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On the Current State of Field-Emission Electronics

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Abstract—The current state of field-emission electronics is reviewed and the basic types of field-emission cathodes (FECs) are analyzed (the results are presented in the form of diagrams). Special attention is paid to FECs made of carbon materials, which, in our opinion, are the most promising direction in the evolution of field-emission electronics. FEC utilization in modern electronic devices is illustrated by several examples. The main sections of the paper are devoted to analyzing the problems and prospects of FECs and field-emission electronics.

Keywords: field electron emission, field-emission electronics, vacuum micro- and nanoelectronics, carbon materials, carbon nanostructures

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INTRODUCTION

Field electron emission is the most economical kind of free-electron emission, making it possible to create new generations of effective electronic devices with enhanced technical and consumer features [1]. This is associated with the following field-emission properties: the absence of a filament, a high current density, resistance to temperature fluctuations, zero lag, exponentially high steepness of the volt–ampere characteristics, and low sensitivity to external radiation.

PRINCIPLES OF FIELD ELECTRON EMISSION

In essence, the field-emission phenomenon is electron tunneling through a potential barrier on a solid surface. In this case, there appears a region of space beyond the body in which an electron can exist with a total energy equal to that observed inside the body. Thus, field emission arises from the wave properties of electrons [2].

Electron tunneling becomes possible because a potential barrier bends under the action of an external electric field of sufficiently high level (Fig. 1) [3].

The usual threshold value of the electric field needed to generate significant field electron emission is $\sim 10^8$ V/m.

In the case of suitable operating voltages (0.1–10 kV), such an electric-field intensity can be achieved mainly by decreasing the curvature radius of the emitting-surface vertices, which should look like spikes, film microasperities, etc. with a curvature radius of up to 1 nm [1, 4].

FIELD-EMISSION CATHODES

Figure 2 presents an overview diagram of the basic classes of FECs [5].

The best studied tip FECs trace their origin to the discovery of the field-emission phenomenon in the 1930s [6, 7].

There are many methods for fabricating such cathodes: from chemical and electrochemical etching to ion treatment. The most widely used and simplest procedure for obtaining tip FECs is electrochemical etching in an electrolytic bath. These devices can be produced from practically any material and employed both in the entire range of field-emission investigations and in a number of practical applications [1, 8].

Tip FECs made of different materials possess approximately identical drawbacks, the main of which are small common currents at relatively high anode voltages and an unstable field-emission current in high “technical” vacuum. Below, the term technical vacuum is meant so as to include the device’s vacuum conditions at which the residual-gas pressure is $\sim 10^{-6}$–10^{-7} mmHg.

The aforementioned drawbacks of tip FECs are predominantly caused by their shape. When the emitting surface of FECs is bombarded with residual-gas ions, their microgeometry varies substantially due to both cathode sputtering and the surface migration of

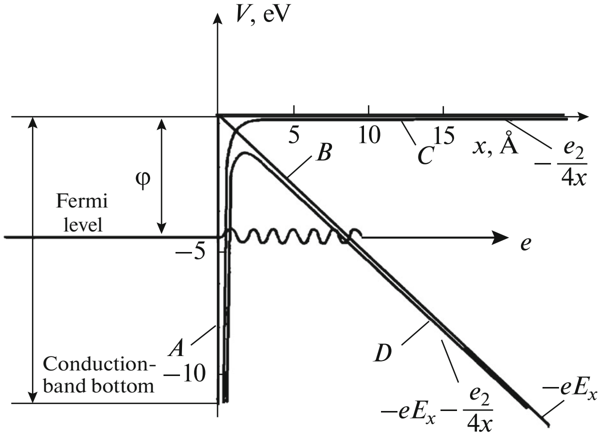

Fig. 1. Surface potential barrier generated at the metal–vacuum interface under the action of a strong electric field. Electron tunneling through the barrier is shown by the wavy line. Here, *A* is the metal surface, *B* is the potential barrier created by the applied electric field, *C* is the potential barrier at the metal–vacuum interface, *D* is the resultant potential barrier, *E* is the electric-field intensity, φ is the electron work function, and *e* is the elementary charge.

atoms. This leads to changes in the size and shape of the emitting surface, which are accompanied by field-intensity variations and an abrupt change in the field-emission current. For example, if the tip radius of a tip FEC is doubled, the field intensity is approximately halved, but the current density decreases by four to five orders of magnitude. In the case of technical vacuum, the operating life of tip FECs is about 1 h at a selected field-emission current of several microamperes, i.e., is clearly inadequate for practical applications.

The limited field-emission currents collected from tip FECs stimulated the development of multitip systems.

The most promising method for creating multitip FECs is photolithography with subsequent deep etching.

A huge step forward in the development of multitip FECs was the fabrication technology proposed by C. Spindt et al. (Fig. 3), which combined thin-film processing and electron-beam microlithography [9, 10].

Restrictions imposed on the applicability of multitip FECs are stimulating efforts to expand the technologies and materials of their fabrication.

In recent years, many publications concerning the production of multitip FECs based on metal oxides, e.g., ZnO and CuO [11] have appeared.

