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Science and Technology in the Twenty-First Century

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1.1 Trend of Science and Technology in the Twenty-First Century

Since the end of the twentieth century, technology has been developing significantly. Personal mobile communication began with pager, then personal handyphone system (PHS), and now into cellular phone. Cellular phone has already become a third-generation system, and one can photograph, film, e-mail, and even surf the Net. Cellular phones will soon become a wearable ubiquitous computer, which can exchange information anytime and anywhere. Various dream technologies in the electronics field are hoped to be realized within 20 years as listed in Table 1.1. These were predicted by the eighth research on the prospect of technical development by the Ministry of Education, Culture, Sports, Science and Technology of the Japanese government (MEXT) in 2005. Accelerated development of information and communication fields based on rapidly developing electronic devices is the driving forces for realization of such dream technologies.

The backbone of rapid progress and development of electronics field is the accelerated miniaturization of semiconductor integrated circuits. Moore's law proposed by Dr. Moore, cofounder of Intel, predicts that "Integration scale of semiconductor chip will become four times for every three years (two times for every 18 months) approximately," and also "Performance of microprocessor will become four times for every three years (two times for every 18 months) approximately," so that the integration scale of semiconductor chip and performance of microprocessor will develop exponentially. By miniaturization, in the case of Intel, cost of one transistor dropped from more than one dollar in 1965 to one ten-thousandth of one cent at 2005, i.e., one part of million after 40 years. This drop can be compared with that of the TV at ten thousand dollars, which dropped to one cent after 40 years. Besides, by miniaturization, in the case of Intel, the performance of microprocessor improved from about 1.5 MIPS (MIPS: million instructions per second) at 1979 to more than

Table 1.1. Prospected year of technical realization in electronics fields

Prospected year of technical realization	Subject
2011	A system that can predict and judge troubles and accidents, with various kinds of sensors distributed in automobiles
2012	An ubiquitous computer made of one chip that can exchange information anytime and anywhere
2015	An artificial intelligent chip that can understand feelings from an individual's face
2015	One maid robot in every home that can clean up and do laundry
2015	A sensor that can detect diastrophism and predict earthquake several minutes before its occurrence
2018	A microrobot in the human body that can examine inward, with sensors/controllers/actuators integrated by micromachine technology
2024	An information machinery that can calculate 1,000 times faster than C-MOS logic circuit in cases of particular use, based on quantum-computing principle

10,000 MIPS in 2005, i.e., 6,667 times after 26 years. This improvement can be compared with the running distance record in 1 s. was improved from 1 m (the 100-m record is 100 s) in the first year to 6,667 m (the 100-m record is 0.015 s) after 26 years. Half-pitch of line and space of dynamic random-access memory (DRAM) semiconductor memory was 80 nm in 2005. As a result, the number of transistors on one Si chip increased up to several hundred millions. To enable proper functioning of all transistors on one Si chip, fluctuation of fine patterning should be less than 10% of pattern (8 nm in the case of half-pitch pattern). Besides, to precisely evaluate the accuracy of fine patterning, measurement error of fine patterning should be less than 1% of pattern (0.8 nm in case of half-pitch pattern). Thus, rapid miniaturization of large-scale integrated circuit (LSI) requires rapid improvement of spatial resolution of measurement and characterization. As a result, requirement in 2005 was 0.8 nm, i.e., single angstrom (= atom scale) region. Further, improvement of spatial resolution makes the measuring area increasingly smaller, so that the signal level for measurement and characterization becomes correspondingly weaker. Hence, for the improvement of spatial resolution, we need improvement of the measurement sensitivity (signal-to-noise ratio).

