Proposal of a Novel Heat Dissipation Soil Moisture Sensor

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Abstract: A novel heat dissipation soil moisture sensor with only one bipolar transistor performing as both heating and temperature sensing element is presented. Due to the fact that the power dissipated in the transistor is a function of both the voltage and the current in the transistor, it is possible to obtain the required levels of heating power with low currents, increasing the battery life of the sensor's interrogator. Experimental results measured in a fabricated sensor show that in soils with high moisture levels the proposed sensor presents a sensitivity that is almost 10 times higher than those found in conventional sensors with separated heating and sensing elements. Since the transistor is used as both the heating and sensing elements, for the same applied energy (80 mW during 45 s) the temperature increase in the proposed sensor is about 7.5°C, while the conventional porous block probe presents a temperature increase of only 0.8°.

Key–Words: Soil moisture measurement, Heat dissipation sensor, Porous ceramic sensors, Precision agriculture.

1 Introduction

One of the goals of modern precision agriculture is to achieve a high efficiency in what concerns water irrigation control. Proper soil moisture measurement can optimize water usage, resulting in less water being wasted, and better crop development [1, 2].

Although the gravimetric technique [3] can lead to very precise results in soil moisture measurement, it is not possible to use this technique on a plantation, since it is a slow procedure (tens of hours to obtain one result) and it is necessary to take samples of the soil and make the measurements in laboratory. To overcome this problem, several types of sensors were developed to measure soil moisture *in-situ*, like the capacitive sensors [4], resistive sensors [5], Time Domain Reflectometry [6], and heat dissipation sensors [7, 8].

For field applications, the heat dissipation soil moisture measurement probes prevailed and are well known in the market. There are basically two types of probes, and both require a heating element and a temperature measuring device. One type does not use a porous ceramic block and the heating/sensing elements are inserted in metal tubes and buried directly in the ground, at a specific distance [9]. The heater is turned on during a determined time, heating the soil around it. The temperature sensor detects the amount of heat that is transferred through the soil from one probe to the other. Since the heat transfer ratio is a function of the thermal conductivity of the soil, which depends on the amount of water in the soil, the maximum temperature detected at the sensing probe is a function of the soil moisture.

The other type of heat dissipation sensor uses a porous ceramic body with one heater and a temperature sensor assembled inside it [10]. Similarly, the heater is turned on during a determined time, heating the porous block. The temperature sensor (usually a thermistor or a thermocouple) detects the temperature that the inner part of the sensor body reaches after the power is applied for a given time. Since the amount of water absorbed from the soil by the porous ceramic changes the thermal conductivity of the water+porous ceramic complex, the probe temperature is a function of the soil moisture.

The novel sensor presented in this paper also uses a porous block, but instead of using one heating and one temperature sensing devices, it is proposed the use of a single bipolar transistor inside the porous block, since the bipolar transistor is an electronic device that can perform both as a heating source and as the temperature sensor.

2 Materials and Methods

The soil moisture sensor proposed in this paper is composed of a single transistor, encapsulated inside a porous block. By forcing a voltage V_{CE} and a current I_C in the transistor, it dissipates a power that is equal to $P = V_{CE}I_C$. This power is dissipated in the porous block+water complex and heats the body of the sensor, just like the resistive heating elements used in the conventional heat dissipation sensors. To measure the temperature that the probe has reached, the well known characteristic of $V_{BE}\ x\ T$ for the bipolar transistor is used.

Since for field applications the measurement equipment is powered by batteries, it is important to notice that the collector current I_C is inversely proportional to V_{CE} ($I_C = P/V_{CE}$) and, for a desired power, by increasing the voltage V_{CE} the current drained from the battery is reduced, increasing the battery life.

Thus, the proposed sensor presents two important features: *i*) it can achieve a high heating power with low current; *ii*) the temperature of the probe is measured using one of the best characterized relationship in the bipolar transistor ($V_{BE}\ x\ T$), leading to high accuracy in the temperature measurement.

Also, since the only electronics device in the probe is a single low-power bipolar transistor (an extremely low-cost device), the manufacturing cost would be lower than for the standard probes, where one heater and one sensing elements are needed. Furthermore, since there is a single active element, the errors due to the variations in both heater and sensing element contacts with the porous block and physical distance between heating/sensing elements [8] can be minimized.

Using a small SMD component, the transistor can be considered a punctual heat source, irradiating evenly across the probe the heat generated by the power applied to the transistor. It is also expected that a higher sensitivity should be reached, since the temperature measurement is performed exactly at the same point of the heating element, as both elements are the same.

