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Cathodoluminescent light sources: status and prospects

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Contents

Abstract. **A feasible alternative to current energy-saving light sources is environmentally friendly new-generation cathodoluminescent light sources (CLSs) based on luminescence produced by electrons emitted from the field emission cathode. Because of the lack of available optimally designed general-purpose lamps with field emission cathodes, the development of an efficient prototype CLS potentially mass-produced at a low cost is currently the top priority.**

Keywords: field emission, field emission properties of materials, field emission cathodes, carbon, carbon fibers, cathodoluminescence, light sources, efficiency of light sources

1. Introduction

The development and wide application of energy-saving and last but not least durable and environmentally friendly light sources are currently a top priority. Despite the great variety of existing light sources, the main problem, viz., creation of general-purpose light sources (for domestic and office exploitation, etc.), remains unresolved. The 'daylight' lamps most often used in offices and increasingly popular light-emitting diode lamps have an adverse effect on human eyes and general well-being.

Today, incandescent lamps are being extensively replaced by energy-saving light sources. Incandescent lamps combine the unquestioned advantages of eye-friendly light and ease of exploitation with such serious drawbacks as a very low performance coefficient and short lifetime. Energy-saving and luminescent lamps are much more efficient and durable but produce a discrete emission spectrum, contain mercury vapors, start flashing when are turned on, and take a few minutes for achieving full brightness after the power is supplied. To be manufactured, light-emitting diodes require very complicated and expensive technologies, as well as ultrapure materials, including highly toxic ones, such as arsenic. Some materials for semiconductor technologies, e.g., indium, rarely occur in nature.

Thus, a primary task is creating light sources free from the above disadvantages that would be highly durable and exhibit high illumination efficiency; importantly, their production, operation, and disposal must have minimal negative environmental effects by virtue of utilizing harmless substances.

2. Principle of operation of cathodoluminescent light sources

The principle of operation of an electroluminescent light source with a field emission cathode reduces to exciting a phosphor to luminesce when exposed to electron bombardment. Bearing in mind that light sources must possess strictly specified properties, it is appropriate to consider certain fundamental concepts accepted in light engineering [1] to resolve discrepancies among the data of individual authors.

Variants of light source design are divided into two main classes (Fig. 1) [2] based on their operating principles, viz.

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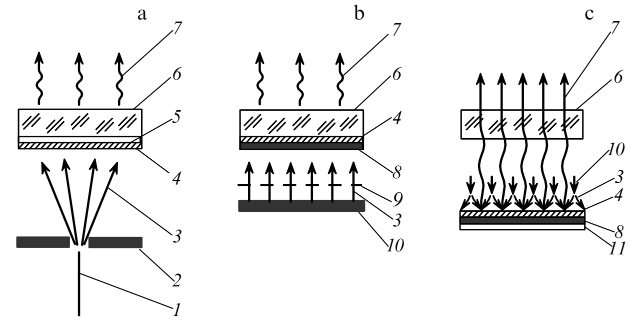

Figure 1. Principles of construction of light sources: (a, b) transmission mode, and (c) reflection mode. *1* — rod type field emission cathode, *2* — modulator, *3* — electron flux, *4* — phosphor, *5* — transparent conductive coating, *6* — outer glass layer, *7* — visible light, *8* — aluminum layer, *9* — grid, *10* — cathode matrix, and *11* — substrate.

transmission-mode and *reflection-mode*. The main (classical) construction is generally that of a conventional field emission microscope. As in Fig. 1a, it comprises a rod type field emission cathode *1* of any configuration: a graphite rod, a bundle of carbon fibers, or nanostructures at the rod end. Electrons are pulled off by a metallic diaphragm. The configuration of the cathode–modulating device is chosen so as to optimize the combination of three mutually exclusive factors: maximum current transmission through the modulator, minimum driving voltage, and maximum uniformity of the electron flux across the screen surface.

This last objective is attained in the simplest way by intercepting field emission electron fluxes from a large number of emission centers using a few rod-shaped field emission cathodes and appropriate modulator apertures circumferentially arranged at regular intervals to obtain a light flux with a circular cross section.

In such 'classical' light sources, only part (30%) of the phosphor brightness is utilized because many photons flow back into the bulb. To enhance the brightness, the positions of the phosphor and the conductive layer (aluminum) must be changed (Fig. 1b). The aluminized sheet makes it possible to increase brilliancy up to approximately 70% of what is maximally possible.

The most impressive improvement in efficiency is attainable in light sources operating in the reflection mode [3] (Fig. 1c). In this case, electrons *3* move toward the luminescent layer *4* deposited onto the aluminum mirror *8*. Losses in the light flux are due only to its insignificant (a few percent) absorption in the outer glass *6* and transparency of the cathode matrix *10*, where the losses can be reduced to less than 10%.

One of the above principles or their modification can be employed depending on the concrete technological requirements for practical application.

Sections 3–7 deal with the factors determining the efficiency of cathodoluminescent light sources and examine variants of their design intended to enhance efficiency.

3. Efficiency of general-purpose light sources

3.1 Physical and economic efficiencies of lighting equipment and devices

Generally speaking, developers of utility type light sources are faced with the problem of reaching a compromise between such characteristics as maximum light flux and luminous efficiency, high durability and low production cost of the device, ease and environmental safety of its production and operation, the spectral parameters of emission (including color rendering index), the stability of properties and consistency of operation, the possibility of exploitation in combination with existing lighting equipment, and the interchangeability of different types of light sources.

This problem is a special case of that of comparative evaluation of the efficiency of many commodity products requiring regular exploitation expenses, such as electrical or lighting appliances and other routine-usage devices, e.g., light sources with predetermined light technical characteristics, refrigeration systems for cooling with predetermined thermodynamic parameters, and electric storage batteries with specified voltage and current characteristics, etc. Exploitation of these devices requires additional expenditures (first of all for energy) for operation and end-of-life disposal. Such comparative evaluation is somewhat simplified when the functional characteristics of the devices of interest can be differentiated from their aesthetic and other properties, including purely subjective consumer ones (size, color, design elements, etc.).

The notion of efficiency as regards lighting equipment usually reduces to that of energy efficiency or luminous efficiency defined as the ratio of intensity of the stationary light flux from a source of visible light measured in lumens to the power supply of this source measured in watts. This simplified approach to the assessment of efficiency disregards the overall advantageous effect (total light flux generated during all the time of the light source operation) and cumulative energy expenditures throughout the complete production cycle, exploitation, and disposal of a given light source. It is the ratio of these two variables that could be the most correct physical characteristic of the efficiency of a light technical device. However, such a calculation of physical efficiency requires an evaluation of total direct and indirect energy expenditures on the production, operation, and disposal of a device, which is sometimes impracticable.

Of special importance for the evaluation of economic efficiency is the ratio of overall advantageous effect to the total cash costs. It is worth noting that there is a close analogy between physical (energy) and economic (monetary costs) characteristics of the efficiency due to the relationship between the cost of a product and the free energy (ecological) cost of its complete production cycle (see, e.g., Refs [4, 5] for a discussion of this issue).

Also, it is worthwhile mentioning that the efficiency of any product, including physical instruments, must be evaluated from the standpoint of its user or society at large. These assessments are equivalent only when all expenditures on the use of the product (putting into operation, operation proper, and disposal) are related, by legal and managerial practice, to consumer costs. In other words, all external effects (externalities), first and foremost environmental costs suffered by third parties, are fully internalized, i.e., referred to consumer costs.

By way of example, a mechanism of such internalization for environmentally unsafe gas-discharge mercury lamps may be the mandatory payment by the consumer of all disposal costs and the collection of mean risk payments for environmental damage under contingency situations. It is the authors' opinion that the optimal mechanism of such payments would be introducing a mortgage value on the purchase of an environmentally unsafe lamp (and similar commodities) to cover both the costs of conventional disposal and the average risk payments for mitigation of the consequences of the loss of the product (e.g., leakage of mercury from the broken lamp) during its exploitation or as a result of a contingency utilization. In this case, the mortgage value is refunded minus standard disposal expenses after the lamp is sent to a waste treatment plant. Also, it should be taken into consideration that all the expenses incurred should be related to one and the same time, e.g., to the onset of a product use, by the standard discounting method used, in particular, to assess investment projects in accordance with conventional economic theory and practice [6, 7].

The following universal model algorithm is proposed for the comparative evaluation of the functional efficiency of the product of interest.

(1) Formulation of a quantitative criterion for the requirement to be met [e.g., light flux intensity multiplied by operating time (hours) for light sources, heat removal during operation time for refrigeration systems, or the work performed for batteries, etc.].

(2) Construction of a concrete model for estimating installation expenses (and estimations proper), including purchasing and putting into operation a given product (device). As regards a light source, these expenses may include not only the cost of purchase (production, delivery, sale) of a single lamp for an individual user but also the costs incurred by an investor or an owner associated with installation of the light source, including the cost of purchasing and mounting the relevant equipment, stationary drivers (or separate starting devices), delivering distinct power to the illuminated object as a whole in terms of a single lighting unit.