The role of scanning probe microscope (SPM), which is the tool for observation and characterization with the spatial resolution of single nanometer and subnanometer (= atomic scale = angstrom), is becoming increasingly important because of the progress of rapid miniaturization. In this book, we introduce our future prospect on SPM research and development, i.e., "SPM roadmap 2005," related to the improvement of better sensitivity, better performance, greater functionality, better spatial resolution, and higher measurement speed, which can measure various physical properties of diverse materials in wider varieties of environments. In Chaps. 2–4, we introduce our future prospect on major SPMs such as scanning tunneling microscope (STM), atomic force microscope (AFM) and near field optical microscope (NSOM). In Chaps. 5–9, we introduce our future prospect on the secondary SPM, i.e., the SPM family except for the major SPM. In Chaps. 10–17, we introduce our future prospect on the emerging and growing techniques related to SPM. In Chaps. 18–22, we introduce our future prospect on the application fields of SPM. In Chap. 23, we introduce our future prospect on the theory and simulation of SPM. Finally, in Chap. 24, we discuss the future prospect on SPM.

1.2 Previous Prospect in SPM Roadmap 2000 and the State-of-the-Art

"SPM Roadmap 2005" is the second future prospect on SPM following the previous "SPM Roadmap 2000," which was published in Japanese with the title of "Scanning Probe Microscope – Its Basis and Future Prospect" on February 10, 2000. We have listed a part of the previous future prospect in SPM in Table 1.2. Hereinafter, we evaluate the previous future prospect "SPM Roadmap 2000" by comparing it with the current state (as of 2005).

In the last five years after the release of previous future prospect "SPM Roadmap 2000," atomic force microscope (AFM) has become one of the most rapidly developed SPMs. As shown in Table 1.2, one of the future prospects

Table 1.2. Future prospect in SPM roadmap 2000 and the result

Microscopes and others	Subject	Prospect in SPM Roadmap 2000	Note (the achieved year, etc.)
AFM	Fundamental experiment of atom manipulation with AFM	2003	2002 (atom extraction by vertical atom manipulation)
AFM	Manipulation of atoms and molecules with AFM	2010	2003 (removal and repair by vertical atom manipulation) 2005 (lateral atom manipulation) 2005 (embedded atom letters [atom inlay])
AFM	True atomic resolution under liquid environment	2010	2005 (mica)
Tip	Sample shipment of carbon nanotube tip	2000	2001

on AFM, "Fundamental experiment of atom manipulation with AFM," was achieved in 2002, 1 year earlier than the future prospect in "SPM Roadmap 2000," where Si adatom in Si(111)7×7 at a low temperature of 9.3 K was mechanically extracted by the vertical atom manipulation using the mechanical vertical contact between the tip apex Si atom and the surface Si adatom [1]. Besides, another future prospect on AFM, "Manipulation of atoms and molecules with AFM," was achieved in 2003 with full reproducibility, seven years earlier than the future prospect in "SPM Roadmap 2000," where Si adatom in Si(111)7×7 at a low temperature of 80 K was mechanically removed and then repaired (deposition of Si atom from the tip apex to the created Si adatom vacancy) by the vertical atom manipulation using the mechanical vertical contact between the tip apex Si atom and the selected surface site [2]. Further, in 2005, a single atom adsorbed on Ge(111)-c(2×8) substrate was laterally manipulated one by one along $[1, \bar{1}, 0]$ crystal axis using the raster scan method [3]. Moreover, in the same year, lateral atom-interchange manipulation phenomenon, which interchanges the embedded heterogeneous atom such as the selected Sn adatom embedded in Ge(111)-c(2×8) substrate with the selected adjacent Ge adatom, was discovered at room temperature (RT) [4]. Such tip-induced lateral atom-interchange manipulation was understood as the tip-induced directional thermal diffusion of the selected atom. Using such a newly discovered lateral atom manipulation method that can be applicable even to the system consisting of multiatom species, "Atom Inlay" ("that is the embedded atom letters "Sn" (the symbol of tin atom) consisting of 19 Sn atoms embedded in Ge(111)-c(2×8) substrate"), was successfully created as shown in Fig. 1.1 at RT [4]. Besides, one of the future prospects on AFM, "True atomic resolution under liquid environment," was achieved in 2005, five years earlier than that in "SPM Roadmap 2000" [5]. Such rapid progresses of AFM at least partly owe to the stimulation by the future prospect in "SPM Roadmap 2000."

