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High-T_c superconductivity from an atomic point of view via tunneling

Jung Hoon Yoo [a,b], Jinho Lee [a,b,*]

[a] Department of Physics and Astronomy, Seoul National University (SNU), Seoul 08826, Republic of Korea
[b] Center for Correlated Electron Systems, Institute for Basic Science (IBS), Seoul 08826, Republic of Korea

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ABSTRACT

Even after 30 years of discovery of the high temperature superconductivity (HTSC) from the cuprate compounds by Bednorz and Müller, the mechanism of the formation of Cooper pairs well above the liquid nitrogen boiling temperature is still remained to be elucidated. The discovery of a yet another HTSC family of the iron-based superconductors seemed to add more complexity to this puzzle, but also seems to render a prospect of finding a universal principle shared by the entire HTSC family. The tunneling experiments, on the other hand, also witnessed remarkable breakthroughs ever since Giaever succeeded the first tunneling experiment on a superconducting aluminum. The scanning tunneling microscopy (STM) invented by Binnig and Rohrer began to be heavily applied to the research of the condensed matter and became one of the most versatile spectroscopic tools as well as the most powerful microscope available also in the HTSC research field as of today. In this review, we would like to convey a snapshot of the current application of the STM in the research of HTSC, mainly focusing on the studies using the spectroscopic imaging scanning tunneling microscopy (SI-STM) which eventually led to the scanning Josephson tunneling microscopy (SJTM) by which we can visualize the superconducting Cooper pairs in an atomic scale.

1. Brief history of tunneling

Quantum mechanical concept of tunneling played a vital role in the history of superconductivity. Giaever used the very first tunneling in superconducting aluminum below 1 K, taking advantage of the naturally growing aluminum oxide (Al_2O_3) which is an excellent insulator with superior stability [1]. The fact that the first experimental demonstration of the tunneling – which was a conceptual notion as of 1950's - was realized in SIS (Superconductor –Insulator- Superconductor) junction is an example of the significant role of superconductivity in the history of tunneling and vice versa. Since then, the tunneling experiment became a mainstream, an indispensable experimental tool in the modern condensed matter physics. In 1965, McMillan and Rowell applied this SIS tunneling technique on the superconducting Pb to extract what we call $\alpha^2 f(\omega)$ [2] or the electron-photon interaction function which established a phonon-mediated pairing mechanism in the conventional superconductors as Bardeen-Cooper-Schrieffer suggested in their famous BCS theory [3]. In 1962, a young graduate student named Josephson was working at the Cavendish laboratory while P. W. Anderson was visiting. Encouraged by Anderson, Josephson realized that not only electrons but also the superconducting pairs can tunnel through an insulating layer in an SIS junction if the barrier is weak enough. Meanwhile, a remarkable breakthrough was made in the tunneling as an experimental technique. R. Young et al. came up with an idea of using a vacuum as a tunneling barrier to realize a non-invasive probe which can detect atoms on the solid surfaces (Topografiner [4]), and in 1981, Binnig and Rohrer invented the first actually working tunneling probe which can visualize as small features as atomic corrugations [5]. They named their invention as the Scanning Tunneling Microscopy (STM). Since then, the rest is the history. The STM became a topographic and spectroscopic experimental tool with the highest spatial magnifying power in a broad spectrum of the field of science.

2. Discovery of high-temperature superconductors

In 1986, almost exactly 30 years ago as of this review is written, the world has witnessed one of the most exciting scientific discoveries in history. Bednorz and Müller discovered a high critical temperature superconductivity (HTSC) in cuprate compounds [6]. In Fig. 1 (a), a topographic image of $La_{1-x}Ba_xCuO_4$ which is the first

* Corresponding author. Department of Physics and Astronomy, Seoul National University (SNU), Seoul 08826, Republic of Korea.
E-mail address: jinholee@snu.ac.kr (J. Lee).

