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Multiprobe SPM

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12.1 Present Status

The multiprobe scanning probe microscope (SPM), in which several tips or cantilevers are independently driven and arranged in arbitrary configurations on samples surfaces, has recently attracted considerable attention as a very versatile tool for electrical characterization at nanometer scales. The SPM tips/probes are employed as current sources, voltage pick-up probes, and field-gate electrodes as well as tweezers for structure manipulations. Several groups are developing different types of multiprobe SPMs [1–7], and some companies begin to deliver the products [8]. These commercial machines are mainly for testing electrical characteristics of nanometer-scale electronic devices, and regarded as a tool evolved from conventional electrical probers. Some of them are for electrical measurements of biological cells and proteins. In order to control the contact pressure between the probes and sample surfaces, many of them have ability of atomic force microscopy not only for imaging, but also for electrical measurements with conductive cantilevers. But they do not necessarily have atomic resolutions, and control precision of tip/probe positions is poorer than 10 nm. The apparatus and operation system are not yet fully developed, and still have much room for evolution in many aspects. Especially the operation system for controlling the multiprobes with atomic precisions as an organic whole is still lacking, and therefore it seems that the true value of multiprobe SPM is not yet realized.

Figure 12.1a shows a schematic of the four-tip scanning tunneling microscope (STM) apparatus in an ultrahigh vacuum (UHV) chamber developed at the University of Tokyo, and Fig. 12.1b shows a photograph of the goniometer stage on which the sample and four sets of scanners are mounted [9, 10]. The four tips of STM are driven independently under scanning electron microscope (SEM) for positioning the tips precisely with arbitrary arrangements on specified areas on the sample surface. Each tip points to the sample at the center with 45° from the sample surface, and is driven by a special type of a piezo-scanner for fine positioning and by three sets of piezo-actuators

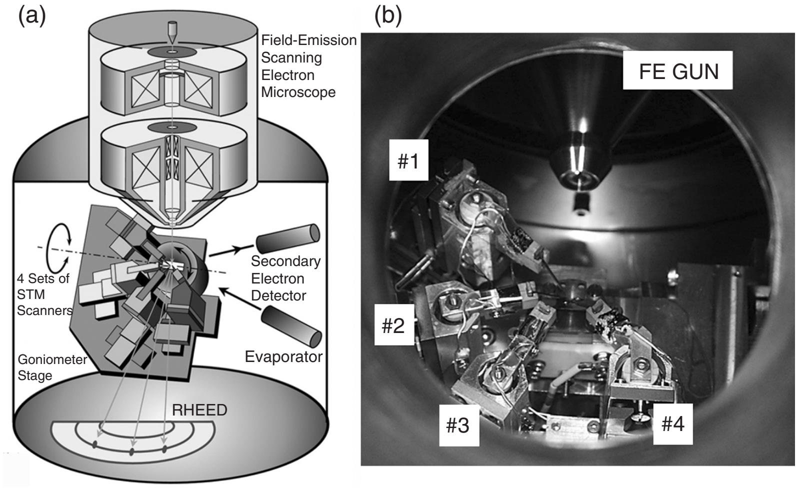
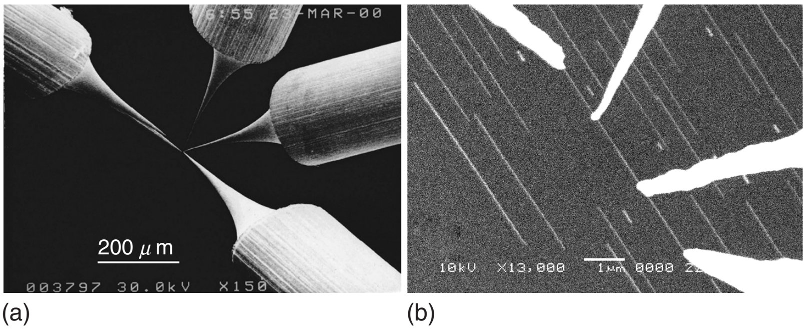


Fig. 12.1. (**a**) Schematics of the independently driven four-tip STM, installed in an UHV-SEM-RHEED system. (**b**) A photograph of the goniometer stage on which a sample and the four-tip scanners are mounted under the SEM column [9,10]

