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Low-temperature scanning tunneling microscopy

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Soon after Gerd Binnig and Heinrich Rohrer invented the scanning tunneling microscope (STM) in 1982, Khaĭkin [1] developed the first STM in the USSR, which signalled the beginning of research in scanning tunneling microscopy and spectroscopy in our country. In his laboratory, Khaĭkin and collaborators [2] developed a number of microscopes used for various purposes: a STM with a wide field of view compatible with a scanning electron microscope [3]; a simple high-vacuum STM [4]; a high-vacuum STM with its sharp tip positioned within a range of several millimeters along the three coordinate axes [5], and a low-temperature STM submerged into a transport Dewar vessel containing liquid helium [6].

The logical development of this work was the production of a cryogenic high-vacuum installation used in scanning tunneling microscopy [7, 8]. The need for low-temperature scanning tunneling microscopy stems primarily from the fact that many phenomena and processes, such as superconductivity, the transition to a state with charge density waves, magnetic ordering, and sorption of gases, are realized only at very low temperatures. The cooling of the sample makes it possible to eliminate the thermal fluctuations of the atomic terrace boundaries, namely, fluctuations that sometimes already manifest themselves at room temperature [9]. Even for research that can be done at room temperature, the cooling of STM to helium temperatures proves to be effective since in this case the thermal drift of the device is eliminated, i.e. for all practical purposes it is zero.

Usually low-temperature high-vacuum devices employ costly industrial ultrahigh-vacuum systems augmented by cryogenic insertions (see Volodin's review [10]). The present author used a different approach and placed the STM in a cavity whose walls were cooled to liquid-helium temperatures, which automatically solves the problem of achieving ultrahigh vacuum. This method makes it possible not only to maintain the necessary conditions for conducting the experiments but also to eliminate the problem of poor thermal contact between the sample and the liquid helium in the vessel by feeding gaseous helium into the chamber. According to observations, the presence of helium has no effect on the results of experiments involving scanning tunneling microscopy and spectroscopy.

The apparatus uses an STM [5] with a sample holder that allows *in situ* heating up to 500 – 600 K with a heater power amounting to approximately 1 W [11]. To remove heat from the microscope in the event of prolonged annealing, we used a copper heat conductor and a mechanical heat switch connecting the microscope with the liquid-nitrogen bath. In this way the heat load on the vessel with liquid helium could be reduced to the acceptable level of 0.1 – 0.2 W.

The apparatus was used to study the structure of a surface of Bi formed by *in situ* cleavage (Fig. 1). It was found that, for cleavage of the crystal at low temperatures, atomically smooth terraces with straight boundaries oriented strictly along atomic rows are usually formed [12, 13]. This is an indication that there is a certain 'inertia' in the motion of a terrace boundary as the crystal is destroyed.

It was also found that the atomically smooth portions do not possess strict translation symmetry, since on the perfect atomic pattern some relief is superimposed with a random structure and characteristic dimensions in the plane amounting to several interatomic distances. Accordingly, the current – voltage characteristics vary from point to point over the surface. This suggests that the density of the electron states is nonuniform. Probably, these features are related to the presence of defects beneath the surface, which are generated in the process of crystal cleavage [14]. The nonhomogeneity of the surface is retained when the sample is heated to virtually the melting point, which makes it possible to estimate the activation energy of the defects at 1.5 – 2 eV. Such values are typical of vacancies.

The most interesting and unexpected phenomenon is the emergence of twin microlayers of quantized width (see Fig. 1). Their width is determined by the fact that the atomic layers in the microlayer that are inclined (at a small angle of 2.34°) to the layers in the rest of the crystal, which are oriented at right angles to the trigonal axis, are 'matched' at the boundaries. Only the uppermost layer 'matched' with the matrix on one side forms a step of height 0.2 nm on the other side [15, 16]. According to the results of measurements of current – voltage characteristics, in a region whose width is one to two atomic rows near the step, a one-dimensional conductor forms with a concentration of conduction electrons much higher than on the rest of the surface. A similar phenomenon is also observed near the boundaries of ordinary terraces.

