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Modeling, simulation and testing of a silicon soil moisture sensor based on the dual-probe heat-pulse method

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Abstract

A silicon soil moisture sensor, based in the dual-probe heat-pulse (DPHP) method, was modeled, simulated and tested for achieving, with low-cost, accurate and reliable measurements. This method is based on the application of a heat pulse during a fixed interval of time. The maximum rise in temperature (ΔT_M) is monitored by the measurement probe, placed at a certain distance of the heater source. A low-cost high-performance and small temperature sensor (a dynamic V_{PTAT} generator) was designed and fabricated to be placed into the probe which have 0.912 mm inner diameter and 20 mm long. If one considers the range of water contents, ratio of water mass to dry soil mass, in a typical agricultural soil (0.05–0.35 $m^3\,m^{-3}$), the average sensitity of the dual probe is about 1.95 °C per unit change ($m^3\,m^{-3}$) in water content for $q = 400\,J\,m^{-1}$.
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Keywords: Soil moisture sensor; DPHP method; CMOS temperature sensor; PTAT; Dynamic element matching

1. Introduction

Efficient short and long-term management of irrigation systems requires the use of reliable and accurate soil moisture sensors. Today, a large number of sensors, based on nuclear, electromagnetic, tensiometric, capacitance, among others, techniques are available for measuring soil moisture. Generally, these methods have several limitations that restrict their integration in the management of irrigation systems. The main disadvantages are: soil dependency, inaccuracy and high-cost sensors.

Time domain reflectometer (TDR) sensors [1,2], 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.

The dual-probe heat capacity sensor has been developed to provide small scale, frequent measurements of soil thermal properties: volumetric heat capacity (ρc_p), thermal conductivity, and thermal diffusivity [3,4]. The heat capacity of soil influences both the storage and transfer of heat,

so it is a necessary parameter in models of soil temperature and heat flow. In a non-swelling soil, changes in ρc_p are due primarily to changes in soil water content; hence, an application of the dual-probe will allow determination of volumetric soil water content (θ_v) [5,6].

Bristow et al. [4] applied the heat-pulse technique to determine θ_v using dual-probe sensors with two needle probes probes that were 28 mm long, constructed from No. 20 hypodermic tubing, and mounted 6 mm apart. Valente et al. [7] constructed a combination dual-probe—capacitance apparatus but with No. 18 hypodermic tubing. Power consumption, for stand-alone battery powered sensors, is the main drawback of this method. Since thermocouples are used to measure the maximum temperature rise, ΔT_M, analog-to-digital converters with adequate resolution (e.g. 0.33 μV) are required to detect small changes in θ_v [5]. To obtain ΔT_M the ambient temperature is subtracted to the temperature in temperature probe. Since, for both cases the CMOS temperature sensor is used, good accuracy is needed in temperature measurements.

A high-resolution temperature sensor enables measurements of smaller temperature differences, which in turns allows for a reduction of the heating power. Therefore, the development of a low-cost miniaturized temperature sensor with high accuracy and 0.01 °C resolution that fits into a hypodermic needle will be a breakthrough. This

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solution allows the use of an interface with electronics, network solution, and external communications that could be implemented in the sensing system near the temperature sensor. Although the reports of a bulk-micro-machined sensor [8] documented the performance of the dual-probe heat-capacity micro-sensor in measuring θ_v, their experiments were conducted in laboratory setting. Robustness of the micro-sensor under field conditions have to be improved.

Hence, the development of a low-cost dual-probe heat-pulse (DPHP) sensor of about 30 mm long $\times 10$ mm wide $\times 3$ mm in height; with a probe pitch of 3 mm will provide small-scale spatial measurements of soil moisture, which can be made near the soil surface where large root densities are found. The use of steel hypodermic needles mounted in an acrylic block will provide robustness of the soil moisture sensor and minimize errors due to deviations in probe spacing.