Another way of increasing the emitting-surface area and, consequently, the field-emission current is the utilization of sharp blades. The given approach was pioneered by W.D. Dyke in 1960 [12] and, in Russia, by Russian scientist E.G. Shirokov in 1965 [13].

FECs with sharp blades can be metallic and semiconducting. Modern multiblade silicon FECs are depicted in Fig. 4 [14, 15].

However, the wedge-like shape of FEC blades is a fundamental drawback because ion bombardment blunts their sharp edges, leading to a decrease in the field-emission current.

Departure from the wedge-like shape is accompanied by the appearance of film FECs. In this case, the radius of curvature, i.e., film thickness, remains fixed. Thus, FEC tips are not blunted upon ion bombardment. This effect is especially noticeable at small film thicknesses.

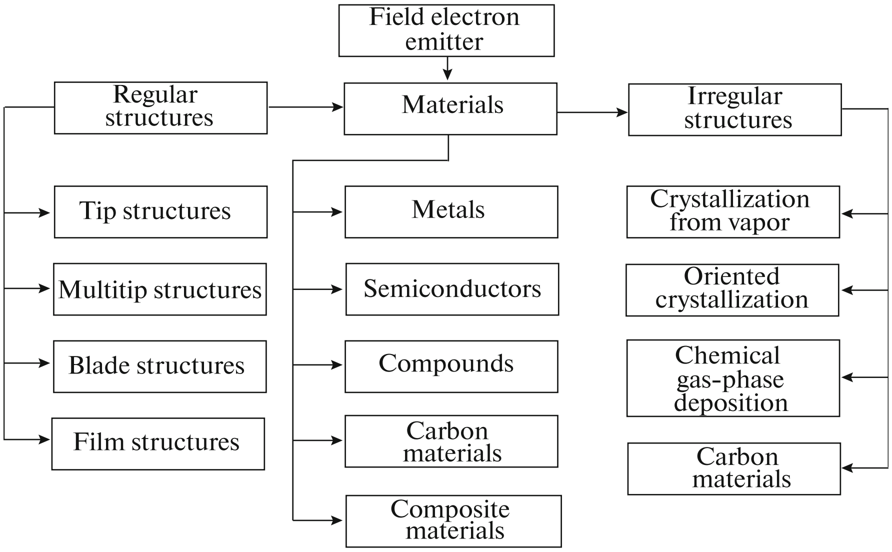

Fig. 2. Overview diagram of the basic classes of field electron emitters.

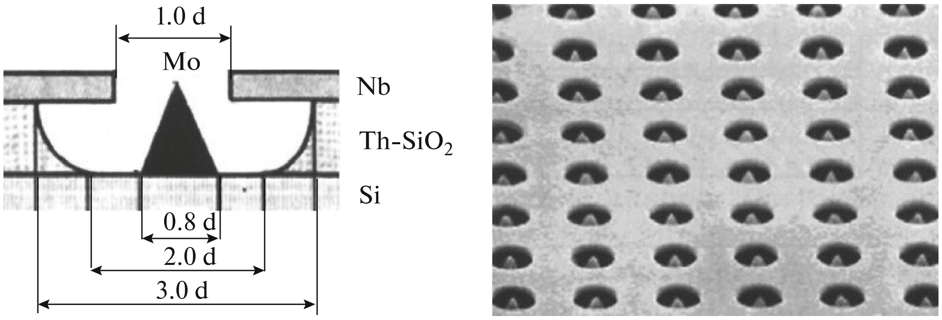

Fig. 3. Structure of the Spindt-type multitip FEC with molybdenum emitters (sizes are shown in micrometers).