(Microslide, Omicron) for coarse motion. The goniometer stage enables parallel shifts in three directions and tilt rotation with respect to the SEM electron beam. The sample can be rotated azimuthally by 360° with respect to the stage. These positioning mechanisms enable fine adjustments with respect to the SEM electron beam, required to perform reflection-high-energy electron diffraction (RHEED) and scanning reflection electron microscopy (SREM) observations of the sample surface simultaneously. These supplementary electron microscopy/diffraction techniques are indispensable not only for positioning the four tips properly, but also for confirming the surface structures of sample. The STM tips and sample can be exchanged and installed by transfer rods from load-lock chambers without breaking vacuum.

This apparatus enables usual STM operation by each tip independently, and also four-point probe (4PP) conductivity measurements with various probe arrangements and spacing. The four tips approach the sample surface simultaneously with feedback control by tunnel-current detection. After that, the tips are brought into direct contacts with the sample surface, and then the 4PP conductivity measurement is performed. The preamplifier is switched from the tunnel-current mode to the 4PP conductivity measurement mode. Control system for the four-tip STM is still in its infancy. Each tip is independently controlled, but not in an integrated way. If the positions of all tips are controlled by their xyz coordinates at nanometer-scale precision by a single controller, we do not need SEM for tip positioning anymore. A method for navigating two STM tips is developed by using a special type of sample [11].



(a) (b)

Fig. 12.2. (**a**) SEM images of the four W tips in the four-tip STM [9]. (**b**) The four tips contacting a Co-silicide nanowire on an Si(110) surface [12]

Figure 12.2a shows an SEM image of four tungsten tips in the four-tip STM [9, 12]. The probe spacing can be changed from ca. 100 nm to 1 mm, and arranged in arbitrary ways such as in linear or in a square with equidistant probe spacings [13]. These four tips are used for the 4PP conductivity measurements of microscopic regions and objects. When the probe spacing is reduced on the order of microns, we can measure the electrical conductivity through the topmost atomic layers on a crystal with high sensitivity [14, 15] as well as individual microscopic objects such as nanowires [12]. When the four tips are arranged in a square on a sample surface, we can measure the anisotropy of conductivity [13].

12.1.1 Improvements

The following two issues should be improved from technical points of view in order to make the multiprobe SPM a more versatile tool for nanometer-scale measurements.

1. *Control system.* Many of the multiprobe SPMs need an auxiliary microscope such as SEM and optical microscope to observe and position the tips/probes in the designed arrangements on a sample surface. And in many cases the tips/probes are independently driven with separate sets of controllers without mutual communication. These make the operation very troublesome. Therefore, a user-friendly controller, by which the multiprobes are controlled with nanometer precisions in integrated ways by a single computer, is highly desired. Furthermore, it becomes much more convenient if we can control each tip by its xyz coordinates. For this purpose, we need a so-called closed-loop system in which the probe movements driven by scanners are simultaneously measured by some kinds of displacement sensors, and the results are used for feedback of tip positioning. Such a controller is recently produced experimentally, while the tip-positioning precision is not yet enough for the nanometer-scale measurements.

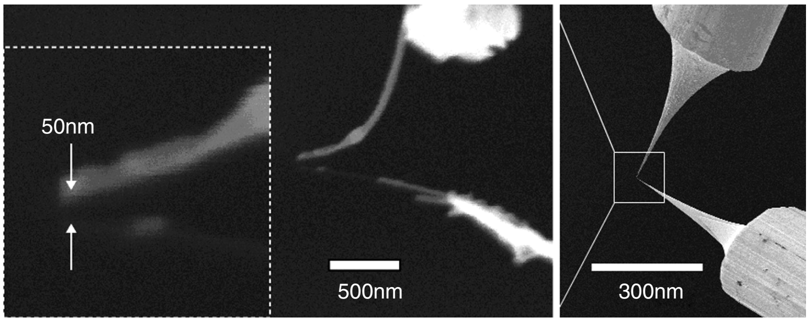


Fig. 12.3. SEM images of the two metal-coated carbon nanotubes arranged with ca. 50 nm spacing in the four-tip STM [17]

