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Comparison and analysis of field emission characteristics of carbon cathodes based on PAN fiber and CNT filaments

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Abstract: In this paper, we experimentally compare the field emission characteristics of two different cathodes based on polyacrylonitrile fibers (PAN fibers) and carbon nanotube fibers (CNT filaments). The main purpose of the study was to compare the field emission properties of materials for the cathode unit of a cathode luminescent lamp. The current-voltage, current and watt-watt characteristics of the fabricated cathodes were measured. A comparison of the current-voltage characteristics of cathodes made of the two studied materials shows that the minimum field for the occurrence of field emission current for a cathode made of a CNT filament (accelerating voltage in the diode version of measurements is about 625 V) is approximately 3 times lower than for a cathode made of PAN fibers (accelerating voltage is about 1850 V. Accordingly, the current value of about 100 μA for a cathode based on a CNT filament is achieved at an accelerating voltage of about 1300 V, and for a cathode based on PAN fibers, about 2630 V. Structural changes in cathodes were studied using scanning electron microscopy methods. Based on the totality of the results, it was concluded that it is preferable to use a CNT filament as a cathode material. The emission current of a cathode based on a CNT filament, when a constant high voltage is applied, demonstrates an increase during the transition period and reaches a stable value of more than 75 μA, apparently due to the activation of additional emission centers when a high accelerating voltage is applied. The paper also analyzes the factors that determine the efficiency of light sources created on the basis of the materials studied in the work.

Keywords: field emission; carbon materials; field-emission cathode; PAN fiber; CNT filament, cathodoluminescent light sources.

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Сравнение и анализ автоэмиссионых характеристик углеродных катодов на основе ПАН-волокна и УНТ-нити

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Аннотация: В данной работе проводилось экспериментальное сравнение автоэмиссионных характеристик двух различных катодов, изготовленных на основе полиакрилонитрильных волокон (ПАН-волокон) и волокна из углеродных нанотрубок (УНТ-нити). Основная цель работы заключалась в сравнительном анализе автоэмиссионных свойств материалов для катодного узла катодолюминесцентной лампы. Были измерены вольтамперные, токовые и ватт-ваттные характеристики изготовленных катодов. Сравнение вольтамперных характеристик катодов из двух исследованных материалов показывает, что минимальное поле возникновения автоэмиссионного тока для катода из УНТ-нити (ускоряющее напряжение в диодном варианте проведения измерений около 625 В) примерно в 3 раза ниже, чем для катода из ПАН-волокон (ускоряющее напряжение – около 1850 В). Соответственно, величина тока порядка 100 мкА для катода на основе УНТ-нити достигается при ускоряющем напряжении порядка 1300 В, а для катода на основе ПАН-волокон – порядка 2630 В. Структурные изменения катодов исследовались с помощью методов растровой электронной микроскопии. По совокупности результатов был сделан вывод о предпочтительности использования УНТ-нити в качестве материала катода. Эмиссионный ток катода на основе УНТ-нити при приложении постоянного высокого напряжения демонстрирует рост в течение переходного периода и достигает стабильного значения более 75 мкА. Полученный эффект, по-видимому, обусловлен активацией дополнительных эмиссионных центров при приложении высокого ускоряющего напряжения. В работе проанализированы факторы, определяющие эффективность источников света, создаваемых на основе исследованных материалов.

Ключевые слова: автоэлектронная эмиссия; углеродные материалы; автоэлектронный катод; ПАН-волокно; УНТ-нить, катодолюминесцентные источники света.

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1. Introduction

The Minamata Convention on Mercury was signed in 2013. According to the provisions of this convention, since 2020 restrictions have been imposed on the production of various mercury-containing products, including some types of fluorescent lamps [1]. Thus, one of the tasks today is to find alternative sources of lighting that are comparable in efficiency and cost to mercury fluorescent lamps, but do not contain environmentally hazardous substances. One of the promising solutions is lamps with semiconductor LEDs, which are slightly superior to mercury lamps in terms of efficiency, but are much more expensive to manufacture and have a shorter resource. A separate controversy deserves the issue of any semiconductor production from an environmental point of view.

Another option for light sources is cathodoluminescent lamp, which is a vacuum diode (rarely a triode) with a phosphor deposited on the anode [2]. The glow of the phosphor occurs under the action of accelerated electrons, and the emission spectrum of such a lamp is determined by the composition of the phosphor. Cathodoluminescent lamps have a number of advantages over semiconductor LEDs when used as sources of ultraviolet radiation [3], including such an important characteristic as efficiency.

The efficiency characteristic, in particular, for cathodoluminescent light sources, was considered in more detail in [2], which describes the approach we developed earlier to assessing the economic efficiency, based on a comparison of the consumer effect of the product (for a general-purpose light source, it is the generation of a luminous flux of a given spectral composition for the operational period of time, and for an ultraviolet light source it is the energy of UV radiation received from the corresponding light source during its operation) and discounted to the initial period of the time-distributed costs for the installation, operation and disposal of the light source in question.

