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Miniaturization of Electrical Conductivity Sensors for Multimodal Smart Microchip

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1. Introduction

Recently "ubiquitous network society" and/or "traceability" are key words to keep our safety and security. To realize these demands, it is necessary that various environmental information should be observed and measured on real time and continuously. Our group investigated a smart microchip that fuses LSI with several kinds of sensors to satisfy these demands. Up to now, the group has aimed at a real time observation of human's health condition, and it has developed the chip sticking to human's skin and measuring human's perspiration, pH, temperature [1].

It seems that "Safety of food" and "Stable supply of food" are important, and the EC (Electrical conductivity) sensor is a very important technique for real time grasp and diagnosis of it that is nutrient state of plant, environment of soil, pollution of water, health care of domestic animal, etc [2]. However, the size of a current EC sensor is large (the length is ten centimeters or more and the diameter is centimeters or more), and has been developed to know one mere information. If several kinds of environmental information including EC become possible in real time measuring, it comes to be able to use actually into the soil, faucet, and the farm, etc. The current EC sensor was not able to measure a small amount solution, and it is impossible to insert to a soil. If EC sensor that can be measured into the soil, manure of excessive fertilizer and watering of excessive moisture, etc. can be stopped, and it is thought that the environment-friendly agriculture becomes possible. In this paper, we fabricated a EC sensor, which is able to be measured in real time and is possible to insert in the artificial soil (rock wools), and we confirmed that the EC sensor was able to operate in an agricultural field.

2. Theory

The EC sensors are fabricated by using the semiconductor fabrication technology keeping with the compatibility with CMOS LSI technology. Up to now, to measure human's perspiration, the sensor chip has been fabricated. Fig1 shows the photograph of EC sensor chip for measuring with human perspiration. The feature of this device is to measure impedance by using Ag/AgCl electrodes in direct current in consideration of a high electric conductivity and a large amount of chlorine ion's existing in the sweat. However, the sensor needs measuring of wide range that is from 0.1mS/cm to 10mS/cm, because the electric conductivity changes greatly by the absorption of nourishment from the root and the evaporation of water, etc. Moreover, in a preliminary examination, the state on the surface of the electrode was found becoming unstable because the chlorine ion in the solution is a little and it dissolves from the Ag/AgCl electrode. Then, the electrode material was changed from Ag/AgCl to Pt, that is resisted to chemicals etc. and that is widly used for EC meter on the market. Fig2 shows the new EC sensor chip that is using the Pt electrodes. Fig. 3 shows a cross section structure of the chip. The chip size is 5mm square, its electrode material is Pt/Ti/Al and its protection film is parylene. The measurement calculates electric conductivity from the voltage and the current that flows between two terminals. The electric conductivity σ is requested by the following calculation.

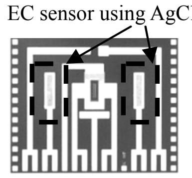

Fig. 1 EC sensor chip for measuring with human perspiration

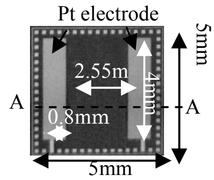

Fig. 2 EC sensor chip of Pt electrode

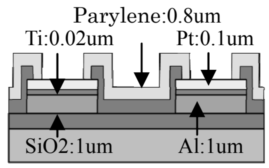

Fig. 3 a cross section structure of EC sensor chip of Fig. 2

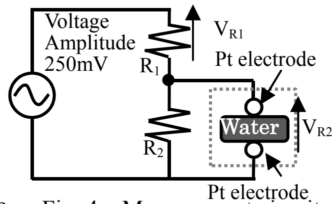

Fig. 4 Measurement circuit

$$\sigma = \frac{1}{\rho} = \frac{D}{R \times S} \times a \quad (1), \qquad R = \frac{VR2}{\left(\frac{VR1}{R1} - \frac{VR2}{R2}\right)} \quad (2)$$

R is resistance of EC interelectrode. S is an area of the electrode ($3.2mm^2$). D is an interelectrode distance. a is a correction value of the opposite electrode and the electrode of going side by side (1.31).R1 is 13.1kΩ. R2 is 574kΩ.

