V. I. Panov. *Scanning tunneling microscopy and surface spectroscopy.* The development of the scanning tunneling microscope (STM)[1] has made it possible to extend the methods of tunneling spectroscopy to research on the relief and local density of the electronic states at the surfaces of metals, semiconductors, and tunneling-transparent insulating layers at the atomic scale. The record high resolution of STM's ($\sim 10^{-2}$ Å along the normal to the surface and ~ 1 Å in its plane), achievable both in ultrahigh vacuum and in dielectric media in a tunnel gap, has stimulated the use of STMs for the diagnostics of clean and real surfaces, for the spectroscopy of electronic states, for research on adsorption and catalysis effects, for research on biological objects, and for applications in microelectronics. The studies which have been carried out by various groups of investigators with STM's are described in the review by Hansma and Tersoff[2] and in the proceedings of the first international conferences, STM '86 (Ref. 3) and STM '87 (Ref. 4).

This report discusses the results of the use of high-resolution STM's[5,6] to study the microrelief of disordered surfaces, to study biological objects, and to observe structural changes of surfaces at the atomic time scale. The report also demonstrates the use of the forces of the interatomic (or intermolecular) interaction between the probing needle and the surface for the spectroscopy of the surfaces of insulators.[10]

1. The example of a study of the surface self-diffusion of silver adatoms has been used to demonstrate the possibility of using STM's to study temporal changes in the state of a surface at the atomic scale. The successive frames in part a of Fig. 1 show the time evolution of the microscopic relief of the same part of a silver surface as a result of the self-diffusion of adatoms (which are seen as protuberences in the figure). The diffusion process results in a gradual healing of the microscopic depression, 5–8 Å in size, at the points of localization of the adatoms on the silver surface. A depression was

