Multimodal Water Content and Nutrient Concentration Sensor for On-Site Soil Monitoring

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***Abstract*— We have fabricated a new multimodal sensor chip that is capable of measuring water content and nutrient concentration on-site simultaneously. Heretofore in agriculture, water content sensors, for example the TDR sensor, could not provide water content information correctly, since the results of these sensors are affected by the nutrient concentration in the soil solution. Therefore, tensiometers (shown in Fig. 1 (a)) have generally been used in agriculture. These are large-scale sensors and are not suitable for precision agriculture. Our proposed sensors are the world's first to be able to monitor water content without being influenced by the nutrient concentration, and nutrient concentration without influence from the water content.**

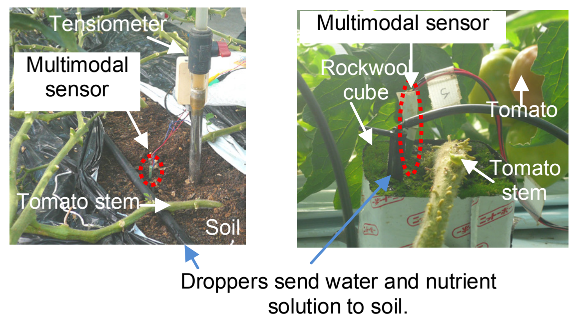
Keywords-water content; ion concentration; phase; electrical conductivity; on-site monitoring; agriculture

I. INTRODUCTION

On-site monitoring to enable precise control is becoming a requirement in agriculture. In particular, accurate determination of the water content in soil and of the nutrient concentration in water is considered to be the most important information for increasing the production of agricultural crops. The water content is the proportion of water by volume with respect to everything else, usually air and soil clod. The nutrient concentration (which has the same meaning as 'ion concentration') [1] in water can generally be observed by electrical conductivity measurements.

Fig. 1 shows how tensiometers can measure water content by utilizing the moisture-holding ability of soils. Because tensiometers have simple mechanisms and are reasonably priced, many farmhouses use them. However, they can't measure the ion concentration and can't be set near the roots of plants because of their large size. Hence, tensiometers are unsuitable for precise on-site monitoring.

In the case of on-site monitoring in soil, it is difficult to separate electrical conductivity information from water content information. For example, when the nutrient ion concentration is 1 S/m and the water content is 0.5 m^3/m^3, the measurement result of electrical conductivity is 0.5 S/m.



(a) A tomato plant bed, in which soil is used, monitored by a multimodal sensor.

(b) Tomato plant bed, in which Rockwool is used, monitored by a multimodal sensor.

Figure 1. These pictures show how a multimodal sensor is used for on-site monitoring of two kinds of plant beds in precision agriculture.

Therefore, for the measurement of water content and to obtain information about the nutrient concentration in soil, time domain reflectometry (TDR) sensors [2][3] and thermal type sensors [4] have been studied by other groups. These sensors measure water content information and electrical conductivity information separately, and then information about nutrient concentration is elicited by eliminating water content data from the electrical conductivity data. These water content sensors require high frequency (> 1 GHz) operation, or for the soil to be heated in order to measure complete water content values without the effects of nutrient concentration. In addition, the sensor sizes are not small enough (length, width: > 2 cm) to be incorporated with an electronic control system.

We have proposed a new multimodal sensor chip that is capable of measuring water content and nutrient concentration on-site simultaneously. The sensor is small in size and is capable of operating at lower frequency than TDR by employing new calculation methods.

In this paper, after introducing the basic concepts regarding the background and motivation of our research in Section I we formulated the theoretical and mathematical concepts in Section II. In later sections such as in Section III, we described the material structure of the sensor; in Section IV, measurement and results, finally in Section V we

 ISBN: 978-1-61208-145-8

articulated our conclusion based on the results of our research.

II. New Measurement Methods

A. Ion Concentration Measurement Method using Phase

Measurement methods for water content are gauged against the dielectric constant. The relative permittivity of water, which is about 80, is larger than that of other materials commonly found in soil; for example, the relative permittivity of air is 1, and that of soil is about 5. In order to measure water capacitances and to eliminate the effect of ion concentration, TDR sensors operate at high frequencies of between 100 MHz and 1 GHz. However, the operating circuits that are required for high frequency operation are complex and costly, and the relative permittivity of water is also changed by ion concentration; the relative permittivity is 80 at 7 mS/m ion concentration (tap water) and is 70 at 7 S/m (seawater) [5].

