Has Japan Begun to Move Toward Atomic Level Material Processing?

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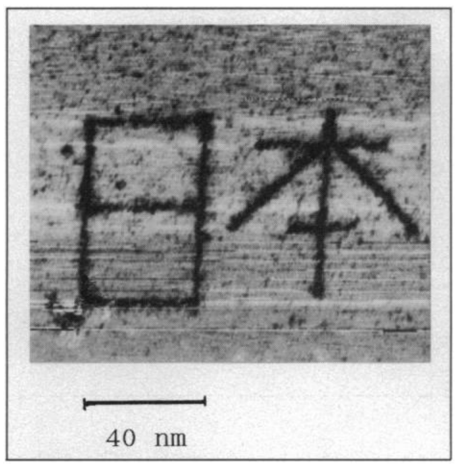
The scanning tunneling microscope (STM) invented by Binnig and Rohrer (*1*) can map out the topographic and electronic structures of a solid surface at the atomic level by means of a tiny metal tip. In addition to imaging the STM also provides a promising method for manipulating single atoms and processing materials at the atomic level. Preliminary demonstrations, such as the creation of single-atom bits on a germanium surface by Becker and colleagues (*2*) and the manipulation of single xenon atoms on a nickel surface by Eigler and co-workers (*3*), suggest the power of this approach. Challenges remain, however, in clearly understanding the physical mechanisms involved, as well as issues of technological feasibility.

Judging from Japan's success in microelectronics, and noting that miniaturization in conventional microelectronics will meet an ultimate limit sometime around the year 2010, it is natural to suppose that we will move toward atomic level material processing with the STM and related methods. Considerable progress has already been made in this field in Japan. Hosoki and colleagues (*4*) at the Hitachi Central Research Laboratory (HCRL) wrote the letters "PEACE '91 HCRL" on the surface of molybdenum disulfide by extracting sulfur atoms with an STM tip; each letter was only about 1.5 nm high. Although writing such letters itself has no significant value, it is one of the best ways to demonstrate the feasibility of creating bits for data storage and devices with a novel technique at the atomic to nanometer scales. Kobayashi and co-workers (*5*) of the Aono Atomcraft Project (AACP) [Research Development Corporation of Japan (JRDC)] have written nanometer-scale letters on a silicon surface by extracting silicon atoms using an STM tip (see figure). They have also studied the physical mechanisms of the extraction of silicon atoms on the basis of extensive experiments (*6*), which have made it possible to extract single silicon atoms routinely (*7*). Iwatsuki and co-workers (*8*), JEOL Corporation, also wrote nanometer-scale lettering on a silicon surface with a similar method using a stable STM capable of observing atomic images even at temperatures as high as several hundred degrees Celsius without significant tip drift. Utsugi (*9*), NTT Corporation, selected a unique, chemically fragile inorganic material, silver selenide, as a substrate and also wrote nanometer-scale letters with an STM tip.

Research on atomic level material processing has two objectives. One is to construct novel nanometer-scale electronic devices such as the single-electron tunneling (SET) transistor. Nejoh (*10*) (AACP) has observed the single-electron charging effect (Coulomb blockade) at room temperature by taking a single nanometer-scale liquid-crystal molecule as the "intermediate electrode," the outer pair of electrodes being a platinum substrate and an STM tip. This suggests that if we can construct such a three-electrode system and place an additional electrode on an appropriate substrate on the nanometer scale, we would be able to create a SET transistor working at room temperature. It is also expected from theory that if we could use each atomic vacancy created on a substrate as a bit of digital information, we would be able to store data of about 10,000 terabits on a silicon disk, for example, with a diameter of 10 cm. This is not necessarily mere fancy; Avouris and co-workers (*11*) and workers at AACP (*6*) have already demonstrated that single silicon atoms could be extracted from a silicon surface routinely. Mamin (*12*) has succeeded in recording his voice as a sequence of holes created on a resist film (PMMA) using an atomic force microscope (AFM), although each hole has a diameter of about 100 nm at present. The problem of writing and reading speeds would be solved technologically by using multi-tips, for example, which will be possible to be integrated and independently controlled with recent or future silicon microactuator technology.



Nanocalligraphy. Characters written with an STM tip on clean silicon in ultrahigh vacuum by extracting silicon atoms from the surface. The characters stand for "Japan" in Japanese [A. Kobayashi and F. Grey, Aono Atomcraft Project, Research Development Corporation of Japan (JRDC).]

The second objective is that of fundamental scientific research. If we create novel micromaterials with an atomic arrangement that cannot be created by any conventional methods, they might exhibit interesting and unexpected electronic properties. This would open up new directions in material science and possibly give us some new ideas for revolutionary electronic devices.

For these purposes, however, we must overcome many scientific and technological hurdles. As for the scientific hurdles, we must first clarify the physical mechanisms in the processing; otherwise no well-controlled processing can be accomplished. What we see between tip and sample in the STM is often beyond our everyday experience. Even if we apply a potential of only 10 V between the tip and sample, an electric field of the order of 100 million V cm^{-1} is created. The tunneling current between them is usually as small as 1 nA, but the current density is of the order of 100,000 A cm^{-2}. The close proximity of tip and sample may also result in an interatomic chemical interaction between them. In order to understand the physics and chemistry under such extreme conditions, a number of experimental and theoretical investigations will be required. The stability of atomic-scale structures created in this way is also an important subject to be investigated. One of the technological hurdles is the preparation of the tip. For the purpose of reliable atomic-scale structure fabrication, we must develop techniques to routinely prepare atomically sharp tips, to effectively compensate for the drift of the tip, and to supply foreign atoms to the tip continuously in order to deposit the desired atoms onto a substrate. Furthermore, we must devise means of measuring the electronic properties of these newly created nanometer-scale structures directly.

