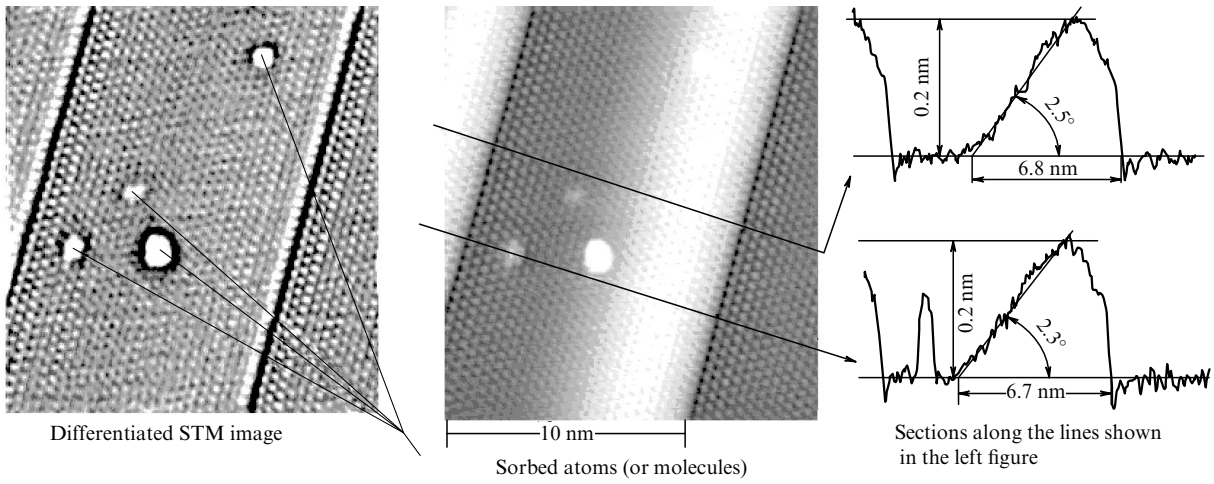

Figure 1. STM image of a portion of the Bi surface with a twin microlayer (central figure). To emphasize the atomic structure, the image was subjected to a two-dimensional Fourier transformation, the spectral components corresponding to the atomic structure were multiplied by four, and an inverse Fourier 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.

2. Khaĭkin M S, Volodin A P, Troyanovskiĭ A M, Edel'man V S *Prib. Tekh. Eksp.* (4) 231 (1987)
3. Volodin A P, Stepanyan G A, Khaĭkin M S, Edel'man V S *Prib. Tekh. Eksp.* **32** (5) 185 (1989) [*Instrum. Exp. Tech.* **32** 1180 (1989)]
4. Edel'man V S *Prib. Tekh. Eksp.* **32** (4) 149 (1989) [*Instrum. Exp. Tech.* **32** 901 (1989)]
5. Edelman V S et al. *J.Vac. Sci. Technol. B* **9** 618 (1991)
6. Al'tfeder I B, Volodin A P, Khaĭkin M S *Prib. Tekh. Eksp.* **32** (5) 188 (1989) [*Instrum. Exp. Tech.* **32** 1184 (1989)]
7. Khlyustikov I N, Edel'man V S *Prib. Tekh. Eksp.* (1) 158 (1996)
8. Edelman V S, Khlyustikov I N *Czech. J. Phys.* **46** (Suppl., Pt. S5) 2839 (1996)
9. Troyanovskiĭ A M, Edel'man V S *Pis'ma Zh. Eksp. Teor. Fiz.* **60** 104 (1994) [*JETP Lett.* **60** 111 (1994)]
10. Volodin A P *Prib. Tekh. Eksp.* (6) 3 (1998) [*Instrum. Exp. Tech.* **41** 745 (1998)]
11. Edel'man V S *Prib. Tekh. Eksp.* **37** (4) 203 (1994) [*Instrum. Exp. Tech.* **37** 528 (1994)]
12. Troyanovskiĭ A M, Edel'man V S *Poverkhnost'* (2) 51 (1998)
13. Troyanovskiĭ A M, Edel'man V S *Kristallografiya* **44** 336 (1999) [*Crystallogr. Rep.* **44** 300 (1999)]
14. Troyanovskiĭ A M, Edel'man V S *Zh. Eksp. Teor. Fiz.* **115** 2214 (1999) [*JETP* **88** 1212 (1999)]
15. Edelman V S *Phys. Lett. A* **210** 105 (1996)
16. Edelman V S et al. *Europhys. Lett.* **34** 115 (1996)