(3) Creation of a concrete model for the estimation of environmental costs associated with the production, exploitation, and disposal of a product. Once a mortgage value is introduced, the environmental costs taking into consideration all possible risks are automatically included in installation expenses, and a partial refund of the collateral after the end of the lamp lifetime less the discount must be taken into account in the total expenditures incurred by the onset of exploiting the light source.

(4) Development of a model for estimating time-distributed expenditures to calculate operating costs incurred by the onset of exploitation (purchase or installation time) of a light source taking into account:

- operating mode (e.g., a light source having an operational life of 50,000 h is utilized daily during a strictly specified period and its useful lifetime amounts to 20 years (over 175,000 h);
- time-distribution of operating costs (e.g., regular monthly electricity bill payments taking into account rate adjustments during the lifetime of the light source).

(5) All the expenditures including discounts are summarized and the result is the overall discounted cost needed to achieve the desired effect on consumption (in the case of a light source, the integral light flux in lm h).

It is sometimes difficult to implement this algorithm for estimating expenditures in energy units, although we believe the calculation of physical (energy) efficiency by this method is the best for the evaluation and choice of the most advanced general-purpose light sources.

The proposed algorithm for the calculation of economic (monetary) efficiency can be implemented by introducing certain simplifications, as illustrated in Section 3.2.

The economic assessment of light source efficiency and, most importantly, the proposed approach to its quantification permit us to identify the key physical, technological, manufacturing, and operational limitations determining the prospects for the application of existing general-purpose light sources and the elaboration of new varieties thereof.

3.2 Evaluation of economic efficiency of general-purpose light sources

In this section, we present our original approach (see, e.g., reports [8, 9]) to the evaluation of the economic efficiency of utility type light sources based on a comparison of a product's consumer effect (specifically, generation of a light flux with the predetermined spectral composition during a certain period) with time-distributed installation, operation, and disposal costs discounted by the onset of its use. We propose a simple integral criterion for the evaluation of economic efficiency Ef (in lm h per monetary unit) of light sources with similar spectral characteristics (all other features being equal):

$$\mathrm{Ef} = \left(\frac{P}{ST} + \frac{P_{\mathrm{el}}}{ED}\right)^{-1} \tag{1}$$

that takes account of

— physicotechnical parameters of the source itself:

- S is the light flux (the total amount of radiant power emitted from a source) in lumens;
- E is the energy efficiency or luminous efficiency (the ratio of the light flux to the electric power delivered to the light source) in lm W^{-1};
- T is the service life in hours;
- P stands for production and environmental characteristics: production and disposal costs in monetary units (installation cost, including environmental costs associated with the production, operation, and disposal reduced to the onset of exploitation);

— characteristics of light source exploitation and changes in the economic conditions, as well as the consumer expectations in time;

- P_{el} is the electricity tariff in monetary units per W h at the time of light source installation;
- $1/D$ is the discount factor, i.e., the single index reflecting the dynamics of electricity price adjustment and energy consumption dynamics (light source operating regimes), taking into account the dynamics of integral economic characteristics and psychological aspects of the consumer's expectations as regards time distribution of payments. The discount factor reflects the reference of time-distributed operating costs to the time of light source installation, taking account of the user's expectations and possible risks. To recall, factor D depends on the service life T of the light source and its operating mode (the time period during which it exhausts its performance potential); all other things being equal, the remaining life of the light source is inversely proportional to the frequency of its operation. Factor D increases with prolonging the service life of the light source and its performance potential in a given regime.

Parameter D may vary extensively (supposedly from 2 to 10) depending on expectations of the economic conditions, consumer psychology, overall period of payments, product's operating time and the dynamics of their time distribution.

In what follows, we present estimates of the efficiency of various light sources obtained on the following assumptions:

— electricity tariffs do not change with time;

Table 1. Efficiency of existing and projected light sources of different types producing a 1000-lm light flux depending on their technical and economic characteristics and operating regimes given an electricity tariff of 3 rubles per kW h (parameter $n = 3$).

Type of light source	Srvice life, h $T = 10^4 t$	Useful lifetime, months $T_e = 48t$	Estimated discount factor $D(t)$	Luminous efficiency, lm W^{-1} $E = 10^2 k$	Price of light source, rubles $P = 10^2 p$	Efficiency of light source Ef, klm h/ruble
Incandescent lamp	1000 $t = 0.1$	4.8 $t = 0.1$	1	12 $k = 0.12$	7 $p = 0.07$	≈ 4
Halogen lamp	4000 $t = 0.4$	19.2 $t = 0.4$	1.1	28 $k = 0.28$	400 $p = 4$	≈ 5
Metal halogen (metal haloid) lamp	4000 $t = 0.4$	19.2 $t = 0.4$	1.1	73 $k = 0.73$	400 $p = 4$	≈ 7.3
Compact luminescent lamp*	10,000 $t = 1$	48 $t = 1$	1.26	50 $k = 0.5$	150 $p = 1.5$	≈ 16
Luminescent lamp*	10,000 $t = 1$	48 $t = 1$	1.26	90 $k = 0.9$	150 $p = 1.5$	≈ 22
Light-emitting diode	30,000 $t = 3$	144 $t = 3$	1.9	70 $k = 0.7$	200 $p = 2$	≈ 34
Light-emitting diode**	50,000 $t = 5$	240 $t = 5$	2.64	70 $k = 0.7$	200 $p = 2$	≈ 49
Light-emitting diode**	50,000 $t = 5$	240 $t = 5$	2.64	100 $k = 1$	300 $p = 3$	≈ 57.6
Light-emitting diode**	50,000 $t = 5$	240 $t = 5$	2.64	100 $k = 1$	250 $p = 2.5$	≈ 61
Field emission cathodoluminescent (FECL)** lamp	50,000 $t = 5$	240 $t = 5$	2.64	35 $k = 0.35$	30 $p = 0.3$	≈ 30
FECL**	50,000 $t = 5$	240 $t = 5$	2.64	50 $k = 0.5$	100 $p = 1$	≈ 40
FECL**	50,000 $t = 5$	240 $t = 5$	2.64	50 $k = 0.5$	50 $p = 0.5$	≈ 43
FECL**	50,000 $t = 5$	240 $t = 5$	2.64	70 $k = 0.7$	100 $p = 1$	≈ 55
FECL**	50,000 $t = 5$	240 $t = 5$	2.64	70 $k = 0.7$	30 $p = 0.3$	≈ 59

* Price of the lamps without regard for disposal costs of those containing mercury.
** Promising light sources with expected technical and economic characteristics.

— energy consumption by a light source is uniformly distributed in time (so that a source with a service life of 50,000 h has a useful lifetime of 20 years);

— the monthly discount rate equals 0.01 (12% per year).

Let us reduce expression (1) to a dimensionless form using the above assumptions and introducing dimensionless parameters t, k, n, and p in the form that follows:

$$T = 10^4 t\,, \tag{2}$$

$$T_e = 48t\,, \tag{3}$$

where T is the service life measured in hours, and T_e is the useful lifetime in months, with coefficient t for the known light sources varying in a range from 0.1 to 5 (it is assumed here that the light source with a service life of 10,000 h is exploited for 48 months, i.e., 4 years), and

$$E = 10^2 k\,, \tag{4}$$

where E is measured in lm W^{-1}, and k for the known light sources lies in a range from 0.12 to 1, while

$$P_{el} = 10^{-3} n\,, \tag{5}$$

where the electricity tariff P_{el} is measured in rubles per W h, $n = 2-4$, and finally

$$P = 10^2 p\,, \tag{6}$$

where P is the price of the light source for the consumer in rubles, and p changes from 0.07 to 10 or more.

Bearing in mind the above assumptions, the efficiency of a light source producing a 1000-lm light flux is given by the expression (in klm h per ruble):

$$\mathrm{Ef} = 10^2 \left(\frac{p}{t} + \frac{n}{kD(t)} \right)^{-1}. \tag{7}$$

Formula (7) also reflects the fact that parameter D unambiguously depends on parameter t in the framework of the above assumptions: $D = D(t)$.

Table 1 presents efficiency characteristics of various light sources with the respective technical and economic parameters and assumed operating modes.

Estimates of the efficiency based on formula (7) suggest that a real alternative to existing energy-saving light sources and those being developed around light-emitting diodes is constituted by environmentally safe energy-saving field emission cathodoluminescence (FECL) lamps of the new generation, in which a phosphor is excited to luminesce by electron bombardment from a field emission cathode made of a nanostructured carbon material.