We propose a new measurement method that measures the phase characteristics of water. This method analyzes the ion concentration information and is unaffected by the water content value. Equations 1 through 3 show the water characteristics using a parallel circuit model of resistance and capacitance.

$$Z_{total} = \frac{1}{\frac{1}{R_{water}} + j\omega C_{water}} = \frac{R_{water}(1 - j\omega C_{water} R_{water})}{1 + \omega^2 C_{water}^{\ 2} R_{water}^{\ 2}} \tag{1}$$

$$R_{water} = \frac{D}{\sigma_{water} LW} \quad , \quad C_{water} = \varepsilon_{water}\varepsilon_o \frac{LW}{D} \tag{2}$$

$$\theta_{total} = \tan^{-1}\left(-\omega C_{water} R_{water}\right) = \tan^{-1}\left(\frac{-\omega\varepsilon_{water}\varepsilon_o}{\sigma_{water}}\right) \tag{3}$$

where, Z_{total} is the combined impedance, R_{water} is the resistance of water, C_{water} is the capacitance of water, D is the distance along the direction of passing current, L and W are the length and width of the section area of the path of the passing current, σ_{water} is the electrical conductivity (which provides information about ion concentration), ε_{water} is the relative permittivity, ε_0 is the permittivity of vacuum, θ_{water} is the phase of Z_{total}.

In the case of 50 % water per unit volume of soil, equation 3 changes to equation 4. In this equation, the phase remains almost unchanged with respect to water content information!

$$\left.\begin{aligned} &\theta_{total} = \tan^{-1}\left\{\frac{-\omega(0.5\varepsilon_{water} + 0.5\varepsilon_{soil})\varepsilon_o}{0.5\sigma_{water} + 0.5\sigma_{soil}}\right\} \approx \tan^{-1}\left(\frac{-\omega\varepsilon_{water}\varepsilon_o}{\sigma_{water}}\right) \\ &\because \varepsilon_{water} \rangle\rangle \varepsilon_{soil} \quad , \quad \sigma_{water} \rangle\rangle \sigma_{soil} \end{aligned}\right\} \tag{4}$$

In the case when the ion concentration changes from 7 mS/m (tap water) to 7 S /m (seawater) in water without including soil, equation 3 changes to equation 5. In this equation, the phase is changed almost exclusively by the ion concentration for smaller relative permittivity changes!

Because the phase at the highest sensitivity is π/4 rad, suitable frequencies for the input signals are between 500 kHz and 10 MHz. Hence the frequencies used in our method are smaller than those used in TDR methods.

$$\left.\begin{aligned} &\theta_{total} = \tan^{-1}\left\{\frac{-\omega\left(\frac{70}{80}\varepsilon_{tapwater}\right)\varepsilon_o}{\frac{7}{7\times10^{-3}}\sigma_{tapwater}}\right\} \approx \tan^{-1}\left(10^{-3} \times \frac{-\omega\varepsilon_{tapwater}\varepsilon_o}{\sigma_{tapwater}}\right) \\ &\because \varepsilon_{tapwater} = 80, \varepsilon_{seawater} = 70, \\ &\quad \sigma_{tapwater} = 7\times10^{-3} S/m, \sigma_{seawater} = 7S/m \end{aligned}\right\} \tag{5}$$

B. Water Content Calculation Method using Phase and Electrical Conductivity Information

Electrical conductivity sensors have been studied by our group in the past [6]. Since these sensors operate at the low frequency of 10 kHz, equation 1 changes to equation 6. This equation shows that the ion concentration of water without other materials can be measured using electrical conductivity. The value σ_{water} represents exactly the electrical conductivity information.

$$\left.\begin{aligned} &Z_{total} = \frac{1}{\frac{1}{R_{water}} + j\omega C_{water}} \approx R_{water} = \frac{D}{\sigma_{water} LW} \\ &\because \frac{1}{R_{water}} \rangle\rangle \omega C_{water} \end{aligned}\right\} \tag{6}$$

In the case of 50 % water per unit volume of soil, the total electrical conductivity σ_{total} changes to equation 7. The equation shows that electrical conductivity is affected by the volume of water per unit volume, which is the same as being affected by the water content!

$$\left.\begin{aligned} &\sigma_{total} = 0.5\sigma_{water} + 0.5\sigma_{soil} \approx 0.5\sigma_{water} \\ &\because \sigma_{water} \rangle\rangle \sigma_{soil} \end{aligned}\right\} \tag{7}$$

From these equations, the electrical conductivity can be determined by multiplying the water content by the ion concentration, and water content information can be calculated by using equation 8.

$$WC[m^3/m^3] = \frac{EC[S/m]}{IC[S/m]} \tag{8}$$

where WC is the water content information, IC is the ion concentration information shown by equation 5, and EC is the electrical conductivity information shown by 7.

