Electrical Transport between Superconducting Niobium and a Zinc-Oxide-based Electric Double-layer Transistor

T Narita¹, H Takayanagi² and R Ishiguro¹,*

¹Japan Women's University, Department of Mathematical and Physical Sciences, Tokyo, Japan
²Tokyo University of Science, Research institute of science and technology, Tokyo, Japan
*E-mail: ishiguror@fc.jwu.ac.jp

Abstract. We report electrical transport measurements between a metallic state induced on the surface of an insulating zinc oxide film by an electric double-layer transistor and superconducting niobium electrode. A superconductor/electric double-layer transistor channel/superconductor was created that can be a superconductor/metallic state/superconductor junction and is expected to function as a Josephson junction. The metallic state on the zinc oxide surface and a low contact resistance between niobium and zinc oxide were realized by high carrier doping arising from the electric field effect of the electric double-layer transistor. However, there was no supercurrent through the metallic state at the junction down to a temperature of 0.3 K. Nevertheless, temperature variations of the differential resistance of the junction below the superconducting transition temperature suggest the existence of a superconducting proximity effect between the superconducting Nb and the channel of the zinc oxide-based electric double-layer transistor.

1. Introduction
Recently, electric double-layer transistors (EDLTs) have attracted considerable attention as novel devices to control solid-state properties [1–10]. An EDLT is a type of electric field-effect transistor (FET) that uses ionic liquids, which are salts in liquid state without any additional solvents, as a gate insulating layer of conventional FETs. The upper limit of the sheet carrier density in conventional FETs is restricted by the dielectric breakdown field. By contrast, the upper limit of the sheet carrier density in EDLTs can be more than a factor of ten larger than that in FETs and can have values as large as $10^{14}$–$10^{15}$ cm$^{-2}$ [2,9]. Previous studies have reported that as a high-density carrier accumulation is induced at the surface by EDLTs, the insulating channel of EDLTs becomes a metal and moreover a superconductor [1,5].

Although the junction between the EDLT channel and the metal superconductor is a new interface where novel functions can arise, no studies have analyzed such junctions. Moreover, investigating the bonding between the new substance and the metal electrode should be very important for industrial applications.

In this study, the fabrication of a junction between zinc oxide (ZnO) and Niobium (Nb) is presented. Zinc oxide is a wide-gap semiconductor with a band gap of $E_g = 3.4$ eV at 300 K that has already demonstrated metallization at the surface due to high-density carrier accumulation induced by an
EDLT [2]. Niobium is a type II superconductor with a superconducting transition temperature $T_c = 9.2$ K. We present a study of the electrical transport properties of the junction in the temperature range of 0.3–300 K.

2. Fabrication

A schematic of our device is shown in figure 1. An epitaxially grown 500-nm-thick ZnO film was used on a single-crystal sapphire substrate, which is commercially available from MIT Co.

The fabrication of the ZnO-based EDLT involved the following three processes. In the first process, micropatterns of ZnO were made. Firstly, a 50-nm-thick SiO$_2$ film was deposited on the ZnO film to protect ZnO from over-etching. Micropatterns of ZnO were formed by etching both the ZnO and SiO$_2$ films in the outer region by using maskless laser lithography and a reactive ion etching (RIE) technique. The SiO$_2$ film on the micropattern was subsequently removed by using RIE.

In the second process, superconducting electrodes on the ZnO micropattern separated by a 100-nm-wide gap were made by using an electron beam lithography lift-off technique with niobium (Nb) sputter deposition, as shown in figure 2. These electrodes are expected to work as a superconductor-normal-superconductor (SNS) Josephson junction. Immediately before deposition of Nb, the contact surface was treated by argon sputter cleaning. The 100-nm-thick Nb electrodes were sputtered at a backing pressure of $\sim 10^{-6}$ Pa. Subsequently, an Au covering layer with a thickness of 5 nm was deposited on the Nb electrodes by electron beam physical evaporation.

Then, large structures such as bonding pads, electrodes and the gate electrode were formed by using maskless laser lithography and electron beam physical evaporation. The deposition of 10-nm-thick Ti and 150-nm-thick Au films was performed under a pressure of a few $10^{-5}$ Pa. Finally, immediately before performing measurements, ionic liquids were dropped as gate dielectrics on the device to cover the Nb/ZnO/Nb structure and a part of the gate electrode. In this work, N,N-Diethyl-N-methyl-N-(2-methoxyethyl)ammonium tetrafluoroborate (DEME-BF$_4$) was used as an ionic liquid.

Two samples, A and B, with the mostly same structure were fabricated to perform different experiments.

3. Results and discussion
All transport measurements were performed in a helium-3 evaporative refrigerator with a base temperature of ~300 mK, which was well below the superconducting transition temperature $T_c \sim 9$ K of our samples. Several filtering systems were used, consisting of LC filters at room temperature and RC filters at the base temperature.

Figure 3. Transfer curve for the ZnO-based EDLT measured at room temperature and a source-drain voltage $V_{SD} = 10$ mV.

Figure 4. Temperature dependence of the resistance at a gate voltage $V_G = 3$ V.

Figure 3 shows a transfer curve for the ZnO-based EDLT of sample A measured at room temperature and for a source-drain voltage $V_{SD}$ of 10 mV. The drain current $I_D$ is equal to 0.08 μA at $V_G = 0$ V and increases monotonically for increasing $V_G$ up to a value of 9.7 μA at $V_G = 3.5$ V. The on/off ratio of the device is about 120, indicating that DEME-BF$_4$ could penetrate into the 100-nm-wide gap between the Nb electrodes and the EDLT works properly in such a narrow gap.

