Electric-field-induced superconductivity in electric double layer transistors

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We report that interface superconductivity can be induced through electrostatic charge accumulation at the electric double layer (EDL) formed at interfaces between liquid and solid. This interface has been of central importance from the view point of battery applications and catalytic activities. However, their ability to accumulate high charge density at the interface can be used as a transistor with high capacity and high maximum carrier density, which might provide a significant impact on solid state physics.

When voltage is applied between two electrodes in an electrochemical cell, mobile ions in electrolyte move toward corresponding electrodes driven by the electric field. Finally, ions are stabilized right above the electrode surface to form an EDL, a kind of capacitor, where an electric field in the order of 10 MV/cm, which is difficult to achieve in solid capacitors, is produced without any difficulty. This capacitor device, called an electric double layer capacitor (EDLC), is well known for its capability of high density charge accumulation, and is already on market as a high density and high speed capacitor. When one of the electrodes is replaced by a semiconductor with a source and drain electrodes, this device works as a field effect transistor, which can be called an electric double layer transistor (EDLT). A schematic diagram is displayed in Fig. 1. This electrochemical device has been investigated for application to ion sensors. Since 2005, we have been investigating EDLT devices aiming at accumulating high density carriers and hopefully inducing electronic phase transitions using organic semiconductors [1]. Recently, we started to apply this technique to oxide semiconductors, and have successfully demonstrated the electric field induced insulator-metal transition in ZnO [2], followed by superconductivity in $SrTiO_3$ [3]. Fig. 2 shows the resistance drop of electric field induced superconductivity of $SrTiO_3$.

These results may suggest that EDLT could offer a novel direction in materials research at the electrochemical interface between ionic conductors (generally liquid) and electronic conductors (solid). This is not only because both ionic and electronic conductors are of enormously rich variety, but also because this transistor involves rich chemical processes, ranging from electrostatic charge accumulation to chemical reactions at the surface and in the bulk. For example, we found that ionic liquid displayed superior charging capability [4], as shown in Fig. 3. This enabled us to observe new electric field induced superconductivity in a layered compound ZrNCl with increased T_c of about 15 K [5]. Fig. 4 displays the temperature-dependence of resistivity of ZrNCl gated by an ionic liquid, DEME-TFSI for various gate voltages. Superconductivity emerged at V_G = 3.5 V, and complete superconductivity was achieved at V_G = 4.5 V. The present results indicate that EDLT could be a versatile technique for inducing and manipulating superconductivity at interfaces between solid-liquid interfaces.

References

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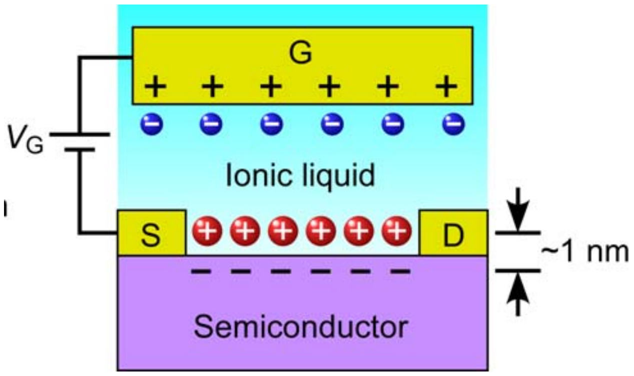

Fig. 1 Schematic figure of electric double layer transistor (EDLT) using ionic liquid.

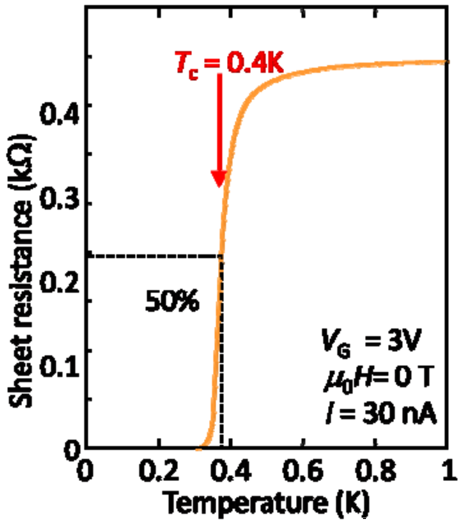

Fig. 2 Temperature dependence of resistivity at V_G = 3 V for an EDLT with $SrTiO_3$. A clear resistive transition with a zero resistance was induced by application of voltage.

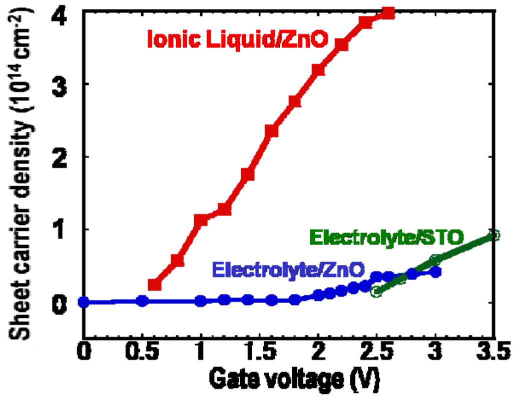

Fig. 3 Accumulated carrier density vs. gate voltage for several EDLT devices. The carrier density was determined by the Hall effect measurements. Ionic liquid was found to have an ability to accumulate higher carrier densities than electrolyte as a polyethyleneoxide solvent.

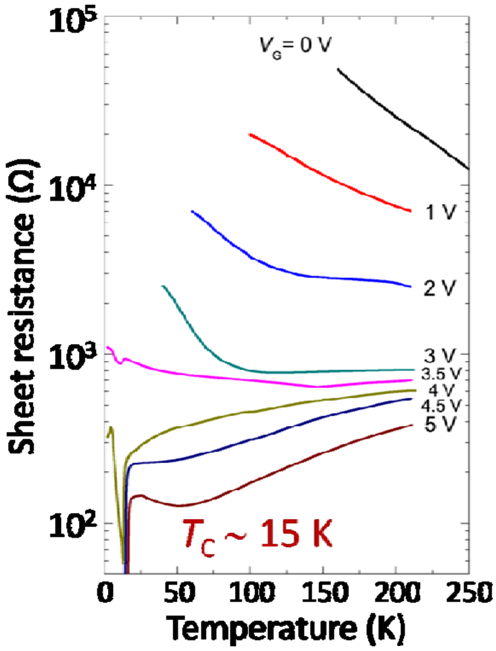

Fig. 4 Temperature dependence of resistivity of ZrNCl EDLT for various gate voltages.