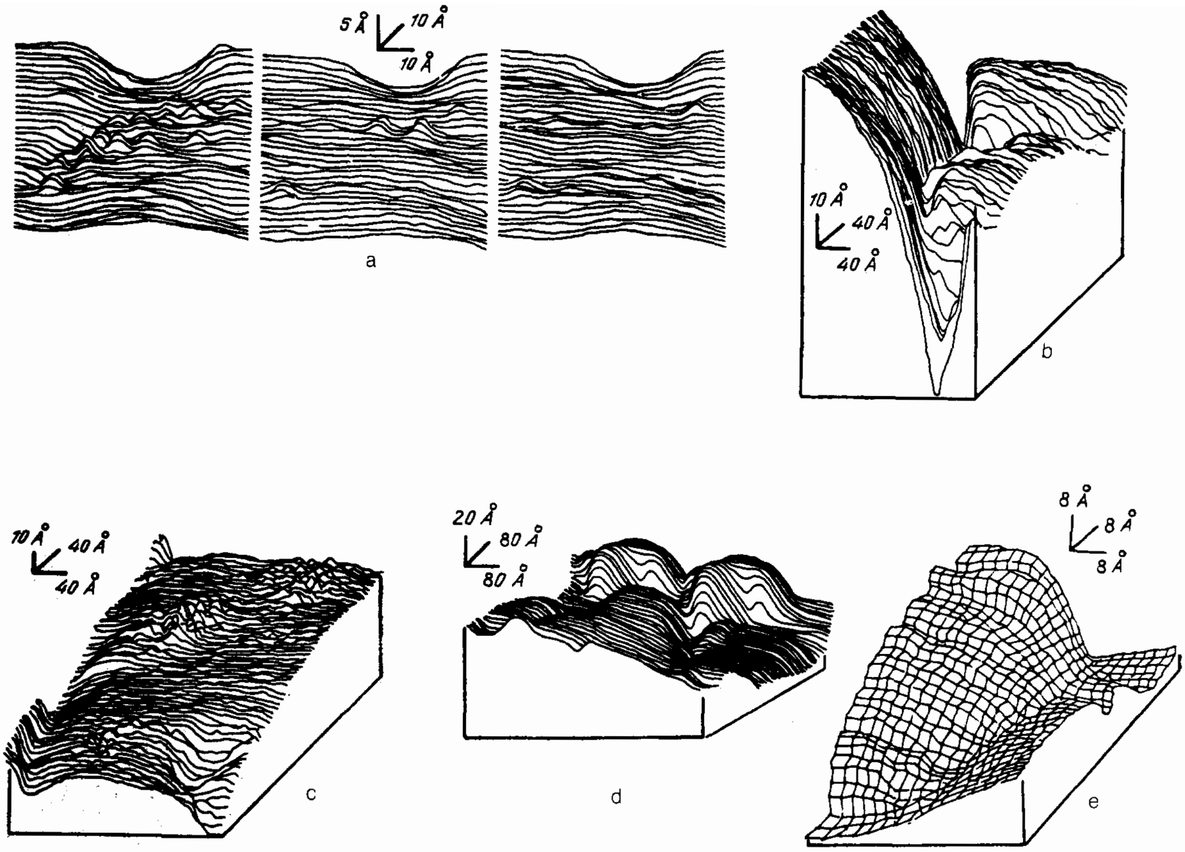

FIG. 1.

produced by bringing the tip of the probing needle into contact with the surface. The observed effects are not associated with variations in the local height of a tunnel barrier and do not depend on the magnitude of the tunnel current I_T. The time required to obtain each frame was ~ 30 s.

2. Scanning tunneling microscopes have been used to identify the mechanisms for the surface intensification of nonlinear-optics effects during the reflection of light from a rough surface of a metal. These intensification effects, specifically, the increase in the intensity of the reflected second harmonic and in the Raman-scattering cross section, depend strongly on geometric parameters, the distribution of relief irregularities, and the electronic properties of the surface.[7,8] The generation of a surface-enhanced ("giant") second harmonic has been observed, in particular, on films of silver deposited in ultrahigh vacuum on a substrate cooled to 77 K and also during the electrochemical monolayer oxidation of a silver surface, followed by a reduction of the oxidized layer. Research on their microrelief and electronic properties has made it possible to establish the electromagnetic nature of the surface enhancement of the Raman effect. Parts b and c in Fig. 1 show images of one of the breaks between crystallites (b) which remain in a Ag film (deposited at 77 K) after it is heated to room temperature at a pressure $P = 10^{-7}$ Pa and also a reduced surface (c) with a granular roughness which contains $\lesssim 10^2$ atoms in an individual microscopic irregularity. These images were obtained at the parameter values $I_T = 0.5$ nA and $V_T \approx 10^{-2}$ V.

3. Scanning tunneling microscopy stands in contrast with other methods in that it yields information on the structural, chemical, and electronic (or ionic) properties of biologically active systems at the atomic scales without destroying the specimen. Scanning tunneling microscopes have been used to study molecules of the intracellular enzyme reverse transcriptase. Molecules dissolved in a liquid have been placed in a gap between the electrodes of a tunnel gap (between the needle and the conducting surface of the substrate, on which the molecules have been deposited). In the course of the scanning, the tip of the probing needle was in the solution. Part d in Fig. 1 shows images obtained of two molecules of the enzyme. Part e shows a fragment of this enzyme at atomic scale. Measurements were taken at $I_T = 0.5$ nA and $V_T \approx 10^{-2}$ V. The results demonstrate the promising outlook for the use of STM's to study biological specimens with an atomic resolution.

4. The possibilities of STM's, which have been limited to the study of conducting substances, have motivated a search for methods for analyzing local characteristics of the surfaces of insulators. For this purpose, the use of the forces of an interatomic (or intermolecular) interaction between a surface and a needle brought up to within ~ 1–100 Å of the surface has been proposed and demonstrated.[9] The method has been labeled "scanning atomic force microscopy." This method furnishes information on the relief and local interatomic interactions at the surfaces of any substances with an atomic resolution. The report discussed the use of an atomic force microscope[10] based on a STM[5] to study the microscopic relief at the surface of an insulating single crystal of Al_2O_3 cleaved in the $\{10\bar{1}1\}$ plane and the observation of localized defects at the cleaved surface.

The combination of scanning tunneling microscopy with atomic force microscopy will apparently make it possible to obtain exhaustive information on the state and physical-chemical properties of the surfaces of many substances.

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