MINIATURIZED SOIL SENSOR FOR CONTINUOUS, IN-SITU MONITORING OF SOIL WATER POTENTIAL

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ABSTRACT

This paper presents a miniature embedded sensor for direct, in-situ, continuous monitoring of soil water potential variations during the growth of plants. The sensor has a small form factor due to the seamless integration of an ultra-shallow water reservoir, a nanoporous ceramic disk, and a miniature optical displacement detection unit. By increasing the hydrophilicity and smoothness of the inner surface of the water reservoir, a high cavitation pressure was obtained. The sensor makes it possible to conduct continuous, in-situ measurement of soil water potential near the roots of plant for almost two weeks.

KEYWORDS

Soil water potential, agricultural sensor, plant, in-situ measurement

INTRODUCTION

Soil water potential is a main factor to determine the dynamics of water in soils and impacts plant growth and yield. Many methods have been developed to monitor soil water potential such as using electrical impedance and tensiometric measurements [1-3]. In general, the electrical impedance measurements rely on changes in the electrical properties of soils that are associated with water contents in soils. Soil water potential can be estimated according to the relationship between the water content and water potential. However, because soil water potential is often affected by soil types such as sand, loam clay, and their mixtures, soil samples obtained from different locations (even with a same water content) will have different levels of soil water potential [4], thus leading to a relatively poor measurement accuracy for the sensors on the principle of measuring soil water contents [5]. Therefore, existing soil water potential sensors by the means of detecting soil impedance could only provide coarse information on soil water status.

In contrast, the tensiometric method can directly monitor soil water potential. Generally, tensiometers work on the principle of establishing a pressure equilibrium between a water-filled reservoir and surrounding soils through a porous ceramic head. These tensiometers are relatively bulky and expensive, and require frequent water refilling to measure an induced negative pressure inside the water reservoir using an external pressure gauge [6]. In addition, the dynamic range of soil water potential of these devices is often limited to -100 kPa due to a notorious cavitation issue with the water reservoir [7][8]. In general, cavitation of soil water potential sensors happens when undissolved gas nuclei, in forms of air bubbles or water vapor, are trapped in the corners or crevices of water reservoir. When a pressure equilibrium between the reservoir and external soils is established, a negative pressure inside the reservoir will enlarge and pull out the air bubbles through the nanopores embedded inside the ceramic head, thus forming a free cavity and device failure [9]. In order to minimize or avoid cavitation, an osmoticum could be added to the reservoir but it took a few weeks to obtain an initial water pressure saturation [10]. A saturated nanoporous ceramic disk has recently been demonstrated effective to increase the dynamic range of soil water potential sensor [11][12]. Further, the improvement of the surface smoothness and hydrophilicity on the inner wall of the size-reduced reservoir could minimize cavitation due to the reduction of undissolved gas nuclei [13][14].

In this work, we present a miniaturized soil sensor for continuous, in-situ monitoring of soil water potential.

DEVICE STRUCTURE AND DESIGN

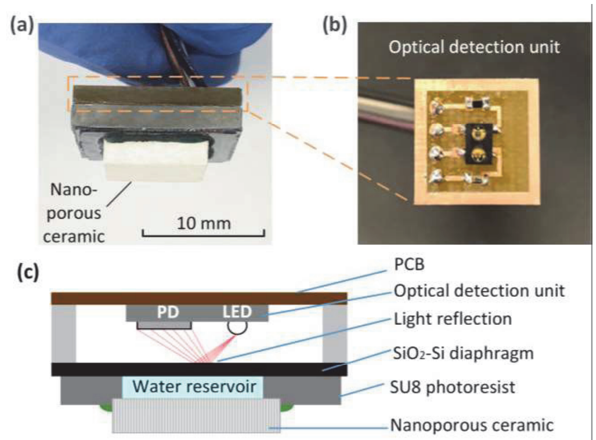

Figure 1: (a) Image showing the fabricated soil water potential sensor. (b) Image showing the back of the sensor. (c) Schmatic of the cross section for the sensor with an optical displacement detection unit mounted on a PCB.