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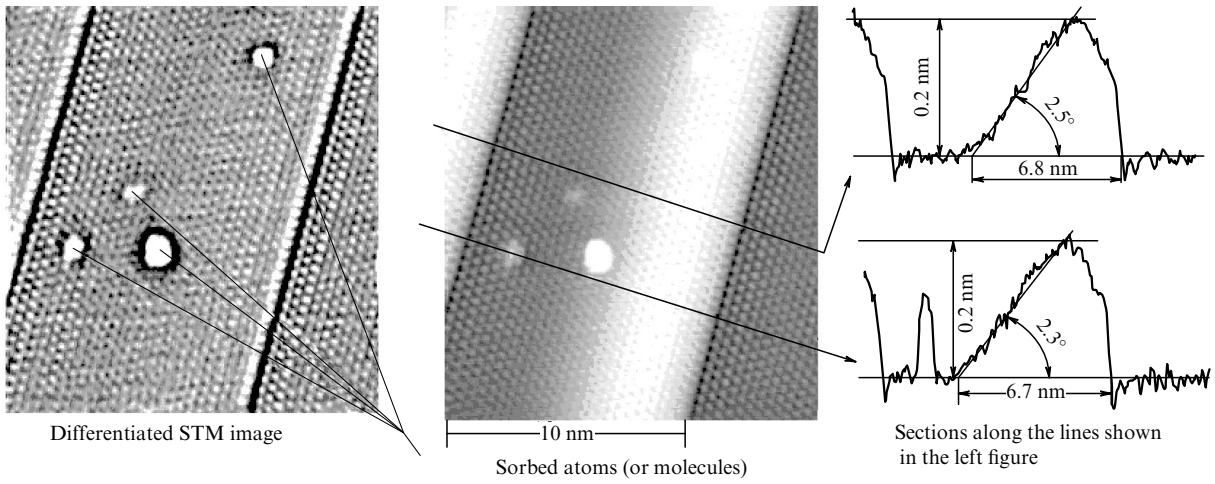

Figure 1. STM image of a portion of the Bi surface with a twin microlayer (central figure). To emphasize the atomic structure, the image was subjected to a two-dimensional Fourier transformation, the spectral components corresponding to the atomic structure were multiplied by four, and an inverse Fourier transformation was performed. The left figure depicts the differentiated initial image in which the atomic structure is also clearly visible without a Fourier transformation. The right figure depicts the sections of the image along the corresponding lines. One of these passes through a sorbed atom, which makes it possible to estimate the instrument function of the STM. The slope of the flat segment of the layer coincides, to within the measurement error, with the angle between the trigonal cleavage plane and the plane of the twin outcrop. This suggests that the layer is a twin one.

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Autoemission cathodes (cold emitters) on nanocrystalline carbon and nanodiamond films: physics, technology, applications

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An autoemission cathode is defined as a source of electrons whose principle of operation is based on the phenomenon of field emission, i.e. the tunneling of electrons through the potential barrier at the solid – vacuum boundary by the action of an applied electric field. The probability of such tunneling is dictated by the height of the potential barrier (the electron work function) and the strength of the applied electric field. The work function is determined by the fundamental properties of the material and amounts to 4 – 5 eV for most metals, while to generate an electron emission current that can be used in practice the electric field strength must be of order 10^7 V cm^{-1}.

The common approach to generating electric fields of such large strengths is to employ the effect of amplification of an electric field near microtips. Hence the traditional way of developing autoemission cathodes is the generation of a field of identical microtips at the surface of metallic or silicon cathodes [1]. At present many laboratories on all continents are developing this approach, using various variants of production of the microtip structures. However, this direction of research has a substantial drawback: the production of microtip structures requires using submicrometer technology, with all the consequences that follow from this. Furthermore, the use of traditional metals or silicon leads to rapid decline in their emission properties as a result of sputtering and chemical degradation even in a high vacuum.

An alternative approach to developing autoemission cathodes is to search for materials in which electron emission currents are generated even in relatively low electric fields of order 10^5 V cm^{-1} (10 V μm^{-1}). Among the known materials that, on the one hand, possess this property and, on the other, can be used in applications, carbon-based films are among the most studied (so far diamond-like films and carbon nanotubes have produced the best results) [2].

In this report we describe the production and investigation of a new carbon-based material with exceptionally good electron emission characteristics. The material consists of thin films that can be deposited on conducting substrates or insulating substrates by the plasma gas-phase deposition method. Here, the plasma was excited by a dc glow discharge [3]. What is remarkable is that the physical properties of the deposited carbon-containing film vary substantially depending on the plasma-excitation regime. In particular, the