M. S. Kaĭkin. *Scanning tunneling microscopy and spectroscopy.* The scanning tunneling microscope (STM)[1] operates through the scanning of the tip of a metal needle along the X, Y coordinates over the surface of the conductor under study, at a distance $z = 5$–10 Å. As a result, a tunnel current j flows. The current j is held at a constant magnitude by an electronic circuit which adjusts the distance z. A recording of the adjustment voltage in the X, Y coordinates maps out the surface $S(x,y)$ of a constant tunnel current $j = j_0 \exp(-Az\varphi^{1/2})$, where $A \approx 1$ Å$^{-1} \cdot$ (eV)$^{-1/2}$. At a constant local height of the potential barrier (at a constant work function), φ, the surface S corresponds to the geometric surface of the sample.

If φ is not constant over the surface of a sample, then the value of φ at the surface point below the needle can be found by modulating the distance z with a frequency ν higher than the frequency band of the regulation of z. The signal at the frequency ν is proportional to the quantity $\varphi^{1/2} = \partial \ln j/\partial z$. Scanning the needle over the part of the surface under study thus simultaneously yields a map of the profile of the surface $S(x,y)$ and a map of the S distribution of the local height of the potential barrier $\varphi(x,y)$.

This method for measuring φ is one of many ways in which STM's can be used to study localized energy states of electrons in a surface layer of a sample. These various methods are known collectively as "scanning tunneling spectroscopy." Examples of such studies can be found in reports at the last conference on scanning tunneling microscopy[2]; one example is discussed below.

The spatial resolution of scanning tunneling microscopy and scanning tunneling spectroscopy reaches ~2 Å in the X, Y plane and ~0.02 Å along the normal to it (along the Z direction), so the positions of individual atoms can be measured, and particular features of the electronic properties of a sample can be localized—at the same resolution.[2,3] Figure 1 shows a topogram recorded in the course of an experiment with a scanning tunneling microscope (depth ~1 Å) of a crystalline surface of pyrolytic graphite.[4] The bright spots are carbon atoms which emerge at the surface. The recording noise can be eliminated through a subsequent computer processing. The writing conditions are characteristic of scanning tunneling microscopy: The voltage across the needle-sample gap was 10 mV; the tunnel current was 5 nA; and the duration of the recording was ~20 s. The surface of the sample must be clean. Graphite is particularly convenient in this regard since a graphite surface produced by cleavage remains clean even in the atmosphere. In other cases, e.g., in a study of silicon,[3] it is necessary to clean and anneal the surface in vacuum. Immersion in a gas or liquid does not prevent the operation of a scanning tunneling microscope; these fluids are important only for performing a required processing of the surface of a sample or putting the surface in a required state.[5]

Using a scanning tunneling microscope at a lower resolution, 10–20 Å along X, Y, is a far simpler matter than working at the highest possible resolution, in particular, because the requirements in terms of the isolation from vibrational noise are less severe. Even in this case, however, the scanning tunneling microscope can solve many problems of a scientific or technological nature which cannot be solved by other methods.[2,6]

The use of scanning tunneling microscopy to study superconductivity is particularly interesting and important. In particular, it can be used to study the properties of high-temperature superconductors. Figure 2 shows a distribution of the energy gap $n = 2\Delta/kT_c$ over the surface of a $YBa_2Cu_3O_x$ microscopic crystal near its boundary with the normal region of the sample, with $n = 0$. This distribution was obtained at 4 K by scanning tunneling spectroscopy.[7] It

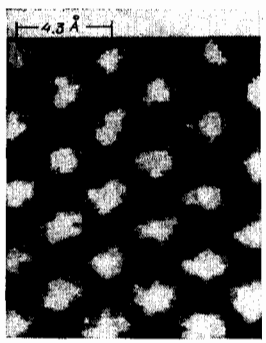

FIG. 1.

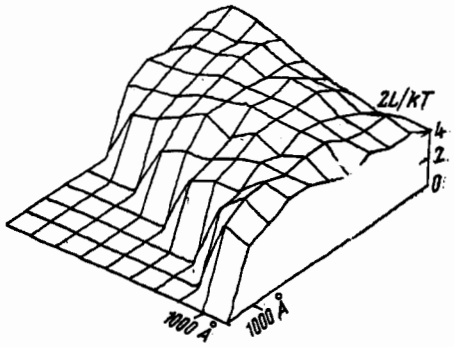

FIG. 2.

turned out to be impossible to scan the needle along the surface of the sample in a study of substances of this type, since they become covered by a nonconducting layer 100–200 Å thick, apparently because of a loss of some of the oxygen. The needle is immersed into the surface layer in order to achieve a tunneling contact. In the experiment, the needle was moved in the following way: After a measurement at some point, the needle was withdrawn from the sample along Z; a step was made along X; and then the needle was brought back up to the sample along Z at the new measurement point. In the standard operation of a scanning tunneling microscope, the needle is also "stepped" along the surface of the sample under computer control, but the motion along Z occurs exclusively under the control of a feedback system which maintains a constant tunnel current—without any significant withdrawal along Z.

These examples illustrate the completely unusual capabilities of research methods using scanning tunneling microscopy, scanning tunneling spectroscopy, and versions thereof which will be of decisive importance for making progress in all branches of the physics and technology of surfaces.

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