In direct current, the impedance is about 10kΩ because of no polarization in the Ag/AgCl electrode surface. However, the Pt electrode becomes the high resistance body of 100kΩ or more because of the polarization and EC of a correct solution cannot measure it [3]. However, when making it to the alternating measurement, impedance falls by going up of the frequency through the capacity element in the interface, and Pt becomes small resistance becomes below 100 ohm at 1 kHz than Ag/AgCl. Even if the frequency increase from it, the decrease in impedance is not, and is thought that 1 kHz is a verge of the interfacial impedance change. There are a lot of commercialized EC sensors, which are used a frequency of 1 kHz, and it is presumed in consideration of the influence of this electrode surface impedance. Then, on the alternating measurement, device of the Pt electrode fabricated on this time is found the character of the frequency dependency by what characteristic in the next paragraph. And, the possibility of the miniaturization of the sensor is described by clarifying the parasitic of the resistance and the capacity of the device.

3. Experiments and results

The frequency dependency of the solution with different electric conductivity was measured with the fabricated EC sensor. Fig. 5(a) shows result of it. In a low frequency domain, each solution is a low electric conductivity. Oppositely, the rise of the electric conductivity is seen in a high frequency of 100 kHz. 0.082 mS/cm and 0.47 mS/cm show the pure electric conductivity because of no frequency dependence and without parasitic capacitance from 1 kHz to 10 kHz. Especially, Fig. 5(b) is a graph of the correlation between the electric conductivity and the solution in 10 kHz. It can be found that the sensor is possible to EC measurement of a wide treble (from 10^{-1} to 10^{2} mS/cm) because it is suitable for a straight line approximation curve well in this graph. EC of tap water is about 10^{-2} mS/cm order, and EC of NaCl limit equivalent is about 10^{2} mS/cm order. And it can be said that the range of real use can be covered enough in agriculture field. Moreover, the equivalent circuit of the sensor was calculated based on the result of Fig. 4. Fig. 6(a) shows the equivalent circuit chart, and Fig. 6(b) shows the calculation overwrited in the graph of Fig. 5(a). Thus, measurements by 10 kHz can be said showing electric conductivity of solution as considered by the above-mentioned. Here, when the equivalent circuit of parasitic resistance and capacity is simplified in consideration of changing Line A, B and C in Fig. 6(b), it becomes the following expressions.

$$\mathrm{EC} = \frac{1}{\mathrm{Rs}} + \omega\mathrm{Cs} + \frac{1}{\frac{2}{\omega\mathrm{Cc}}+\mathrm{Rw}} \quad (3), \quad \mathrm{LineA}: \omega\mathrm{C_C} = \omega\varepsilon_{Polar}\frac{S_{Electrode}}{d_{Polar}} \quad (4)$$

$$LineB: \omega C_S = \omega\varepsilon_{sub}\frac{S_{Electrode}}{d_{Electrode}} \quad (5), \quad \mathrm{LineC}: \frac{1}{\mathrm{R_S}} = \frac{\mathrm{S_{Electrode}}}{\mathrm{d_{Electrode}}\rho_{\mathrm{S}}} \quad (6)$$

The ε_{Polar} and d_{Polar} are the fixed values because it depends on the polarization of the Pt electrode on the surface. If $S_{Electrode}$ of the Pt electrode area becomes small, the Line A, B, and C become small.

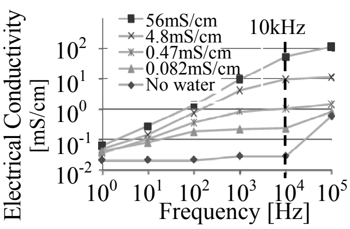

Fig. 5(a) The frequency dependency of the solution with different electric conductivity

