Volatile and non-volatile superconductivity in cuprate by ionic liquid gating opens novel roads for superconductivity research

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Volatile and non-volatile superconductivity in cuprate by ionic liquid gating opens novel roads for superconductivity research

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Changing carrier density is one of the most remarkable but common aspects of unconventional superconductors. Both for understanding the mechanism of exotic superconductivity and for novel technological applications, this “semiconductor-like” property plays a crucial role. Usually, this can be achieved by chemical substitution. However, in the chemical substitution technique, the substitution is possible only within the realizable crystal structure, and the maximum amount of carrier density is limited to $10^{21}$ cm$^{-3}$. Chemical substitution also introduces disorder, which often hinders extracting intrinsic aspects from the measured results. Therefore, different methods of carrier doping were considered, such as doping by the electric field. In 2008, superconductivity by electric field doping was realized in SrTiO$_3$, using electric double layer transistor (EDLT) structure with ionic liquid gating (ILG) [1]. Remarkable thing is that the density of doped carrier is $10^{15}$ cm$^{-2}$ $(10^{22}$ cm$^{-3}$). Since, this technique was applied for many other superconductors, including high-$T_c$ cuprate [2]. The ILG also has a merit to realize a very clean and thin two-dimensional platform of superconductivity, which casts a question of the so far believed understanding of superconductor-insulator transition [3]. Thus, the EDLT doped superconductivity has attracted growing interests in the modern research of superconductivity.

One might immediately expect that electric field doping has a great merit that both hole doping and electron doping are possible, just by changing the polarity of the gate voltage. The reality is, however, not simple at all. In particular, for the ILG, other than simple electrostatic doping of the carrier, electrochemical interactions, such as deoxygenation and protonation, should take place, which are likely to be asymmetric for the positive and negative biases. Therefore, systematic investigations of the EDLT doping in terms of this viewpoint have been longed for.

Recently, Jin’s group [4] at Chinese Academy of Sciences performed systematic experiments concerning a liquid gating control on the mother material of a so-called electron doped cuprate, Pr$_2$-CuO$_{2+x}$ (PCO) film prepared by the polymer assisted deposition method, and realized two distinct superconductor-insulator transitions. With positive gate voltages, superconductivity can be reversibly switched on and off by carrier doping effect; superconductivity is volatile (Fig. 1a left). On the other hand, for the negative gating, the material becomes more resistive, first. Surprisingly, however, superconductivity emerges after the gate voltage returns back to 0 V. In this sense, superconductivity is non-volatile (Fig. 1a right). By high-resolution scanning transmission electron microscope (STEM) and electron energy loss spectroscopy (EELS) experiments, together with in-situ X-ray diffraction measurement, they succeeded to capture the signs of structural changes for the non-volatile superconductivity. They ascribed the striking phenomena to the repairing of oxygen deficiencies caused by the negative gate voltage. Their results are remarkable, since the realization of both volatile and non-volatile superconductivity in the same parent cuprate should provide a novel technique of manipulating superconductivity, and may add novel functionalities in superconducting electronics. Also in terms of fundamental physics of superconductivity, their observations provide several interesting issues which deserve further intensive investigations. Apart from the difference of volatile vs. non-volatile, the two kinds of superconductivity form different “dome” structures in the gate voltage – temperature phase diagram (Fig. 1b). This suggests that the bipolar superconductivity is realized in this system. Indeed, they reported that Hall resistivity changes its sign for sufficiently large negative bias necessary for the non-volatile superconductivity to take place. Since this is the only information on the sign of the carrier for the negative bias, more should be done to settle what is going on for the non-volatile superconductivity.

Another important indication is that it is really challenging to realize purely electrostatic doping by ILG. One always has to consider the possibility of mixing the electrochemical reaction. Indeed, this is what was met quite recently in a different exotic superconductor which is being intensively studied, FeSe [5]. The ILG raises $T_c$ of this material from 8 to 40 K [6]. This technique was extended to a series of chemically pressurized Fe chalcogenide (FeSe$_{1-x}$Te$_x$ and FeSe$_{1-x}$S$_x$) [7] and achieved zero resistance $T_c$ of 46 K [8,9]. However, superconductivity realized here is irreversible (non-volatile), suggesting that what happens here is not the electrostatic doping but electrochemical reaction. Therefore, to discuss the mechanism of superconductivity in this system, much more should be done to clarify the exact process taking place at the ILG treated FeSe.

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In any cases, the EDLT superconductivity is fast developing, and opening many novel areas in superconductivity research.

Conflict of interest

The author declares that he has no conflict of interest.

References


Atsutaka Maeda is a full professor of Department of Pure and Applied Sciences/Department of Basic Science, The University of Tokyo. He is an experimental scientist of condensed matter physics, and materials science. He has been engaged in studies of broad aspects of quantum condensate, such as charge-density wave and superconductivity, probed by microwave techniques in many cases. His recent research interest focuses on the physical property investigation of the epitaxial film of Fe chalcogenides, microwave flux flow Hall effect and so on.