PACS numbers: 79.60.Jv, **79.70.+q**, **85.45.–w**, 85.60.Pg
DOI: 10.1070/PU2000v043n09ABEH000808

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

A T Rakhimov

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

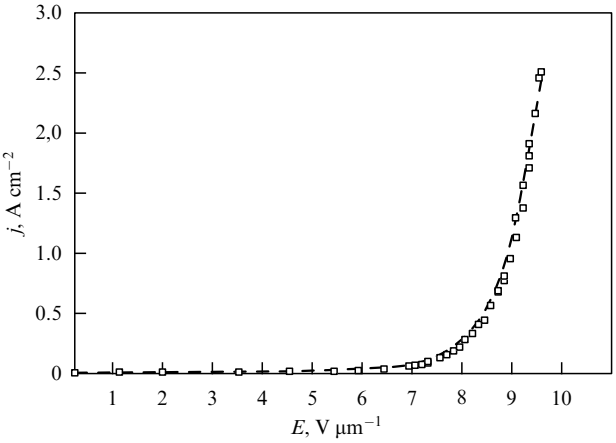

Figure 1. Current – voltage curve demonstrating the exceptionally high field-emission currents.

regimes found in the process of research were such that the deposited films proved to be highly effective emitters [4, 5]. The emission characteristics of the deposited films were measured by a wide-aperture diode tester described in detail in Ref. [6].

Figure 1 depicts a typical current – voltage characteristic that represents the electron emission current density averaged over the sample's surface area as a function of the electric field strength in the diode gap. The sample with the deposited film is the cathode, and a glass plate covered by a layer of indium and tin oxides and a luminophor layer is the anode. The gap between the anode and cathode varied from 100 to 500 μm, and the linear dimensions of the samples varied from 1 to 5 cm.

Figure 1 shows that the emitters guarantee the production of electron emission currents from large surfaces with an average current density up to 2.5 A cm^{-2}. Notice that the majority of the existing thermal cathodes are unable to generate such high currents.

Figure 2 shows a photograph of the luminescence of the anode screen as a result of electron bombardment of the screen. Clearly, the emitters are distributed with a high degree of spatial uniformity.

In addition to the study of the emission characteristics proper [5], a detailed investigation of the newly discovered material was also carried out by the methods of scanning electron and tunnel electron microscopy [7, 8] and by the methods of Raman and X-ray spectroscopy. It was found that the surface structure of the films produced in the process of gas-phase deposition is highly micononuniform in space, i.e. the phase composition, the local work function, and the surface relief are nonuniform.

For example, take the material that in phase composition is most likely to be characterized as micrographite. Figure 3 is a micrograph of the surface of a sample of this material, made using a scanning electron microscope.

The micrograph shows that the material produced as a result of deposition is, on the microscopic level, a ribbed structure with a density of several ribs per square micrometer. The typical thickness of the microribs is several nanometers, and their typical length is about one micrometer. The investigations showed that notwithstanding the apparent brittle surface structure, the material is characterized by a high adhesion to various substrates and is destroyed only if the applied fields are stronger than 30 V μm^{-1}. X-ray

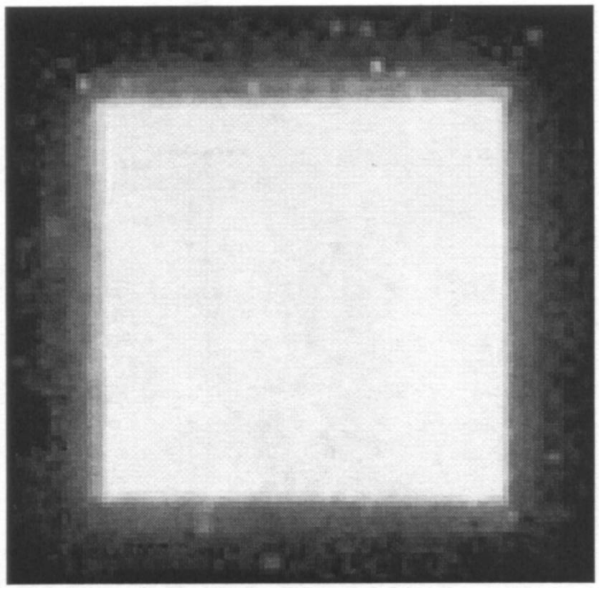

Figure 2. Luminescence of a 20 × 20 mm^2 luminophor screen in the diode tester produced by a 40-mA emission current and a 5.4-V μm^{-1} electric field.