Estimates in Table 1 indicate that projected light sources with the efficiency

$$\mathrm{Ef} \approx 20-30 \text{ klm h per ruble}$$

are perfectly competitive with the existing ones, among which gas-discharge luminescent lamps and light-emitting diodes produced on a large scale appear to be especially effective. The most efficacious among light sources of the new generation are light-emitting diodes and FECL lamps. At present, the efficiency of the former light sources is limited by the production cost, while the main limiting factor determining the efficiency of the latter (see Table 1) is the achievement of high light output, bearing in mind low price sensitivity of single articles within the scope of expected technical and economic characteristics.

3.3 Prospects for design optimization of cathodoluminescent lamps — general-purpose light sources

The estimates presented in Section 3.2 suggest that prospects for the application of different types of light sources depend not only on the economic situation and the operation mode affecting the factor $D = D(t)$ and parameter n but also on physicothechnical and industrial-technological factors determining such dimensionless parameters as t, k, and p.

The physical processes in semiconductors resulting in light emission, such as the generation of laser radiation on their exposure to an electron beam, have been considered in monograph [10], among others. Certain analogous processes also proceed during light generation in the cathodophosphor of cathodoluminescent lamps (CLLs) and to a large extent determine their efficiency.

Luminous efficiency and, therefore, parameter k are the most important CLL characteristics. The luminous efficiency of CLLs depends on the following processes and their features:

- transformation of electricity from a conventional electric network (220 V) in the CLL power supply transformer, i.e., its efficiency;
- overcoming the potential barrier at the vacuum–cathode material interface requiring energy expenditures equivalent to the product of the electron work function and emission current;
- acceleration of electrons emitted from the cathode in the cathode-modulating device, electron beam focusing onto the anode and its phosphor layer. The losses in these processes are due to the inability of a part of the electron beam to reach the cathodophosphor;
- efficiency of secondary electron generation in the cathodophosphor, which is determined by electron beam energy losses during passage through the anode and the phosphor layer due to the generation, scattering, and absorption of secondary electrons in the phosphor layer;
- light generation efficiency in the cathodophosphor;
- absorption of luminescence light in structural elements of the lamp, resulting in a decrease in the light flux.

The choice of materials for the cathode, anode, and phosphor layers; their structure, design, and electron beam generation regimes for CLLs; the accelerating voltage and its temporal characteristics; methods of electron beam focusing and constructive decisions providing the focusing onto the cathodophosphor, and the thickness, structure, and other properties of the cathodophosphor layer is crucial for the efficiency of all the above processes and determines such integral characteristics as light output.

To calculate the luminous efficiency, it is also necessary to take into account the factor of energy unit conversion into light technical units, i.e., conversion of light intensity in watts into that measured in lumens. In the maximum of the photopic luminosity curve corresponding to green light with a wavelength of 555 nm (relative spectral luminous efficiency for a standard photometric observer according to the Commission Internationale de l'Eclairage (CIE)), this coefficient is 683 lm W^{-1}. Subject to the necessity of providing the spectral composition of radiation from the sources of visible light corresponding to the comfortable human visual perception of illumination, this coefficient, in fact, can integrally be much smaller (1.5–2 times and even 3 times, e.g.. for light with a wavelength of less than 500 nm) depending upon the real emission spectrum of the lamp.

Light flux is generally defined as

$$S = 683 \int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda\,, \tag{8}$$

where $\Phi_{\mathrm{e}\lambda}(\lambda) = \Phi_{\mathrm{e}}(\lambda, \mathrm{d}\lambda)/\mathrm{d}\lambda$ is the light flux spectral density in energy units, and $V(\lambda)$ is the relative luminous efficiency curve for the CIE standard photometric observer (visible light) with the maximum $V(\lambda) = 1$ corresponding to the wavelength of 555 nm.

Accordingly, the following expression holds for the luminous efficiency E:

$$\begin{aligned} E = \frac{S}{W} &= \alpha\, \frac{683 \int_{380}^{780} \Phi_{\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\Phi_{\Sigma h\nu}}\, \frac{\Phi_{\Sigma h\nu}}{W_{\mathrm{ee}}}\, \frac{W_{\mathrm{ee}}}{W_{\mathrm{e}}}\, \frac{W_{\mathrm{e}}}{W_1}\, \frac{W_1}{W} \\ &= \alpha\, \frac{683 \int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, \mathrm{d}\lambda}\, k_4 k_3 k_2 k_1 = 683 \alpha k_5 k_4 k_3 k_2 k_1\,, \end{aligned} \tag{9}$$

where α is the light fraction emitted by the phosphor and spent on illumination, i.e., part of the emission minus losses due to absorption by structural elements of the lamp;

W is the power supplied to the lamp;

W_1 is the power delivered to the electron generation system (at the exit from the power supply transformer, i.e., the power consumed by the lamp itself or, more precisely, its cathode-modulating device);

$K_1 = W_1/W$ is the efficiency of the power supply transformer;

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

$K_2 = W_{\mathrm{e}}/W_1$ is the efficiency of electron beam generation (in the case of a thermionic cathode light source, considerable losses decreasing the efficiency are due to energy expenditures on cathode heating);

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

$k_3 = W_{\mathrm{ee}}/W_{\mathrm{e}}$ is the generation efficiency of electron beam-excited electronic states in the cathodophosphor;

$\Phi_{\Sigma h\nu}$ is the total cathodoluminescence power:

$$\Phi_{\Sigma h\nu} = \int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, \mathrm{d}\lambda = \langle h\nu \rangle I_{h\nu} \tag{10}$$

in energy units within the visible light range (380–780 nm), in accordance with recommendations given by *The Reference Book on Lighting Engineering* for averaging the upper and lower borders of a visible light spectrum (see Ref. [1]);

$\langle h\nu \rangle$ is the mean energy of a visible light quantum;

$I_{h\nu}$ is the visible light intensity measured in emission quanta per unit time;

$k_4 = \Phi_{\Sigma h\nu}/W_{\mathrm{ee}}$ is the ratio of luminescence generation efficiency to the energy of excited electronic states in the phosphor layer;

k_5 is the factor of luminescence energy conversion into light flux intensity in light technical units, depending only on spectral characteristics of the light source:

$$k_5 = \frac{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, \mathrm{d}\lambda} = \frac{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\Phi_{\Sigma h\nu}}\,. \tag{11}$$

The value of k_5 is the same for different types of light sources with similar spectral characteristics.

Thus, the light output in formula (9) is determined, in accordance with expressions (10), (11) and the above notations, by the product of coefficients α, k_5, k_4, k_3, k_2, and k_1, each being smaller than unity and characterizing the lowered light output at the respective stage of conversion of the energy supplied to the radiation source into the light flux from the source in the visible spectral range:

$$\begin{aligned} E = \frac{S}{W} &= \alpha\, \frac{683 \int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\int_{380}^{780} \Phi_{\mathrm{e}\lambda}(\lambda)\, \mathrm{d}\lambda}\, k_4 k_3 k_2 k_1 \\ &= 683 \alpha k_5 k_4 k_3 k_2 k_1\,. \end{aligned} \tag{12}$$

Coefficients of light output reduction at the above conversion stages can be defined as follows.

(1) Coefficient α or the lamp exiting light loss factor depends only on the design features of the emission source and can vary from 0.3 to 0.9, tending toward unity in the ideal case.

(2) Coefficient k_5 determined by the choice of the source emission spectrum equals, as a rule, 0.2–0.5 but can deviate from this range and become either lower than 0.2, e.g., for radiation in short (below 490 nm)- and long (above 635 nm)-wave regions of the visible light spectrum, or higher than 0.5 for the lamp radiation in the 510–610 nm region. Coefficient k_5 depends on the source emission spectrum alone and is equal for different types of light sources with similar spectral characteristics. The mean value of $k_5 = 0.3-0.4$ can be used for estimation purposes.

