Field control of superconductivity at insulating oxide interfaces

1. Superconducting interfaces between insulating oxides , N. Reyren, S. Thiel, A. D. Caviglia, L. F. Kourkoutis, G. Hammerl, C. Richter, C. W. Schneider, T. Kopp, A.-S. Ruetschi, D. Jaccard, M. Gabay, D. A. Muller, J.-M. Triscone, and J. Mannhart, Science **317**, 1196 (2007).

2. Electric-field-induced superconductivity in an insulator, K. Ueno, S. Nakamura, H. Shimotani, A. Ohtomo, N. Kimura, T. Nojima, H. Aoki, Y. Iwasa, and M. Kawasaki, Nat. Mater. **7**, 855 (2008).

3. Electric field control of the $LaAlO_3/SrTiO_3$ interface ground state, A.D. Caviglia, S. Gariglio, N. Reyren, D. Jaccard, T. Schneider, M. Gabay, S. Thiel, G. Hammerl, J. Mannhart, and J.-M. Triscone, arXiv:0807.0585.

4. Superconductor-normal and quantum superconductor-insulator transition at the $LaAlO_3/SrTiO_3$ interface, T. Schneider, A.D. Caviglia, S. Gariglio, N. Reyren, D. Jaccard, and J.-M. Triscone, arXiv:0807.0774.

**Recommended with a Commentary by Atsushi Fujimori,
University of Tokyo**

Most of the remarkable physical properties of complex oxides emerge from carrier doping. However, chemical substitution or defect formation, which is usually employed to realize carrier doping, inevitably introduces disorder and degrades or at least complicates the phenomena, hindering our precise understanding of the properties. Furthermore, fine tuning of carrier concentration is limited for chemical doping since one has to prepare separate samples of various chemical compositions. For those reasons, carrier doping by electric field, which enables us to dope a system with carriers in a disorder-free, finely controlled way, has been a dream of researchers working on complex materials. Indeed, field doping has so far been successfully attempted in some complex materials such as organic and oxide semiconductors, and recently doping was realized up to concentrations high enough to induce an insulator-to-metal transition in typical oxide semiconductors such as $SrTiO_3$ (STO) [1,2] and ZnO [3]. In such an experimental set-up, not only the cleanliness of the doping but also the two-dimensional (2D) nature of the interfacial electronic states lead to rich physics.

Recently, superconductivity has been realized in STO by field doping, as reported in the first and second papers recommended above. In the first paper, a polar oxide layer of $LaAlO_3$ (LAO) grown on STO induces negative charge carriers at the LAO-STO interface and further application of negative gate voltage on the other side of the STO crystal induces additional negative charge carriers at the interface, following the method reported in [2]. This eventually drives the STO into a superconducting state. In the second paper, negative charge carriers are induced at the interface between STO and an electrolyte to which a positive gate voltage is applied, using the method reported in [3] for ZnO. As the applied gate voltage increases and the carrier density becomes sufficiently high, superconductivity sets in.

Comparison between the field-induced superconductivity and the superconductivity induced by chemical doping in STO (through Nb doping or oxygen vacancies) gives interesting insight. More remarkably, the thickness of the conducting layer turns out to be as thin as $\sim$10 nm, much thinner than the superconducting coherence length of order 100 nm. This makes the system a truly 2D superconductor, and has lead to the beautiful study of the field-induced normal-to-superconductor quantum phase transition in 2D, reported in the third and fourth papers recommended above. By tuning the 2D carrier density $n_{\rm 2D}$ through changing the applied gate voltage, the quantum critical point is crossed and the critical exponent of the transition temperature T_c versus $n_{\rm 2D}$ is found to be that of the 3D-XY model, consistent with the Berezinskii-Koteritz-Thouless transition of a 2D superconductor.

Returning to the second paper by Ueno *et al.*, however, no such a quantum critical behavior is found in their T_c versus $n_{\rm 2D}$ curve, in spite of the remarkable similarities of the normal-state and superconducting properties to the third and fourth papers. As $n_{\rm 2D}$ reaches a critical value, T_c jumps from zero to near the maximum value of $\sim$400 mK, like a first-order phase transition. Ueno *et al.* attribute this observation to the strong field dependence of the dielectric constant of STO: the reduction of the dielectric constant under strong electric field reduces the thickness of the conducting layer, thereby increasing the 3D carrier density $n_{\rm 3D}$ to the superconducting region. The different sample geometries, particularly the different positions of the gate electrodes relative to the conducting channels or the different dielectric media (STO itself *vs* electrolyte), may be the origin of the apparently different T_c *vs* $n_{\rm 2D}$ relations.

The field control of 2D superconductivity, as reported in the recommended papers, will not be limited to STO if the material can form an interface with a dielectric medium including an electrolyte. If one can induce charge carriers of similar $n_{\rm 2D}$ at the interface between an insulating cuprate and a dielectric and the charge carriers are confined within a few CuO_2 layers, 2D superconductivity may be induced. Then one can address the longstanding issue of interplay between antiferromagnetism and superconductivity in the underdoped cuprates without influence of 'external' disorder. On the other hand, doped holes have inherent tendency to become inhomogeneous in this doping range and may affect the quantum critical behavior of the superconducting transition.

[1] H. Nakamura, H. Takagi, I.H. Inoue, Y. Takahashi, T. Hasegawa, and Y. Tokura, Appl. Phys. Lett. **89**, 133504 (2006).
[2] C. Cen, S. Thiel, G. Hammerl, C. W. Schneider, K. E. Andersen, C. S. Hellberg, J. Mannhart, and J. Levy, Nat. Mater. **7**, 298 (2008).
[3] H. Shimotani, H. Asanuma, A. Tsukazaki, A. Ohtomo, M. Kawasaki, and Y. Iwasa, Appl. Phys. Lett. **91**, 082106 (2007).