Proposed on the basis of the above approach, a simple integral criterion for assessing the economic efficiency of light sources (with close spectral characteristics and other things being equal) *Ef* (dimension – the ratio of the characteristics of the useful effect of the luminous flux: for light sources in the visible range, this is $lm \cdot h^{-1}$, and for UV-light sources – these are energy units, such as *J* to a monetary unit) has the form:

$$Ef = \left(\frac{P}{S \times T} + \frac{P_{el}}{E \times D} \right)^{-1}, \qquad (1)$$

given the physical and technical parameters of the light source itself:

– luminous flux (total power of light energy emitted by a light source) – *S* (in lm for light sources in the visible range or in W for UV – light sources in the corresponding spectral range);

– energy efficiency or luminous efficiency (the ratio of the luminous flux to the power of electrical energy supplied to the light source) – *E* (dimension: $lm \cdot W^{-1}$ – in the visible wavelength range, or a dimensionless value for radiation in the UV wavelength range);

– work resource – *T* per hour;

– industrial and environmental characteristics: production costs and subsequent disposal – *P* in monetary units (the installation cost of the light source, given the environmental costs of its production and the environmental costs of its operation and disposal, reduced to the period of the start of operation);

– operational characteristics of the light source and changes in economic conditions, as well as consumer expectations over time:

– electricity price – P_{el} in monetary units per W·h at the time of installation;

– the dynamics of changes in the price of electricity, dynamics of its consumption (modes of operation of the light source over time during the period of its use), taking into account the dynamics of changes in the integral economic characteristics and psychological aspects of consumer expectations for the distribution of payments over time, combined into a single indicator – the discount factor D^{-1}, which characterizes the reduction of operating costs, distributed over time, taking into account consumer expectations and risks, by the time the light source is installed. Note that the factor D depends on the resource of the light source T and on the mode of its operation (on the period of time during which the resource is depleted – and, all other things being equal, the less often the light source is used, the longer the period of depletion of its resource) and grows with their increase.

In this paper, where the physical and technical aspects of the operation of cathodoluminescent light sources are considered, we will be primarily interested in two of the parameters listed above, namely: energy efficiency or luminous efficiency – E and work resource – T.

In turn, the value of the light output of a cathodoluminescent lamp is determined by the following processes and their characteristics:

– converting electricity (for example, from a standard network (voltage 220 V) in the power supply-converter of a cathodoluminescent lamp) – the efficiency of the power supply-converter;

– overcoming the potential barrier at the cathode material – vacuum interface – energy costs equal to the product of the electron work function and the emission current;

– accelerating electrons emitted from the cathode in the cathode-modulating device and focusing of the electron beam on the anode and the phosphor layer covering it – losses associated with the fact that part of the electron beam does not fall on the cathode luminophor;

– energy loss of the electron beam during the passage of the anode and the phosphor layer, generation, scattering, and absorption of secondary electrons in the phosphor layer – the efficiency of secondary electron generation in the cathodoluminophore;

– generating light quanta in the phosphor layer – the efficiency of light generation in the cathodoluminophore;

– loss of luminous flux associated with the absorption of luminescence in the structural elements of the lamp.

Note that it is the choice of cathode materials and phosphors, the possible modification of their structure and designs that determine the effectiveness of all the processes listed above, which integrally determine such a characteristic as light output. These factors include:

– the choice of cathodoluminophor material, thickness, structure and other characteristics of the anode phosphor coating layer;

– modes of electron beam generation for cathodoluminescent lamps, including the choice of accelerating voltage and time modes of electron beam generation and illumination of the phosphor;

– methods of focusing and selecting design solutions that provide a certain intensity of cathodoluminophore irradiation with an electron beam.

Another important factor is that not all parameters that determine the amount of light output can be determined independently when choosing specific materials for the cathode and anode and choosing certain designs of cathodoluminescent light sources. For example, when the value of the accelerating voltage changes, the conditions for the emission of electrons from the cathode material and the conditions for excitation of luminescence in the phosphor material on the anode simultaneously change.

In addition, the operation modes of the cathode material (current density, voltage accelerating the emitted electrons, the possibility of bombarding the cathode with positively charged particles, for example, formed when the anode is irradiated with an electron beam, etc.) significantly affect the stability of the cathode and its durability [4].

These facts must be taken into account when testing promising materials from the point of view of the possibility of their use in the construction of cathodoluminescent light sources.

Thus, the creation of an efficient cathodoluminescent light source in the ultraviolet radiation range, from the point of view of the selection of materials, in particular, requires the solution of two main problems: (i) the selection (synthesis) of a phosphor with a high efficiency in the ultraviolet region of the spectrum and (ii) the creation of a field emission cathode, characterized by a low field emission threshold and stable operation at operating currents of the order of 100 μA.

Carbon fibers are a promising material for use as field emission cathodes [5–7], since they have a large aspect ratio of length to diameter, due to which a high field amplification coefficient is observed in them [8]. The carbon content in such fibers exceeds 80 %. In addition to carbon, the chemical composition of fibers can contain atoms of oxygen, nitrogen, phosphorus, silicon, iron, as well as various functional groups: hydroxyl, carbonyl, carboxyl [9]. Many types of carbon fibers have been obtained: pitch fibers [10], polyacrylonitrile fibers (PAN) [11], carbon nanotube fibers (CNTs) [12].