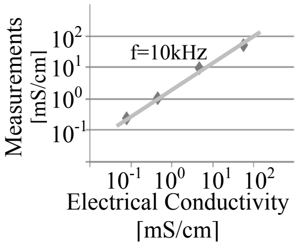

Fig. 5(b) EC sensor chip of Pt electrode

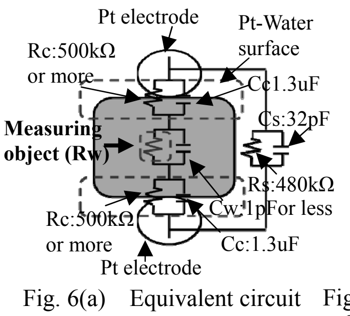

Fig. 6(a) Equivalent circuit of EC sensor

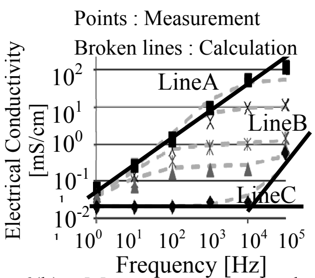

Fig. 6(b) Measurements and calculations of electrical conductivity

As a result, the suitable frequency for measurements, at which sensor outputs are promotional to real EC value, moves to a range higher than 10 kHz. If $D_{Electrode}$ of the Pt interelectrode distance becomes large, the Line B, and C become small. The point to have to pay attention here is that $d_{Electorode}$ doesn't influence Line A. The performance of EC can be improved without changing the chip size, in reducing the width of $S_{Electorode}$ and enlarging interelectrode distance $d_{Electorode}$. Oppositely, $S_{Electrode}$ and $d_{Electorode}$ are reduced when it is good only in the measurement of 1mS/cm or less by limiting the usage, and a further miniaturization is possible.

4. Application

To confirm an ability of our micro sized EC sensor, it was used in agricultural field. The electric conductivity correlation examination of the solution in the state inserted in the rock wool was carried out. It was soaked in the solution. Fig. 7(a) shows the appearance under the measurement, and Fig. 7(b) shows the measurement result. It can be found that it was able to be proven to measure it correctly even when inserting it in the solid such as rock wools because Fig. 7(b) got on the correlation of the straight line. In addition, EC sensor was inserted in the seedling of the tomato, and the change in electrical conductance was observed in real time. Fig. 8(a) shows the appearance under the measurement, and Fig. 8(b) shows the measurement result. The measurement was carried out with the sensor inserted in the seedling of the tomato soaked in the solution of 1.47mS/cm in Fig 8(b). A small amount of water of 0.007mS/cm was able to be dropped even if 80 minutes were passed, and to observe the appearance to which electric conductivity in the vicinity of the root of the tomato decreases. As a result, it was able to be proven to measure it in real time.

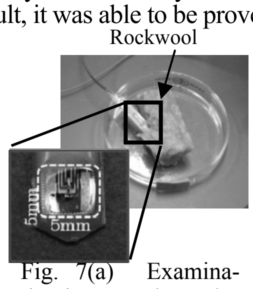

Fig. 7(a) Examination insert rock wool

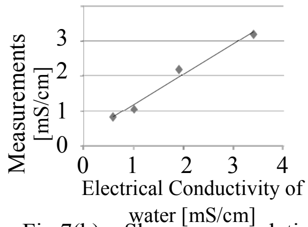

Fig.7(b) Show a correlation between electrical conductivity of water and measurements

Fig. 8(a) Examination in seedling of tomato

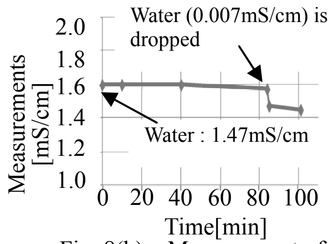

Fig. 8(b) Measurement of real time in seedling tomato

5. Conclusions

EC sensor that uses the Pt electrode on the Si substrate was fabricated by CMOS compatible process. The frequency dependency of electric conductivity is evaluated, and it can be confirmed that the sensor is possible to EC measurement with a wide dynamic range (from 10^{-1} to 10^{2} mS/cm). A fabrication of high performance and tiny smart micro chip further was considered. The sensor chip is inserted in the rock wool and the seedling of tomato, and the measurement of electric conductivity is executed. It was able to be confirmed the measurement even in the state inserted in the rock wools, and to be able to measure electric conductivity in real time.

Acknowledgements

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References

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