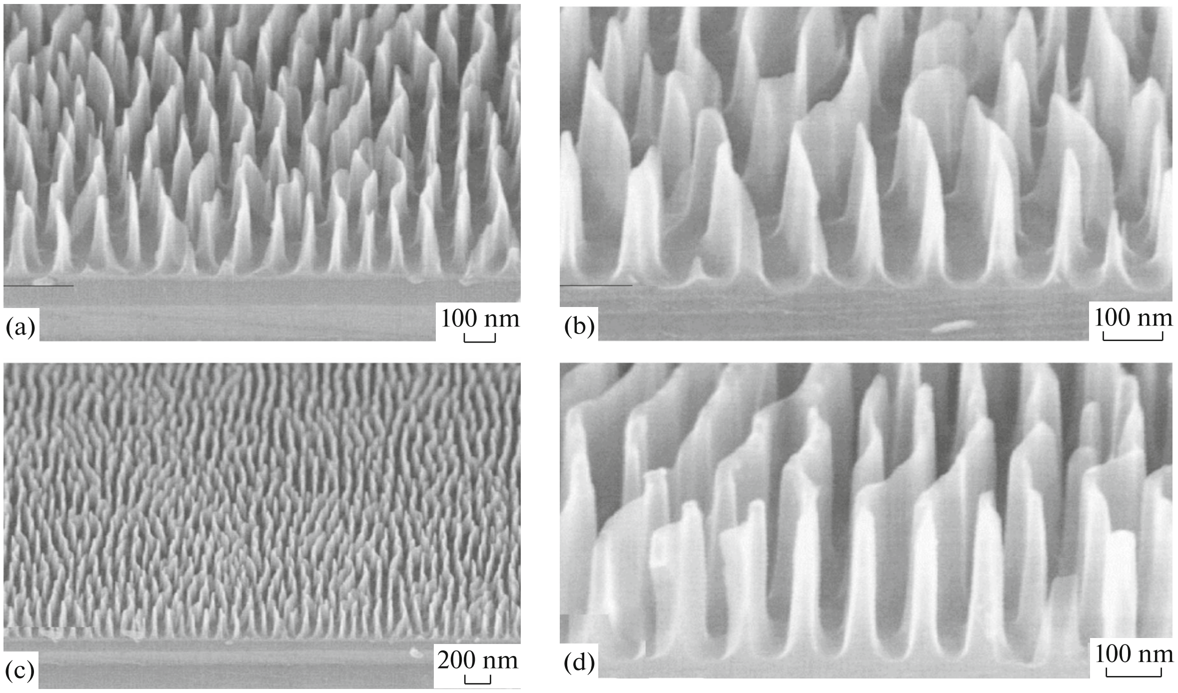

Fig. 4. Modern multiblade silicon FECs.

The material that is most suitable and very promising for implementation of this effect is graphene, the technology and studies of the field-emission properties of which are developing rapidly.

An evident advantage of film FECs over needle-like ones is that the emitting-surface area of the former is four to five orders of magnitudes greater than that of the latter. Therefore, the film-FEC load can be considerably decreased up to field-emission currents required for its stable operation.

Moreover, film FECs open up the possibility of increasing an anode's working area to a great extent, thereby decreasing the specific thermal load of the latter as compared to that inherent to needle-like FECs (at equal values of currents, anode–cathode distances, etc.).

Film FECs can be fabricated from both metals (via sputtering followed by substrate (i.e., rolled hyperfine foil) etching) and semiconductors and carbon materials (with the help of thin-film technology) [16].

Field-emission cathodes made of carbon materials. As was emphasized above, the main condition for creating an effective FEC is correct selection of the material. The publication of paper [17], where the comparatively stable operation of autoelectronic cathodes was indicated to be possible in a vacuum of ~10^{-6}–10^{-7} mmHg, initiated the development of the field emission of carbon materials. Afterward, this trend developed intensively all over the world and covered many types of carbon materials.

As applied to field emission, their classification is presented in Fig. 5.

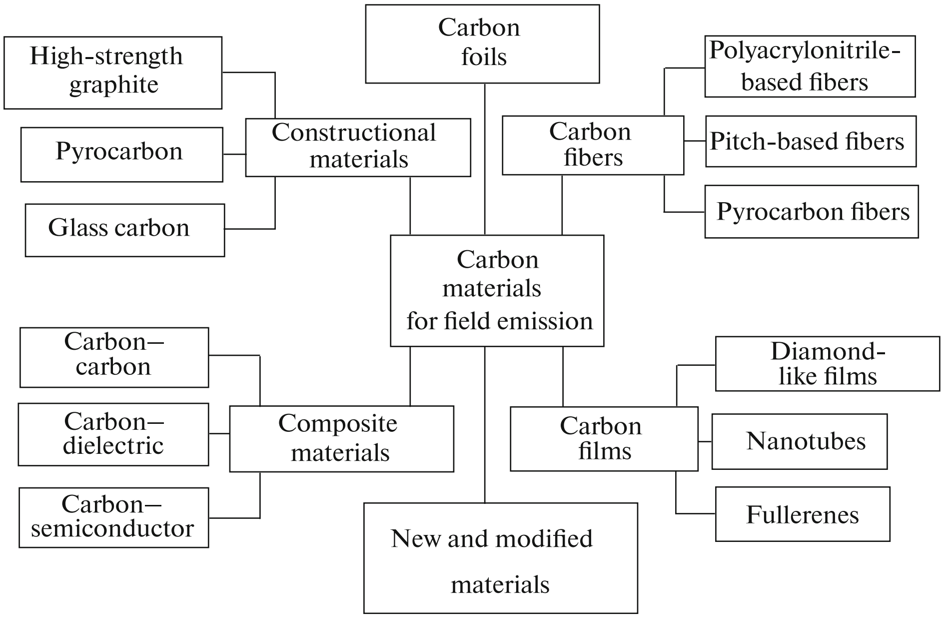

Fig. 5. Classification of carbon materials used in field-emission devices.

We have investigated the field emission of carbon materials for more than 35 years and, in this period, studied the field-emission properties of practically all types thereof [1, 18].

A brief conclusion made from these studies is that, nowadays, fibers, foils [19], nanotubes [20], and nanostructured films (Fig. 6) can be regarded as the basic carbon materials of FECs.

The structural variety of carbon (as is well known, this element supports the life of our planet) enables us to expect that, in the near future, technologies and carbon structures making it possible to create long-lived and stable FECs capable of operating in a vacuum of 10^{-6}–10^{-7} mmHg will be found.

APPLICATION OF FIELD-EMISSION CATHODES

A large amount of electronic devices with FECs has been developed to date. The majority of them are experimental, but some devices are already commercial products, e.g., low-power magnetrons with disk-shaped film FECs [21]. However, the latter cannot be deemed as field-emission equipment (Fig. 7a) because the FEC thereof is employed only to activate the magnetron.