The field cathode based on polyacrylonitrile carbon fibers has a large number of emission centers on the working surface formed by microprotrusions on it [13]. In the case of destruction of single microprotrusions, the emission current of such a cathode practically does not change, which gives the cathode high stability. In [14], an analysis was made of the stability of the emission current of cathodes of their carbon fiber of various grades. It was confirmed that a more stable fiber emitter current and a longer high vacuum lifetime were obtained. In [15], a carbon fiber cathode was studied, the operation of which was 7.5 thousand hours at a current of 50 μA.

In [8] a method for obtaining a beam from carbon fibers was described. For mechanical fastening, a bundle of polyacrylonitrile carbon fibers was enclosed in a dielectric shell of glass. This ensures the orientation of the fibers along the axis of the electron-optical system. Forming a field cathode from carbon materials affects the field emission properties of the field cathode [16]; it makes it possible to create a uniform surface [17].

The combination of miniature size, high mechanical, thermal and chemical stability, and good electrical conductivity makes nanotubes the most suitable field emission cathode material. A carbon nanotube has a diameter of 1 to 10 nm and a length of up to 5 μm. Fibers consist of a large number of CNTs, which may differ in geometric parameters and electronic properties.

At low (threshold) voltages, the main contribution to electron emission usually comes from only a small number of nanotubes, for which the value of the electric field gain is maximum. As the applied voltage increases, the relative contribution to the emission of the remaining CNTs also increases. In addition, the electric field in the vicinity of an individual CNT, which is part of the array, can be significantly distorted due to the shielding effect of the surrounding neighbors in the array. As a result of such action, the gain of the electric field of a nanotube can depend not only on its interelectrode distance, but also on the geometry and density of CNTs in the fiber. Studies show that the maximum emission current density is achieved at an average distance between nanotubes of the order of the height of individual CNTs that make up the array [18]. It should be noted that, in practice, high values (of the order of 100 $A \cdot cm^{-2}$) of the emission current density cannot be obtained under stationary conditions for large-area cathodes, which is primarily explained by the violation of the uniform distribution of CNTs over the cathode surface, as well as the low degree of vertical orientation of nanotubes.

However, the values of the threshold field emission voltage for nanotubes are lower than for other materials [19]. Fibers based on carbon nanotubes [9, 20] and a number of other carbon materials [10, 11] have promising emission characteristics. Nevertheless, to substantiate the prospects for the use of specific materials, a mandatory experimental verification of their emission characteristics, which vary depending on the conditions of their production and operation, is necessary. In the proposed work, a number of these fibers based on PAN and CNTs were tested to understand how these materials are suitable for use as a basis for creating field cathodes of new cathodoluminescent light sources.

2. Materials and Methods

2.1. Materials for fabricating of cathodes

CNT fiber was provided by the Technological Institute for Superhard and Novel Carbon Materials, Troitsk, Russia. The diameter of a CNT fiber obtained by agglomeration of carbon nanotubes was 30 μm. PAN fiber was provided by the Research Center "Uglekhimvolokno", Mytishchi, Russia. Polyacrylonitrile fibers had a diameter of 5–7 μm and were combined into a bundle. There were about 250 individual fibers in the bundle.

2.2. Methods for fabricating cathodes

The fibers were placed on a clean glass surface, after which segments 5 mm long were cut off with a sharp blade; after that, the fibers were placed inside a nickel tube, which was then crimped to ensure electrical contact with the fibers. After that, nickel tubes with carbon materials were fixed on the high-voltage inputs of the vacuum chamber flanges and used as cathodes in the measuring circuit of the model of the cathodoluminescent light source.

2.3. Measurement procedure

All measurements were carried out in a diode (two-electrode) configuration of a cathodoluminescent light source. Glass with a conductive ITO coating was used as an anode, onto which a cathode-luminophore with a luminescence wavelength of 520 nm was deposited. The distance between the anode and the cathode was 1 cm, and the diameter of the anode was 6.5 cm.

The design described above was placed in a vacuum chamber, the pressure in which was 10^{-6} Torr during measurements.

The scheme of the experimental setup is shown in Fig. 1.

When a positive voltage was applied to the anode, electron emission from the cathode occurred. Using an oscilloscope, the current-voltage characteristics (CVCs) and current-time dependences were measured for various cathodes. Photographs of the glow of the phosphor were taken with the help of a camera at various values of the potential difference between the cathode and the anode. Figure 2 shows an example of the glow of the phosphor for the studied cathodes.

The experiment and its subsequent analysis were carried out as follows. The camera shutter speed was chosen so that no overflow of the matrix pixels on any of the RGB channels occurred in all photographs in the considered range of currents and voltages. This shutter speed was recorded and used for all photographs. Also, the camera lens and the camera window were connected by a tube made of black matte paper to eliminate stray light from external radiation. The photographs taken were converted into black and white format and converted into numerical tables. Numeric values of pixel brightness: 0 – black color and minimum brightness, 255 – white color and maximum brightness. Photos in Fig. 2 for cases of different cathode materials were made with the same system power consumption. The above algorithm was used to find the ratio of the average phosphor emission intensity to the maximum emission intensity depending on the power consumption. It is more convenient to make a comparison depending on the power, since the values of the electric current when using PAN fibers and CNT filaments differ at equal supply voltages.