2.1 Probe Design

To test the concept, a simple probe prototype was designed and constructed. The probe is comprised of a low-cost off-the-shelf BC556 NPN bipolar transistor and a porous block, as seen in Figure 1. The transistor is soldered to three long plastic insulated wires that will be connected to the driver/measuring equipment. The emitter, base and collector must be insulated from each other and from the porous block, to avoid any leakage currents that could flow through the pores filled with water, leading to false measurement results.

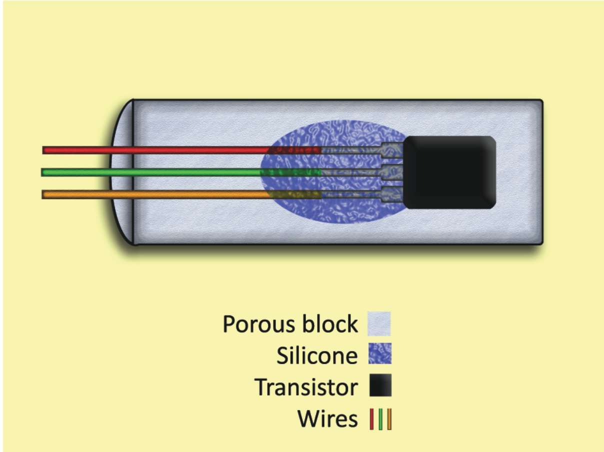

Figure 1: Cutaway drawing of the proposed soil moisture probe.

In the constructed prototype, a silicone protective coating was used to electrically insulate the transistor leads. It is very important to leave the transistor plastic header exposed, and cover only the metal leads with the silicone. The fact that the sensor depends on the heat transfer between the transistor and the porous block, a silicone layer over the transistor header could interfere with that heat exchange ratio. After the silicone insulation is cured, a gypsum mix is made, placed into a tube and the insulated transistor is then inserted in the middle of the wet gypsum. After the porous block is completely dried, the probe is removed from the tube, and is ready to be used.

2.2 Measurement Setup

All measurement tests were made in laboratory, with bench-top programmable equipments, all from Keithley [11]. As shown in Fig. 2, the emitter of the transistor was connected to a programmable current source (Model 220), the base was grounded and the collector was connected to a programmable voltage source (Model 230). The value of V_{BE} is read using a Model 177 4-1/2 digits multimeter (actually the value read is $-V_{BE}$).

The program created for the measurement is started with 100μA in the current source and $V_{CB} = 0$, in order to keep the power dissipated by the transistor extremely low (approximately 55μW if $V_{BE} = 550$ mV @ $I_C = 100\mu$A). In the next step, both the voltage source and the current source are simultaneously raised to 10 V and 8 mA respectively, and the value of the initial V_{BEi} is read. This state, where a power of approximately 80 mW is dissipated in the

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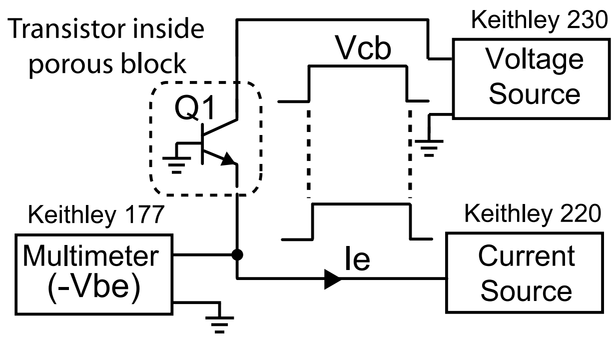

Figure 2: Diagram of the measurement laboratory set-up for the soil moisture probe.

transistor, is maintained for 45 seconds. After 45 s, the value of the final V_{BEf} is read, and the voltage and current sources are returned to their initial values.

Since a constant emitter current of 8 mA is kept during the 45 s, the measured difference $\Delta V_{BE} = V_{BEf} - V_{BEi}$ is due only to the temperature difference in the transistor caused by the power dissipated by the transistor into the porous block+water complex. Since the very well known relationship for the variation of V_{BE} with temperature can be assumed to be linear for small values of ΔT [12], the probe can be calibrated using the ΔV_{BE} measured values, and there is no need to convert these voltage values to temperature. This will make the calibration procedure for the sensor inserted in the soil (required for all soil moisture probe sensors) much easier, faster and precise.

3 Experimental Results and Discussions

A photograph of the a manually fabricated probe using the described method is shown in Fig. 3. The measurement set-up was used to characterize the probe, which was moisturised with several amounts of water volumes.

To start the characterization, the probe was dried for 12 hours inside an air oven at 100°C, to guarantee that the water content in the porous block was negligible. Then the probe was connected to the measurement circuit and submitted to the test cycle, to read the value of $\Delta V_{BE} = V_{BEf} - V_{BEi}$. Next, the probe was soaked in a controlled volume of water until all the water was absorbed by the porous block. After a period of 5 minutes, when the water is evenly distributed inside the porous block, a new measurement cycle is executed. This procedure was repeated until the values of ΔV_{BE} indicated that the porous block was saturated with water.

