On-chip integrated silicon bulk-micromachined soil moisture sensor with electronics and bus interface

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***Abstract* – This paper presents an on-chip silicon bulk-micromachined Soil Moisture Sensor (SMS) for irrigation control in greenhouses. The system-on-a-chip includes the SMS, readout electronics, self-test, calibration facilities and a digital bus interface for external data transmission. Moreover, this low-cost device can be applied in several locations (e. g. per each plant root), and networked together with the 1-wire bus. The heat-pulse technique is used (for measuring the maximum temperature on a distant point) to determine the volumetric heat capacity and hence the water content of a porous media, such as soil. In order to validate this method, experimental results were achieved with a macrosensor based on the heat--pulse and capacitance methods. The capacitance method relates the volumetric water content with the capacitance change (dielectric properties) of a probe, inserted in the soil. Several tests were performed for different type of soils and water contents. These results are compared with the measurements achieved using the conventional thermo-gravimetric method.**

1. INTRODUCTION

The need to determine the amount of water contained in the soil arises frequently in many agronomic, ecological, and hydrological investigations. The aim is to understand the soil's chemical, mechanical, hydrological, and biological relationships. Today, a large number of sensors, based on different methods: nuclear, electromagnetic, tensiometric, capacitance, are available for measuring soil moisture. Generally, these methods have several limitations that restrict their integration in irrigation systems. Among others, the main disadvantages are: soil dependency, inaccuracy and high cost.

Time domain reflectometer (TDR) sensors, which are based on the influence of soil water content over the propagation of electromagnetic waves, are independent of soil texture, temperature and salt content, but its high cost restricts the applicability to these systems [1]. Therefore, the development of a miniaturised system with electronics, network solution, low-cost, with external communications and allowing its implantation next to the plant roots will be a breakthrough.

The same basic fabrication concepts and materials, which have made microelectronics successful, are now being adapted to making low-cost, small, high-performance sensor systems devices, e.g. a silicon bulk-micromachined soil moisture sensor. The compatibility with CMOS standard fabrication processing allows integrating the sensor and electronics in the same chip.

2. THEORY

Soil moisture content can be determined by measuring the capacitance between two electrodes covered with soil, which varies with the dielectric properties of soil constituents. When dealing with a dielectric possessing appreciable conductance, such as soil, it is convenient to use the concept of a complex permittivity (ε) that is defined by

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

where, the real part of the permittivity (ε') is a measure of the polarisability of the soil elements, including water. The imaginary part of permittivity (ε'') represents the energy absorption by ionic conduction mainly and, more rarely, by dielectric losses. The insulation of the sensor rods makes this imaginary part almost negligible.

For cylindrical rods, at a given temperature, the capacitance is given by,

$$C = \frac{\pi \varepsilon L}{\cosh^{-1}\left(\frac{r_m}{2r}\right)} \tag{2}$$

Where r_m is the distance between the rods centre, r is the rod radius, L the length and ε the media permittivity. Since the dielectric constant of common soil mineralogical materials ranges from about 2 to 14 while the dielectric constant of water is approximately 80, the dielectric constant of soil is a potentially sensitive indicator of soil moisture [2]. Therefore, for a fixed geometry, C is linearly dependent to the dielectric constant, which varies with the soil water content.

A second method is based on the heat-pulse technique. When a finite quantity of heat (q) is instantaneously liberated in a line source placed in an infinite medium, the reciprocal of the maximum temperature rise ($1/\Delta T_m$) at a distance (r_m) from the line is related to the volumetric specific heat (ρc) of the soil by [3],

$$\rho c = \frac{q}{(e \pi r_m^2)} \cdot \frac{1}{\Delta T_m} \tag{3}$$

In addition, ρc is closely related to the sum of specific heats of the water and mineral components,

$$\rho c \cong \rho_w c_w \theta + \rho_b c_m \tag{4}$$

where, ρ_w is the density of water, c_w is the specific heat of water, θ is the volumetric water content, ρ_b is the soil bulk density and, c_m is the specific heat of the soil minerals [4]. Combining (3) and (4), the water content could be expressed as,

$$\theta = \frac{q}{(e \pi r_m^2) \rho_w c_w} \cdot \frac{1}{\Delta T_m} - \frac{\rho_b c_m}{\rho_w c_w} \tag{5}$$

which is linear in relation to the reciprocal of the maximum temperature rise.

