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Fabrication of Impedance Sensor with Hydrophilic Property to Monitor Soil Water Content for Slope Failure Prognostics

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To minimize the damage caused by slope failure, knowledge of the increase in water content in mountain soil is important. Our group has been studying miniaturized impedance sensors for multipoint measurements in soil. Conventional sensors with a SiN_x top film sometimes cannot detect changes in the water content in soil resulting from rain. Experiments on the slide distances of water droplets were performed using SiO_x and SiN_x films. As the slide distance of the SiO_x film was shorter than that of the SiN_x film, it was confirmed that the SiO_x film is more hydrophilic than the SiN_x film. To improve contact characteristics between the sensor surface and free water in soil, we covered our conventional sensor chip with a hydrophilic SiO_x film. As a contact property test, the sensor chip measured the impedances of model soils. The proposed sensor achieved stable contact with the free water in the soil. Moreover, the chip operated for a long period of time on a mountain slope. The sensor could measure nearly theoretical outputs in response to rainfall. Thus, we succeeded in fabricating a stable soil monitor sensor with a hydrophilic SiO_x film.

1. Introduction

Natural disasters due to rainfall-induced slope failure and soil fall happen all over the world. Peoples' lives and their houses suffer serious damage in the disasters.[1] Wired sensors, tilt sensors,[2] and GPS sensors, which can detect the start of soil sliding, are useful for facilitating

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the announcement of an evacuation signal just before the slope fails. When the degree of hazard can be detected well before a slope failure, evacuees have enough time to evacuate. Therefore, a prognostic of slope failure is needed. On the other hand, some groups have been studying the monitoring of water content in soil.(3–5) When the water content in soil is increased, the soil frictional force is decreased and the soil weight is increased. Measurement of the water content can thus be used to evaluate the danger level of slope failure.

Water content sensors have several types of devices: a tensiometer(6–8) to measure the suction force, and electrical impedance sensors, which are mainly of the capacitance measurement type,(9–11) time domain reflectometry (TDR) type,(12–16) or electrical conductivity type.(17,18) Sensors for electrical impedance measurements of soil are generally superior in terms of longevity and they lack the need for periodic maintenance. Our group has been studying miniaturized impedance sensors fabricated by Si LSI technology(18,19) for the measurement of soil water content. Additionally, we have been conducting research on slope failure prognostics using water content sensors. An electrical-conductivity-type sensor with low-power and low-frequency operation succeeded in monitoring the changes in water content in soil on a mountain slope, corresponding to the amount of rainfall.(20) Before installing the sensor on the mountain, its measurement sensitivity was confirmed using model soil with several different water contents in our laboratory. In this experiment, it was also confirmed that each water content was detected correctly. Therefore, the sensor was installed on the slope of the mountain. However, sometimes the sensor failed to respond to rainfall, as shown in Fig. 1. In order to achieve stable measurements, it was imperative to determine the cause of the problem and devise solutions. In this study, we confirmed that the use of SiN_x and SiO_x films, which have the property of water retention, can serve as a solution. After experiments, a new sensor chip with a SiO_x film to solve the problem of measurement failure was fabricated. The new sensor chip and conventional sensor chip measured model soils with different water contents to verify their effectiveness. Finally, on-site and continuous measurements using the chips embedded in a mountain slope were performed.

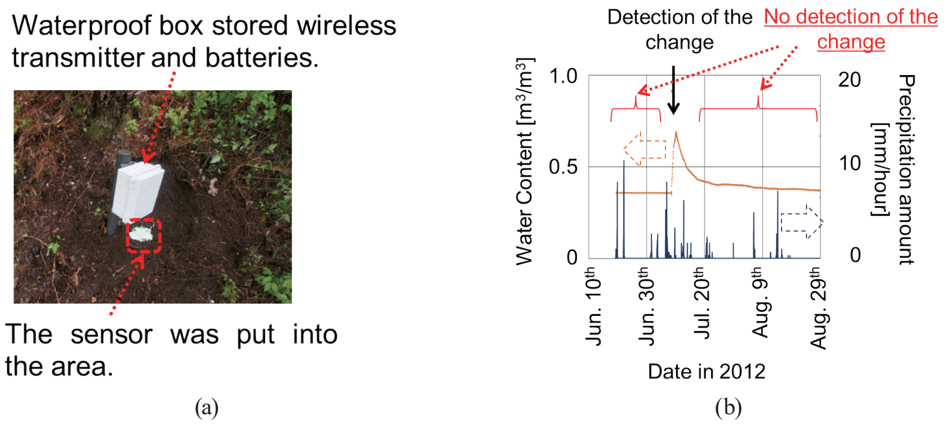


Fig. 1. (Color online) Photograph of previous sensor and measurement results of the sensor. The sensor monitored the soil on the slope of a mountain but sometimes failed to measure changes in water content. (a) Photograph of the sensor system. (b) Measurement results of the sensor.