 ISBN: 978-1-61208-145-8

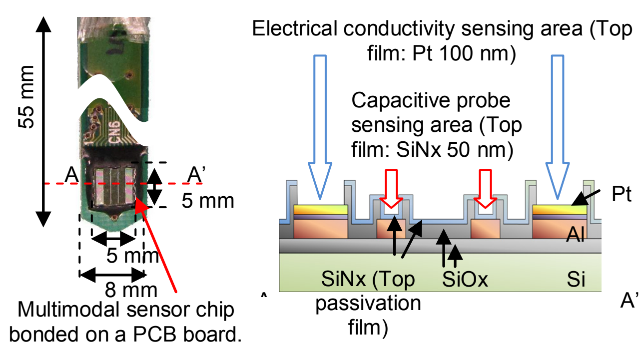
III. STRUCTURE OF A SENSOR DEVICE

We fabricated a multimodal sensor with a Pt electrode area to measure electrical conductivity and a capacitive probe area to measure phase information, as shown in Fig. 2. Because the multimodal sensor is very small and can be fabricated by CMOS process technology, it was possible to insert the sensor into several kinds of plant beds. Images of two kinds of experiments using our multimodal sensor in agricultural applications are shown in Fig. 1.

The Pt electrodes for sensing electrical conductivity had been studied previously [6]. The sensing method is capable of measurement covering a wide range, between 1 mS/m and 10 S/m. The voltage was applied using a 10 kHz sine-wave and was of 250 mV in amplitude. Characteristically, the Pt electrodes can apply an electric current to a solution at low frequency, for example, 10 kHz, since the effects of electrical double layers on the Pt electrodes and of the parasitic capacitance of water can be minimized at this frequency.

In the capacitive probe area, Al electrodes were covered with a thin SiNx film (50 nm thickness) to protect them from the solution and to lower the electrical current. The SiNx parasitic capacitance had to be designed to be larger than the capacitance of water since the SiNx and the parasitic capacitance of water were connected in series. The SiOx parasitic capacitance under the Al electrode-area had to be designed to be smaller than the capacitance of water, because the SiOx and parasitic capacitance of water were connected in parallel.

The SiNx on the top film and the SiOx under the Al electrodes were designed to be 50 nm and 1 µm in thickness respectively. In this experiment, the applied voltage used a 500 kHz sine wave of 250 mV amplitude. Measurement at 500 kHz produced a larger range of phase changes for (θ_{water}) between 0 and -90 degrees.



(a) The picture shows a multimodal sensor. The sensor has a small chip size, and is bonded on a PCB board that is inserted into the beds.

(b) A cross-sectional view of picture (a) is shown. A multimodal sensor is integrated with an electrical conductivity sensing area and a capacitive probe sensing area.

Figure 2. These pictures show an image of the sensor format and the structure of the sensor areas.

IV. MEASUREMENT RESULTS AND DISCUSSION

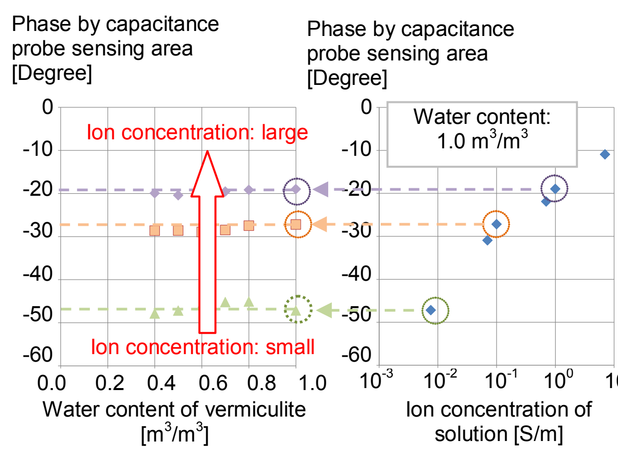
Fig. 3 shows images of an experiment to determine changes in water content (shown in Fig. 3 (a)), and in ion concentration (shown in Fig. 3(b)). A solution of tap water and common salt (NaCl) was used for the ion concentration test. When the water content is 1.0 m^3/m^3, as shown in Fig. 3 (b), then the electrical conductivity and the ion concentration are the same.