3. THE SILICON BULK-MICROMACHINED SOIL MOISTURE SENSOR SYSTEM

The heat-pulse method is being studied to allow its implementation in an integrated silicon sensor microsystem. This method is based on the Joule effect (heater) and in Seebeck effect (thermopile – temperature sensor). Moreover, applying the Peltier effect a temperature reference is obtained for allowing calibration and self-test of the microsystem.

The heater and the thermopile are fabricated in bulk-micromachining technology (anisotropic etching of the silicon with an aqueous KOH solution) after the fabrication of the electronics in a standard CMOS process. Unfortunately, silicon is a very good heat conductor, so it turns out to be very rewarding to deposit a thin-film of silicon nitride (a poor heat conductor) on the silicon (the etching of the silicon also reduces the bulk and the heat conductivity).

Figure 1 shows the first prototype used for mechanical and thermal simulations in a Finite Element Analysis CAD. The electronics is on the top of the device. Finally, the packaging of all microsystem will be done with an epoxy resine.

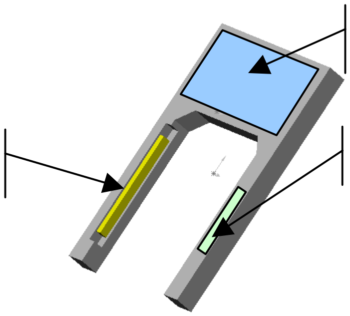

Figure 1. Prototype of the Silicon soil moisture sensor.

A block diagram of the electronics used to control the sensor is showed in Figure 2. The method is based in a sigma-delta A/D converter with a logic control for switching the heat-pulse on (about 8 s), and to read the current (heat input to the line source) and the thermopile value (temperature rise). These data is computed and the achieved result (soil moisture) is sent via 1-wire protocol.

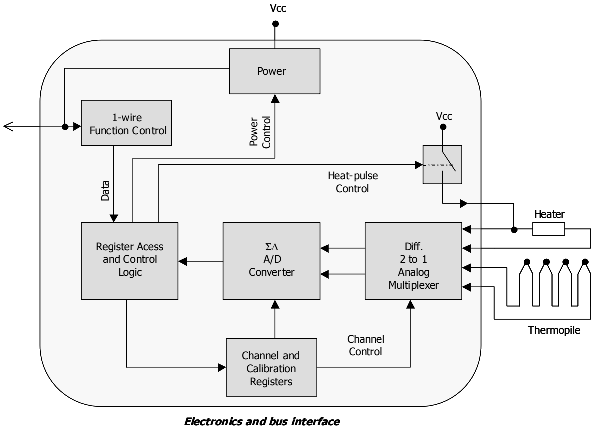

Figure 2. Diagram of the implemented electronic.

4. THE SOIL MOISTURE MACROSENSOR

A soil moisture sensor [5], based on the capacitance and heat-pulse methods, was developed and implemented with the aim to be achieved accurate and reliable measurements.

In the first method, the soil moisture can be determined by measuring the capacitance between two electrodes buried in the soil. Its fast response and low cost implementation were the main reasons for the choice of this technique. However, it must be referred that it exhibits dependence with soil type and temperature. To reduce these disadvantages, as well to improve sensor robustness, a second method is performed. It is based on the heat-pulse technique, which is practically independent on soil type. This technique is used for calibration and fault detection purposes, as a complementary method to the first one. This is due to its high power consumption and long time responses, which restricts its operation to lower sampling rates.

Sensor calibration was performed for different types of soils using the standard gravimetric method, which involves the determination of the mass of water content in relation to the mass of dry soil.

Several simulations are being preformed to integrate the sensor in silicon. Using only the heat-pulse method it is possible to design a silicon sensor with integrated thermopiles [6].