2. Examining Cause of Measurement Problem and Proposed Solutions

Figure 1 shows a photograph of the previous sensor system[20] and measurement results of the sensor. The conventional sensor sometimes could not detect changes in the water content in the soil when it rained. We speculated on the causes of this and proposed solutions.

2.1 Conventional sensor chip and failure mechanism

To understand the cause of nondetection, the measurement setup and a cross-sectional view of the measurement space are shown in Fig. 2. The measurement current flowed in the space above the sensor surface between the Pt electrodes. The height of the measurement range is approximately 5 mm from the surface because the distance between the Pt electrodes is 2.27 mm. The surface material of the space between the Pt electrodes is a SiN_x film. As the soil particles are hydrophilic, it is estimated that free water does not reach the sensor surface when the sensor surface is more hydrophobic than the soil, as shown in Fig. 3(a). In this situation, there are air pockets on the sensor surface. Therefore, conventional sensors sometimes cannot

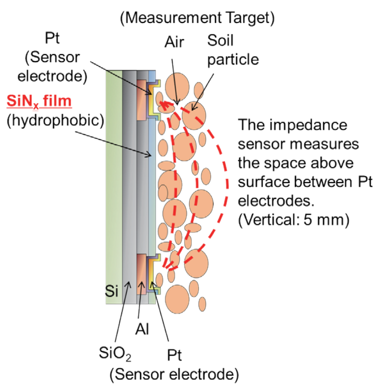
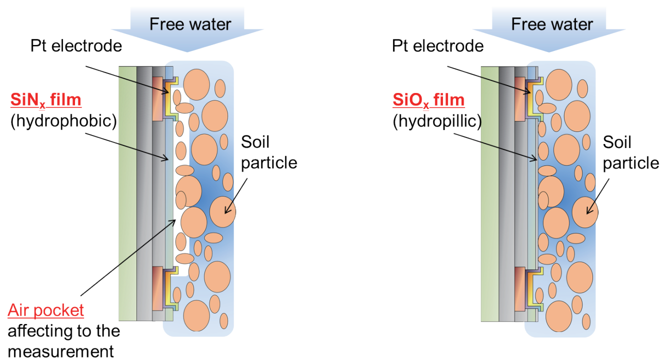


Fig. 2. (Color online) Image of impedance measurement in soil. Our previous sensor chip measured the space between the Pt electrodes of the sensor chip. One Pt electrode applied voltage and the other Pt electrode measured current.



(a) (b)

Fig. 3. (Color online) Images of the flowing water on sensor surfaces. (a) Hydrophobic surface on previous sensor chip. (b) Hydrophilic surface on proposed sensor chip.

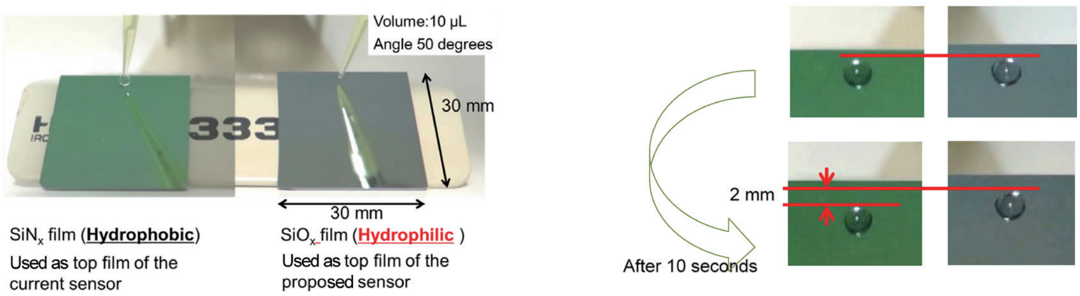
detect changes in water content. To solve this problem, we proposed a new sensor chip in which a SiO_x film is added on the SiN_x film as shown in Fig. 3(b). When the SiO_x film is almost as hydrophilic as the soil, the sensor can measure changes in water content.