2.4. Materials characterization methods

The microstructure of all studied samples was observed using a scanning electron microscope (SEM) before and after electrical measurements in a vacuum chamber. The photographs were taken with a JEOL JSM 7001F scanning electron microscope. The accelerating voltage was 30 kV, the focal length was 8–10 mm.The nature of the degradation of the cathode material was visually assessed from the SEM images.

3. Results and discussion

As a result of the study, it was shown that when using a cathode made from a CNT filament, the emitting area of the phosphor is larger than when using a cathode made from PAN fibers (Fig. 2). Moreover, a comparison of the current-voltage characteristics of the two studied cathodes shows that the minimum field for the occurrence of field emission current for a CNT filament cathode is about 3 times lower than that for a PAN fiber cathode (Fig. 3).

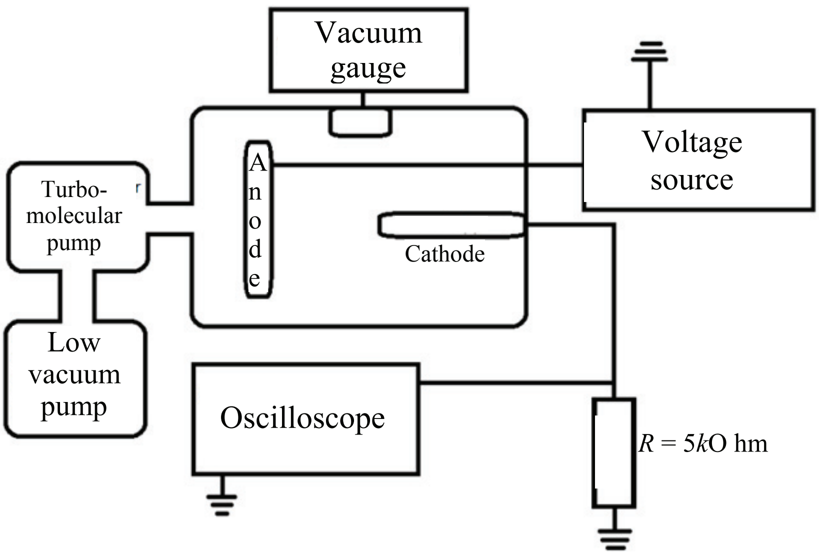


Fig. 1. A block diagram of the experimental setup

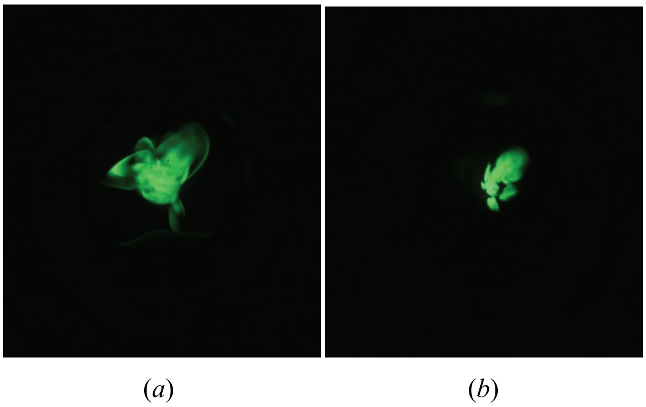


Fig. 2. Glow of a phosphor in a system with a cathode made of a CNT filament (*a*) and PAN fibers (*b*)

The ratio of the average radiation intensity to the maximum one, depending on the power consumption, is shown in Fig. 4. The comparison of the radiative characteristics when using different cathode materials was carried out at the same power consumption. The use of power as a variable was due to the fact that for different cathode materials at the same voltage, the current values could differ significantly.

As can be seen from the graph, at the same electrical power consumption, the radiation intensity of the diode with a CNT cathode is greater. First, the area of phosphor activation by electrons turned out to be larger for the CNT filament, which is related to the structure of its emission centers. Secondly, the green

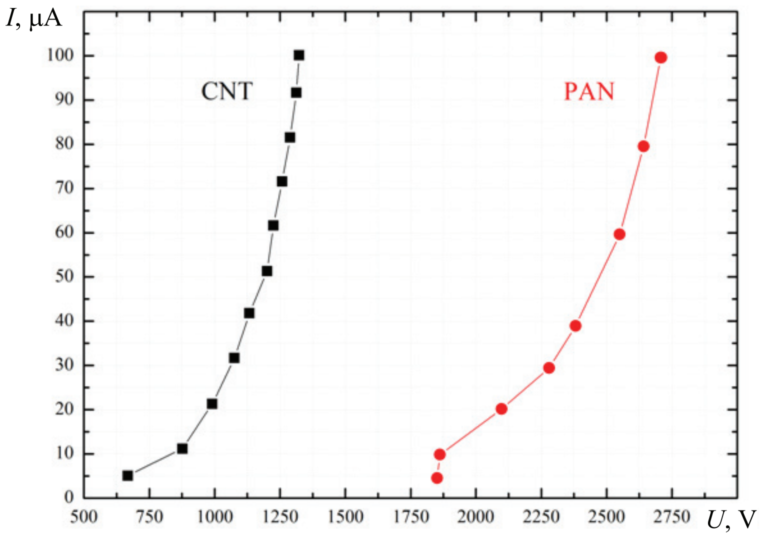


Fig. 3. Current-voltage characteristics for cathodes made of PAN fibers and CNT filaments