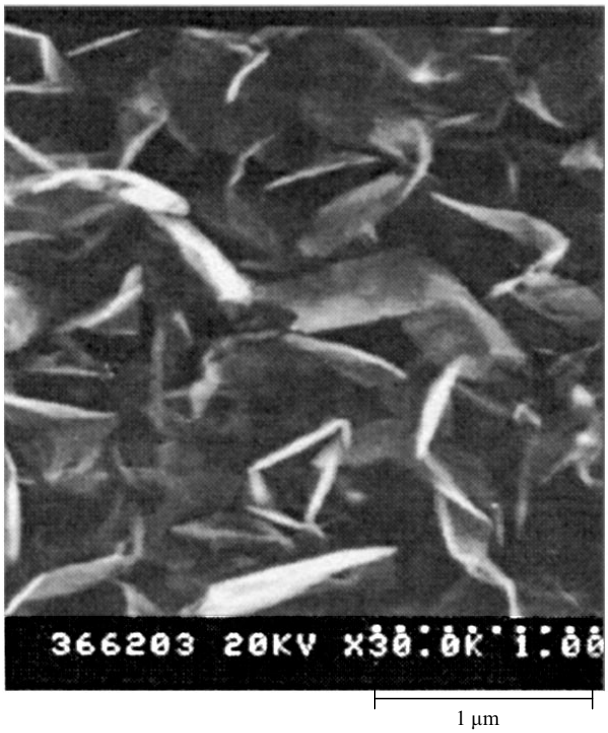

Figure 3. Micrograph of a portion of the surface. The bright dots in the lower part of the figure indicate a ruler with a total length of 1 μm.

structural analysis and Raman spectrometry have shown that the material produced may be classed as a micrographite with crystallite sizes ranging from 50 to 70 Å.

To establish how the indicated surface microrelief is related to the local emission properties, a special method that uses a scanning tunnel electron microscope was developed [7, 8]. The main result of this investigation was the proof of the fact that the new materials have a record high density of electron emission centers, which, as is known, opens the

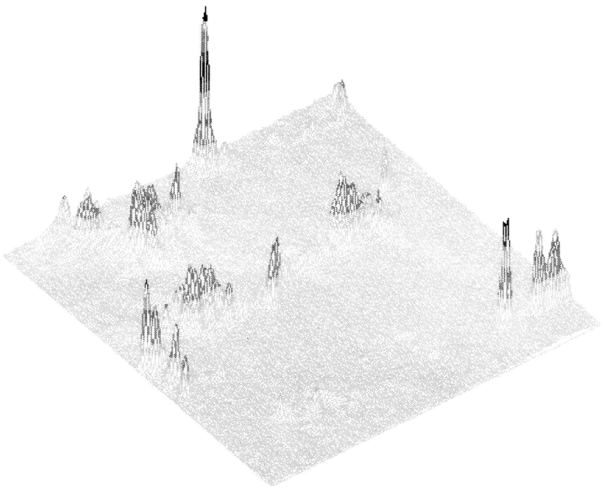

Figure 4. Map of the distribution of electron emission currents over a 0.6×0.6 μm^2 arbitrary area of the surface. The map was produced using a scanning tunnel electron microscope operating in the emission regime [8].

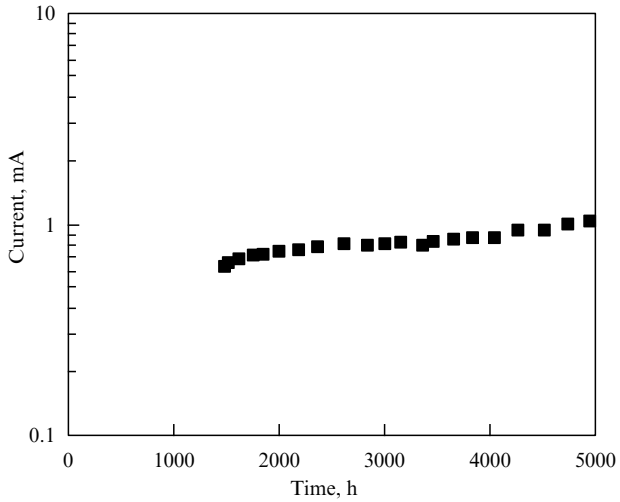

Figure 6. Time variation of the field-emission current (the section from 1400 to 5000 h is shown) measured for a sealed-off vacuum diode with a residual gas pressure of 10^{-8} Torr [9].

possibility of using these autoemitters in the most perfect modern flat displays with a high resolution. Figure 4 depicts the map of the electron emission currents over a 0.6×0.6 μm^2, which demonstrates an exceptionally high density of emission centers.

