A-3-04 Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp35-36

# Electric Signal Transmission in Seawater using Diamond Solution Gate FET as Receiver

Kaito Tadenuma[1], Yutaro Iyama[1], Yu Hao Chang[1], Yukihiro Shintani[1] and Hiroshi Kawarada[1,2]

[1] School of Fundamental Science and Engineering, Waseda University. 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
Phone: +81-3-5286-3391 E-mail: tadenuma-509@fuji.waseda.jp
[2] The Kagami Memorial Laboratory for Materials Science and Technology, Waseda University
2-8-26 Nishiwaseda, Shinjuku-ku, Tokyo 169-0051, Japan

## Abstract

**We researched the characteristics of the electric signal transmission in seawater utilizing a solution gate FET (SGFET). The transmission method consists of two components: Ag/AgCl as a transmitter and SGFET as a receiver. AC electric signals are transmitted from Ag/AgCl to SGFET via seawater. We mainly investigated switching characteristics and propagation distance in the seawater environment. In addition, we examined whether common potential line between Ag/AgCl and SGFET affects the results or not. In conclusion, frequency response of SGFET at least 10 MHz was confirmed; propagation distances were 50 m with the common potential line and 2 m at least without the common potential line. These results suggest that SGFET can be applied to electric seawater wireless communication.**

## 1. Introduction

Seawater wireless communication has been required for scuba divers' communication, seawater drone control, development of seabed resources, etc. However, the conventional methods such as acoustic wave, visible light wave and electromagnetic wave still have unsolved problems. Thus, electric communication is one of the methods to overcome these challenges because of high electrical conductivity of seawater [1].

We have studied diamond electrolyte solution gate FETs (diamond SGFETs) that electrically operate in solutions [2]. Diamond SGFETs are directly immersed in solutions and the drain current ($I_{DS}$) is remotely controlled by electric signals ($V_{GS}$) from Ag/AgCl. Since they are usually used for ion or bio-sensing [3,4], diamond SGFETs are promising candidates for operating in seawater such as wireless communication.

In our previous work, we focused on AC electric signal transmission from Ag/AgCl to SGFET. The results were conducted at 1 MHz to 50 m in Tokyo Bay [5]. An electric seawater communication method was then proposed. However, the previous work was not considered wireless because there was a common potential line connected Ag/AgCl to SGFET to keep reference potential (Fig.2 (a)). In this work, we removed the common potential line, investigated switching characteristics of SGFET, and proposed an electric seawater wireless communication method.

## 2. Experimental methods

Fig.1 shows the cross-sectional view of diamond SGFET in a solution. The channel area of diamond SGFET was directly immersed in a solution to achieve capacitance of electric double layer. Utilizing SGFET, two types of circuits were set up: common source circuit, which has a common potential line as shown in Fig.2 (a) and floating circuit, which does not have the common potential line as shown in Fig.2 (b). The electric transmission from the transmitter to the receiver in solutions can be modelled with a simple equivalent circuit in Fig.3, where $C_{EDL}$ is the capacitance of electric double layer, and $R_{Sol}$ is the solution resistance.

The transmission and frequency responses were measured in NaCl 35 g/L solutions. Distance between Ag/AgCl and SGFET was gradually increased from 0.01 m to 2 m using a cylindrical tube (diameter = 2 cm). In each distance, Ag/AgCl was applied with an input AC voltage $v_{GS}(= V_{Bias} + v_{gs})$ in common source circuit and $v_G(= v_g)$ in floating circuit. Both were applied from 100 kHz to 10 MHz. Then, the switching characteristics, $v_{DS}$ of SGFET, were measured.