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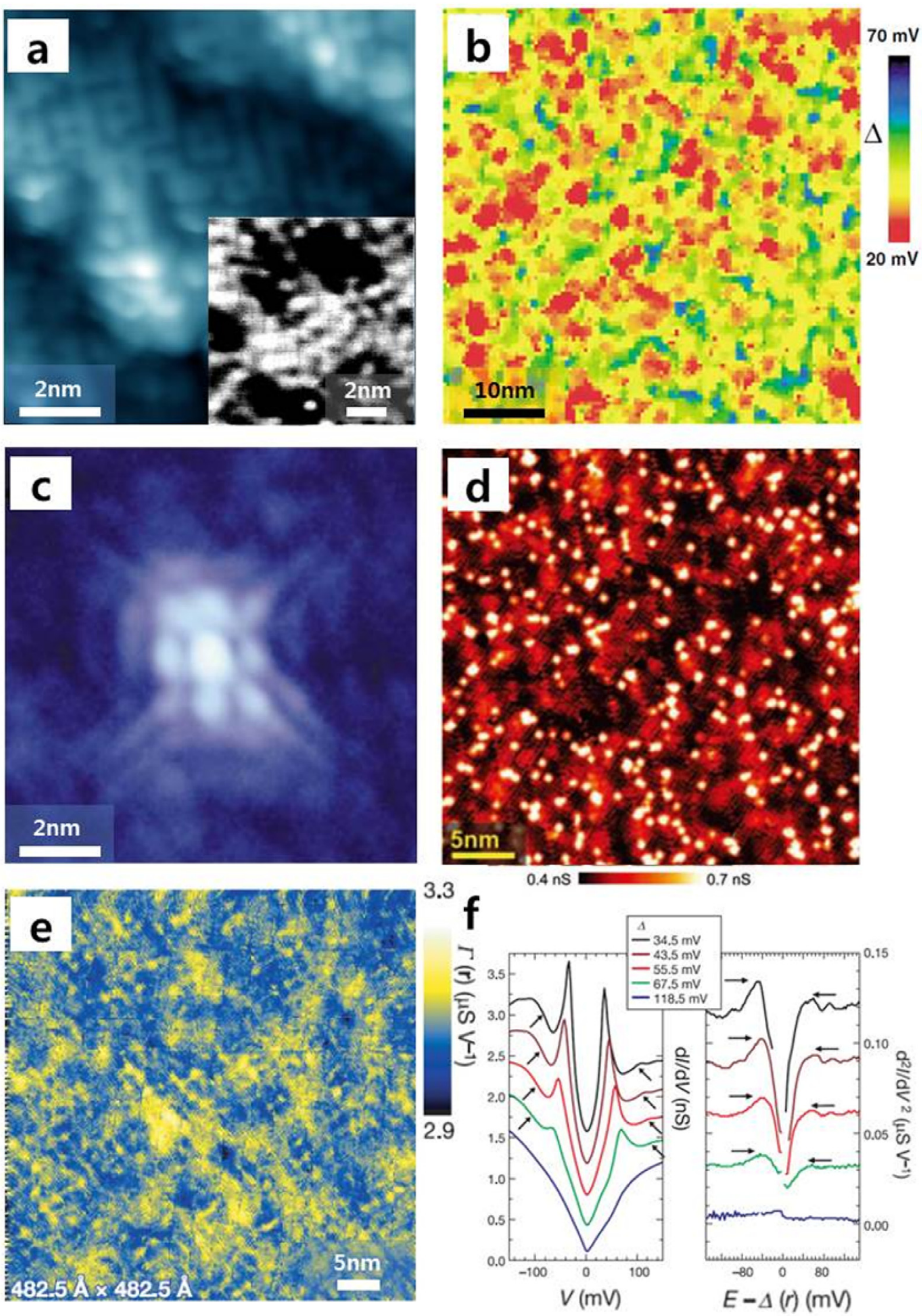

Fig. 1. Various spectroscopic quantities in the form of a map.**(a)** Topographic image of $La_{1-x}Ba_xCuO_4$ single crystal at 4.2 K [7]. From [7]. Reprinted with permission from AAAS. (inset) Image before Current-imaging tunneling spectroscopy (CITS) of YBCO. Bias voltage is 300 mV and current is 200 nA. Field of View is 10 nm × 10 nm [8]. Reprinted figure 1a (inset) with permission from Edwards et al., Phys. Rev. Lett., **75**, 1387 (1995). Copyright (1995) by the American Physical Society. **(b)** 50 nm square gap map $\Delta(\vec{r})$ of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with 19% doping (89 K OD). Color scale ranges 20 meV < $\Delta(\vec{r})$ < 70 meV. The gap distribution is heterogeneous spatially with an average gap value of 33 meV [15]. **(c)** High spatial resolution LDOS map(V = −1.5 meV). Zn impurity is located at the center of a resonance site. Zn dopants replace Cu sites on CuO_2 planes [16]. Reprinted by permission from Macmillan Publishers Ltd: Nature 403: 746–750, copyright 2000. **(d)** An LDOS ($\vec{r}$, E = −0.9 eV) map of $Bi_2Sr_2CaCu_2O_{8+\delta}$ where non-stoichiometric oxygen atoms are visible. Bright maxima reveal random distributions of impurities [18]. **(e)** A typical map of the d^2I/dV^2 modulation integrated over the range of energy 40 meV–60 meV **(f)** dI/dV spectra(left) and d^2I/dV^2 spectra(right) [19].

HTSC discovered [7], and a current image of $YBa_2Cu_3O_{7-x}$ [8] which is the first HTSC whose critical temperature (T_c) was recorded to be above the liquid nitrogen boiling temperature are shown. This new ceramic compound family with an perovskite structure defied almost all the empirical rules related to the conventional superconductivity: T_c as high as 150 K, high H_c, doping dependence, an