2. Theory

The volumetric heat capacity of soil, ρc_p (J m^{-3} °C^{-1}), is evaluated by adding the volumetric heat capacities of soil constituents [9]:

$$\rho c_p = 1.92 X_m + 2.51 X_o + 4.18 \theta_v \tag{1}$$

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 (MJ m^{-3} °C^{-1}) of each soil constituent.

The temperature distribution due to an instantaneous release of heat from an infinite line source ([10], p. 258) is:

$$T(r, t) = \frac{Q}{4\pi\kappa t} \exp\left(\frac{-r^2}{4\kappa t}\right) \tag{2}$$

in which T is the temperature rise (°C), t is time (s), r the radial distance from the heater (m), and κ is the thermal diffusivity (m^2 s^{-1}). The source strength per unit length (m^2 °C), Q, is defined as:

$$Q = \frac{q}{\rho c_p} \tag{3}$$

where q is the heat input (J m^{-1}) or quantity of heat liberated per unit length of heater.

The maximum rise in temperature (ΔT_M) at some distance from the heater is measured. As mentioned by Campbell et al. [3] the relationship between the ρc_p and ΔT_M is:

$$\rho c_p = \frac{q}{e\pi r^2 \Delta T_M} \tag{4}$$

where e is the base of natural logarithms. Substituting Eq. (1) into Eq. (4) and rearranging yields an expression that shows the relationship between θ_v and ΔT_M:

$$\Delta T_M = \frac{q}{e\pi r^2 (1.92 X_m + 2.50 X_o + 4.18 \theta_v)} \tag{5}$$

or,

$$\theta_v = \frac{1}{4.18}((q/e\pi r^2 \Delta T_M) - (1.92 X_m + 2.50 X_o)) \tag{6}$$

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 for a typical agricultural soil (0.05–0.35 m^3 m^{-3}).

From a oven-dry to saturated soil, ΔT_M varies by only about 1.2 °C; therefore, accurate measurements of ΔT_M are required to correctly estimate θ_v. Taking the partial derivative of ΔT_M with respect to θ_v yields the sensitivity of temperature rise to the change in soil water content:

$$\frac{\partial \Delta T_M}{\partial \theta_v} = \frac{-4.18\,q}{e\pi r^2 (1.92 X_m + 2.50 X_o + 4.18 \theta_v)} \tag{7}$$

If one considers the range of water contents in a typical agricultural soil, the average sensitivity of the dual-probe is about 2.5 °C per unit change (m^3 m^{-3}) in water content; that is, a 1% change in θ_v cause a 0.025 °C change in ΔT_M.

3. Projected system

The system consists of two needle probes mounted in parallel to provide a heater and a sensor probe. The needles will be made from stainless steel tubing, 1.27 mm outer diameter, which will protrude 20 mm beyond the edge of the acrylic mounting [7].

The heater will be made from Stablohm 800A wire and placed in the middle of 'heater' needle. A high-accuracy CMOS temperature sensor with amplifier will be placed in the center of the 'probe' needle. The needles will be filled with high-thermal-conductivity epoxy glue to provide water-resistant, electrically insulated probes. The complete projected system is illustrated schematically in Fig. 1. ΔT_M measurements will be obtained from the difference between the CMOS temperature sensor placed in the acrylic mounting (reference) and one identical temperature sensor placed in the middle of the temperature probe.

4. Heat-pulse simulations

Experimentally, it is not possible to heat the line source instantaneously, so a short-duration heat pulse is used. The
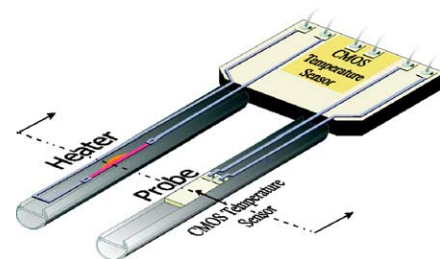