One of the first officially fabricated field-emission devices was a field-emission display based on Futaba Spindt-type field electron cathodes with tips (Fig. 7b) [22].

An area of rapid progress in field-emission electronics is the creation of light sources with different radiation wavelengths. Various modifications of prototypes of white, red, blue, and green lamps [23–26] and the full-color module (192 lamps) of a stadium television system [27] are depicted in Fig. 8.

It is obvious that the range of devices under development is not confined by the above examples.

PROBLEMS OF FIELD-EMISSION CATHODES

Let us consider the cardinal problems of FECs inhibiting their wide application in electronic devices.

For any cathode thought of as a free-electron source, the main issue of practical applicability is to ensure the time and space stability of an emission current and the cathode durability.

Hence, work concerned with enhancing the field-emission current stability is versatile and is now performed in the following basic nine directions.

1. Creating ultrahigh vacuum in devices with FECs. Effects related to the ion bombardment of a FEC surface (cathode sputtering, surface migration, etc.) decrease sharply under the given conditions. In this case, the characteristic sizes of a FEC, e.g., the tip curvature radius, undergo extremely slow variations. This trend of improvement in the field-emission current stability is implemented in a complicated manner because not only the obtainment of an ultrahigh vacuum, but also its retention over a long period, meet with extreme difficulties. In the case of devices with a glass shell through which helium diffuses comparatively rather easily, this problem is scarcely solvable.

2. FEC heating with the aim of cleaning its surface and recovering the surface shape. It was ascertained that, in a strong electric field, FEC atoms migrate toward the tip center, thereby sharpening it. At room temperature, the activation energy needed for migra-

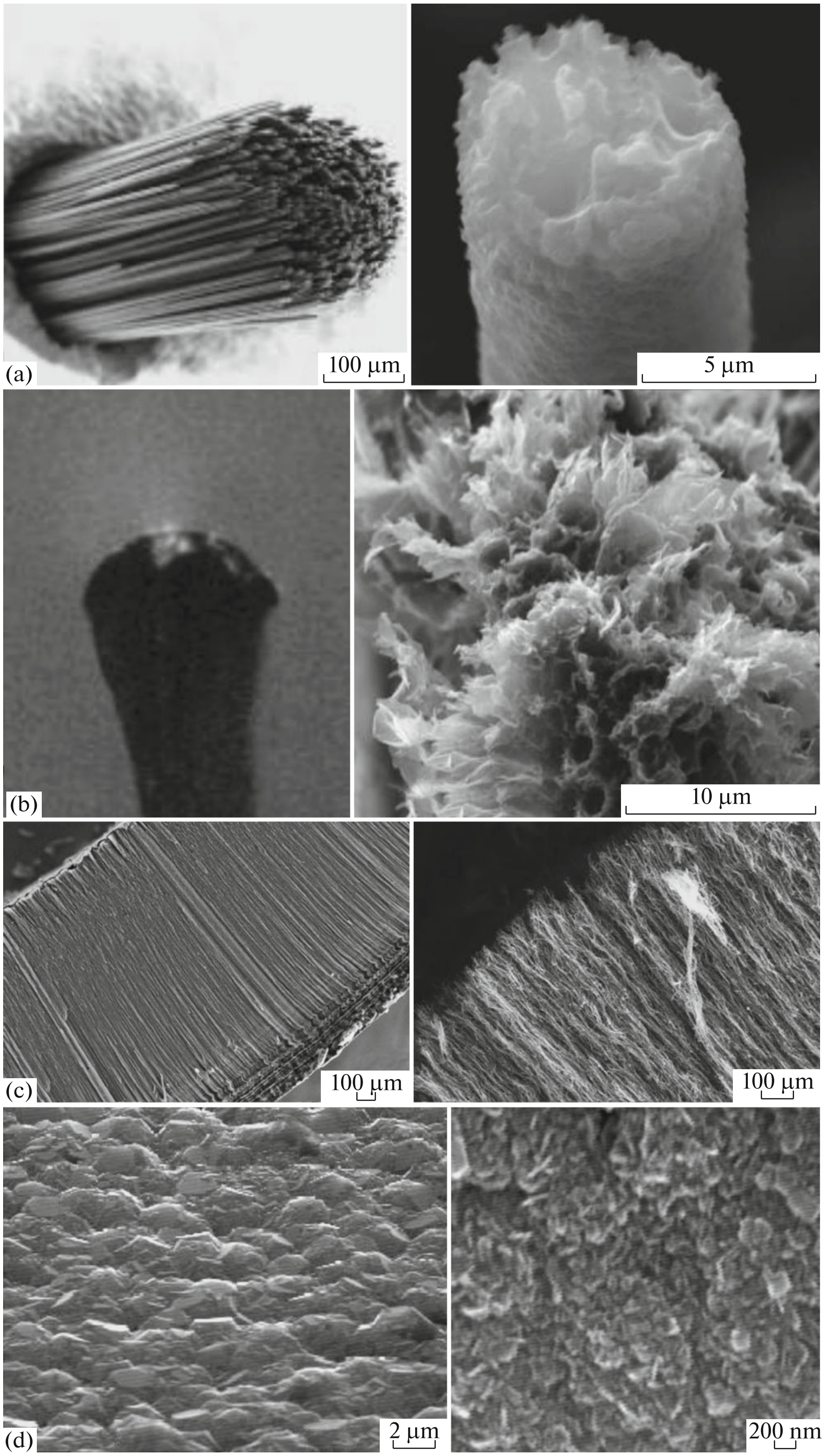

Fig. 6. Basic carbon materials of FECs: (a) fibers, (b) foils, (c) nanotubes, and (d) nanostructured films.