## 3. Results and Discussion

Fig.4 shows the switching characteristics of diamond SGFET at 1 MHz in each circuit (distance = 1 m). In both circuits, Diamond SGFET responds to $v_{GS}$ or $v_G$. As a result, AC electric signals are transmitted from Ag/AgCl to diamond SGFET. Especially, $v_{DS}$ in common source circuit is observed with reverse amplitudes to $v_{GS}$ and differential pulses responding the $v_{GS}$ potential change. On the other hand, in floating circuit, only differential pulses are observed. We assume that the missing of reverse amplitudes is due to the absence of common potential line. By comparison, differential pulses mainly occur due to series CR (high-pass filter) circuit with the electric double layer capacitance $C_{EDL}$ and the load resistance $R_D$. These results suggest that, under the absence of common potential line, low frequency component $V_{Bias}$ does not transmit to SGFET from Ag/AgCl; SGFET can respond only to high frequency part of electric potential $v_g$.

Fig.5 shows the dependence on distance between Ag/AgCl and diamond SGFET in each circuit at 1 MHz. In common source circuit, the voltage peak $V$peak of amplitude and differential pulses shows slight decrease as the distance increases from 0.1 m to 2 m. In floating circuit, $V$peak of differential pulses decreases as the distance increases. This is because the series solution resistance $R_{Sol}$ increases as the electric signals transmit in longer path. $R_{Sol}$ is defined as

$$R_{Sol} = \rho \frac{l}{A} \tag{1}$$

where $\rho$ is resistivity of solutions, $l$ is distance and $A$ is cross sectional area. $\rho$ in NaCl 35 g/L solutions is 0.2 $\Omega \cdot$ m. $A$ is $\pi \times 10^{-4}$ m$^2$ using the electrically insulating tube with 2 cm diameter. Then, the value of $R_{Sol}$ is calculated as $(0.2/\pi)l \times 10^4$ Ω. However, $R_{Sol}$ might become much smaller in a large cross-sectional area such as seawater.

As a result, AC electric signals can transmit 2 m from Ag/AgCl to SGFET through the tube with 2 cm diameter in floating circuit. Differential pulses observed in the switching characteristics have possibility to be applied for digital communication.

## 4. Conclusion

We investigated the characteristics of an electric signal transmission utilizing SGFET. It is confirmed that high frequency electric signals can transmit from Ag/AgCl to SGFET at least 10 MHz at an insulating tube. Propagation distances are 50 m in common source circuit and 2 m in floating circuit. In the switching characteristics, differential pulses are observed and have possibility to be applied to digital electric wireless communication in seawater.

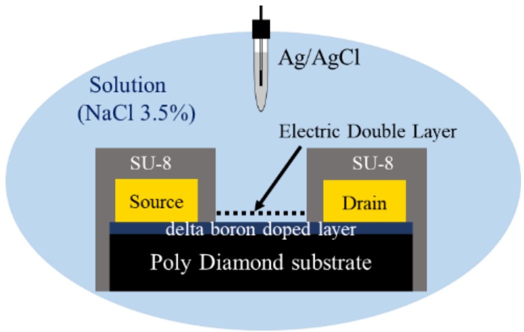


Fig.1 The cross-sectional view of Diamond SGFET

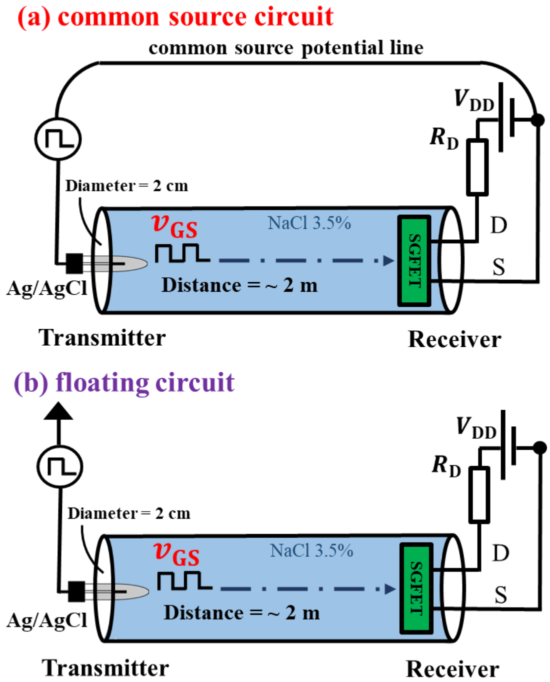


Fig.2 Illustration of electric signal transmission methods ((a) Common source circuit, (b) Floating circuit)