It should be emphasized that the range of possible applications of the new autoemitters is extremely broad: from devices of vacuum electronics to bright sources of light of various purposes. One of the most promising applications, nonetheless, is the fabrication of flat field-emission displays with parameters highly competitive with those of modern cathode-ray tubes used in TV sets and monitors. In this connection it must be noted that the new technology of depositing film emitters guarantees not only uniform deposition of the films onto the substrate surface (see Fig. 2) but also their selective deposition onto a specified region of the substrate. This provides a real possibility of forming a field-emission source of an arbitrary, controlled geometry.

Figure 5 depicts the micrographs of a luminophor screen (the same screen as in Fig. 2), in which the cathode is a dielectric substrate with metallic strips of varying width deposited on it. A field-emission film was deposited onto this substrate by gas-phase deposition. The micrographs demonstrate the possibility of selectively depositing the emissive films. Figures 5a and b correspond to the case where the emissive film is deposited only on the metallic strips. Figure 5c shows a micrograph made in similar conditions but with selective deposition of the emissive film within the metallic strips.

In conclusion it must be noted that the new carbon-containing material is stable both mechanically and chemically and retains the acquired field-emission characteristics for a long operating time. For instance, the time variations of the field-emission parameters of the new autoemission cathodes have been studied in a number of laboratories in the United States (Oxford Instruments, Sarnoff Labs, and others) [9]. It was found that our autoemitters can operate for

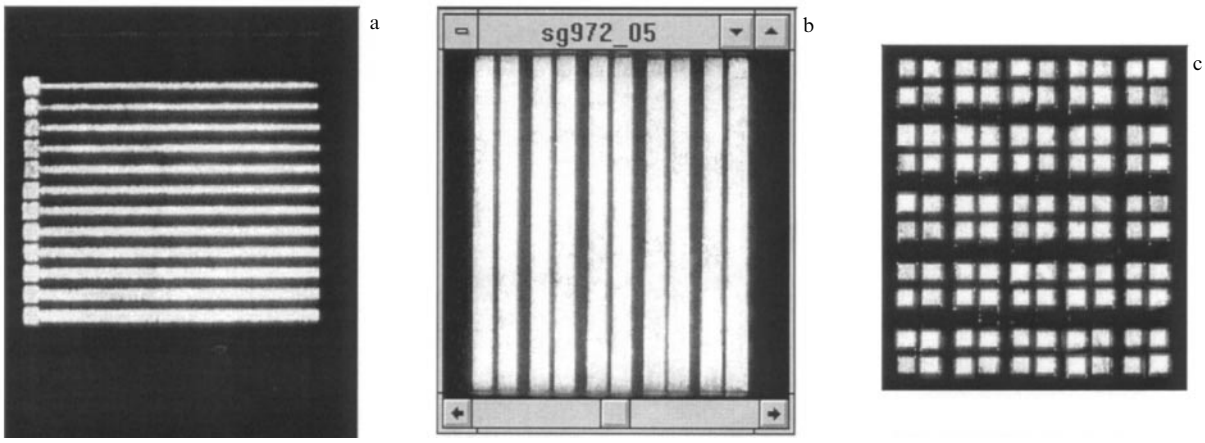

Figure 5. Samples of micrographs of a luminophor screen in a diode tester, obtained through the use of an autoemitter with a selective deposition of the film material. (a) Total area of the deposition region is 20×20 mm^2; the widths of the metallic strips are 20, 40, 60, 80, 100, 125, 150, 200, 250, 300, 350, and 400 μm, and the contact areas are 800×800 μm^2. (b) The total area of the deposition region is 33×37 mm^2, and the width of the metallic strip is 2 mm. (c) The total area of the deposition region is 33×37 mm^2, and the area of each spot is 2×2 mm^2.

more than 5000 h without substantial degradation of the emission characteristics. This is illustrated in Fig. 6, which shows the results of measurements made by Busta et al. [9] with an electron emission current density of about 1 A cm^{-2}.