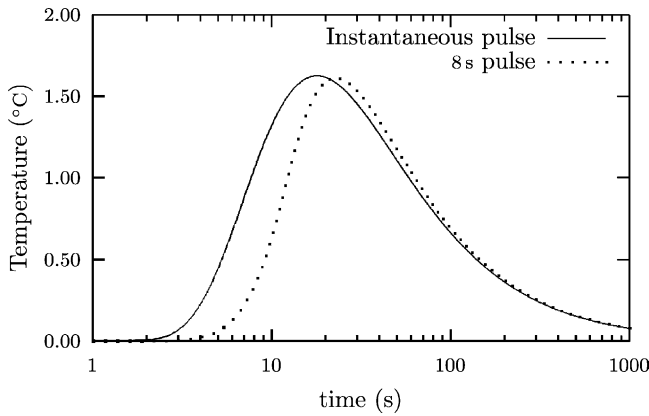Fig. 1. The complete soil moisture sensor projected system.

Fig. 2. Temperature results based on analytical models for instantaneous and pulsed line source.

solution for radial conduction of a short-duration, t_0 (s), heat pulse away from a cylinder of radius a (m) and length $2b$ (m) is:

$$T(r, t) = \frac{Q'}{4\pi\kappa} \int_{r^2/4\kappa t}^{r^2/4\kappa(t-t_0)} u^{-1} \exp(-u) \exp\left[-\left(\frac{a}{r}\right)^2\right]$$
$$\times I_0\left(\frac{2au}{r}\right) \text{erf}\left(\frac{b}{r}\sqrt{u}\right) du, \quad t > t_0 \quad (8)$$

from a heater coincident with the z-axis between $z = -b$ and $z = +b$. Here, Q' is the source strength per unit length per unit time $(m^2 \, {}^\circ C \, s^{-1})$, equivalent to $q'/\rho c_p$, where q' is the quantity of heat liberated per unit length of time $(J \, m^{-1} \, s^{-1})$. Also, $I_0(x)$ represents the modified Bessel function of order zero and $\text{erf}(x)$ represents the error function.

Fig. 2 shows the calculated temperatures at a distance $r = 0.006$ m following application of equivalents amounts of energy via instantaneous, Eq. (2), and short-duration, Eq. (8), heat pulses. The short-duration heat pulse causes a significant delay in time at which the maximum temperature change is obtained, but has very little effect on ΔT_M. Because of this minimal effect on ΔT_M, it is possible to use the instantaneous theory with short-duration heat

pulses to obtain accurate heat capacities, and hence soil moisture.

For a given θ_v, the sensitivity of ΔT_M increases as more energy is applied to the probe q, but decreases with larger probe spacing and higher bulk densities. The temperature distribution were simulated, using FEMLAB, and the Fig. 3(a) shows the results of the temperature distribution 35 s after heat-pulse ($q = 400 \, J \, m^{-1}$) application on a dry soil (5%). This simulated results are in agreement with the analitical results showed in Fig. 2. Fig. 3(b) shows a FEM-LAB thermal simulation of the sensor where is possible to see that there is no thermal short-circuit between the heater and the temperature probe for the used 6 mm distance after a 8 s heat-pulse ($q = 400 \, J \, m^{-1}$). The simulations also show that the position of the CMOS temperature sensor (reference) in the acrylic block will be in the opposite corner of the heater probe.

5. Temperature sensor

A low-cost, small, high-accuracy (better than 0.1%), and 0.01 °C resolution temperature sensor is required to be placed in a stainless steel needle with 0.912 mm inner diameter and 20 mm long to obtain a 1% resolution in soil moisture measurements. A proportional to absolute temperature (PTAT) circuit with bipolar devices fabricated in the CMOS process meet these criteria. Meijer et al. [11] showed that the application of dynamic voltage processing, using dynamic element matching (DEM) and dynamic amplification, will enable to get a very high-performance temperature sensor.