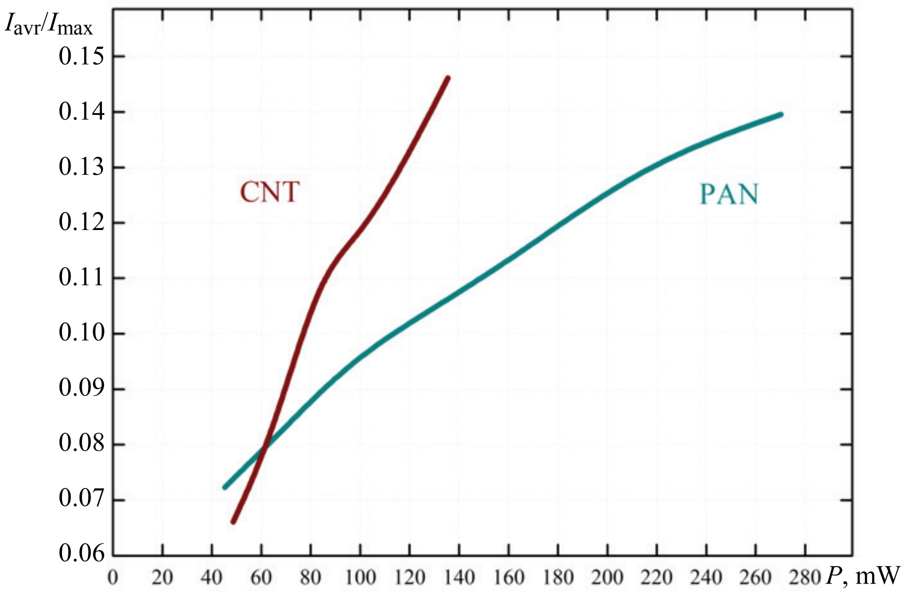


Fig. 4. Normalized radiation intensity depending on the power consumption of cathodoluminescent diodes for cathodes made of PAN fibers and CNT filaments

phosphor is likely to be more efficiently excited by lower energy electrons (at equal powers, the supply voltage in the case of a CNT filament cathode is lower than in the case when the cathode is made of PAN fiber). Also, the effect of saturation of the phosphor cannot be ruled out, in other words, the regions of the phosphor irradiated with higher energy electrons, which are characteristic of PAN fiber cathodes, approach the luminescence intensity limit, due to which the efficiency of such electrons is lower.

We also measured the dependence of the current on time at fixed interelectrode voltages. Figures 5 and 6 show graphs of these dependences at different voltages for the CNT cathode and PAN cathode, respectively.

The graphs clearly demonstrate the higher and more stable emission characteristics of CNT filaments compared to PAN fibers. We also note that at low voltages, the emission current gradually decreases with time for two cathode materials, and as the voltage increases, the current, on the contrary, increases and after some time reaches a constant value. Presumably, the decrease in field emission current is associated with a decrease in active emission centers through which high current densities pass. Probably, at a high voltage, ponderomotive forces change the structure of the cathode, thereby activating additional emission centers.

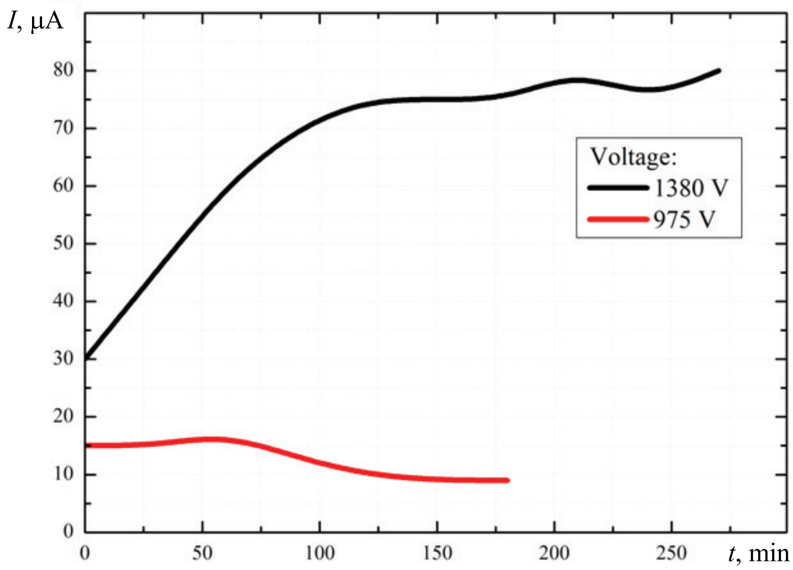


Fig. 5. Time dependence of the current for a CNT filament cathode at different anode voltages