2. *Tips/probes*. The minimum spacing between two tips is determined by the radius r of the tip end; it is impossible to bring the two tips close to each other less than $2r$, because the two tips touch each other. In the case of electrochemically etched tungsten tips which are usually used for STM, $r \sim 50$ nm, which means that the minimum tip spacing is ca. 100 nm. Therefore, it is necessary to utilize much thinner tips such as carbon nanotubes (CNTs) and whiskers. Figure 12.3 shows two CNT tips in the four-tip STM, by which we can make the two tips approach each other less than 50 nm [16–18]. A multiwalled CNT is glued on the end of a W tip, and wholly coated by a thin W layer to make the junction between the CNT and W supporting tip conductive. Such coating by a thin metal film is indispensable to make the tip conductive enough for the STM and electrical measurements. With this technique by utilizing CNTs, we will be able to reach the minimum tip distance around 15 nm. In addition to metal layers, it is possible to coat the CNT tips with other materials such as dielectric, magnetic, and superconducting materials [19, 20], the multiprobe SPM will have various uses in different ways not only for electrical conductivity measurements.

12.1.2 Roadmap

If the technical issues mentioned earlier are improved and the probe spacing reaches down to ca. 10 nm routinely, various measurements and applications by the multiprobe SPM will become possible as shown in Fig. 12.4. We will be able to measure the electrical conductance of individual nanometer-scale objects such as DNA molecules, atomic chains, and nanodots. In the measurements, then, the influence of tip contact will be a serious problem. The electrical probes with direct contact to the sample will easily disturb the states and structures of such nano-objects. To avoid this disturbance, the simultaneous tunneling contact of multiprobes will be indispensable.

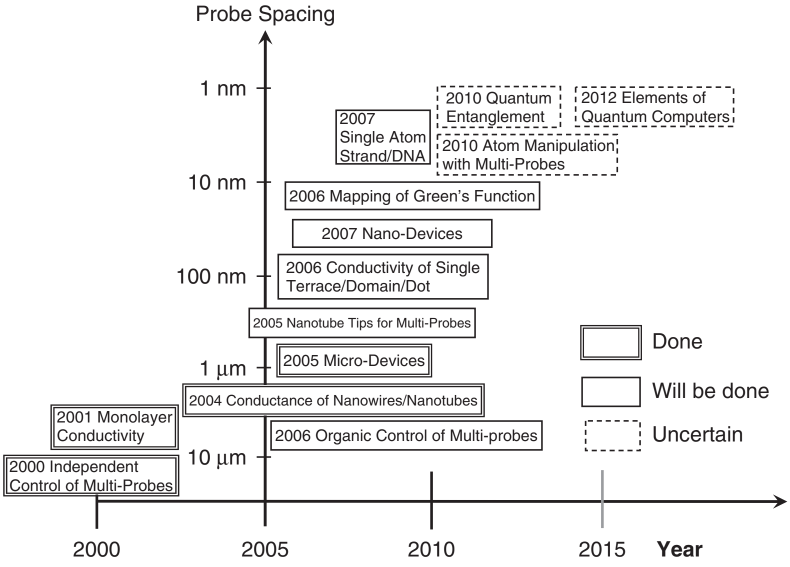


Fig. 12.4. Future prospect about the multiprobe SPM

When the tip spacing is comparable to the coherence length of carriers in the sample, a new type of measurement, i.e., real-space mapping of Green's function, will be possible by the multitip STM [21,22]. This "Green's function STM" measures the change of tunneling current through a tip during changing the tunneling bias voltages of other tips. Such nonlocal phenomena including electron correlation effects can be measured when the tips are brought close to each other in a range of carrier coherence length. With this new type of multiprobe SPM, it will be possible to measure quantum entangled states in nanostructures which will be useful as elements of quantum computers.

The multiprobe SPM will be also utilized for structural modifications and atomic/molecular manipulations. With use of multiprobes, such structure constructions and characterizations will be simultaneously possible.