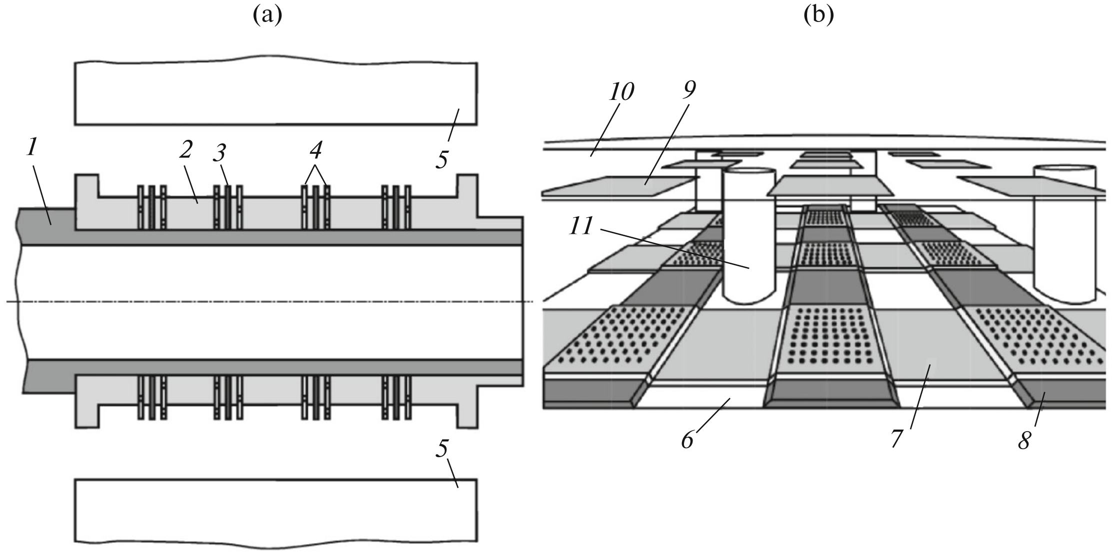

Fig. 7. Block diagrams: (a) magnetron with disk-shaped film FECs and (b) a flat display screen with Futaba cone-shaped FECs, which incorporate a guiding core *1*, secondary-electron emitter *2*, autoelectronic cathode *3*, dielectric films *4*, cylindrical anode *5*, cathode substrate *6*, controlling electrode *7*, cathode electrode *8*, phosphor *9*, anodic substrate *10*, and spacer *11*.

tion processes is delivered by residual-gas ions. When a tip is heated without a field, its blunting occurs under the action of surface tension forces. By alternating the cycles of FEC operation and “breaks” accompanied by heating, the service life can be increased by recovering the emitting-surface shape. In practice, such an operation mode is very inconvenient because the FEC structure and the device as a whole are complicated and a number of advantages thereof over hot cathodes disappear.

3. Employment of ion traps. The design of such a kind of devices was first proposed by M.I. Elinson et al. The results of studies indicate that the given devices enable a substantial decrease in the number of ions bombarding the working region of a tip emitter and, consequently, an increase in its service life. However, the use of ion traps and gates is not always possible in practice even at relatively large interelectrode spacings due to the complication of the structure of cathode assemblies. Such structures have not yet found wide practical applications.

4. Utilization of pulsed operating conditions. Numerous experiments demonstrated that the field-emission current is significantly more stable in the pulsed mode rather than in the continuous one. However, the utilization of the pulsed operation mode severely restricts the primary potential range of their applications.

5. Search for materials resistant to cathode sputtering. For this purpose, high-strength metals, namely, tungsten, rhenium, tantalum, and metal-like compounds from carbide and boride groups, have been investigated most thoroughly. As a result, it was demonstrated that FECs fabricated from a number of materials, e.g., rhenium and lanthanum hexaboride, exhibit a higher field-emission current stability than those of tungsten. In our opinion, this direction of increasing the current stability is promising, and its content must be expanded by adding the search for materials with a stable electron work function in technical vacuum.

6. Creating an artificial atmosphere of residual gases. M.I. Elinson was the first to suggest that an artificial atmosphere of residual gases (among which light gases (hydrogen and helium) are predominant) could be formed in unsoldered devices. It is known that light-gas ions are ineffective from the viewpoint of cathode sputtering. In practice, the creation of the foregoing atmosphere involves considerable difficulties. Under real conditions, the parts of electric-vacuum devices and their shell release gases slowly, but continuously, even at room temperature, thereby polluting the residual-gas atmosphere, the composition of which, in this case, will be actually unregulated.