2.2 Comparing the hydrophilicity of SiN_x and SiO_x films

The test chips with SiN_x and SiO_x films were fabricated on SiO_2/Si substrates. The films were made by the plasma CVD method. To confirm the hydrophilic properties, we added 10 μL of the water dropwise on the test chips, which were tilted at an angle of 50º from the horizontal, as shown in Fig. 4(a). Then, the slide distances of the chips were compared. We confirmed that we could visually capture the ability of free water to be retained on the surface of the chip. Figure 4(b) shows the water drops 10 s after adding the water. The slide distance of the SiO_x film was shorter than that of the SiN_x film. These results suggest that the SiO_x film is more hydrophilic than the SiN_x film. Therefore, we propose a new sensor chip with a SiO_x film added on top of the SiN_x film of the previous sensor chip.

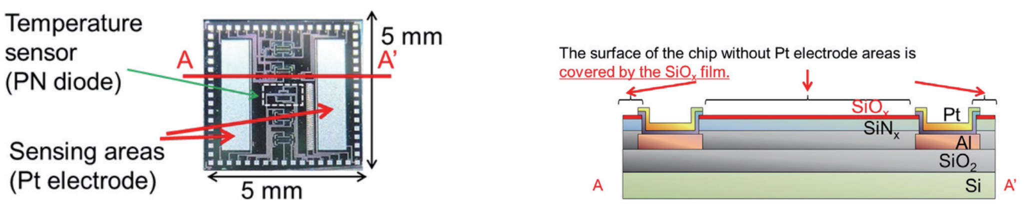
3. Fabrication of New Sensor Chip

The new sensor chip was fabricated by Si LSI technology and is shown in Fig. 5. Figure 5(a) shows a photograph of the new sensor chip. The size of the chip is 5 × 5 mm^2. Pt electrodes



(a) (b)

Fig. 4. (Color online) Experiments on adding water drops for comparison between hydrophobic and hydrophilic materials. (a) Photographs of the experimental setup. (b) Water flow distances of hydrophobic and hydrophilic wafers.



(a) (b)

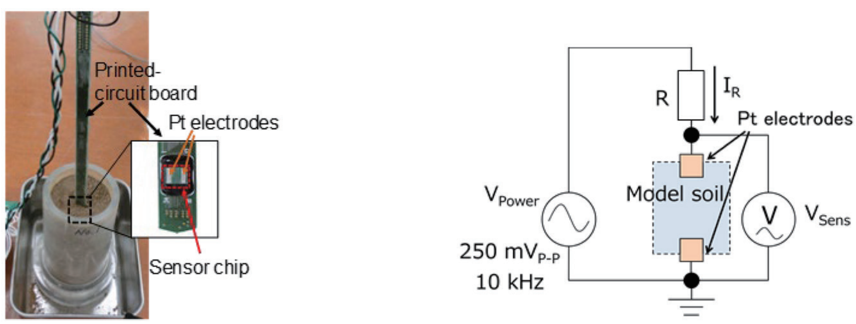
Fig. 5. (Color online) Proposed sensor chip fabricated by LSI process. (a) Photograph of the sensor chip. (b) Cross-sectional view along line A–A' in (a).

for impedance measurement and a PN junction diode for a temperature sensor were integrated into the chip. Figure 5(b) shows a cross-sectional view of the chip. The thickness of the top film of SiO_x placed on the SiN_x film is 200 nm. When there was no SiN_x under the SiO_x, the Al electrode corroded and electric leakage occurred, so the SiN_x film was not removed from the new chip. The thickness of the Pt electrodes, to which voltage and current were applied for the impedance measurement, was 100 nm.

4. Experiments

4.1 Model soil experiment

When an air pocket exists on the sensor surface, the measured impedance becomes larger than the measurement results under a stable contact condition without the air pocket. In our experiment, the SiN_x sensor of a conventional sensor and the SiO_x sensor of the proposed sensor were used to measure the model granite soil, as shown in Fig. 6. A photograph of the model soil experiment is shown in Fig. 6(a). To make the water content of the soil uniform, the soil was mixed and packed in the container to the same density. The water mixed with the model soils was made by mixing NaCl with pure water. The ion concentrations of the water were 0.16, 10, and 100 mS/m. By using the water with the three concentrations, model soils with three different water contents, 0.15, 0.3, and 0.45 m^3/m^3, were prepared. The impedances of the model soils were measured using the previous and proposed sensors with the measurement circuit shown in Fig. 6(b). The impedance Z of the soil was calculated by dividing the voltage V_{Sens} by the current I_R as shown in Fig. 6(b). The measurement results of the SiN_x and SiO_x sensors were compared. Figure 7 shows the ratio of the impedance measurement results using model soils with water contents of 0.15, 0.3, and 0.45 m^3/m^3 and ion concentrations of 0.16, 10, and 100 mS/m in the water. The graph shows the ratio of impedances measured by the SiN_x sensor and the SiO_x sensor. When the ratio was one, the measured impedances of the two sensors were equal. When an air pocket existed above the SiN_x sensor surface, the ratio was larger than one. These results show that the ratio increased with the water content. This finding suggests that the SiO_x chip is more capable of stable measurements owing to its better contact with free water.