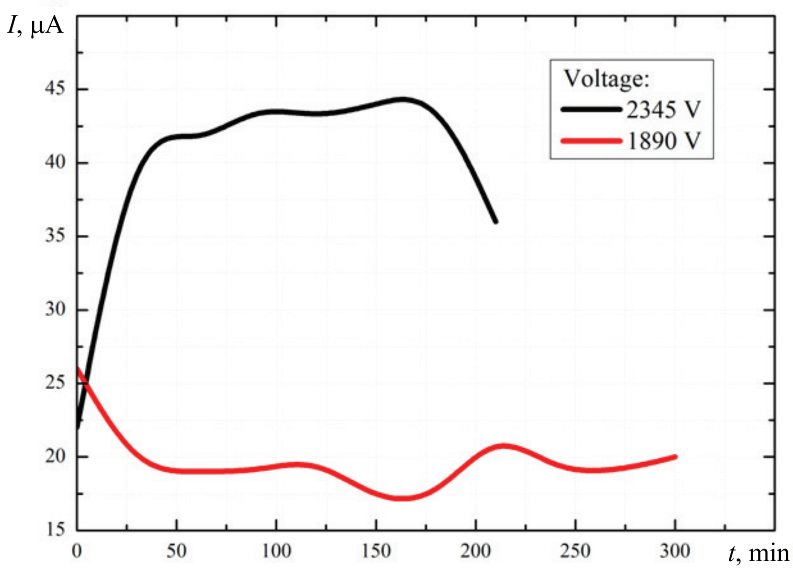
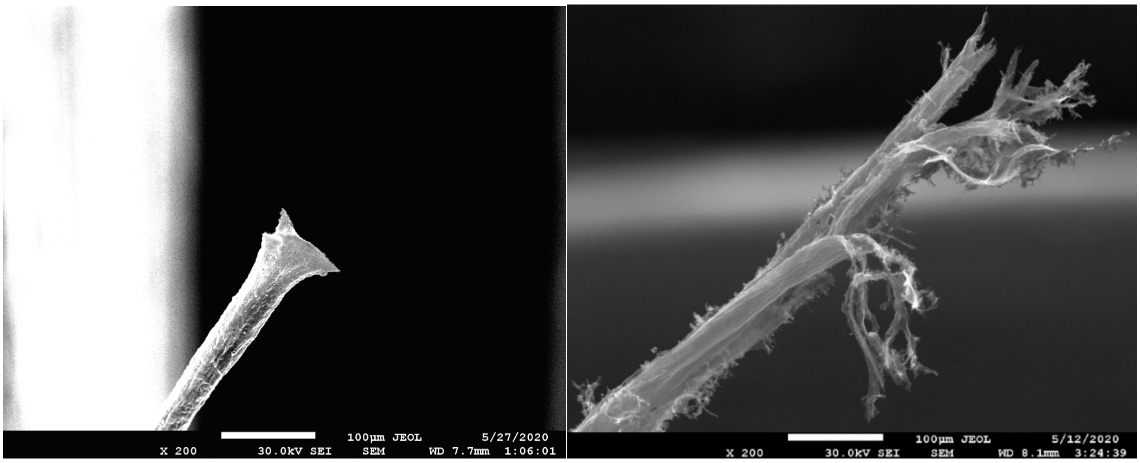


Fig. 6. Time dependence of the current for a cathode made of PAN fibers at different anode voltages

Thus, during the operation of electron guns with a number of carbon materials at high voltages, the destruction of individual microscopic protrusions does not lead to a significant change in the emission current, since their average number remains constant due to the appearance of new additional emission centers when the structure of the cathode material changes under the action of ponderomotive forces, arising under the action of high voltage. This ensures high stability of the emission current and a long service life of these field emission cathodes under high vacuum conditions. Moreover, under certain operating conditions, it is possible to increase the number of emission centers and improve the emission properties of field cathodes, which should be confirmed by a change in the structure of the carbon material during its operation as a cathode.