A heater element and three thermocouples were assembled in a four-needle probe as showed in Figure 3. The capacitive sensor is formed by the three closely needles. The needles were made from thin stainless steel tubing, 0.8mm in diameter and 34mm beyond the surface of the probe container. The space between the three needles that form a capacitance, a heater, and a temperature sensor is 6 mm and between the heater and the reference temperature sensor, is 20 mm.

The heater is made from enamelled *Evanohm* wire with 0.0254 mm diameter, 2952.81 Ωm^{-1} of resistivity and is 13.5 mm long, which was pulled into the heater needle. The heater resistance is approximately 40 Ω. Heat pulses are generated by applying 12 V to the heater resistance for 8 s, which leads to a nominal value for q of 2126 Jm^{-1}. The voltage pulses are applied at a rate of 15 minutes. The three thermocouples are mineral-insulated type K NiCr-Ni with 50 mm length and 0.5 mm diameter and are inserted into the needles. High-thermal conductivity and chemical resistant epoxy glue was used to fill and provide electrical insulation of the needles.

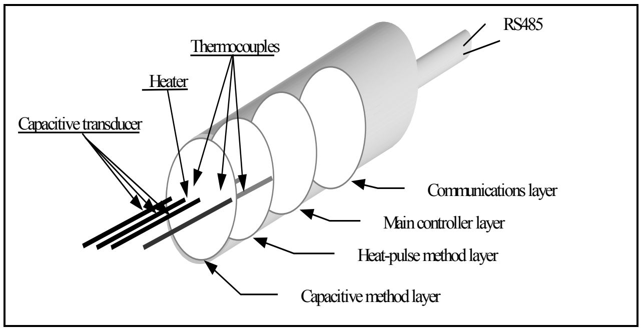

Figure 3. Sketch of the soil moisture sensor

In the Capacitance Block circuit, the capacitive sensor and a precision reference capacitor are connected to a dual Voltage-Controlled Oscillator (VCO). The input voltage is connected to a precision voltage reference to produce a variable frequency due to capacitance variation. The output signal frequency is related to the capacitance by,

$$freq = \frac{8\times10^{-5}}{C} \tag{6}$$

The full system is described in the next block diagram:

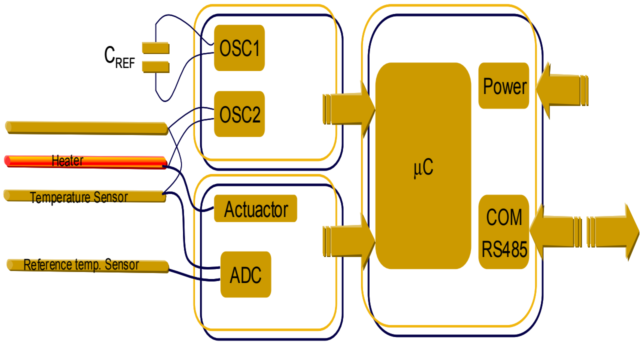

Figure 4. Block diagram of the probe unit

5. EXPERIMENTAL RESULTS

An experimental setup, Figure 5, was implemented on the laboratory in order to perform sensor calibration for different soil types. The calibration experiments were conduced for three categories of soils, peat, sand and clay and for each of them different textures were analyzed. Sensor readings were stored by the two methods for different volume water content in soil and compared with the values determined by the use of a gravimetric method. This calibration technique involves the determination of the mass of water content in relation to the mass of the dry soil sample.

In the heat pulse method the soil temperatures are measured at 6 mm and 20 mm from the heater, directly affected and reference temperatures, with a sampling rate of 300 ms. The heat pulse is applied during 8 s. Figure 6 shows the readings of the reference and sensing thermocouples for peat soil with volumetric water content of 1.5 %. In normal operation, the readings are made while the maximum deviation between the two temperatures has not been detected.