7. Decrease in interelectrode spacing. Due to a decrease in the interelectrode spacing of electric-vacuum devices, the number of ions generated in the interelectrode volume decreases and, as a consequence, an emitter is bombarded with ions to a lesser extent. Moreover, a reduction in the operating voltage of the anode is observed. The latter more strongly decreases the ion-bombardment intensity because the ion energy decreases. For example, there are known practically implemented methods for attaining small interelectrode spacings (up to tenths and even hundredths of a micrometer). For electric-vacuum devices of wide practical application, we should apparently restrict our consideration to the interelectrode spacings of several tens of micrometers. A further decrease in the spacing generates difficulties arising from technical and physical causes even if there is no need to allow for the technical difficulties of maintaining the distances of tenths and hundredths of a micrometer during temperature fluctuations. Evidently, only diodes whose electrodes have small sizes can be created if the interelectrode spacings are small. The development of any current-controlled electronic device requires additional electrodes that must be located in the "cathode–anode" space. To create controlled electronic devices, the required interelectrode spacings are at least several tens of micrometers, which must be employed in practice.

8. Utilizing the specific emission stability of the field-emission current of semiconductors. Let us consider another direction of improving the field-emission current stability, which is related to the peculiarity of the emission characteristic of field-emission currents in semiconductors. This characteristic has a "saturation" area in the certain external-voltage range (or an external field intensity). In this region, the field-emission current depends very weakly on the potential-barrier penetrability, i.e., the FEC surface state. In other words, an adatom layer on the semiconductor FEC surface, which is formed during residual-gas adsorption, barely affects the field-emission current. Hence, the latter is stabilized. However, the current is weakly controlled in the saturation area. As a result, the cathode-assembly design is appreciably complicated.

9. Creating the statistically stable microstructure of emitting centers. The maximum amount of emitting centers that are uniformly distributed over the surface and almost identically contribute to the total emission current can be created on the surface of FECs made of semiconductors; i.e., a developed emitting surface can be formed. In this case, thanks to the internal structure of carbon materials, some emitting microasperities destroyed during ion bombardment are replaced by emitting centers with analogous parameters emerging from the material structure. As a result, the high long-term stability of field electron cathodes of the given materials is achieved under high technical vacuum inherent to unsoldered electronic devices.

Thus, the performed brief analysis of the known trends of enhancing the stability of the field-emission current demonstrated that even successful advancements in some of them does not solve the problem related to the creation of field electron cathodes with stable electron emission under technical vacuum or excludes the implementation of a number of clear advantages of such devices over hot cathodes. Naturally, this limits the interest of scientists (designers of devices) in the given kind of investigations. Hence, together with efforts in the aforementioned directions, it is reasonable to continue the search for new scientific directions to solve the field-emission current sta-