References

1. S. Tsukamoto, B. Siu, N. Nakagiri, Rev. Sci. Instrum. **62**, 1767 (1991)
2. M. Aono, C.-S. Jiang, T. Nakayama, T. Okuda, S. Qiao, M. Sakurai, C. Thirstrup, Z.-H. Wu, J. Surf. Sci. Soc. Jpn. **19**, 698 (1998), in Japanese
3. H. Okamoto, D.M. Chen, Rev. Sci. Instr. **72**, 4398 (2001)
4. H. Grube, B.C. Harrison, J. Jia, J.J. Boland, Rev. Sci. Instr. **72**, 4388 (2001); Rev. Sci. Instr. **73**, 1343 (2002) [ERRATA]
5. H. Watanabe, C. Manabe, T. Shigematsu, M. Shimizu: Appl. Phys. Lett. **78**, 2928 (2001); **79**, 2462 (2001)

6. K. Takami, M. Akai-Kasaya, A. Saito, M. Aono, Y. Kuwahara, Jpn. J. Appl. Phys. **44**, L120 (2005)
7. M. Ishikawa, M. Yoshimura, K. Ueda, Jpn. J. Appl. Phys. **44**, 1502 (2005)
8. Omicron NanoTechnology GmbH (http://www.omicron.de/), MultiProbe, Inc (http://www.multiprobe.com/), Zyvex Co. (http://www.zyvex.com/)
9. I. Shiraki, F. Tanabe, R. Hobara, T. Nagao, S. Hasegawa, Surf. Sci. **493**, 643 (2001)
10. S. Hasegawa, I. Shiraki, F. Tanabe, R. Hobara, Current Appl. Phys. **2**, 465 (2002)
11. H. Okamoto, D.M. Chen, J. Vac. Sci. Technol. A **19**, 1822 (2001)
12. H. Okino, I. Matsuda, R. Hobara, Y. Hosomura, S. Hasegawa, P.A. Bennett, Appl. Phys. Lett. **86**, 233108 (2005)
13. T. Kanagawa, R. Hobara, I. Matsuda, T. Tanikawa, A. Natori, S. Hasegawa, Phys. Rev. Lett. **91**, 036805 (2003)
14. S. Hasegawa, I. Shiraki, F. Tanabe, R. Hobara, T. Kanagawa, T. Tanikawa, I. Matsuda, C.L. Petersen, T.M. Hansen, P. Boggild, F. Grey, Surf. Rev. Lett. **10**, 963 (2003)
15. S. Hasegawa, I. Shiraki, T. Tanikawa, C.L. Petersen, T.M. Hansen, P. Goggild, F. Grey, J. Phys.: Cond. Matters **14**, 8379 (2002)
16. T. Ikuno, M. Katayama, M. Kishida, K. Kamada, Y. Murata, T. Yasuda, S. Honda, J. Lee, H. Mori, K. Oura, Jpn. J. Appl. Phys. **43**, L644 (2004)
17. Y. Murata, S. Yoshimoto, M. Kishida, D. Maeda, T. Yasuda, T. Ikuno, S. Honda, H. Okada, R. Hobara, I. Matasuda, S. Hasegawa, K. Oura, M. Katayama, Jpn. J. Appl. Phys. **44**, 5336 (2005)
18. S. Yoshimoto, Y. Murata, R. Hobara, I. Matsuda, M. Kishida, H. Konishi, T. Ikuno, D. Maeda, T. Yasuda, S. Honda, H. Okada, K. Oura, M. Katayama, S. Hasegawa, Jpn. J. Appl. Phys. **44**, L1563 (2005)
19. M. Kishida, H. Konishi, Y. Murata, D. Maeda, T. Yasuda, T. Ikuno, S. Honda, M. Katayama, S. Yoshimoto, R. Hobara, I. Matsuda, S. Hasegawa, e-J. Surf. Sci. Nanotech. **3**, 417 (2005)
20. T. Ikuno, T. Yasuda, S. Honda, K. Oura, M. Katayama, J.-G. Lee, H. Mori, J. Appl. Phys. **98**, 114305 (2005)
21. Q. Niu, M.C. Chang, C.K. Shih, Phys. Rev. B **51**, 5502 (1995)
22. J.M. Byers M.E. Flatte: Phys. Rev. Lett. **74**, 306 (1995)