These hurdles are high enough to make researchers wonder if atomic level material processing will be of some use in the next one or two decades. Many of them ask themselves: "To go or not to go" forward with research and development. Nevertheless, Japan has undoubtedly begun to move toward such a goal. AACP aims to produce systematic research on atomic level material processing. The Ministry of International Trade and In-

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dustry (MITI) is planning to organize a large-scale project in this field and to invest $200 million over the next 10 years. The Institute of Physical and Chemical Research (RIKEN), of the Science and Technology Agency (STA), is also organizing another project, although not on such a grand scale. Some private companies have also begun to move forward. For example, recent newspaper articles indicated that NEC Corporation has succeeded in creating bits with a diameter of 10 nm on a film of amorphous vanadium oxide with an STM tip. Such a report is encouraging for research on the material processing at the smallest scales.

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Astronomy in Japan

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For a long time, the Japanese astronomy community has remained small relative to the physics community, while the latter has steadily expanded. International activities, in particular, have been limited to individual scientists rather than larger institutional groups. A radical change in this trend has occurred over the last 20 years. During this time, radio astronomy and x-ray astronomy have grown strongly. These new fields, including the still newer field of neutrino astronomy, have prompted an internationalization of Japanese astronomy.

A major advance in Japanese radio astronomy took place when a 45-m telescope was completed in 1982 at the Nobeyama Radio Observatory (NRO), about 100 km west of Tokyo. At present, the NRO belongs to the National Astronomy Observatory (NAO), an interuniversity institute. Six 10-m telescopes to constitute a mm-wave interferometer were also installed. This 45-m dish facility is still the largest mm-wave telescope in the world, and it is widely used by international observers.

Among the many objectives addressed by these telescopes, the following are two examples of the major achievements. Star-forming regions have been extensively investigated, and important results about the nature of protostars have been obtained. Innovative acousto-optical spectrometers (*1*) at Nobeyama played a powerful role in the discovery of numerous molecular species in the interstellar clouds, some of which do not exist on the Earth. In addition to the Nobeyama Observatory, a Nagoya University group built its own mm-wave telescopes and is actively conducting investigations, including sky mapping in the wavelength of a carbon monoxide line.

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Japanese radio astronomers are not content with their present success, and they have ambitious plans for the future. A large mm-wave interferometer array (LMA) and an extension to submillimeter astronomy would be their next steps, in addition to the space very long baseline interferometry (VLBI) project currently in preparation (see below).

Japanese astronomy from space is relatively young but has been developing vigorously. The Institute of Space and Astronautical Science (ISAS), an interuniversity institute, is responsible for implementing space research programs for the Japanese space science community. Scientists from all over the country participate in the preparation, operation, and data processing in each ISAS mission. ISAS has developed its own launch vehicle, the Mu-rocket, of modest payload capability. With this tool, ISAS has maintained a regular launch pace of one mission per year. Although ISAS missions are modest in scale, we believe that regular opportunities are essential for healthy development and that modest missions can perform frontier research well if they are given unique capabilities. In the area of astronomy, ISAS has launched two solar physics satellites and three x-ray astronomy satellites so far.

With these satellites, x-ray astronomy in Japan achieved rapid growth after a late start. The first satellite, Hakucho (1979), was launched 10 years after the U.S. x-ray astronomy satellite UHURU, and was a small spinning satellite weighing less than 100 kg. The second, Tenma (1983), was several times more sensitive, and the third, Ginga (1987), was a real x-ray astronomy observatory at an international level, equipped with a 4000-cm^2 x-ray detector array (one of the largest of its kind) jointly developed with the U.K. scientists. Ginga was used for a great many observations of virtually all classes of astronomical objects, from nearby stars to distant quasars, during its orbital life of nearly five years.

Still fresh in our memory is supernova 1987A in the Large Magellanic Cloud, which occurred less than 3 weeks after the launch of Ginga. At that very moment, the Japanese neutrino detector in Kamioka (see below) detected a burst of neutrinos from the supernova (*2*). The detection of neutrinos from this supernova marks a turning point in the history of astronomy. We immediately began observation of the supernova with Ginga, and anxiously watched for x-rays emergent through the expanding debris. In late August, we confirmed the emission of x-rays from the supernova (*3*). Later analysis showed that x-rays had become visible already in July, several months earlier than theoretically predicted. This implied large-scale turbulence inside the bursting star. With these two observations, Japanese astronomy made leading contributions to the dramatic advance of supernova astrophysics.

Ginga yielded exciting results in other areas as well. Cyclotron resonance features were found in the spectra of gamma-ray bursts (*4*). The implied magnetic field of $\sim 2 \times 10^{12}$ Gauss strongly suggests a neutron-star origin of gamma-ray bursts. Several bright transients suspected to be black hole binaries were discovered (*5*). The detailed study of them gave us much better insight into the common properties of the black hole candidates. And many active galactic nuclei, including a number of quasars, were newly observed. Their time variabilities and wide-band spectra have been extensively studied.

At the same time Ginga demonstrated the increasing international involvement of overseas scientists in Japan. Nearly 50% of the time of Ginga has been made available to foreign investigators, mostly from the United Kingdom, the United States, and European countries. These international collaborations have stimulated young Japanese astronomers, and have established