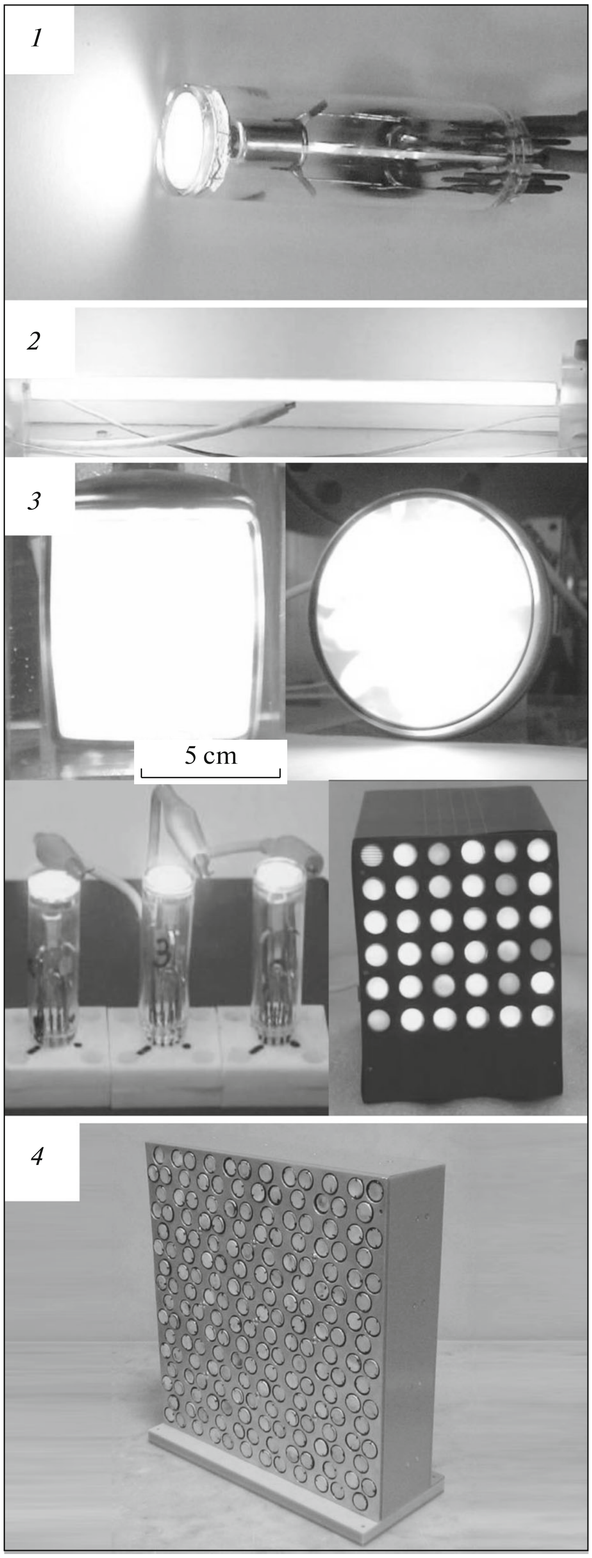

Fig. 8. Light sources: (*1*) external view of a lamp with a FEC composed of a carbon fiber beam, (*2*) cylindrical light source with end FECs, (*3*) various modifications of prototypes of white, red, blue, and green lamps and a photograph of the dynamic color illumination module of liquid-crystal screens, and (*4*) external view of the 8 × 8 pixel full-color video module (192 lamps).

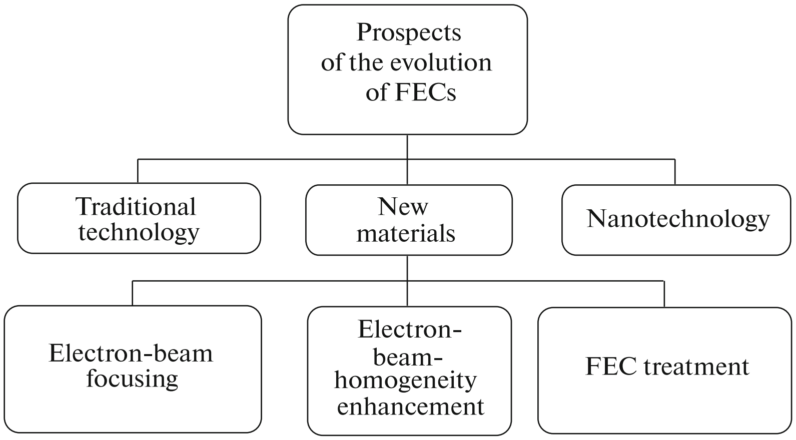

Fig. 9. Prospects of the evolution of FECs.

bility problem, which is the key problem in this field of field-emission electronics.

PROSPECTS OF FIELD-eMISSION eLECTRONICS

Finally, let us consider the prospects of the development of field-emission electronics. In this context, it is necessary to advance traditional technologies and develop new approaches with the aim of creating new generations of electronic devices.

Figure 9 presents the guidelines of the evolution of field electron cathodes.

The development of existing technologies implies that not all the possibilities of these technologies have been implemented. For example, due to the development of Spindt field electron cathodes and lithography technologies, the tip density can be increased up to 10^8 tip/cm^2 [28]. In this case, the intertip distance is 1 μm (the control-electrode diameter is 0.35 μm). In the given configuration, a standard cathode 1 mm in diameter comprises approximately 785000 tips. At an average current load of 1 μA, it is possible to obtain a pulse current of 1 A and its density of about 130 A/cm^2, which are more than enough for the majority of electric-vacuum devices.

The technology of Futaba field electron cathodes found application in microwave devices and flat display screens was sufficiently well developed. Hence, they are promising for occupation of the niche of special devices in which vacuum higher than 10^{-9} mmHg can be attained.

As was indicated above, an increase in the common level of the current collected from field electron cathodes can be achieved by increasing the total emitting area of cathodes during their parallel operation, i.e., if a large number of separate emitters simultaneously make their contributions to emission. However, a simple increase in the number of emitters is not accompanied by a proportional increase in the emission current because the height and curvature radius of emitters have a wide spread and they shield each other.

Hence, limiting resistors are employed in field electron cathode systems. They can be implemented either as external resistors or as structural layers with a relatively high resistance.

This resistor plays the role of a negative feedback that stabilizes the field-emission current and hinders the appearance of breakdowns.

Hence, the optimal FEC structure is built around isolated fragments with individual limiting resistors. Moreover, due to this approach, the currents of separate fragments are set equal to each other. And finally, there is a way that can be attained due to technological expansion and is implementable even at the current stage. It is assumed that a large-area FEC can be divided into small isolated fragments, each of which is connected in series with a transistor serving as a controlling limiting resistor. In this case, the field-emission current can be made completely uniform within the FEC area and controlled by the same transistors.

The natural trend of the evolution of field electron emission consists in developing and synthesizing new materials and structures with better field-emission properties. Since the number of pure elements is restricted and the time of refractory metals, carbides, etc. has already passed, the main breakthroughs (discoveries) must be expected upon the creation of different composite materials and new structures.

First of all, such a new material as graphene is noteworthy (Fig. 10, panel *1*). The field-emission investigations of graphene structures are gaining momentum worldwide, and we suppose that they can lead to the creation of practically important FECs.