(3) Coefficient k_4 is the ratio of luminescence generation efficiency to generation efficiency of excited electronic states in phosphor; it is determined by the physical processes of transformation of phosphor excited electronic states to light emission of a desired spectral composition. For currently available cathodophosphors, coefficient k_4 is as high as 0.2–0.25 [11–14]. Indeed, since cathodophosphors are based on semiconductors or dielectrics, multiple scattering of fast electrons in the beam generated in a cathodoluminescent light source with energies of several keV and the absorption of their energy by the cathodophosphor material result in a large number of excited states (electron–hole pairs) that dissipate their excess energy till it becomes equal to the electron–hole pair energy commensurate with the bandgap width. This thermalization process is followed by radiationless deactivation of electron–hole pairs or their trapping by luminous centers accompanied by Stokes losses and further emission of a light quantum with an energy smaller than the bandgap width. Thus, each excited state of a cathodophosphor (without regard for cascade luminescence possible, in principle, under certain conditions [15, 16]) can give no more than one light quantum. Therefore, the following relation holds for k_4:

$$k_4 = \frac{\Phi_{\Sigma h\nu}}{W_{\mathrm{ee}}} = \frac{\langle h\nu \rangle I_{h\nu}}{\gamma E_{\mathrm{G}} N_{\mathrm{ee}}} = \frac{\langle h\nu \rangle}{\gamma E_{\mathrm{G}}}\, \frac{I_{h\nu}}{N_{\mathrm{ee}}}\,, \tag{13}$$

where, as before, the following notation was used:

$\langle h\nu \rangle$ is the mean energy of a visible light quantum;

$I_{h\nu}$ is the visible light intensity measured in emission quanta per unit time;

$\Phi_{\Sigma h\nu} = \langle h\nu \rangle I_{h\nu}$ is the light flux intensity in energy units;

$W_{\mathrm{ee}} = \gamma E_{\mathrm{G}} N_{\mathrm{ee}}$ is the generation power of excited electronic states (secondary excited electrons or electron–hole pairs, in terms of the band theory) in the phosphor (cathodophosphor) layer;

N_{e} is the generation intensity of excited electronic states (secondary excited electrons or excited electron–hole pairs) in the phosphor (cathodophosphor) layer;

γE_{G} is the mean energy of the generated excited state in the cathodophosphor (an excited electron–hole pair formed as a result of fast electron scattering in the phosphor material);

$\langle h\nu \rangle/(\gamma E_{\mathrm{G}})$ is the transformation efficiency of the excited electronic state (excited electron–hole pair) to the light quantum energy;

$I_{h\nu}/N_{\mathrm{ee}}$ is the quantum yield of luminescence relative to generated excited electronic states (excited electron–hole pairs) in the cathodophosphor material;

E_{G} is the bandgap width of the cathodophosphor material;

γ is the coefficient characterizing energy losses in the thermalization process, i.e., the energy of the initially excited state of an electron–hole pair in excess of the bandgap width. The value of $\gamma = 3$ is usually taken based on experimental findings [17].

A similar estimate ensues from theoretical reasoning for direct bandgap semiconductors in Ref. [11], where the effective electron and hole masses were assumed to be roughly equal. This means that $\langle h\nu \rangle/(\gamma E_{\mathrm{G}})$ cannot be higher than 0.33. Bearing in mind Stokes losses and the fact that the quantum yield of luminescence is less than unity, k_4 may range 0.25–0.30. This estimate is not final in view of the data that coefficient γ for wide bandgap insulators ($E_{\mathrm{G}} > 6-8$ eV) equals 2 [15, 16], giving reason to think that $\langle h\nu \rangle/(\gamma E_{\mathrm{G}})$ can be as high as 0.5. However, such a value is possible only upon the generation of light quanta with an energy of 6–8 eV that is inconsistent with the visible light quantum energy. This means that in the case of the creation of one photon in the single-quantum cathodoluminescence regime, when no more than one photon (in the visible range with an energy of 2–3 eV) is generated per excited electron–hole pair, this value falls to 0.1–0.25. Moreover, the possibility, in principle, of increasing the efficiency of the transformation of the excited electronic state (an excited electron–hole pair) to the light quantum energy in carrying out the multiquantum (cascade) luminescence mechanisms should be taken into consideration.

In the anti-Stokes luminescence processes [18] (to be precise, in its stepwise and cooperative variants, including sensitized photoexcitation [19–24]), the energy of long wavelength (infrared (IR) or visible) radiation quanta absorbed in the material is sequentially or cooperatively summarized, giving rise to a highly excited state capable of emitting (directly or upon transfer to the luminescence center) a light quantum with an energy exceeding that of the absorbed long-wave radiation quanta. In contrast, the essence of multiquantum, cascade in particular, luminescence [25–49] lies in the sequential or cooperative emission of two or more quanta of IR or visible light being enabled through the energy of the state excited in the material by absorption of the electron beam or shorter wavelength photons of visible or ultraviolet (UV) light.

The phenomenon of multiquantum luminescence, in which one highly excited state or one high-energy photon generates two or more photons with a lower energy, has been extensively investigated in the recent past with a view to creating cascade phosphors converting UV radiation into visible light for application in high-efficiency luminescent light sources, such as gas-discharge luminescent bulbs, light-emitting diodes, or FECL lamps or other devices [37, 50–52].

The most thoroughly studied process is the conversion of a quanta of UV or short-wave visible radiation into two quanta of longer wavelength radiation (the quantum cutting (QC) process), which can enhance the efficacy of light sources by a factor of two or even more in the cascade emission of three [47] or more photons.

The QC process or cascade emission is possible to realize based on at least two different mechanisms [37]. In one of them, the energy is simultaneously transferred from a donor to two acceptors between which the energy of the highly excited states is divided, with the subsequent emission of two photons as, for example, when utilizing Ln ions [25]. This mechanism holds just as well for Tb:Yb, Bi:Yb, Ce:Yb, Eu^{2+}:Yb, and other systems [28]. The second cascade luminescence mechanism is also realized in systems doped with rare-earth elements, such as Pr^{3+} [32]. Cascade luminescence involving two-step energy transfer in a $LiGdF_4:Eu^{3+}$ system is also described in Ref. [29], where a photon with a wavelength of 202 nm absorbed by Gd^{3+} ions was transferred to Eu^{3+} ions with subsequent intense emission in the visible range. Low-energy photons can be obtained as well during energy transfer by phonons in systems containing Eu:Yb dopants [31].

Although most authors focus their attention on the conversion of UV into visible light, in particular, the process of multiphoton cascade photoluminescence, certain recent publications (see paper [38]) suggest the possibility of cascade photoluminescence in the visible and near UV bands using vacuum UV radiation: hence, the possibility of effective multiquantum cathodoluminescence.

We are of the opinion that more extensive experiments in this field are needed, bearing in mind the possibility, in principle, of transferring energy in cathodoluminescence process [53] and the growing number of publications on new materials having good prospects for application in the development of novel field emission cathodoluminescent sources of visible and UV radiations [54–71].

The aforesaid gives reason to expect that a reduction in the Stokes losses in wide bandgap materials by cascade luminescence mechanisms will allow, in the case of the successful development of research, increasing the cathodoluminescence efficiency to 0.3–0.4 [72].

(4) Coefficient k_3 or the generation efficiency of cathodophosphor excited electronic states by an electron beam depends on beam focusing and the fraction of its energy absorbed in the cathodophosphor material. This coefficient, which does not exceed the fraction of electrons absorbed in the cathodophosphor layer, is defined by the electron beam reflection coefficient from the phosphor layer and the beam transmission coefficient through this layer. The value of k_3 strongly depends on the design features of the light source, such as the geometry of the relative arrangement of the cathode (cathode-modulating device), anode, and phosphor (cathodophosphor) layers, material, thickness and structure of this layer, etc. It may vary in a wide range and amount (by our estimates) to more than 0.9.

(5) Coefficient k_2 corresponds to the electron beam generation efficiency and may reach, for a field emission-based light source, a value practically equal to unity. However, it may be significantly smaller than that for thermionic cathode light sources due to energy consumption for cathode heating.

(6) Coefficient k_1 or the coefficient of light output reduction by the power supply transformer can be estimated at 0.7–0.95.

The employment of the above coefficients for evaluating the light output of cathodoluminescent sources of visible radiation gives an estimate of 40–80 lm W^{-1}. However, such values are possible to achieve only for an optimal design solution ensuring high luminous efficiency of the cathodoluminescent lamps. Light output ranging from 25 to 37 lm W^{-1} has been obtained under practical conditions [73, 74].

As noted in a preceding section, the number of publications concerned with research on new materials promising for novel variants of field emission cathodoluminescent sources of visible and UV radiations has increased recently [54–71]. For example, Refs [56, 58, 61, 63, 64, 70, 71] deal with new materials for field emission cathodes, including those based on carbon nanostructures [56, 64] and other nanostructured materials [58, 61, 63, 70, 71]. References [54, 59, 62, 65, 67, 68] consider the possibility of using various cathodophosphors, including metamaterial-based ones [54]. Of special interest are publications devoted to the possibility of creating ultraminiature and nanoscale sources of cathodoluminescence [60, 67] and the application of the cathodoluminescence effect to nanostructure investigations [55]. An important research area also deals with the choice of optimal design concepts, including the creation of relevant models, based on the knowledge of the influence of geometrical and electrical parameters of field emission cathodoluminescent lamps on their light and electronic characteristics [66].

Section 4 is designed to consider embodiments proposed to enhance CLL efficiency and results obtained from their practical implementation.

4. Light sources with thermionic cathodes

The design of thermionic cathode bulbs developed by the Vu1 Corporation (NY, USA) accounts for their serious disadvantages as compared with field emission cathode light sources.

The illuminating system proposed in Refs [75, 76] is a cathodoluminescent light-emitting device consisting of (Fig. 2)

- a transparent evacuated housing;
- an anode with a phosphor layer deposited on the transparent surface of the housing through which the light is transmitted and a conductive layer;
- a wide-angle electron gun emitting essentially non-focused electrons and comprising the thermionic cathode and a reflector electrode.