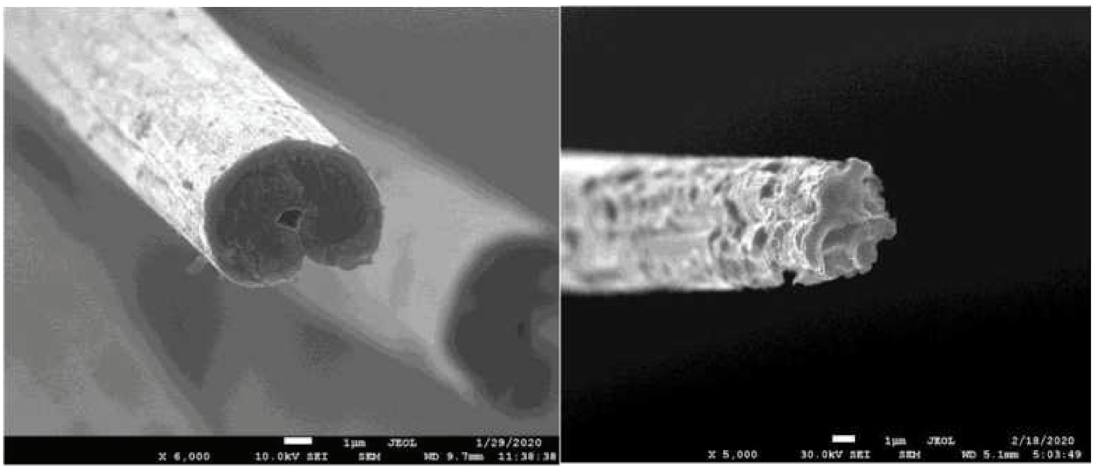
Scanning electron microscopy methods were used to determine changes in the structure of cathodes made of carbon materials. Figure 7 shows the SEM images of the CNTs of the cathode. The original shape of the CNT filament after current sampling underwent serious structural changes. An inhomogeneous branched structure with carbon nanotubes protruding in different directions has many emission centers with high field amplification factors, which as a result leads to an improvement in field emission characteristics.

As can be seen in Fig. 8, PAN fibers during current extraction experience degradation due to their sintering. A large current density per PAN fiber leads to heating. Upon reaching a local temperature above 90 °C, the glass transition process is initiated, and the field emission properties of an individual fiber deteriorate irreversibly.



(*a*) (*b*)

Fig. 7. SEM image of a carbon nanotube cathode before (*a*) and after (*b*) the experiment



(*a*) (*b*)

Fig. 8. SEM image of a polyacrylonitrile fiber before (*a*) and after (*b*) the experiment

Another aspect that is interesting for discussion and follows from the obtained experimental data is the relationship between the magnitude of the electron emission current and the intensity of the luminescence of the phosphor depending on the magnitude of the accelerating voltage between the anode and cathode.

On the one hand, an increase in voltage in accordance with the current-voltage characteristic increases the emission current, and on the other hand, the energy of the electron interacting with the phosphor layer on the anode increases, which should undoubtedly affect the quantum yield of luminescence in terms of one electron reaching the anode (a value proportional to the ratio of the intensity of the glow to the strength of the cathode-anode current). These characteristics are directly related to both the potential resource of the light source and the value of its light output. The relation of the light output value to the design characteristics of the light source and the cathode material are discussed below.

4. Analysis of the influence of the light source design characteristics and the cathode material on the value of light output

In accordance with [2], for the value of light output in the visible spectral range E (lm h/W), the expression is valid:

$$E = S/W = \alpha \frac{683 \int_{380}^{780} \Phi_{\lambda}(\lambda) V(\lambda) d\lambda}{\Phi_{\Sigma hv}} \frac{\Phi_{\Sigma hv}}{W_{\mathrm{ee}}} \frac{W_{\mathrm{ee}}}{W_{\mathrm{e}}} \frac{W_{\mathrm{e}}}{W_l} \frac{W_l}{W} =$$

$$= \alpha \frac{683 \int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda) d\lambda} k_4 k_3 k_2 k_1 = 683 \alpha k_5 k_4 k_3 k_2 k_1, \quad (2)$$

and for the value of light output in the UV spectral range E (dimensionless value), the expression is valid:

$$E = S/W = \alpha \frac{\Phi_{\Sigma hv}}{W_{\mathrm{ee}}} \frac{W_{\mathrm{ee}}}{W_{\mathrm{e}}} \frac{W_{\mathrm{e}}}{W_l} \frac{W_l}{W} = \alpha k_4 k_3 k_2 k_1, \quad (3)$$

where α is the fraction of light emitted by the phosphor used for illumination (coming out of the light source), i.e., emitted by the phosphor minus the light absorbed by the structural elements of the lamp);

W is power supplied to the lamp;

W_l is power supplied to the electron generation system (at the output of the power source – converter, i.e. power consumed directly by the lamp (its cathode-modulator unit));

$k_1 = W_l/W$ is efficiency of the power supply – the converter;

W_{e} is power of the electron beam cathode – anode;

$k_2 = W_{\mathrm{e}}/W_l$ is the efficiency of electron beam generation (in the case of a light source with a thermionic cathode, significant losses that reduce this efficiency are due to the energy spent on heating the cathode);

W_{ee} is the generation power of excited electronic states (secondary excited electrons) in the phosphor (cathodoluminophore) layer;

$k_3 = W_{\mathrm{ee}}/W_{\mathrm{e}}$ is the generation efficiency of excited electronic states of the cathodoluminophore by an electron beam;

$$\Phi_{\Sigma hv} = \int_{\lambda_1}^{\lambda_2} \Phi_{\mathrm{e}\lambda}(\lambda) d\lambda = (< hv >)(I_{hv}), \quad (4)$$

where $\Phi_{\Sigma hv}$ is the total cathodoluminescence power in units of energy in a given spectral range ($\lambda_1 - \lambda_2$);

