Superconducting Dome in MoS_2 Electric Double Layer Transistor

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August 11, 2013 (HP62). In the past several years, electric field effect using electric double layer transistor (EDLT) has shed new light on a variety of materials, particularly on superconductivity in carrier-doped systems. EDLT is a kind of field effect transistor (FET), in which a gate dielectric is replaced by ionic conductor or electrolyte (Fig. 1). Application of voltages between electrolyte and semiconductors causes formation of an electric double layer (EDL), a self-organized nano-gapped capacitor. This electrochemical concept was first proposed by H. von Helmholtz almost 150 years ago. An important consequence is that the voltage drop occurs only at the EDL, which results in an extremely large electric field reaching 50 MV/cm produced at EDL. This value is one-two orders of magnitude larger than those produced in conventional FETs with solid gate dielectrics, and thus the accumulated carrier density can reach 1 x 10^{15} cm^{-2}, which is impossible to achieve in conventional FETs.

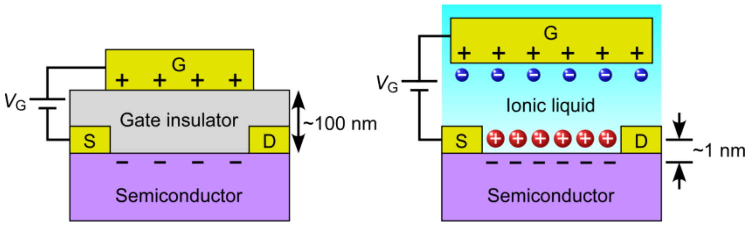

Fig. 1: FET device structures (left) Conventional FET device with a solid gate insulator. (right) Electric double layer transistor (EDLT). The EDL interface works as a capacitor.

Electric double layer transistor (EDLT) enables us to probe the electronic states at EDL, more specifically of the semiconductor channels. We applied this technique to a variety of materials to establish a new paradigm of materials science at ultrahigh electric fields, and so far demonstrated electric field induced superconductivity [1-4], ferromagnetism [5, 6], Mott-Hubbard transition [7], and even spin state manipulations [8]. We have used band insulators whereas another group demonstrated field-induced superconductivity in high T_c cuprates [9].

Superconductivity by the EDLT technique was first demonstrated in $SrTiO_3$, which is known to be a superconductor having very low volume carrier concentration [1]. We subsequently discovered gate-induced superconductivity in ZrNCl [2] and $KTaO_3$ [3]. ZrNCl has a layered structure, which is suitable for fabricating atomically flat surfaces by means of mechanical exfoliation used in graphene research. Flat surfaces are of crucial importance for transistors since the carrier transport occurs only at the surface of semiconductors. The discovery of electric-field-induced superconductivity in $KTaO_3$ is particularly important, since it is not known to superconduct in bulk. In other words, $KTaO_3$ is a new superconductor discovered by the electric field effect. This discovery became possible, because the electric field effect doping overcame the limit of chemical carrier doping.

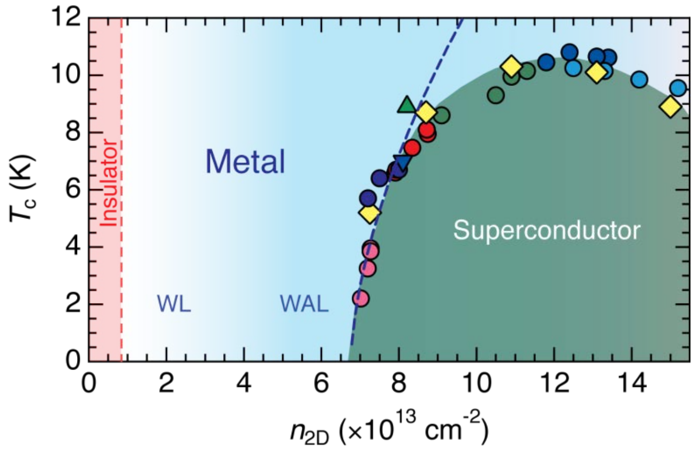

Fig. 2: Superconductivity phase diagram of MoS_2 EDLT: With increasing carrier density, a crossover from weak localization (WL) to weak antilocalization (WAL) was observed in magnetoresistance at 2 K. The dashed line indicates fit to the equation of the critical phase transition.

Recently, we have reported occurrence of superconductivity in MoS_2 EDLT [4], which was fabricated by an exfoliation technique identical to that used in the ZrNCl research [2]. Figure 2 displays a T_c *versus* carrier density phase diagram established by taking the advantage of tunable carrier density in field effect devices. We unexpectedly found a dome like phase diagram with the maximum T_c at 10.5 K. This T_c is the highest among those in MX_2 series of compounds, indicating that the field effect technique is quite useful for finding an optimum carrier density for superconductivity. Also, the dome-like phase diagram is reminiscent of those found in high-T_c cuprates and many other strongly correlated superconductors. MoS_2 is a well known band insulator or semiconductor, which has nothing to do with strong correlation. The dome shaped phase diagram in MoS_2 EDLT indicates that there exists a competing mechanism for realization of superconductivity even in simple doped semiconductors. Such dome shaped phase diagrams are nowadays frequently observed at interfaces of doped band insulators, such as $KTaO_3$ EDLT [3] and $LaAlO_3/SrTiO_3$ interfaces [10].

Electric-field-induced superconductivity is offering an interesting playground of two dimensional superconductors, because its thickness should be in a scale of Thomas-Fermi screening length (~1 nm). Also, since electric field effect is a perturbation which inherently breaks space inversion symmetry, the non-centrosymmetric nature may cause mixing of singlet and triplet pairing. To summarize, electric field effect, particularly EDLT, will be quite powerful in searching for new materials, as well as for investigating superconducting properties. This highlight was invited by the SNF Editor to attract readers' attention to references listed below and especially to ref. [4].

References

[1] K. Ueno et al., *Nat. Mater.* **7**, 855 (2008).
[2] J. T. Ye et al., *Nat. Mater.* **9**, 125 (2010).
[3] K. Ueno et al., *Nat. Nanotechnol.* **6**, 408 (2011).
[4] J. T. Ye et al., *Science* **338**, 1193 (2012).
[5] Y. Yamada et al., *Science* **127**, 1065 (2011).
[6] J. G. Checkelsky et al., *Nat. Phys.* **8**, 729 (2012).
[7] M. Nakano et al., *Nature* **487**, 459 (2012).
[8] H. T. Yuan et al., *Nat. Phys.* (2013). Advanced Online
[9] A. T. Bollinger et al., *Nature* **472**, 458 (2011).
[10] A. D. Caviglia, *Nature* **456**, 624 (2008).