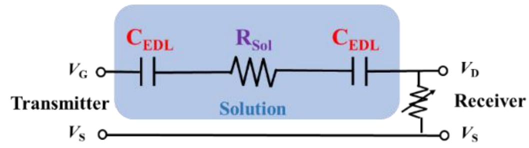


Fig.3 The equivalent circuit of electric transmission
$C_{EDL}$: capacitance of electric double layer
$R_{Sol}$: solution resistance

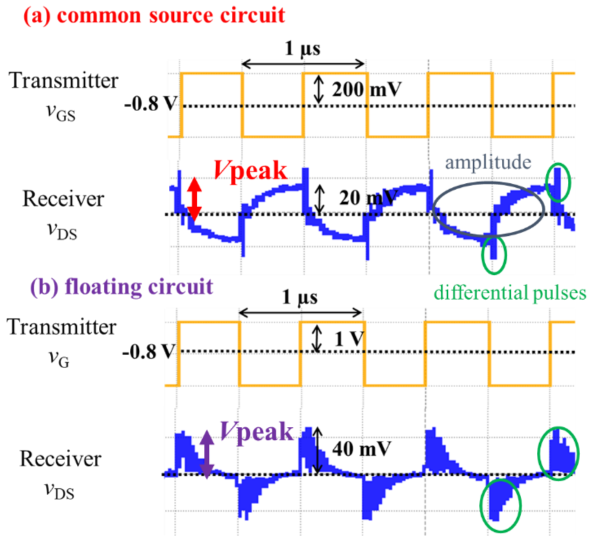


Fig.4 Switching characteristics of Diamond SGFET at 1 MHz
(a) $v_{GS}$ = -0.8 ± **0.2** V ($v_{GS} = V_{Bias} + v_{gs}$)
(b) $v_G$ = ± **1.0** V ($v_G$ = + $v_g$)
$V_{DD}$= -1.0 V, $R_D$= 1 kΩ

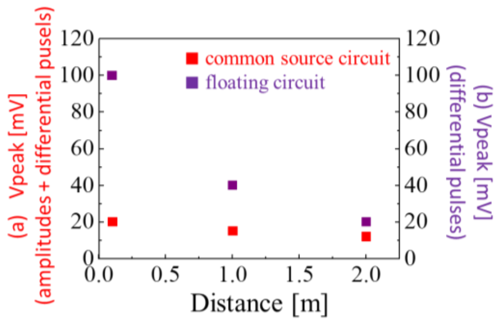


Fig.5 The distance dependence of $V$peak at 1 MHz (Diamond SGFET)
(a) $v_{GS}$ = -0.8 ± **0.2** V ($v_{GS} = V_{Bias} + v_{gs}$)
(b) $v_G$ = ± **1.0** V ($v_G$ = + $v_g$)


## Acknowledgements

This study was partially supported by Creation of Life Innovation Materials for Interdisciplinary and International Researcher Development.


## References


[1] C.W. Kim, E. Lee and N.A.A. Syed: (2010) 1.
[2] H. Kawarada, Y. Araki, T. Sakai, T. Ogawa and H. Umezawa: Phys. Stat. Sol. (a) 185 (2001) 79.
[3] Y. Sasaki and H. Kawarada: J. Phys. D 43 (2010) 374020.
[4] H. Kawarada and A. Ruslinda: physica status solidi (a) 208 (2011) 2005.
[5] Y. Iyama, H. Kawarada *et al.*, MRS Fall 2018.