$< hv >$ is the average photon energy of visible radiation;

I_{hv} is the intensity of visible radiation, measured in radiation quanta per unit time:

$k_4 = \Phi_{\Sigma hv}/W_{\mathrm{ee}}$ is the efficiency of luminescence generation with respect to the energy of excited electronic states of the phosphor;

$$k_5 = \frac{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda) d\lambda} = \frac{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda) V(\lambda) d\lambda}{\Phi_{\Sigma hv}}, \quad (5)$$

k_5 is the coefficient for converting the energy of light radiation of luminescence in the visible spectral range into lighting engineering units (in this expression $V(\lambda)$ this visibility curve in the visible spectral range) of the intensity of the light flux, a coefficient that depends only on the spectral characteristics of the radiation source, and for light sources of various types, but with the same spectral characteristics is the same quantity.

Thus, the light output value in expressions (2) and (3) in accordance with expression (4) and the notation adopted above is determined by the product of the following coefficients: α, k_5, k_4, k_3, k_2, k_1, the value of each of which is less than 1, and each of which characterizes the decrease in light output associated with the corresponding stage of converting the energy supplied to the radiation source into the luminous flux of the source radiation in the visible radiation range [2]:

$$E = S/W = \alpha \frac{683 \int_{380}^{780} \Phi_{e\lambda}(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \Phi_{e\lambda}(\lambda) d\lambda} \times$$

$$\times k_4 k_3 k_2 k_1 = 683 \alpha k_5 k_4 k_3 k_2 k_1 \qquad (6)$$

and in the ultraviolet radiation range for light output it is trueexpression:

$$E = S/W = \alpha k_4 k_3 k_2 k_1 . \qquad (7)$$

The light output reduction coefficients of the above conversion steps can be characterized as follows:

1. The coefficient α – the loss coefficient at the exit of radiation from the lamp – is determined solely by the design features of the radiation source, in the ideal case approaching a value equal to 1;

2. The coefficient k_5 is the coefficient determined by the choice of the emission spectrum of the light source in the visible or ultraviolet radiation range; this coefficient depends solely on the emission spectrum of the light source and is the same for radiation sources of various types, if their spectral characteristics coincide.

3. The coefficient k_4 is the efficiency of luminescence generation in relation to the generation of excited electronic states of the phosphor, is determined by the physical processes of converting the excited electronic states of the phosphor into light radiation of a given spectral composition and, in particular, depends on the material, structure and geometry of the phosphor layer and on the energy and density of the electron flux on the surface of the anode.

4. The coefficient k_3 is the efficiency of the generation of excited electronic states of the cathodoluminophore by an electron beam, which is determined by the focusing of the electron beam and the fraction of its energy absorption in the cathodoluminophor material. This coefficient does not exceed the fraction of electrons absorbed in the cathodoluminophore layer and is determined by the coefficients of reflection and transmission of the electron beam through the phosphor layer. The value of the coefficient k_3 essentially depends on the design solution of the light source, in particular, on the geometry of the mutual arrangement of the cathode (cathode-modulating unit),the anode and the phosphor layer (cathodoluminophore), on the material, thickness and structure of the phosphor layer, etc. and can vary widely;

5. The coefficient k_2 is the coefficient corresponding to the efficiency of electron beam generation, can reach values close to 1 for an autocathode radiation source, in contrast to the case of a light source with a thermal cathode, which is due to the energy consumption for heating the cathode;

6. The coefficient $k_1$is the coefficient of light output reduction due to the source-converter;

Assuming that such parameters as α, k_5, k_1 are set when choosing certain structural elements of the light source or choosing the conditions for conducting the experiment, the selection of the cathode material and its operating modes will largely determine not only the value of the coefficient k_2, but also the values of the coefficients k_3 and k_4. In particular, the experimental data obtained using the same anode and different cathodes indicate the possibility of making quantitative estimates for the coefficients k_3 and k_4, or at least their product. This fact makes it possible to purposefully plan further studies of the characteristics of phosphors and anode design, as well as design parameters of the cathode-modulator unit and cathode material. In particular, it will be possible to provide the necessary emission current density from the cathode surface at appropriate accelerating voltages and the energy of electrons that excite luminescence on the anode surface.

Further on, it is planned to determine the optimal modes of operation of the cathode-anode unit. The strength of the cathode plays an important role in the operation of cathode luminescent lamps. The stability and durability of the device depends on it. Therefore, further research is needed in this area.

5. Conclusion

The studies of the field emission properties of cathodes made of PAN fibers and CNT filaments showed that the former rapidly degrade, undergoing sintering due to high currents, while the latter strongly change their structure under the action of an electric field. At the same time, both materials demonstrate a high emissivity that meets the requirements for cathodes of fluorescent lamps. In the course of the research out, which is mainly focused on studying the characteristics of cathode materials and their operating modes, the results were obtained that make it possible to study the characteristics of the design of the anode and phosphor material by using various cathodes, recording the dependence of the ratio of radiation intensity and current strength on the value accelerating voltage.

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7. Conflict of interests

The authors declare no conflict of interest.

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