References

1. Spindt C A, Brodie I, Humphrey L *J. Appl. Phys.* **47** 5248 (1976)
2. Wei Zhu (Ed.) *Fundamentals of Vacuum Microelectronics* (New York: Wiley & Sons, 2000)
3. Polushkin V M, Polyakov S N, Rakhimov A T et al. *Diamond Related Mater.* **3** 531 (1994)
4. Rakhimov A T et al., US Patent No. 6042900 (appl. 12.03.96)
5. Blyablin A A et al., in *Proc. of the XI Intern. Vacuum Microelectronics Conf.* (Esheville, 1998) (Technical Digest (DLC) 99110922) (Piscataway, N.J.: IEEE, 1998) p. 234
6. Rakhimov A T, Seleznev B V, Suetin N V, Timofeev M A, in *Proc. Applied Diamond Conf.* 11 Suppl. (Gaithersburg: NIST5692, 1995)
7. Rakhimov A T et al., in *Proc. of the XI Intern. Vacuum Microelectronics Conf.* (Esheville, 1998) (Technical Digest (DLC) 99110922) (Piscataway, N.J.: IEEE, 1998) p. 224
8. Rakhimov A T, Suetin N V, Soldatov E S et al. *J.Vac. Sci. Technol. B* **18** 76 (2000)
9. Busta H H, Espinosa R J, Rakhimov A T et al. *Solid State Electronics* (Special Issue on Vacuum Microelectronics) (2000) (in press)

PACS numbers: **07.90.+c**, **81.10.–h**, 81.10.Fq
DOI: 10.1070/PU2000v043n09ABEH000809

Development of new-generation equipment for crystal growth from melt. The RAS Experimental Factory of Scientific Engineering in the novel economic conditions

V A Borodin

1. Introduction

The present report discusses the results in developing technologies for growing crystals of a specified shape and equipment for single-crystal growth by the Czochralski and Stepanov methods and by modifications of the Stepanov method developed at the Institute of Solid-State Physics of the Russian Academy of Sciences (Chernogolovka). In addition, the main areas of development of the Experimental Factory of Scientific Engineering (EFSE) of the Russian Academy of Sciences are covered.

2. Shaping of crystals from melt and the equipment for crystal growth

The standard Stepanov growth allows the production of profiled crystals with a given shape of cross section along the growth axis. However, various technical applications also require crystals with more complicated shapes that could have been grown directly from melt if a technology for changing the shape of the cross section of the growing crystal directly during growth existed.

The research conducted at the Institute of Solid-State Physics, RAS since 1982 has led to two main technologies in this field. The first, which became known as variational shaping [1, 2], ensures discrete changes in the shape of the cross section of the pulled profile. The second technology, known as local dynamic shaping, makes it possible to grow complex crystalline products with the shape of the lateral surface of the crystal changing continuously according to a program [3–7]. Previous papers (see Refs [1, 2, 4, 6, 7]) discussed complex sapphire products grown by these methods, including products of hemispherical shape, in the shape of hollow cones, etc. This research made it possible to build new growth equipment that has no analogs, a crystallization center, so to say, that permits the following [4, 6]:

(a) growth of crystal with a constant cross section (the common Stepanov growth);

(b) discrete changes in the shape of crystals during growth (variational shaping);

(c) continuous changes (according to a given program) in the shape of the lateral surface of solid and hollow bodies of revolution (local dynamic shaping), and

(d) growth of crystals with a helical relief on the lateral surface.

Growing crystals of complex shapes using variational shaping and local dynamic shaping has shown that it is possible to construct a new promising technology that ensures three-dimensional changes in the shape of the growing crystal during its growth.

The experience in growing single crystals by the Czochralski, Stepanov, variational shaping, and local dynamic shaping methods has revealed that raising the quality of the crystals, increasing the productivity of manufacturing crystals by increasing the yield of acceptable crystals, and introducing new crystallization-center type technologies have no meaning without building new equipment for crystal growth. On the one hand, the new-generation equipment must be precise so as to allow for active investigations in growing various types of crystals and profiles and must provide the possibility of establishing the effect of various parameters of the growth process on the quality of the crystal. On the other hand, such equipment must comply, in reliability and operating characteristics, with commercially produced equipment. One of the main criteria for compliance with this dual requirement is the presence in the growth facility of a modern hardware–software complex (HSC), which incorporates data acquisition, computational, and controlling functions.

The data acquisition and computational functions of the HSC in the newly developed ROSTOKS-01 facility amount to acquiring and initial processing of the analog and digital data, displaying and recording the data for the operating staff, generating technological signals, detecting potential emergencies, recording events, storing data in an archive, and keeping a log of all the data.

The controlling functions of the HSC amount to automatic control, logical control, and the possibility of remote control. The control program NIKA2000 is written in Microsoft Visual C++ 6.0 language and operates in Windows95/98/NT. The block construction of the program ensures its rapid adaptation to different methods of crystal growth from melt and to new peripherals. The program consists of the following separate blocks: the block for forming the influx of data from the crystal growth process, the block responsible for manually controlling the growth process and for controlling the peripherals according to fixed regimes, and the block responsible for the computer simulation of the growth process and the automatic control through the power channel.

The automated system with negative feedback incorporates the algorithms needed to estimate the state of the object