As an example, let us now consider a carbon nanocomposite material developed in Saint Petersburg [30], the major elements of which are diamond powder and pyrographite. Such a material contains diamond particles surrounded by an electroconducting sp^2 carbon matrix. On the whole, diamond powder with an average particle size of 5 nm was employed. The pores between the diamond particles were filled via a special chemical vapor deposition process. In so doing, the sp^2/sp^3 ratio and the pyrolytic-layer thickness are rather simply controlled (Fig. 10, panel *2*).

During the experiments, the sp^2/sp^3 ratio and the pyrographite-layer thickness varied from 0 to 0.5 and 0 to 1 nm, respectively. In this case, the conductivity was in the range of 10^7–0.1 $1/\Omega$ m^2.

Moreover, two phases (diamond and pyrographite) of the material decrease the electron work function significantly due to the bending of the energy bands of pyrographite thin films. FECs based on the given composite material (with a porous structure and a relief surface of specified shape) were proposed.

In the last few years, the problems of low-field electron emission from nanostructured materials have attracted the increasing interest of researchers all over the world.

Low-field electron emission originates from a nanoscale electrically conducting object (material nanophase) surrounded by an insulating phase or vacuum. The high emittance of the given nanoobject is determined by both the geometric factor of electric-field amplification and a reduced potential barrier for electron tunneling in vacuum from this region. The latter is related to the manifestation of the fundamental property of solids: the physical (electric, magnetic, optical, acoustic, etc.) characteristics of material nanoparticles differ from the "macroscopic" properties of a substance [31, 32].

When quantum-dimensional effects begin to play a dominant role in the substance, the electron energy states become discrete, and emitted electrons are characterized by a narrow energy spectrum. In accordance with estimates, such behavior is observed at a nanoobject size of less than 5 nm. In the case where the distances between nanoemitters are comparable with the coherence length, the interaction of nanoemitters must manifest itself and interference of the emitted electron-beam should occur if the distance is 10 nm or the matrix density reaches ~10^{12} element/cm^2.

It should be noted that, in "self-organizing" carbon nanostructures, e.g., nanocrystalline diamond films (Fig. 10, panel *3*), which are disordered systems to a considerable extent, nanoobjects are formed in certain surface regions depending on many uncontrolled factors. This implies that, in this case, the creation of electron nanoemitters with specified parameters is practically unfeasible.

Measurements of the FEC durability and the stability of the electron current emitted by them demonstrated that, in the cathode-fabrication process, heavy-gas ions are more efficient in treatment than metal ions. Probably, this is caused by the fact that the former case has bearing on the emission of pure carbon materials while the latter case has relevance to the work function of carbon (graphite) which was partially metalized and implanted with metals [33].

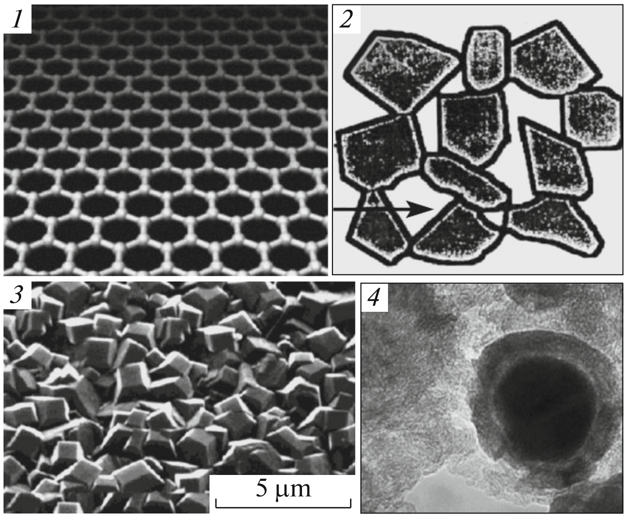

Fig. 10. Promising carbon materials: (*1*) graphene, (*2*) diamond powder–pyrographite nanocomposite structure, (*3*) diamond-like film structure, and (*4*) carbon with an onion-layer structure.

The foregoing suggests that FEC treatment has great and, sometimes, decisive importance for the efficiency of an electronic device as a whole. Hence, the development of principles and modes of FEC treatment (more precisely, their combination) is extremely promising.

An electron beam and its uniformity can be increased if electrodes with a high secondary-emission coefficient are installed between an anode and a cathode. This idea was conceived at the same time as the appearance of microchannel plates. However, their application did not ensure the necessary electron-beam parameters. This is explained by the fact that emitted field electrons have large energies while the channels of microchannel plates are characterized by small angles; i.e., the secondary-emission coating efficiency turned out to be very small.

In the last years, new interesting constructive components were proposed to solve this problem: secondary-emission elements [34] and polycrystalline diamond membranes developed by Gavrilov et al. [35].

The problem concerning the focusing of field electrons has not yet been solved because the initial energies of electrons and, accordingly, spreads in direction and velocity were too large.

A decrease in the electron velocity, e.g., due to their transformation into emitted secondary electrons, makes it possible to decrease their energy and, consequently, increase the opportunity of the effective focusing thereof.

CONCLUSIONS

The brief review and analysis of modern problems related to field-emission electronics, which are discussed in the given paper, instill confidence that, in the near future, stable field-emission cathodes applicable to different electronic devices will be created with the help of complex approaches.

We are sure that field-emission electronics has excellent prospects.

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