Figure 1 shows our soil water potential sensor that consists of a thin water reservoir sandwiched between a nanoporous ceramic plate (Al_2O_3; mean pore size: 30 ± 15 nm) and a double side polished 200 μm-thick silicon diaphragm with a layer of 300 nm-thick thermal oxide. The water reservoir was set to be 200 μm deep by SU8 photoresist using soft lithography. To inject water into the reservoir, the sensor was placed inside a high-pressure chamber containing deionized (DI) water. A positive high pressure was applied to the chamber at a speed of 1 bar/min until 60 bar was reached. The sensor was pressurized for 24 hr to allow water to fill both the reservoir and porous ceramic disk. It should be noted that the air-entry-value of the nanoporous disk is ~1.5 MPa, close to the wilting point for plant growth. When the sensor was exposed to unsaturated soil water environments, the diaphragm would bend into the reservoir due to an induced negative pressure inside the reservoir. The displacement of the diaphragm could be quantified by the optical displacement detector (OPR5005, TT Electronics) mounted on a printed circuit board (PCB). This unit was composed of a light-emitting device (LED) and a photodetector (PD) and integrated with the sensor as shown in Fig. 1c. The light intensity reflected from the bendable diaphragm could be detected by the PD, which is inversely proportional to the square of the distance from the LED to PD.

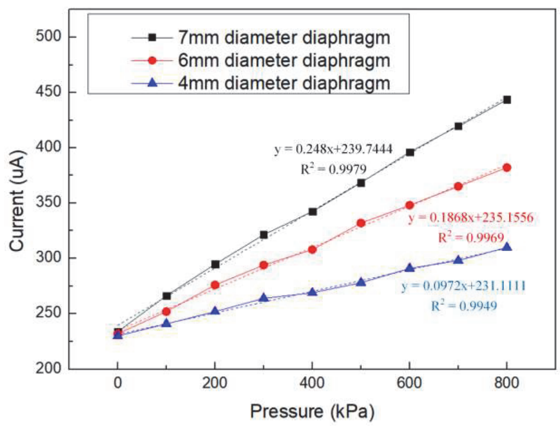

Figure 2: Output current vs. pressure for the sensors with different thicknesses of the SiO_2-Si diaphragm.

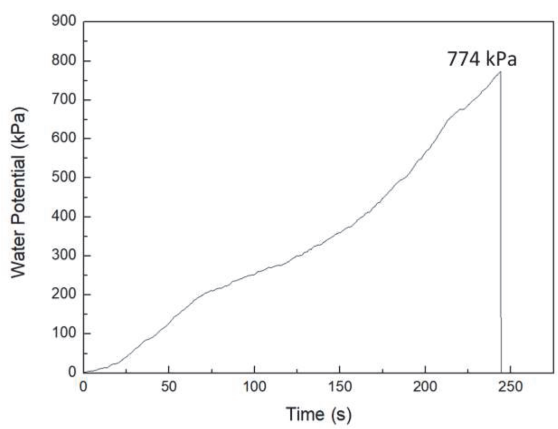

Figure 3: Free evaporation test result for the soil water potential sensor.

RESULTS AND DISCUSSION

Three sensors with different diaphragm diameters (3 mm, 5 mm and 7 mm) were prepared and calibrated using a positive air pressure method. These sensors were immersed into DI water for one hour, allowing water to fill out all the nanopores of ceramic. Similarly, the sensors were placed into the high-pressure chamber with a gradually increased air pressure from 100 kPa to 800 kPa. The corresponding current signal from the optical detector was recorded and plotted in Fig. 2. The pressure resolution of the sensor is mainly determined by the electrical current resolution of the meter used in this test (here, 0.01 µA). Based on the obtained current vs. pressure calibration curve in Fig. 2, the resolution of water potential was about 0.04 kPa. Also, our result demonstrates that the device with the 7 mm-diameter diaphragm exhibited the highest resolution, and thus was chosen for the following free evaporation test to evaluate the dynamic range of the sensor. This sensor with pre-filled water was directly exposed to the air and the dynamic water potential is shown in Fig. 3.

