe drawbacks concerning pattern noise associated to DC inputs and low signal-to-noise ratio (SNR). DC stability and noise rejection are achieved here by signal chopping methods. The solution adopted was inverting periodically the input signal before the Σ-Δ converter (Fasoli*, et al*., 1997).

The modulator's output bit stream is then applied to the first order decimation filter (a up-down counter in this case) thus providing a 12-bit result for a conversion time of 40ms. After that, data is pushed into a FIFO for later transmission.

The control logic is responsible for generating all clock signals for the ΣΔ converter, the FIFO and for keying transmitter (serial) with data fed through a shift register. The data is transmitted using a commercially available transmitter operating at 433 MHz.

This module is currently being implemented using the Alcatel-Mietec 0.7 μm CMOS process.

5. RESULTS

5.1 Macrosensor results.

Soil samples of Almendra silt loam, wetted to a predetermined water content and mixed, were packed into a cylinder 77 mm in diameter by 70 mm long. The soil moisture macrosensor was placed at the center. Measurements were taken and after that soil was weighed and dried at 105 ºC for 24 h to determine bulk density and water content (thermo-gravimetric method):

$$\theta = \frac{(wet\ weight) - (dry\ weight)}{dry\ weight} \qquad (6)$$

Table 1 lists the thermo-gravimetric soil water content (θ_g) and the measured values: maximum temperature rise (ΔT_m), heat applied per unit length (q) and macrosensor readout (θ_v).

Table 1: Macrosensor measured values.

θ_g (m^3m^{-3})	ΔT_m (ºC)	q (Jm^{-1})	θ_v (m^3m^{-3})
0	1.25	100	**0**
0.1	0.88	100	**0.106**
0.2	0.71	100	**0.190**
0.3	0.56	100	**0.308**
0.4	0.48	100	**0.401**

In soils with low organic matter such as Almendra, X_o is neglected. The value of X_m is determined by dividing the soil bulk density by the particle density. An average value of 2.65 Mgm^{-3} is often used for soil particle density. This leads to a good agreement between the calculated values (θ_v) and thermo-gravimetric values.

Figure 4 a shows typical temperature response for heat-pulse measurements.

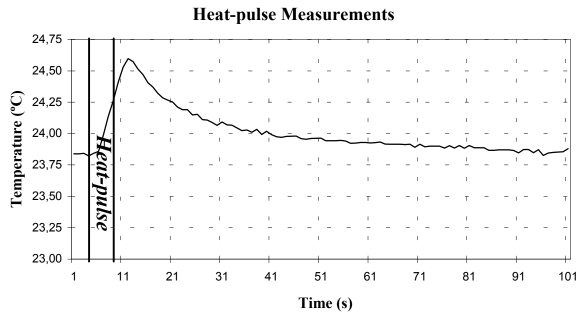

Fig. 4: Typical heat-pulse response.

5.2 Microsensor simulation results.

Thermal simulations were made to ensure that there is no thermal short-circuit between the heater and the temperature probe through the substrate. Figure 5 shows the simulation results for the heater cross-section.

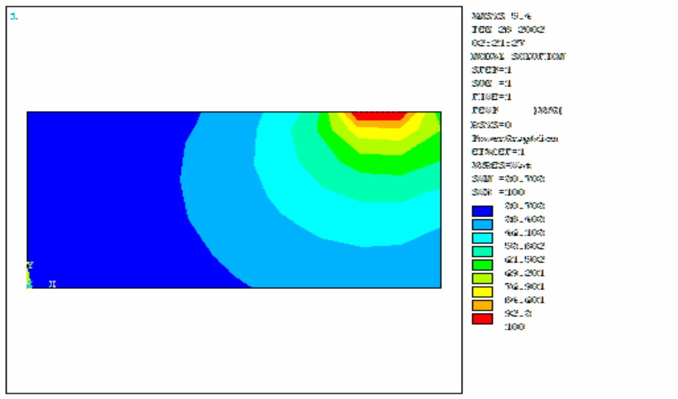

Fig. 5. Heater probe thermal simulations

5.3 Mixed-signal simulation results.

Simulations have shown that it can be expected an effective resolution of 12-bit for the ΣΔ modulator (13-bit using off-chip digital filtering) with a conversion time of 40 ms (clock frequency 200kHz).

6. CONCLUSIONS

In this paper a MCM-based microsystem for soil moisture measurements using the Dual-Probe Heat-Pulse (DPHP) method has been proposed. At this time the microsystem includes the soil moisture sensor, the first order Σ-Δ converter and the signal processing circuits.

The DPHP method proved to be the most appropriate to measure soil moisture at different depths, in a non-destructive and automated manner. This is the first time that the DPHP method is implemented in a MCM-based microsystem and the first integrated sensor for soil moisture.

A next generation of this system will use more elaborate circuits and chopping techniques to improve accuracy and SNR. This will make possible to reduce the power applied for the heat pulse. A RF transmitter operating in the 2 MHz range is being designed to be implemented in the same chip.

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