(a) (b)

Fig. 6. (Color online) Experimental setup to measure impedance in model soil. (a) Photograph of impedance measurement in model soil. (b) Measurement circuit to measure model soil using the sensors.

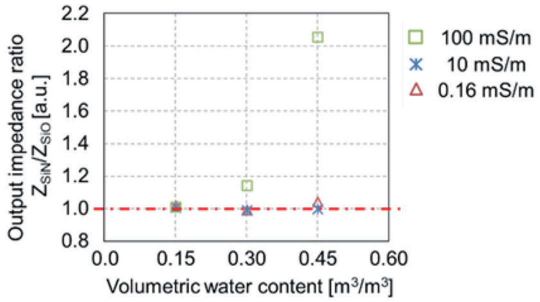


Fig. 7. (Color online) Results of stability test in which impedances were measured with the SiO_x sensor and the SiN_x sensor.

4.2 On-site and long-term measurement on slope of mountain

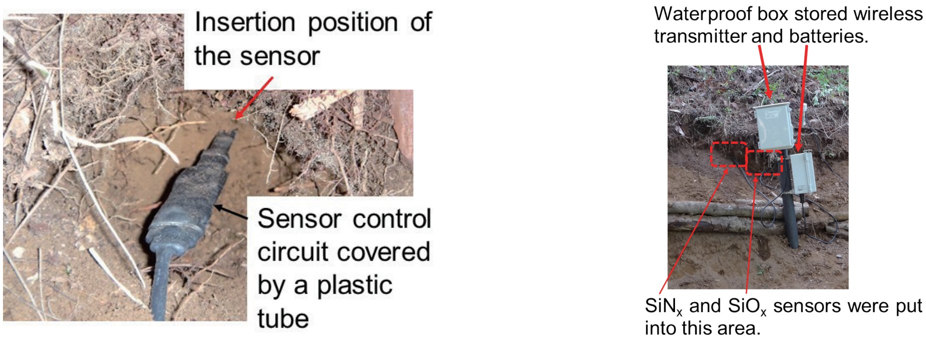
For on-site and continuous monitoring on a mountain slope, a wireless sensor system was fabricated, as shown in Fig. 8. As shown in Fig. 8(a), a hole was dug in the slope of the mountain, into which a sensor was inserted. The SiO_x and SiN_x sensors were inserted into separate holes. The sensor control circuit applied a voltage and measured the current of the Pt electrodes of the sensors. The circuits also converted the signal from analog to digital. The circuits were covered by a plastic tube for waterproofing and were buried in the soil. Figure 8(b) shows the area where the sensors were inserted and the waterproof box used to store the wireless transmitter and batteries. The wireless transmitter(21,22) used a radio frequency of 429 MHz because the influence of trees on a 429 MHz radio signal is smaller than that if a higher radio frequency is used.(23)

The SiO_x and SiN_x sensors performed measurements for around five months. Figure 9 shows the conductivity, the reciprocal of impedance, of the two sensors plotted over the five months. When the water content in the soil became large, the conductivity signal also became large. The changes in the SiN_x sensor signal were small when it rained, as shown in Fig. 9(a). In contrast, the changes in the SiO_x sensor signal were large, as shown in Fig. 9(b). The measurement results in Fig. 9(b) were converted into volumetric water content information using the calibration curve, as shown in Fig. 10. The graph was obtained by using model soils with uniform water content.(20)

The approximate curve is represented by Eq. (1). The coefficient of determination R^2 of the curve is 0.9441, indicating satisfactory measurement accuracy.