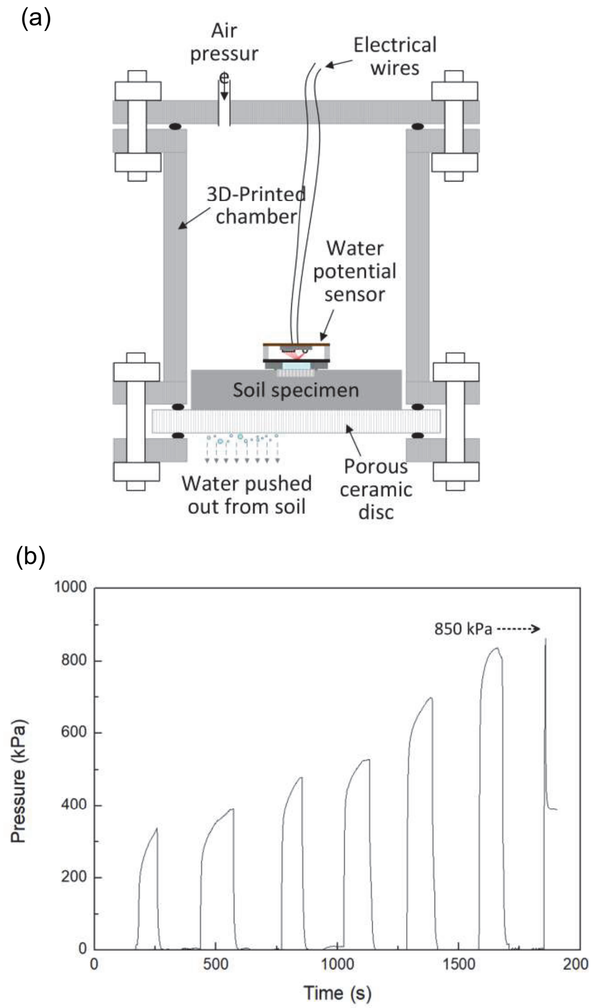

Figure 4: (a) Schematic of a cyclic evaporation measurement chamber. (b) Cyclic evaporation test for the soil water potential sensor.

The responses of the soil sensor to rapidly changing water pressures were evaluated using a cyclic evaporation test [15]. This test was performed using a home-made test chamber (Fig. 4a), where the other ceramic disc was placed at the bottom opening. The sensor was surrounded by a soil specimen on top of the ceramic disc. Therefore, the soil water potential could be determined by applying a positive air pressure into the test chamber to force soil water to come out through the ceramic. At an equilibrium, the soil water potential equals the applied external air pressure. The air pressure was applied for multiple cycles to the test chamber. After an evaporation cycle, free water was added to the soil specimen to reset the sensor. By using this method, the sensor cavitation was found at ~850 kPa as shown in Fig. 4b. The cavitation pressure obtained using the cyclic evaporation test was close to that obtained using the free evaporation test.

The soil sensor was embedded ~10 cm deep into the soil (see inset of Fig. 5) with a corn plant for testing the ability of the sensor in-situ monitoring of soil water potential. The sensor was initially wrapped by a thin layer of muddy soil to enhance the contact between the ceramic disk and the soil in the pot. Also, a commercial bulky tensiometer (non-continuous measurement with a low dynamic range below -100 kPa) was installed next to the miniature sensor for comparisons. Our sensor was connected to a home-made datalogger with the Bluetooth module for wirelessly transmitting data to a cellphone. The water potential data was obtained remotely and continuously. After the corn plant was irrigated, a dramatic potential drop was captured by the sensor (Fig. 6). The output of our sensor was seen comparable to that from the commercial one (see the dotted data in Fig. 6). It should be noted that the commercial tensiometer provided only discrete data in a low dynamic range of water potential below 100 kPa. In contrast, our miniature sensor could perform continuous measurements for soil water potential.

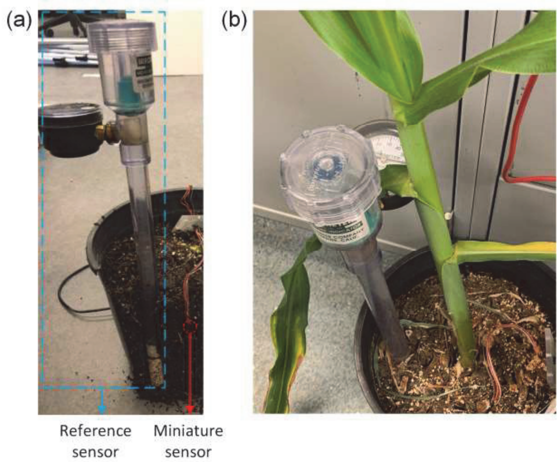

Figure 5: Soil water potential measurement setup using the developed minature sensor. A commerical sensor was also installed for comparison.