The measured results for ΔV_{BE} as a function of the water content in the porous block are plotted in

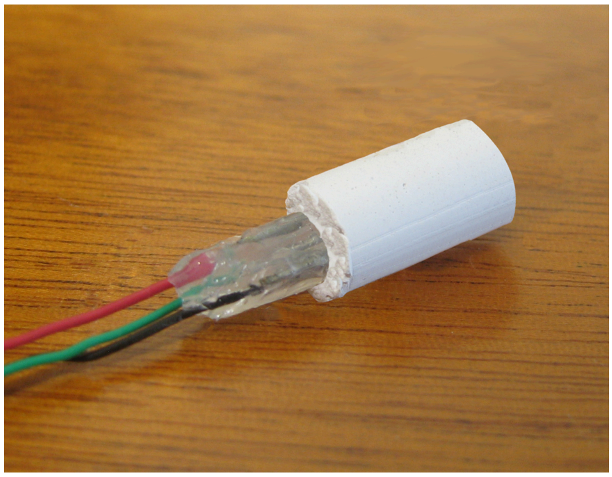

Figure 3: Photograph of a manually fabricated soil moisture sensor probe.

Fig. 4. As it can be observed, a variation of ΔV_{BE} in the order of tens of mV is measured for the whole operation range (completely dry to near water saturation), making it easy to be measure the soil moisture without amplification or sophisticated equipment.

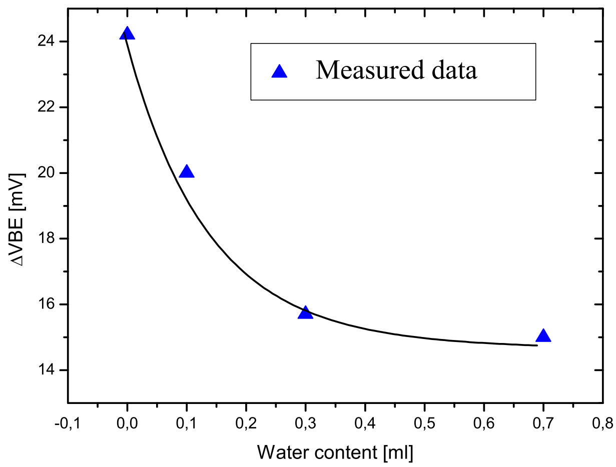

Figure 4: Measured results of ΔV_{BE} as a function of the probe water content for the fabricated soil moisture probe.

It is important to notice that the measured values of ΔV_{BE} show that in the region of low sensitivity (when the water content in the sensor body is high), the sensitivity of the proposed probe is almost 10 times higher when compared to the standard porous ceramic probes commercially available [10], since the temperature variation observed in the proposed sensor probe is about 7.5°C ($\Delta V_{BE} = V_{BEf} - V_{BEi} \approx 15$ mV), while the standard probe shows a temperature variation of only 0.8°C.

This is explained by the fact that the transistor performs as both heating and sensing elements, and

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the point where the temperature is being measured is exactly the same point where the heat is produced, since there is no insulating material between the heating and sensing element.

This feature of the proposed sensor eliminates a drawback of the conventional sensors with separated heating and sensing elements, which requires calibration of each sensor. Individual calibration is necessary because of the variations in both heater and sensing element contacts with the porous block as well as the physical distance between heating/sensing elements, which cannot be accurately controlled in the fabrication process, leading to different thermal behaviour for each fabricated sensor.

4 Conclusion

A proposal of a novel sensor for the measurement of soil moisture was presented. The probe uses only one bipolar transistor as the heating and sensing element, resulting in a compact, easy to fabricate and low-cost moisture sensor. Since the measured variable is the ΔV_{BE} of a bipolar transistor at a fixed collector current, which presents a well known dependence with the temperature, the accuracy of the measured data depends only on the measurement equipment used to read the ΔV_{BE} values.

Measured results obtained from a manually constructed probe showed that in wet conditions, when these sensors are most needed to guarantee a precise soil humidity to the plants, the sensitivity of the proposed sensor is almost 10 times higher than the sensitivity found in similar probes with separate heating and sensing elements.

The next steps in the development of the proposed moisture sensor is the design and development of a portable interrogator circuit that would apply the required voltage/current signals, read the ΔV_{BE} data with a high resolution and high precision A/D converter and calculate the soil humidity with microcontroller, showing it on a display. This would allow measurements of soil moisture in the field, which is an important feature for real "planted" sensors.

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