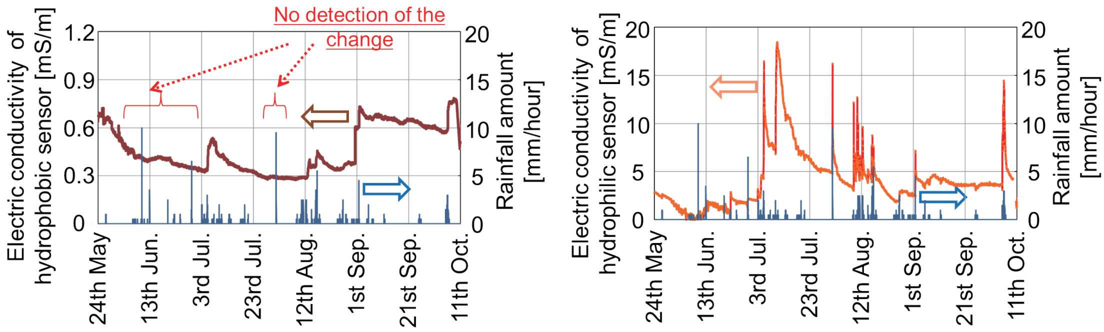
$$WC = 0.1989\left\{\log_{10}\left(EC\right)\right\}^3 + 1.8365\left\{\log_{10}\left(EC\right)\right\}^2 + 5.7115\log_{10}\left(EC\right) + 6.3054 \tag{1}$$

Here, WC is volumetric water content and EC is electric conductivity. The converted results are shown in Fig. 11. We confirmed that the water content values were consistent with the expected values. These results confirm that the SiO_x sensor can measure changes in the soil water content resulting from precipitation.



(a) (b)

Fig. 8. (Color online) Photographs of the sensor system for continuous monitoring of a mountain slope. (a) Sensor chip and sensor control circuit board buried in soil on slope of mountain. (b) Setup of sensor system with wireless transmitter and batteries.



(a) (b)

Fig. 9. (Color online) Measurement results of the sensors and rainfall amount. The upper arrows indicate the conductivity, whereas the lower arrows indicate the rainfall amount. (a) Conventional SiN_x sensor. (b) Proposed SiO_x sensor.

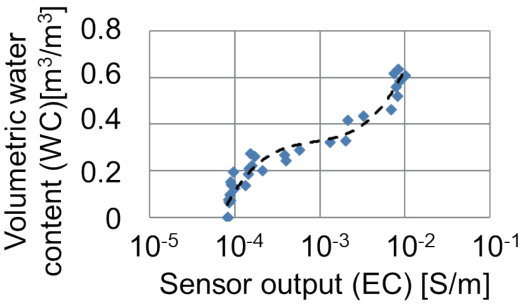


Fig. 10. (Color online) Calibration curve of *WC* and *EC* using model soil. The points are the measurement data of the model soil and the broken line is the approximate curve.

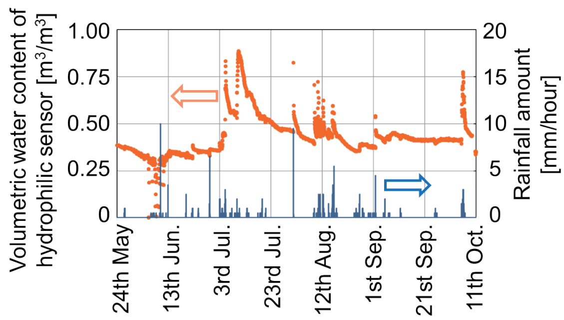


Fig. 11. (Color online) Results of Fig. 9. converted to *WC* values.

5. Conclusions

Our group has been studying miniaturized impedance sensors to minimize the damage caused by slope failure. Our conventional sensor with a SiN_x top film sometimes failed to detect changes in the water content in soil resulting from rain. It was speculated that the problem was due to the fact that the SiN_x film was more hydrophobic than the soil. Experiments on the slide distances of water droplets were performed using SiO_x and SiN_x films. Because the slide distance of the SiO_x film was shorter than that of the SiN_x film, we confirmed that the SiO_x film was more hydrophilic than the SiN_x film. To improve the contact characteristics between the sensor surface and free water in soil, a new sensor chip was fabricated with a SiO_x film in the space between the Pt electrodes of the conventional sensor chip using LSI technology. To confirm the contact condition between free water and the sensor surface, impedance measurements were performed in model soils using the conventional SiN_x and proposed SiO_x sensors. We confirmed that the impedance using the SiO_x sensor was smaller than that using the SiN_x sensor. The results showed that the contact condition of the SiO_x sensor was better than that of the SiN_x sensor. On-site and long-term measurements on a mountain slope were performed using these sensors for five months. The changes in the SiN_x sensor signal were small when it rained, whereas the changes in the SiO_x sensor signal were large. The water content values obtained using the SiO_x sensor conformed to the expected results. Thus, we succeeded in fabricating a stable soil monitor sensor by using a hydrophilic SiO_x film.

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