The temperature dependence of the resistance at $V_G = 3$ V for the ZnO-based EDLT of sample B containing a Nb/ZnO-based EDLT/Nb structure is plotted in figure 4. The resistance decreases with decreasing temperature for temperatures between 100 K and 300 K, indicating that a metallic state in the ZnO film was realized. Moreover, it can be inferred from the data that quantum tunneling of electrons between Nb to ZnO is more dominant than thermionic transfer and that the potential barrier between ZnO and Nb at $V_G = 3$ V is small.

Figure 5 shows the differential resistance $dV/dI$ against the bias voltage of the Nb/ZnO-based EDLT channel/Nb structure of sample A at a temperature of 350 mK. The figure exhibits three sharp peaks and two valleys for absolute bias voltages $|V|$ smaller than ~1 mV, which is about the same as the voltage corresponding to the superconducting gap. However, since there were voltage drops at the ZnO-based EDLT channel with a resistance of about 440 Ω, the voltage actually applied to the junction was sufficiently lower than the voltage corresponding to the superconducting gap of Nb in this measurement.
Figure 5. Differential resistance $dV/dI$ against bias voltage $V$ for the Nb/metallized ZnO100nm/Nb structure at 350 mK.

Figure 6. Temperature variation of the differential resistance $dV/dI$ against bias voltage $V$ for the Nb/metallized ZnO100nm/Nb structure at temperatures ranging from 0.4 K to 2 K.

As the maximum value of differential resistance at the zero bias was 455 $\Omega$, it was impossible for the two superconducting electrodes to be coherently connected and for the superconducting current to flow.

Figure 6 shows the temperature variations of the differential resistance $dV/dI$ against the bias voltage $V$ for the Nb/metallized ZnO100nm/Nb structure at temperatures ranging from 0.4 K to 2 K. The differential resistances for voltages below the voltage corresponding to the superconducting gap vary significantly with temperature at these low temperatures. This means that there was a superconducting proximity effect in the SN junction between the Nb superconducting electrode and the carrier-doped metallic channel with high carrier concentration induced by the EDLT.

4. Conclusions
We fabricated a superconducting Nb/ZnO-based EDLT channel/superconducting junction and examined its transport characteristics. The ZnO-based EDLT channel with a length of 100 nm and a width of 5 $\mu$m was metalized under a gate voltage of 3 V.

Electrical transport measurements between the metallic state induced on the surface of the ZnO by the EDLT and the superconducting Nb electrodes showed that there is no supercurrent between the junctions down to a temperature of 0.3 K. However, measured data suggest that a superconducting proximity effect in the SN junction between the normal state in the EDLT and the superconducting electrode can be observed.

In order to realize coherent transport between the superconducting electrodes, improvement of the contact resistance is necessary, which could be accomplished by increasing the gate voltage or/and inserting a bonding layer such as a Ti layer between the Nb electrodes and the ZnO based EDLT channel.

Acknowledgments
We would like to thank S. Nomura from the Univ. of Tsukuba, S. Kashiwaya and K. Tsumura from AIST, Y. Nago from Keio Univ. and D. Sakuma from the Tokyo Univ. of Science for stimulating discussions. This work was supported by JSPS KAKENHI C (Grant No. 17K05551). Device fabrication was supported by the NIMS Nanofabrication platform of the “Nanotechnology Platform Project”, sponsored by MEXT.
References

[1] Ueno K, Nakamura S, Shimotani H, Ohtomo A, Kimura N, Nojima T, Aoki H, Iwasa Y, and Kawasaki M 2008 Nat. Mater. 7 855.
[2] Yuan H, Shimotani H, Tsukazaki A, Ohtomo A, Kawasaki M and Iwasa Y 2009 Adv. Funct. Mater. 19 1046.
[3] Ye J T, Inoue S, Kobayashi K, Kasahara Y, Yuan H T, Shimotani H and Iwasa Y 2010 Physica C 470 S682.
[4] Ye J T, Inoue S, Kobayashi K, Kasahara Y, Yuan H T, Shimotani H and Iwasa Y 2010 Nat. Mater. 9 125.
[5] Ueno K, Nakamura S, Shimotani H, Yuan H T, Kimura N, Nojima T, Aoki H, Iwasa Y and Kawasaki M 2011 Nat. Nanotech. 6 408.
[6] Yamada Y, Ueno K, Fukumura T, Yuan H T, Shimotani H, Iwasa Y, Gu L, Tsukimoto S, Ikuhara Y and Kawasaki M 2011 Science 332 1065.
[7] Ye J, Zhang Y, Akashi R, Bahramy M, Arita R and Iwasa Y 2012 Science 338 1193.
[8] Katase T, Hiramatsu H, Kamiya T and Hosono H 2014 Proc. Nat. Acad. Sci. USA 111 3979.
[9] Du H, Lin X, Xu Z and Chu D 2015 J. Mater. Sci. 50 5641.
[10] Saito Y, Nakamura Y, Bahramy M S, Kohama Y, Ye J, Kasahara Y, Nakagawa Y, Onga M, Tokunaga M, Nojima T, Yanase Y and Iwasa Y 2015 Nat. Phys. 12 144.