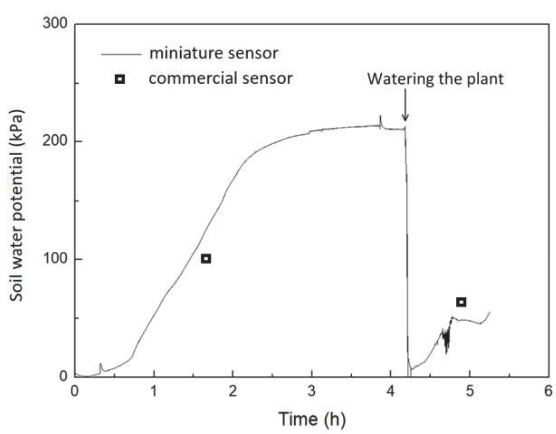

Figure 6: Soil water potential measurement in a pot with a corn plant (shown in Fig. 5).

Figure 7 demonstrates long-term (about two weeks) continuous measurement of soil water potential using the sensor. Similarly, the sensor was initially saturated with a sufficient amount of water (i.e., 0 kPa water potential). With this, the sensor was installed in the pot with a corn plant. After about 2 hours, a pressure equilibrium between the inner reservoir and soils was established, and the sensor started recording soil water potential data. The first watering of the plant occurred at 20 hours. After 50 mL tap water was poured the soil surface, the water potential was found to immediately drop by about 20 kPa. The second irrigation (with 100 mL tap water) took place at 1.6 days, leading to a pressure drop to about 80 kPa. Due to the water evaporated from the soil, the water potential slowly rose to 180 kPa at 4.5 days. At the same time, the third irrigation (using 200 mL tap water) was conducted to lower the water potential to about 55 kPa. Following that, the soil water potential gradually increased due to water evaporation. Repeating the irrigation (with 200 mL tape water) at 9 days caused to reduce the water potential the similar level at 55 kPa as that observed for the third irrigation. Interestingly, at 12.4 days, slight sprinkling with 25 mL tap water over the pot surface led to a gradual reduction of water potential. This may be due to a possible competition between the slight watering and rapid evaporation. Therefore, the embedded soil sensor could detect potential changes due to slight watering (e.g., quick drizzling).

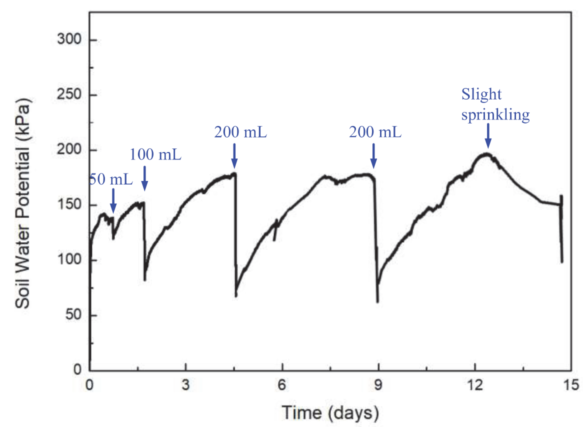

Fig. 7. Long-term continous monitoring of changes in soil water potential for two weeks using the fabricated soil sensor.

CONCLUSIONS

A miniature sensor is reported, capable of continuous monitoring of soil water potential over almost two weeks. The miniaturization of sensor makes it suitable for direct measurement near the roots of plant (e.g., rhizosphere). The application of the hydrophilic and smooth-surface SiO_2/Si diaphragm allows the sensor to operate in a large dynamic range with an extended duration for long-term, in-situ measurement. This sensor will not only provide soil wetness for precision agriculture, but also have a great potential for phenotyping the soil water profiles near the roots of plant.

There is much room to improve this soil water potential sensor. For example, further miniaturization and manufacturing upscaling may be achieved via wafer-scale bonding and packaging. In addition, different microfluidic filling and optical detection techniques [16-20] could be integrated with this sensor to simplify the water filling process and improving detection sensitivity, respectively, for the sensor. Because irrigation management is becoming an increasing concern in agriculture as highlighted by drought, flooding and depleting aquifers in different regions, the present sensor technology will help with irrigation management and scheduling, which is critical to precision and smart farming globally in the future.

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