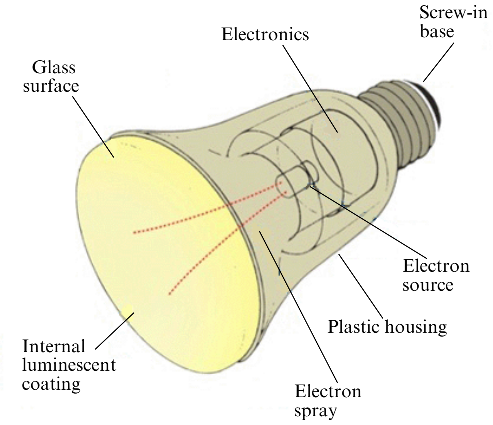

Figure 2. A Vul thermal emission bulb.

One variant of the device is built around a direct-heated thermionic cathode with the flat-top heater element shaped like an upside-down letter U to which a planar substrate is fastened. The emitting layer is deposited on the substrate side opposite to the fastened surface.

An alternative electron gun has a cathode with a heater welded to a disk, the disk having an emissive surface on the side facing a dome-shaped defocusing grid and an anode.

The authors of Refs [75, 76] also proposed an embodiment in which the heater is supported on two metal heater bars. The gun has a metal extraction disk aligned with the emissive material, a metal field-smoothing disk aligned with the metal extraction disk and positioned further from the emissive material than the metal extraction disk, and a metal grid having a convex shape and other parts constituting the gun electrodes.

The employment of a thermionic cathode as the electron source is a cause of the following drawbacks:

- impaired efficiency and durability of the device due to the presence of heated structural elements;
- enhanced inertia because some time is needed to bring the cathode up to the operating temperature.

A power supply for providing power to the cathodoluminescent light-emitting device comprises two power sources. One is capable of providing at least a two thousand volt potential difference between the cathode and the anode of the light-emitting device; the other, intended to heat the cathode, is capable of detecting variations in the input alternating current and adjusting the brightness of the light emitted from the luminescent layer by gradually changing the cathode temperature.

The application of a low potential difference between the cathode and the anode substantially impairs the luminous efficiency of the lighting device (the specified efficiency is roughly 25 lm W^{-1}).

On the other hand, the use of a complicated power source to heat the cathode markedly increases the production cost. By the most conservative estimate, the ultimate cost of the thermionic cathode lamp described in the preceding paragraphs is 5 times that of a field emission lamp.

5. Light sources with field emission cathodes

5.1 Finger type light sources

The design of finger type cathodoluminescent lamps makes them the brightest light sources. It allows producing a high-voltage (up to 25 kV) electron flux with a current up to 1 mA. The brightness of such devices may exceed 100,000 cd m^{-2}. The construction of CLLs is schematically illustrated in Fig. 3.

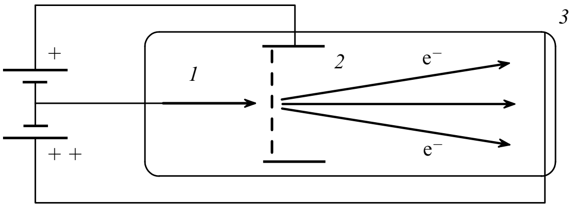

Figure 3. Schematic of a finger type cathodoluminescent lamp.

Electrons emitted from the field emission cathode *1* reach the luminescent screen under the action of the total electric field of control electrode *2* and anode *3* and cause it to luminesce. The anode current can be controlled by both the voltage supplied to the modulator (in the 0.7–5 kV range) and to the anode (5–25 kV). Importantly, these voltages are safe for users due to the low current strength (a few μA) and the possibility of developing a power supply driver inserted into the E27/27, E27/30, E27/40 sockets of cathodoluminescent light sources (CLSs).

A few long-lived CLS prototypes have been designed in laboratories of the Moscow Institute of Physics and Technology; some of them are described below.

A goal of invention [77] was to improve the economic efficiency of electrovacuum light sources by reducing energy consumption with the simultaneous extension of CLS durability, as well as by decreasing internal heat release and the size of the device through enhancement of electron beam divergence.

A 5–6-kV voltage is applied to the screen, while a rod type field emission cathode emits a diverging electron beam with an apex angle of $60° - 90°$ and up to a 400-μA current whose value depends on the voltage supplied to the modulator.

The invention employs a cathode in the form of a rod 20–300 μm in diameter with a flat emitting butt-end. The emitting end lies in the plane facing the modulator surface, with the ratio of opening diameters of the modulator and the emitting end varying from 3:1 to 10:1 to ensure the best performance characteristics, high economic and functional efficiencies of the device. The emitting butt-end and the screen are spaced apart 0.5–1.0 screen diameter due to which the electron beam uniformly excites the screen and causes its bright glow.

Taken together, these features allow the linear dimensions of the device to be reduced by a factor of 3–4 owing to a wide electron beam divergence; simultaneously, the power consumption is decreased by one third, while the light source lifetime is increased due to lower operating temperature and a smaller number of soldered glass–metal joints.

To enhance the light intensity, the authors of Ref. [78] increased the emission current produced by the field emission cathode. The current from a single carbon fiber bundle during long continuous operation being limited to 400 μA, its increase is possible if the field emission cathode contains several such bundles. In the study being considered, the field emission cathode consisted of 5–10 circumferentially disposed bundles of carbon fibers.

Electrons that reach the luminescent screen cause it to glow. The highly uniform glow is due to the efficient overlap between individual field emission images on the screen. The

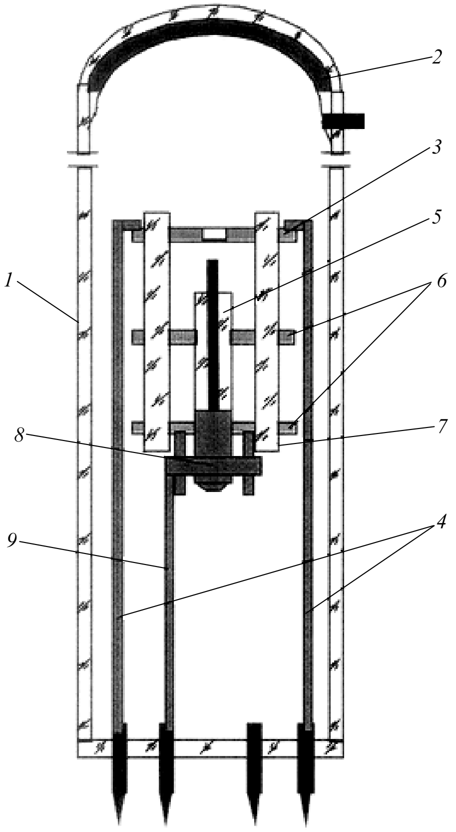

Figure 4. Field emission device: *1* — evacuated container, *2* — anode, *3* — modulator, *4* — contact terminal pins, *5* — field emission cathode, *6* — alignment disks, *7* — rods, *8* — FEC contact node, *9* — FEC contact pin.

size of the bulb remains practically the same as when a single-fiber field emission cathode is used. The large number of fiber bundles in the field emission cathode permits increasing the emission current up to 4 mA, which, however, may overheat the anode.

On the other hand, the design solutions proposed in Ref. [77] can be employed to reduce current drain from each individual field emission cathode and thereby lower the driving voltage, thus decreasing the ponderomotive action on the cathode in order to prolong the lifespan of field emission cathodes and the device as a whole.

The proposed construction renders it possible to significantly increase (1.5–2 times) light intensity and the uniformity of screen glow (from 30–40% to 80–90%), reduce the length of the bulb, and prolong its lifetime.

Thus, the proposed CLS (FECL) is characterized by enhanced brightness and uniform glow, lowered driving voltage, relatively small dimensions, and higher durability.

The field emission device shown in Fig. 4 [79] is intended for use in cathode-ray devices, such as probes, screens, scanning electron microscopes, and research and analytical instruments. The device comprises a field emission cathode made of a bundle of carbon fibers and placed in a vacuum bulb, a modulator with an aperture, and contact terminal pins. The technical result consists in precise focusing of the electron beam, which facilitates optimization of the parameters and operational features of cathode-ray devices.

The objective of the invention under consideration is to improve the field emission characteristics of the device and, in particular, to enhance its durability and vibration resistance by precise fiber bundle orientation relative to the modulator and elimination of mechanical impact on the fibers.

The proposed construction of field emission devices is realized in the following way. A bundle of carbon fibers is enclosed in a sheath of dielectric material, in particular, made of glass. The operation of 'vitrification' permits producing cathodes with the bundle of fibers oriented along the axis and located exactly in the center of the cathode in the absence of mechanical loads on the fibers. Vitrified fibers are cut into segments of a predetermined length, both of their ends are released from the glass sheath, and an electroconducting substance, e.g., an aquadag, is applied to one of them to enlarge the contact area; then, the workpieces are shell-squeezed to obtain a reliable electrical contact with the cathode and terminal pins are welded to the shell contact.