The graph in Fig. 4 shows that the results of the phase measurement of the water element are changed due to the ion concentration alone (shown in Fig. 4 (a)), and not by the water content (shown in Fig. 4 (b))! The graph in Fig. 5 shows that electrical conductivity information is composed of the water content (shown in Fig. 5 (a)) and the ion concentration (shown in Fig. 5 (b)). This graph shows that the electrical conductivity information is the water content multiplied by the ion concentration!

(a) The picture shows a photo of a water content experiment using vermiculite, as shown in Fig. 4 (a) and Fig. 5 (a).

(b) The picture shows an experiment photo of ion concentration of solution. Of course, water content of the solution is 1.0 m^3/m^3! The test results show Fig. 4 (b) and Fig. 5 (b).

Figure 3. These pictures show images of experiments to determine changes in water content and changes in ion concentration.

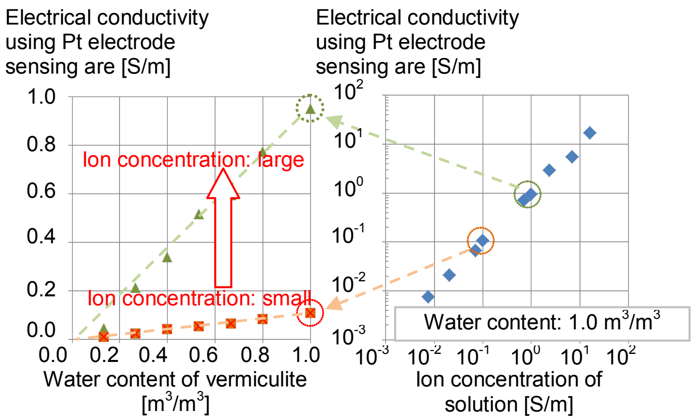


(a) Vermiculites were interfused with three solutions with different ion concentrations. Experiment of the relationship between water content and phase.

(b) Experiment to determine the relationship between ion concentration and phase.

Figure 4. Vermiculite and a solution are measured using the capacitance probe sensing area operating at 500 kHz. These graphs show that the sensor can monitor only ion concentration, and not water content!

The graph in Fig. 6 shows an image of the derivation of water content from electrical conductivity and ion concentration using equation 8. From these measurement results and from equation 8, information about the water content can be determined!



(a) Experimentation to investigate the relationship between water content and electrical conductivity.

(b) Experimentation to determine the relationship between ion concentration and electrical conductivity.

Figure 5. Vermiculite and a solution measured by the Pt electrode sensing area operated at 10 kHz. These graphs show that the sensor can monitor electrical conductivity by multiplying water content by ion concentration!

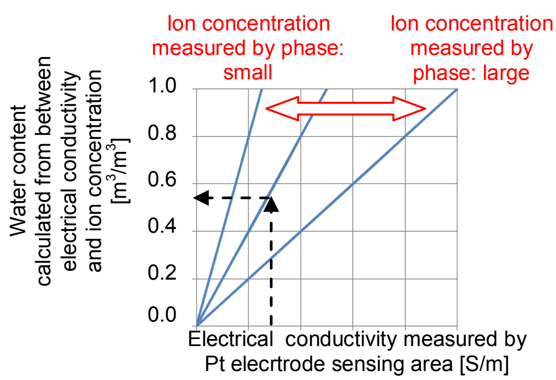


Figure 6. Image of the derivation of water content from the electrical conductivity and the ion concentration using equation 8.

V. Conclusion

A small multimodal sensor capable of providing on-site measurement of water content and ion concentration over a small area (for example, near to plant roots) was fabricated using CMOS circuit process technology. We proposed new measurement methods for ion concentration and water content determination, and designed appropriate film thicknesses, materials and so on for novel multimodal sensor devices. From phase information measured using a capacitance probe, ion concentration information that was unaffected by water content information could be gathered over a wide measurement range. When using Pt electrodes, the electrical conductivity could be determined by multiplying water content by ion concentration. We succeeded in measuring the water content without any effect caused by ion concentration (that is, nutrient concentration) and in measuring ion concentration without any effect from water content when using the new multimodal sensor.

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