Electric field control of high-T_c cuprates in the entire doping range

1. Superconductor-insulator transition in $La_{2-x}Sr_xCuO_4$ at the pair quantum resistance, A. T. Bollinger, G. Dubuis, J. Yoon, D. Pavuna, J. Misewich, and I. Bozovic, Nature **472**, 458-460 (2011).

2. Electrostatic control of the evolution from a superconducting phase to an insulating phase in ultrathin $YBa_2Cu_3O_{7-x}$ films, X. Leng, J. Garcia-Barriocanal, S. Bose, Y. Lee, and A. M. Goldman, Phys. Rev. Lett. **107**, 027001 (2011).

3. Indications of an electronic phase transition in 2D $YBa_2Cu_3O_{7-x}$ induced by electrostatic doping, X. Leng, J. Garcia-Barriocanal, B. Yang, Y. Lee, and A. M. Goldman, arXiv:1108.0083v1

Recommended with a Commentary by Atsushi Fujimori, University of Tokyo

Electric filed control of material properties is a promising future direction of material science and condensed-matter physics. In particular, superconductivity induced by carrier doping utilizing intense electric fields had been a challenging research target for many years, and had been limited by the available carrier density. Recently, there was a technical breakthrough which increased the electric field and hence the carrier density by orders of magnitude through the utilization of electric dipole layers formed between the electrode (sample) and the electrolyte. The first realization of field-induced superconductivity was reported for $SrTiO_3$, a superconductor with the lowest carrier density [1]. More recently, using ionic liquids turned out to be more efficient than using electrolytes, leading to carrier densities in the range of $n_{2D} \sim 10^{14}$-10^{15} cm^{-2} [2]. This n_{2D} value is high enough to turn an insulating CuO_2 plane into a superconductor.

Indeed, Bollinger *et al.* succeeded in controlling the doping level of $La_{2-x}Sr_xCuO_4$ (LSCO) of one unit cell thickness from the underdoped non-superconducting region to the optimal doping region. Leng *et al.* successfully controlled the doping level of $YBa_2Cu_3O_{7-x}$ (YBCO) in the same range, too, and subsequently up to the overdoped region. The notable merit of field doping is that one can unprecedentedly fine tune the doping level. Unlike chemical doping, disorder remains unchanged by the electric field doping. The superconductor-insulator transition (SIT) in the heavily underdoped region was therefore studied using these films by Bollinger *et al.* and Leng *et al.* The observed critical sheet conductance of the SIT was equal to $h/(2e)^2$, indicating that the SIT is due to the localization of charge-$2e$ particles, that is, Cooper pairs. Two-parameter scaling analyses of the electrical resistance of the films were successfully carried out, but with different critical exponents between LSCO and YBCO as well as from those of the SITs of other systems such as Mo-Ge.

In addition to the SIT in the heavily underdoped region, two additional quantum phase transitions (QPTs) are known to exist in the cuprates. That is, the metal-insulator transition (MIT) near the optimum doping under the superconducting dome [3], and the superconductor-metal transition (SMT) in the heavily overdoped region [4]. The scaling behavior of resistance near the MIT under the superconducting dome in a high magnetic field should yield essential insight into the nature of the pseudogap phase, the most outstanding issue of the high-T_c cuprates.

Field doping studies of the various QPTs in the cuprates are in principle possible but experimentally challenging since the measurements have to be made in a high magnetic field for the MIT and with heavy hole doping for the SMT. In fact, the overdoped region of YBCO reached by electric field doping exhibited a puzzling behavior: The Hall carrier density *decreases* with doping, contrary to both the expected increase of hole density and the expected closure of the pseudogap. This may be due to an unkown phase transition or due to field-dependent spatial distribution of doped holes. Also, the doping process in YBCO is complicated because of the presence of Cu-O chains as pointed out by Leng *et al.*. When the microscopic process of field doping becomes well understood in future, considerable insight into the rich physics of the cuprates would be gained.

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