Accurate alignment of the cathode center and setting the distance between the modulator and the cathode are secured by adjusting disks rigidly connected with the modulator, so that the centers of their holes are aligned with each other and with the bore of the modulator by means of rods made of glass and simultaneously attached to the grooves of the adjusting disks and the modulator with the formation of a mechanical joint. The field emission cathode is placed into the holes of the adjusting disks and rigidly attached to the lower disk; then, such cathode-modulating node (CMN) is mounted through a pin modulator on the mounting base and connected to contact terminal pins of the cathode. These operations are followed by sealing the vacuum flask. The thus prepared field emission device is ready for operation.

Studies aimed at optimizing the CLS (FECL) design are currently underway in laboratories at the Moscow Institute of Physics and Technology. An objective of the invention disclosed in Ref. [80] is to provide a simplified construction of the field emission device and lower-cost technology for its production.

In this device, a field emission cathode made of a monolithic nanodiamond–carbon composite material ($1:0.2-1:0.4$) is used. Such a composite is prepared by the treatment of a workpiece formed from a nanodiamond powder in the atmosphere of gaseous hydrocarbons at a temperature above their degradation temperature, resulting in carbon liberation. The end product is a 10–15-mm long bulky rod or a disk of round or square cross section 1–2 mm in diameter.

The advantages of such a device include strong emission currents, operational stability in a relatively low vacuum ($\sim 10^{-6}$ Torr), reproducible field emission characteristics, and high durability. Moreover, electrons are emitted from the rather strong composite that is easy to attach in the field emission device, instead of the flexible fibrous structure needed to be vitrified as described earlier in this section.

In all the above samples and prototypes of the lamps intended for different purposes, standard TV phosphors were utilized and their design was not optimized for general-purpose light sources. Unfortunately, no optimized structures for general-purpose lamps with a field emission cathode have thus far been proposed either in this country or abroad. Therefore, the primary task is to elaborate a working prototype of highly efficient CLSs (FECL) with a low net cost in large-scale production.

At present, many enterprises in the USA, the UK, Republic of Korea, China, and Japan are competing to develop energy-efficient FECL lamps of the new generation having a long lifetime. For example, the authors of Ref. [5] proposed to use a cathode from carbon nanoapexes to improve field emission characteristics. A design of such a light-emitting device analogous to that described in Ref. [81] comprises

(1) a carbon nanoapex cathode having an area from 1 to 100 mm^2;

(2) a control electrode (a metal grid with an area of 1–10 mm^2);

(3) a focusing lens to focus emitted light;

(4) an anode covered with a phosphor layer.

To recall, the vacuum needed for this light-emitting device to operate must be at least 10^{-7} Torr. The voltage between the cathode and the control electrode may be from 100 to 1400 V, depending on the brightness sought, whereas a voltage from 1 to 35 kV is applied to the anode.

The authors of Refs [82, 83] put forward the concept of a field emission device including an evacuated housing with one or two opposite transparent parts covered with a phosphor layer on which the light-transmitting anode is formed. The cathode located opposite the anode is a layer of conducting suspension doped with a nanomaterial. It is electrically connected to a protective cylinder whose end faces the light-transmitting anode.

Invention [84] concerns with a field emission light source and with methods to produce it.

The anode contains a transparent substrate (convex, concave, or flat transparent glass surface or transparent ceramics) covered with a tin-doped indium oxide (ITO) conductive layer. The fluorescent material (colored or three-color phosphor) is applied to the conductive layer. The cathode is made of a metal grid that conducts well, the surface of which is coated with single- or multilayer carbon nanotubes from 1 μm to ≈ 9 mm in length. The grid has an arched cross section to enable it to contain a larger number of carbon nanotubes. Such a structure of the cathode plate facilitates a nanotube distribution at which their ends are spaced rather far apart to reduce mutual screening. The authors argue that such a design makes it possible to significantly increase the number of electrons emitted from the carbon nanotubes and thereby enhance radiation efficiency and the stability of light sources. The shape of the anode and cathode plates is essentially the same, which guarantees a constant distance between them and, therefore, uniform emission.

The method for producing such a field emission light source includes the following steps:

(1) fabrication of a metal wire mesh for the cathode plate;

(2) carbon deposition onto the cathode surface;

(3) preparation of the anode plate and its coating with a fluorescent material;

(4) assembling the cathode and anode plates, base body, and semitranslucent panels into a single field-emission light source.

According to the inventors [84], the production process is simple and easy to apply in practice.

The field emission device suggested in Ref. [85] includes a sealed housing with a light-transmitting part. The phosphor layer and the light-transmitting anode are positioned on the internal surface of the light-transmitting part in succession. The cathode is enclosed in the sealed housing. A carbon nanotube fiber is attached to the cathode surface facing the light-transmitting part. Before being embedded into the sealed housing, the carbon nanotube fiber is processed in the following steps: providing a carbon nanotube array, drawing out at least one carbon nanotube fiber from the carbon nanotube array, treating the carbon nanotube fiber using an organic solvent in a manner such that a bundle of carbon nanotube fibers is formed, and sticking together the bundles of the carbon nanotube fibers.

The authors of Ref. [86] proposed a prototype field emission device, giving special attention to its shielding housing comprising a peripheral wall and a top wall. The peripheral wall surrounds the carbon nanotube filament, whereas the top wall with an opening or a grid functions as electrode.

The luminance of such a pixel tube should be sufficiently high, while using a relatively low voltage. The number of electrons emitted from the carbon nanotube fiber can be adjusted by altering the voltage supplied to the anode, thus adjusting the luminance of the pixel electrode. Furthermore, being enclosed in the shielding housing the carbon nanotube fiber has a prolonged lifetime and is protected against the attacks of a high voltage.

It is clear from the above data that the characteristics of finger type field emission luminescent lamps (finger FECL lamps) make them, especially after design optimization, serious competitors to both existing and projected energy-efficient light sources operating on different physical principles.

5.2 Flat light sources

The main design features of flat light sources are a large anode (cathode) area and a small anode–cathode distance compared with the linear dimensions of the cathode substrate.

A proper production technology renders it possible to achieve a light source with an area in excess of 500 cm^2. Such a device can be implemented in a variety of embodiments [87, 88] determining its end-use functional characteristics.

Field emission cathodes for flat light sources are fabricated by various methods, including screen-printing and electrophoretic deposition. Carbon powders provide the best material to be deposited by various technologies [89]. Also suitable is the mechanical treatment of a bulky carbon workpiece to form flat, large-area field emission cathodes.

A flat light-emitting diode structure (Fig. 5) is presently the most popular option due to the simplicity of vacuum device production. It is employed in flat light sources of moderate brightness (1000–5000 cd m^{-2}). Such sources find application for backlighting liquid crystal displays [90].

In what follows, some of the flat field emission light sources elaborated in the laboratories of the Moscow Institute of Physics and Technology are described.

One of the earliest structures makes use of the bundles of carbon fibers attached to a metal matrix [91–95]. The modulator electrode is positioned in parallel with the emitting surface of the bundles a few tenths of a millimeter from it. The openings of the modulator electrode are in line with the emitting ends of the fiber bundles. Cathode and

Figure 5. Flat light-emitting diode structure: *1* — anode with a phosphor coating, *2* — glass spacer, *3* — exhaust tube, *4* — getter cavity, and *5* — flat field emission cathode.

modulator plates are separated by an insulator placed inside the vacuum cavity bounded by glass plates. The top plate is coated with a layer of conducting transparent material (ITO) and phosphor. The anode, the modulator, and the cathode are connected to the external circuit through electrical outputs.

The unique properties of the cathode made from thermally expanded graphite (TEG) allow it to be used for creating large-area planar field emission cathodes capable of reliably operating in the capacity of a diode. Such cathodes can find application in flat light sources of different areas with continuous illumination or desired patterns (symbols, numerals, signs, etc.), i.e., static information displays. Such devices are easy to manufacture and use up little energy.

The technology for forming emission centers on the TEG foil surface makes it possible to create flat field emission cathodes of different areas (from a few to hundreds of square centimeters). Such field emission cathodes may differ in patterns of emissive surfaces.

The simplest light source with a TEG cathode has a diode type structure. A TEG foil is pasted onto the glass plate coated with the conductive ITO, and craters are formed on the foil following predetermined patterns. The anode is made from glass covered with a TEG layer with a phosphor deposited on it. The distance between the cathode and the anode is set using 1-mm thick glass spacers. The TEG foil being 200 μm thick, the mean crater depth is 200–250 μm, and the distance between the emission centers and the anode is around 550 μm.

The device was operated in a continuous regime. The anode area was 4.8 cm^2. The current density at the anode after the application of 1200 V (electric field strength of 2 V μm^{-1}) was 0.2 mA cm^{-2}. The brightness of the device reached ≈ 3000 cd m^{-2}.