The high-performance CMOS temperature sensor is composed of a dynamic V_{PTAT} generator with thirty two switching stages. This technique is depicted in Fig. 4 were transistors M_1–M_{16} represent 16 current mirrors. One of these transistors supplies current to the bipolar transistor Q_1 while the other 15 supply current to Q_2, so that the current (I_{C2}) passing through Q_2 is 15 times the current (I_{C1}) passing through Q_1.
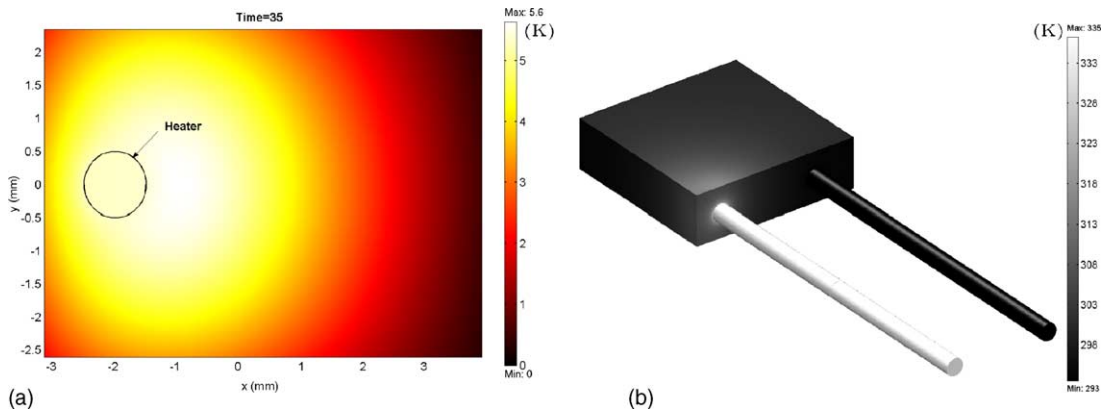

Fig. 3. FEMLAB simulation results: (a) soil temperature distribution at 35 s and (b) thermal simulations of the sensor body.
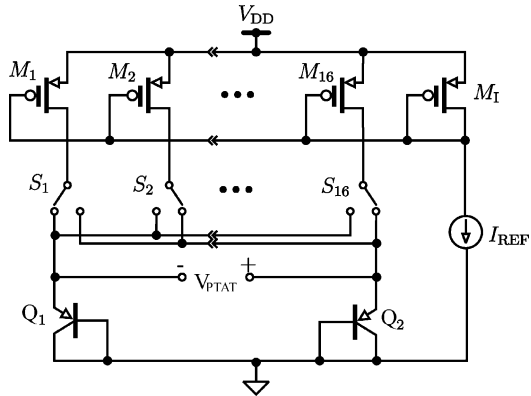
Fig. 4. Generation of V_{PTAT} using DEM, according to [11].

The collector current versus the base-emitter voltage, V_{BE} in a transistor is given by:

$$V_{BE} = \frac{kT}{q} \ln\left(\frac{I_C}{I_S}\right) \tag{9}$$

where I_C (A) is the collector current, and I_S (A) is the saturation current. The difference between the base-emitter voltages V_{BE2} and V_{BE1}:

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{kT}{q} \ln\left(\frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}}\right) \tag{10}$$

represents the PTAT voltage. Next, using switches, the positions of M_1–M_{16} are cyclically interchanged. After a complete cycle the averaged results represent a PTAT voltage in which the effect of any mismatch in the characteristic of the transistors M_1–M_{16} is strongly reduced. In order to eliminate the mismatch in the transistors Q_1 and Q_2 their relative positions are interchanged as well. So, a complete cycle consists of thirty two sub-cycle states producing an average value of V_{PTAT} over these states almost equal to $(nkT/q) \ln 15$ (Fig. 5).