1.3 SPM Roadmap

1.3.1 Roadmap from Both Sides of Seeds and Needs

There are two directions of the SPM roadmap. One is the SPM roadmap from the viewpoint of SPM user (needs' side), while the other is the SPM roadmap from the view point of SPM developer (seeds' side). Chapters 2–17 treat the SPM roadmap on the development of SPM instruments and related techniques from the view point of SPM developer (seeds' side). Chapters 18–22 treat mainly the SPM roadmap from the viewpoint of SPM user (needs' side), but partly from the view point of SPM developer (seeds' side). The SPM roadmap from the view point of SPM developer (seeds' side) discusses the subject, that is, "Until when will such an affair become possible technically?" The SPM roadmap from the viewpoint of SPM user (needs' side) discusses the subject,

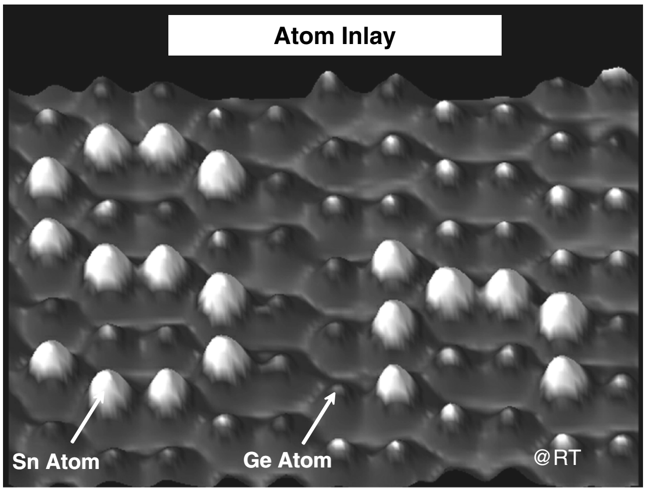

Fig. 1.1. The first "Atom Inlay," that is, atom letters figured by 19s of Sn atoms embedded in Ge(111)-c(2×8) at room temperature

that is, "Until when should such an affair become possible technically?". As a result, there will be some difference in future prospects depending on the view points of either SPM developer (seeds' side) or SPM user (needs' side). Hence, the reader has to be careful of which side the SPM roadmap is written.

1.3.2 Various Directions of SPM Roadmap

There are various directions in SPM roadmap. Pure SPM developer (pure seeds' side) will aim at "Better constituent technologies and instruments" such as better performance, better sensitivity (e.g., improvement of signal-to-noise ratio), higher spatial resolution, more precise control (e.g., tip–surface distance), higher measurement speed, greater functionality, and combined SPM with more functions, while applied SPM developer (applied seeds' side) will aim at usage in wider environments (e.g., in gases and liquids), chemical identification of atoms and molecules and atom manipulation/assembly. SPM roadmap of applied seeds' side includes the viewpoints from not only seeds' side but also needs' side. As a result of such variations in SPM roadmap direction, the SPM roadmap may become a polygon. For example, in the case of the seeds' side, Chap. 9 scanning atom probe (SAP) has six axes namely, detection efficiency, mass resolution, spatial resolution, multiplicity, sample for analysis, and theoretical analysis. In the case of needs' (user) side, Chap. 19 SPMs characterization of LSI devices also has six axes such as microscopic shape, crystal dislocation, contamination by dopant impurities, electric characteristics, chemical states, and stress. Roadmap of all SPMs such as AFM is intrinsically multiaxis. Important axis and/or alternative of AFM, however, are introduced in different chapters such as Sect. 10.2 "Chemical Identification of Atoms and molecules by AFM," Sect. 11.2 "Manipulation of Atoms and Molecules by AFM," Chap. 12 "Multi-Probe SPM," Chap. 13 "AFM Measurement in Liquid" and Chap. 14 "High Speed AFM".

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