The simplest structures were made using construction graphites as a material for field emission cathodes [96]. Fabrication of a light-emitting diode with the field emission cathode from construction graphite proceeds as a three-step process. The first step involves preparation of a 1.0×1.5-cm workpiece cut out from a block of dense fine-grained MPG-6 brand graphite. Grooves 0.5 mm in width are cut in the workpiece by the electroerosion technique with a pitch of 1.5 mm into which 0.5-mm thick plates made of ‘polycor’ corundum ceramics are inserted. The structure thus obtained is embedded in a glass–cement slurry (a thick dough-like mass).

After crystallization of the glass–cement in a muffle furnace at a temperature of 400 °C , it was ground off together with ceramics until the appearance of the graphite surface. Then grinding was continued using an abrasive powder with a calibrated grain size (in this instance, 28 μm). Because polycor is almost as hard as the abrasive, while graphite is much softer, the graphite surface was ground off to the level lying lower than the surface of polycor plate ends by the interplanar spacing close to the size of abrasive grains. With this simple method, a constant small gap of 30 μm was created over the entire cathode surface. The spacers supported the screen with a phosphor layer and a conductive coating.

Among other things, polishing the graphite field emission cathode with the abrasive powder created the surface topography necessary for efficient field emission.

The spacers were needed to maintain not only the strictly set anode–cathode distance but also the uniform anode and cathode load to compensate for atmospheric pressure and ponderomotive action during operation of the device. The prototype device was tested in the constant strain regime in a vacuum chamber at a residual gas pressure of 10^{-6}–10^{-7} mmHg.

The field emission image was built up of tiny bright dots arranged very close to one another. Uniform illumination of the screen from the graphite cathode surface suggests the highly uniform distribution of microtips over the graphite surface. Preliminary experiments on the creation of a diode type structure based on the field emission cathode from construction graphite have demonstrated the excellent prospects of such an approach. Assessments showed that making use of a thin-film phosphor and a finer-grained abrasive powder to polish field emission cathode structures may yield diode structures with an operating voltage of 200–300 V.

At present, many enterprises in various countries are competing for the development of thin but strong and durable flat field emission light sources of the new generation. As mentioned before, most such sources have a diode structure to facilitate production of vacuum devices.

For example, invention [97] relates to a field emission light source and method of its production comprising preparation of the anode plate, fabrication of the glass plate, coating it with a phosphor layer, placement of the phosphor-coated plate on the substrate, circular arrangement of the spacers at a proper height above the glass plate, arrangement of a steel plate over the spacers and the glass plate, putting the assembled anode plate into a high-temperature furnace to soften the glass plate, and pressing of the luminescent layer into its surface layer through the steel plate. The luminescent layer at the anode plate of the field emission light source created by strong pressing against the glass plate cannot be destroyed by an electron beam even during long-term impact, while the dense and smooth aluminum film may be favorable in increasing luminous efficiency.

The authors of Refs [98, 99] proposed an analogous field emission light source and a method to produce it. The field emission anode plate consists of a transparent ceramic base body and an anode conductive layer capable of emitting light when excited by an electron beam. The light source includes anode and field emission cathode plates, the latter being composed of the substrate and the cathode conductive layer on its surface. The anode and cathode conductive layers positioned opposite each other make up a sealed vacuum chamber. The authors of Refs [98, 99] maintain that their invention enhances the efficiency of electron impact, corrosion stability, and wear resistance. Moreover, the field emission anode plate used in the invention provides uniform glow and is cheap in addition. On the whole, the light source is characterized by high luminous intensity, efficiency, and durability.

A similar structure was described in Ref. [100]. The anode of this flat field emission light source consists of a substrate, a conductive layer formed on the conducting substrate, and a luminescent layer deposited on the anode conductive layer. The cathode has a substrate positioned opposite and at some distance from the anode substrate, a cathode conductive layer formed on the cathode substrate, and an electron emission layer deposited onto the cathode conductive layer opposite the anode luminescent layer.

The main difference from the aforesaid inventions consists in the presence of an electron emission layer, including a glass matrix with a plurality of carbon nanotubes, conducting metal particles, and dispersed getter powder. Cathode and anode substrates are hermetically connected to each other.

The field emission cathode proposed in Ref. [101] for application in flat panel displays includes a layer of a conducting material coated with the amorphous diamond film to form emission centers and reduce the electron work function. Each emission center contains at least two subregions with different electronic properties.

The authors of Ref. [102] proposed a field emission planar lamp possessing a stacked structure. The lamp includes an anode plate, a cathode plate, and a flat panel. The anode plate involves a substrate. The cathode plate is stacked with the anode plate and includes an isolation mesh with a plurality of openings and a cathode mesh with a plurality of through holes. The through holes are in line with the openings. The panel is sealed with the anode substrate to form a vacuum chamber to enclose the anode plate and the cathode plate. Electron beams generated by the cathode plate bombard the anode plate for triggering light emission. The light is emitted from one side of the panel through a passage defined by the opening and, moreover, light exits from another side of the panel — it is emitted directly from anode substrate. Therefore, the field emission planar lamp features two-side illumination.

The authors of Ref. [103] designed a field emission light-emitting element with a high luminous efficiency. The emitter is made of carbon nanotubes in which the metal is either exposed at the open part of the tip orifice or contained inside the tip.

In Ref. [104], the author of the same team invented a cold cathode composed of a massive metal substrate and a field emission film formed on its surface and containing

- a substrate made from one or more of the following metals: Li. Na, K, Rb, Cs, Fr, Gd, Ce, Pr, Sm, Eu, Tb, Dy, Er, Ho, Tm, Yb, Mn, Fe, Ni, Co, Ru, Rh, Cu, Al, Ag, Au, Sn, Bi, Zn, Pt, and Pd;
- a field emission substrate;
- an organic adhesive.

The same author [105] aimed to develop a field emission type cathode capable of emitting a large number of electrons and a field emission type lamp with this cathode.

Such a lamp contains cathode and anode substrates positioned opposite each other. Numerous pyramidal tips with a trapezoidal cross section are formed on the cathode substrate. Cathode electrodes with emitters are located on the pyramid faces. A gate electrode is inserted halfway between the apex of a tip and its base adjoining the cathode substrate. A transparent phosphor-coated electrode is installed on the transparent wavy anode substrate, which has an almost semicircular shape over each cathode emitter.

A field emission double-plane light source described in Refs [106, 107] includes a first anode, a second anode, and a cathode separately arranged between the first and second anodes. Each of the first and second anodes comprises an anode substrate, a conductive layer formed on the surface of the anode substrate, and a luminescent layer formed on the anode conductive layer. The cathode has a metallic-based grid with two opposite surfaces, each facing the respective one of the first and second anodes. Each of the surfaces of the grid has a respective electron emission layer thereon, facing a corresponding luminescent layer of one of the first and second anodes. Each of the electron emission layers includes a glass matrix with a plurality of carbon nanotubes, metallic conductive particles, and getter powders dispersed in the glass matrix.

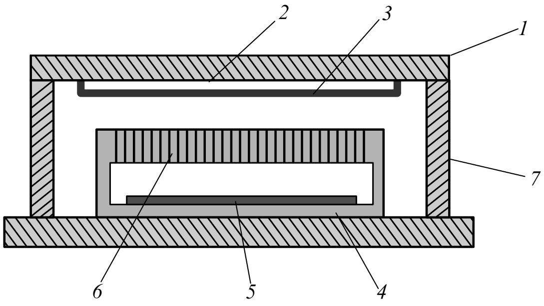

Figure 6. Field emission type source of electrons: *1* — anode, *2* — conductive coating, *3* — photoelectric converter film, *4* — cathode, *5* — emissive material, *6* — secondary emission electrode, and *7* — support elements.

The employment of secondary emissive materials is an efficient method by which uniform luminescence is achieved. The authors of Ref. [108] sought to significantly improve the uniformity of emitted light over the entire luminescent surface. To this end, they designed a field emission light source with a grid electrode from a secondary emissive material having holes through which electrons could pass. The electrode was disposed between the phosphor-coated anode electrode and the field emission cathode electrode. A thin insulation film was used as the secondary emissive material.

An objective of Ref. [109] was to elaborate a field emission type source of electrons with improved capability of detecting signal charges due to reduced current density at the shielding electrode and, therefore, increased operating current density (Fig. 6).

This field emission device comprises an emitter matrix containing a large number of electron sources; a photovoltaic film in which electron beams produced by emitters induce photoelectric conversion, and an electrode placed between the emitter matrix and the photovoltaic film having a plurality of through holes coated on the inside with a film from electron-emitting secondary emissive material.