The PTAT voltage over a sub-cycle is amplified using a dynamic switched capacitor amplifier with a dc gain of 15. Fig. 6 shows half of the DEM amplifier. The DEM technique
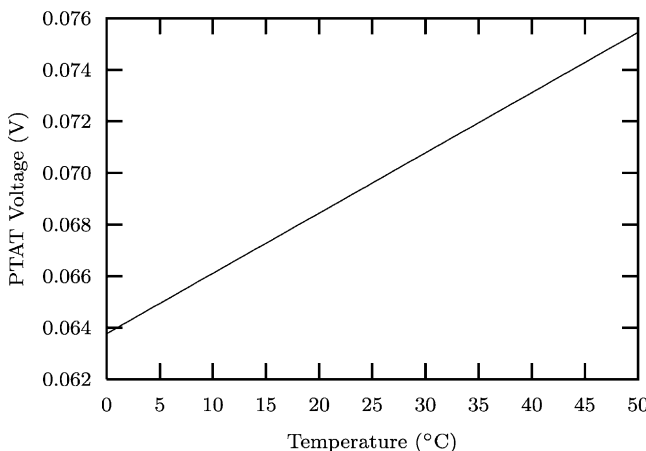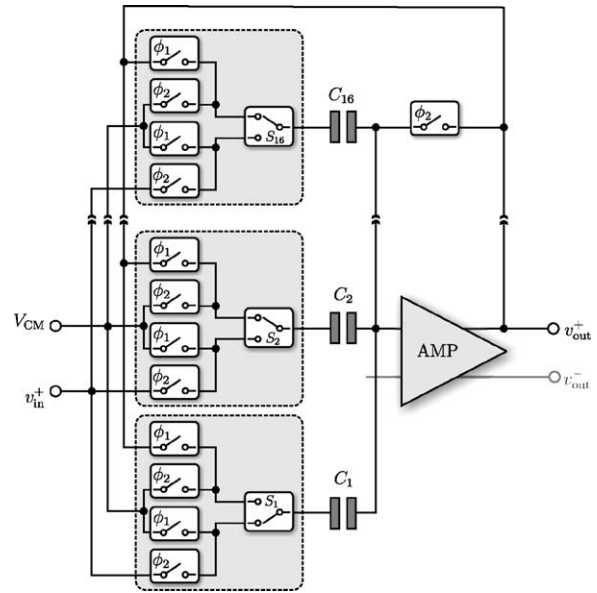

Fig. 6. Half schematic of the DEM amplifier, according to [12].

is realized by sequentially changing the relative positions of the capacitors each clock cycle. In each clock cycle, one of the identical capacitors C_1–C_{16} is in the feedback position (C_F) and all the others are in the input position (C_I). The average value of the amplification factor in a complete cycle is equal to $G = (C_I/C_F) = 15$ where the effect of capacitor mismatching is almost eliminated.

The average of the gain in a complete cycle equals to:

$$\overline{G} = \frac{1}{G+1} \sum_{i=1}^{G+1} \frac{\sum_{j=1}^{G+1} C_j - C_i}{C_i} = G + \Delta G \tag{11}$$

where ΔG represents the residual second-order error of the mismatching. So, a complete temperature signal is obtained, after taking an average of the $32 \times 16 = 512$ sub-cycles (external post-processing).