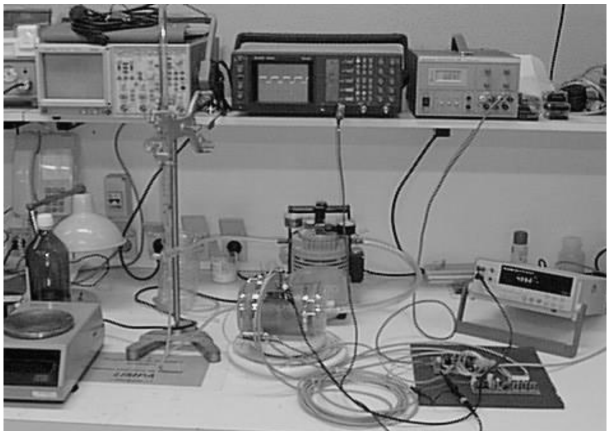

Figure 5. Experimental setup for sensor calibration

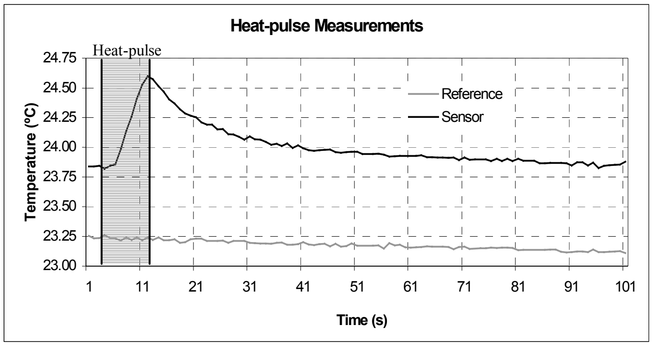

Figure 6. Typical temperature by time data obtained for 1.5% of volumetric water content and a heat-pulse of 10s.

Next figures show the calibration curves for peat and clay soils.

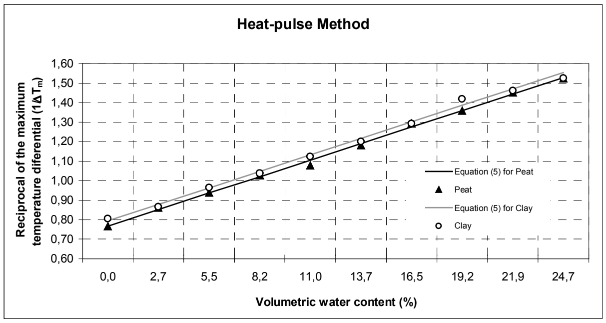

Figure 7. Calibration curves for heat-pulse method

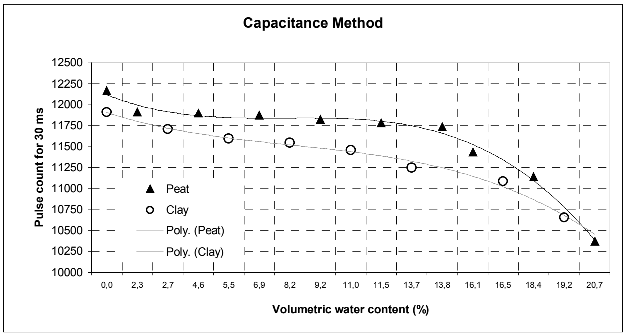

Figure 8. Calibration curves for capacitance method

A third order polynomial fitting employing least-squares method was performed for the second case. The polynomial coefficients are stored in the EEPROM of the micro--controllers to enable automatic computation of soil water content. The user at the sensor configuration procedure can specify these coefficients, by entering the soil type. In addition, automatic setting of the coefficients is performed based on the measurements available by the two methods. Since, the heat-pulse method has a negligible dependency with the soil type, its readings and the frequency readings from the capacitance method define uniquely the coefficients that leads to the water content.

A low-cost sensor, based on capacitive and heat-pulse methods, was designed and implemented to be determined soil water content. Several calibration tests performed for different types of soil and moisture content, showed that the proposed solution could be applied in an effective way to measure the soil water content.

Integrating signal processing, self-calibration, data validation, and networking facilities through the implementation around a low-cost RISC-like microcontroller from Microchip achieved intelligent sensing.

6. CONCLUSIONS

The test results achieved with the soil moisture macrosensor are very encouraging and validate the heat-pulse method - to be used in the soil moisture microsystem. The first simulation and modeling results with the FEM CAD promise a good performance of the microsensor as well as all microsystem.

7. REFERENCES

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