6. Results

Fig. 7 shows a picture of the soil moisture sensor with a microscope photography of the CMOS temperature sensor chip made. The CMOS temperature sensor measures $1108 \,\mu m \times 1156 \,\mu m$ and was made throw EUROPRACTICE program by IMEC using CMOS technology ALACTEL-MITEC $0.7 \,\mu m$, n–well, C07M-A (2M/1P/PDiffC/HR). In the microscope photography of the CMOS temperature sensor is possible to see the DEM PTAT (A), the DEM amplifier (B), the capacitors of switched-capacitor amplifier (C), and the digital section (D). This test version of the CMOS temperature sensor is square-type and have some test pads. To place this CMOS die in the needle a hole is made and the die is placed in a small PCB and only the needed pads were wire-bonded to obtain the desired signals.
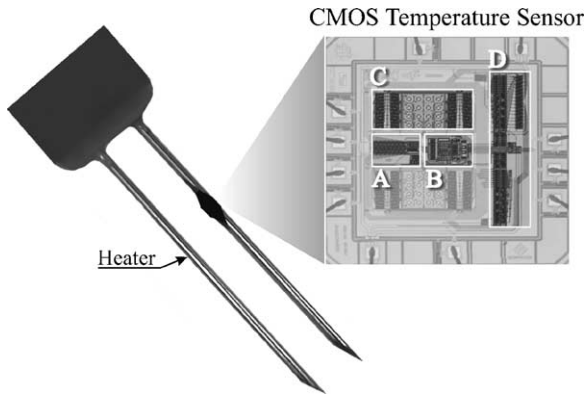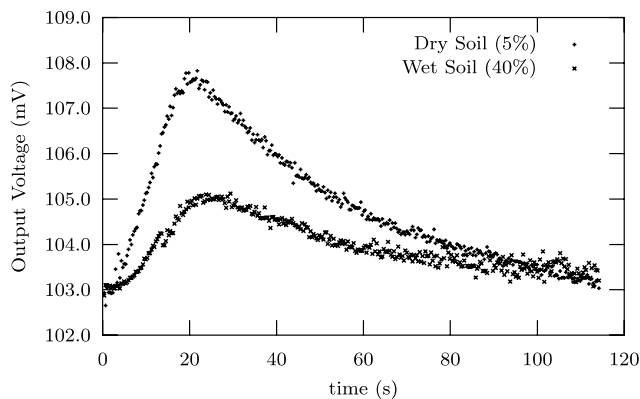

Fig. 5. Simulated PTAT voltage.

Fig. 7. Temperature sensor layout.

Fig. 8. Results of CMOS temperature sensor placed in the temperature probe for dry (5%) and wet (40%) soil.

has broad utility in soil plant science, because values of soil temperature, heat-capacity, water content, and thermal diffusivity can be determined from a single reading.

It is also shown that the sensitivity of the dual probe is about $1.95\,^\circ$C per unit change ($m^3\,m^{-3}$) in water content for a heat strength of q of $400\,J\,m^{-1}$.

More field tests are need to prove the sensor robustness but since the sensor is made from No. 18 steel hypodermic needles (1.27 mm o.d., 0.912 mm i.d., 0.179 mm wall thickness) they improve rigidity and help to maintain a fixed probe spacing when the sensor was inserted into the soil.

Acknowledgements

For testing the sensor are used samples of soil oven-dried at $105\,^\circ$C and then filed with water to produce 5% and 40% of θ_v with a maximum error of $\pm1\%$. Fig. 8 shows the results obtained in the CMOS temperature sensor placed in the temperature probe for wet and dry samples of soil. The values indicate a sensor sensitivity of about $3.5\,mV\,^\circ C^{-1}$ or $6.825\,mV$ per unit change ($m^3\,m^{-3}$) in water content for a heat strength of $400\,J\,m^{-1}$.

7. Conclusions

The modeling and simulation of a soil moisture sensor using the dual-probe heat-pulse method were achieved. A CMOS temperature sensor was fabricated with the use of dynamic PTAT generator and dynamic switched capacitor amplifier in a standard $0.7\,\mu m$ technology. The sensor resolution allows the reduction of the heat-pulse energy to ($q = 400\,J\,m^{-1}$) and enable to produce low-cost high-performance soil moisture sensors. The use of a CMOS temperature sensor will bring the possibility to interface to a analog front-end with network solution and external communications (e.g. radio frequency). This micro-system based on dual-probe heat-pulse method

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Biographies

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J.H. Correia graduated in Physical Engineering from University of Coimbra, Portugal in 1990. He obtained in 1999 a PhD degree at the Laboratory for Electronic Instrumentation, Delft University of Technology, working in the field of micro-systems for optical spectral analysis. Presently, he is an Associate Professor in Department of Industrial Electronics, University of Minho, Portugal. He was the General-Chairman of Eurosensors 2003, Guimaraes, Portugal. His professional interests are in micro-machining and micro-fabrication technology for mixed-mode systems, solid-state integrated sensors, micro-actuators and micro-systems.