A field emission device [110] consists of an insulation substrate, an electron-emitting electrode, a secondary electron emission layer, a dielectric layer, a cathode electrode, and an electron emission layer. The electron-emitting electrode is located on the surface of the insulation substrate. The secondary electron emission layer resides on the surface of the electron-emitting electrode. The cathode electrode is located apart from the electron-emitting electrode by the dielectric layer. The cathode electrode has a surface oriented toward the electron-emitting electrode and governs the location in it of an electron outlet opening. The electron emission layer is located on the surface of the cathode electrode and also oriented to the electron-emitting electrode.

The objective of study [111] was to elaborate both a highly reliable field emission electron source with improved emissive characteristics and a light-emitting device applying this source.

The light-emitting device of Ref. [111] has lower and upper electrodes positioned opposite each other and separated by an electron-passing layer, the optimal thickness of which was found by gradual continuous variation in a series of experiments. The field emission source is located opposite

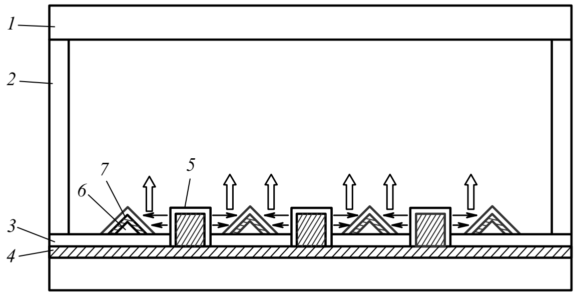

Figure 7. Field emission type light-emitting device: *1* — transparent screen, *2* — support element, *3* — insulating layer, *4* — cathode strip, *5* — emissive protrusion, *6* — anode, and *7* — phosphor.

the phosphor-coated electron collector emitting light by dint of xenon excitation. The light-emitting device is controlled by the voltage applied between the collector and the field emission electron source.

A rather interesting invention is disclosed in Ref. [112] (Fig. 7). It can considerably enhance the light utilization efficiency of field emission light sources.

The design of this light source implies the following:

- at least one cathode strip disposed over the base substrate;
- at least one emissive protrusion disposed over the cathode strip and electrically connected to the latter;
- an insulating layer residing over the cathode strip and having at least one opening to allow the emissive protrusion to protrude out of the opening;
- at least one anode strip disposed over the insulating layer, where the cathode strip and the anode strip are arranged into an $m \times n$ matrix (m and n are the number of cathode and anode strips, respectively);
- at least one anode strip individually controling the corresponding emissive protrusion.

In this light source, the phosphor layer is disposed over the controling surface.

The objective of study [113] was to elaborate and manufacture a cheap field emission device stably emitting electrons. To this end, the field emission device was fabricated as follows. The surface of the conductive substrate is covered with a layer of porous polysilicon by chemical vapor deposition. The gaseous material is sprayed on the metal substrate with a high fusing point heated to a high temperature sufficient for a layer of oxidized or nitrided porous polysilicon to form. Then, a thin metal film is deposited on this layer.

The authors of Ref. [114] proposed an easy-to-produce field emission cathode from a nanocarbon material intended to increase the electric field strength, improve electron emission efficiency, and ensure its uniformity and stability.

The field emission type cathode for emitting electrons under the effect of a strong electric field is supplemented by a three-dimensional structure in the form of a template with a plurality of tips formed on the substrate. The height of each tip is chosen such that the ratio of the gap between adjacent protrusions to their height is roughly 1 : 2 to 1 : 6.

The authors of Ref. [115] suggested an idea on how to prevent phosphor degradation by efficient heat removal in a light source designed so that

- the phosphor and the anode partly overlap on the inner surface of the light-emitting panel;
- the field emission cathode is positioned at a certain distance from the anode;
- the linear conducting elements in the form of strips or a matrix are disposed on the phosphor.

The authors argue that such a design renders it possible to integrate the emissive luminescence of the entire light-emitting surface.

Flat field emission light sources in which multitip electron sources serve as cathodes are worthy of special consideration. An example is provided by Ref. [116] describing a light source comprising a substrate, a cathode conductive layer, and an emissive structure containing a plurality of electron emitters, a transparent substrate, an anode layer, and a fluorescent layer.

The cathode conductive layer disposed on the substrate serves to deposit an emissive structure in the form of a film from carbon nanotubes of a predetermined orientation. The anode layer covered with the luminescent layer on the side facing the electron emitters is formed on the transparent substrate spaced from the cathode conductive layer.

A similar field emission nanotip light source provided in Ref. [117] contains a substrate having a surface, a cathode, an insulating layer, a light-permeable anode, and at least one luminescent layer. A cathode with at least one solid electron emitter formed thereon is located on the substrate surface. The isolating layer is deposited on the cathode. The light-permeable anode faces the field emitters and is spaced from the cathode to form a vacuum chamber. At least one fluorescent layer is formed on the anode. Such a light source can then be incorporated, e.g., into a backlighting module.

The field emission part of the field emission light source proposed by the same authors [118] includes an insulating layer formed on the cathode and an emissive structure with an array of field emission emitters resting on silicon and carbon posts extending from the insulating layer. The field emission emitters from 0.5 to 10 nm in diameter contain molybdenum.

The authors of Ref. [119] proposed a field emission device for emitting white light. The device includes a cathode plate assembly, an anode plate assembly which is opposite to and spaced from the cathode plate assembly, and a supporting body for tightly coupling the cathode plate assembly with the anode plate assembly. The anode plate assembly includes a transparent substrate which can emit yellow light when excited by blue light. An anode and a blue cathode ray luminescent material layer are provided on the surface of the glass substrate.

Many authors have reported inventions in which light reflection is used to enhance the light utilization efficiency and reduce the cost of field emission light sources. For example, Ref. [120] proposes the simplest realization of such a design whose main features are an anode electrode, the thickness of which is chosen depending on input pressure, a reflector with high electric resistance and high reflective capacity formed on the lower glass substrate, a luminescent layer deposited on this anode electrode, an electron-emitting structure, and an upper glass sheet disposed on the cathode electrode. This invention makes it possible to enhance the luminous efficiency, simplify the manufacture, reduce the production cost, and ensure high reliability of the light source due to efficient heat removal during its operation.

In a similar invention (see Ref. [121]), the field emission cathode consists of an electrically conducting layer on which emission centers are formed. The main difference from the device described in the preceding paragraph is that the electron-emitting centers are formed from the material intended to directly emit electrons and the gas-absorbing getter material. The anode is a conductive layer coated with a fluorescent layer.

The authors of Ref. [122] modified a planar light source to simplify and optimize the accuracy of its assembling. To this end, they cut special notches in the cathode structure into which the emissive layer was inserted.

Taken together, this cathode structure, intricate grating structure, and emission layer made up the cathode plate. The cathode and grating structures were disposed parallel to each other on the base plate, with each cathode structure having at least one notch, with the emission layer located in it.

The authors of Ref. [123] proposed a flat light source and its manufacturing method. The field emission light source includes an anode, a cathode, a light guide plate, and a separation body.

The anode and the light guide plate are separated from each other. The pumped volume is formed by the cathode, anode, separation body, and light guide plate. The anode consists of a substrate, a metal light-reflective layer laid on this substrate, and a light-emitting layer deposited on its surface. Such a design allows heat conductivity of the flat field emission light source to be increased. Potential applications of this device include backlighting of liquid crystal displays and utilization in other light sources.

A field emission-based flat light source [124] includes the following: a light-permeable substrate; a plurality of line-shaped cathodes; an electron emitter; an anode; a light-reflecting layer, and a fluorescent layer. The transparent conducting layer of the cathode electrode covers the light-permeable substrate. The electron emitters are disposed on the transparent conducting layer of the cathode electrode. The anode faces the cathodes and is spaced from the cathodes to form a vacuum chamber. The light-emitting layer is formed on the anode and faces the cathode. The fluorescent layer is formed on the light-reflecting layer.

The authors of Ref. [125] sought to effectively prevent deformation of or damage to the front panel resulting from a temperature difference between the panel and the phosphor-coated anode.

To this end, they used an electron source for the flat light source consisting of an array of field emission emitters located in one plane and practically parallel to one another. Moreover, the anode was covered with a phosphor layer emitting light by re-emitting electrons from the field emission portion on the inner surface of the front panel. The proposed design allowed reducing to a minimum temperature stress arising between the front panel and elements of the phosphor-coated anode as a result of thermal expansion and compression.

The main distinctive feature of invention [126] is the bowl shape of the light-reflecting structure. This publication describes the manufacturing method of a field emission light source including the emitter structure with an array of field electron sources on the substrate and a light-reflecting structure from a large number of bowl-shaped reflectors with a deposited luminescent layer. The reflecting structure lies opposite the emitter structure.

The flat field emission light source of invention [127] includes an anode plate with a luminescent layer, besides other elements common to similar devices. The spatial structure of the luminescent layer and the rough surface of the anode plate collectively increase the area of the luminous surface and thereby the overall light utilization efficiency of the flat light source. In practice, the roughness of the anode plate is attained by making numerous protrusions thereon or disposing a large number of concave mirrors.

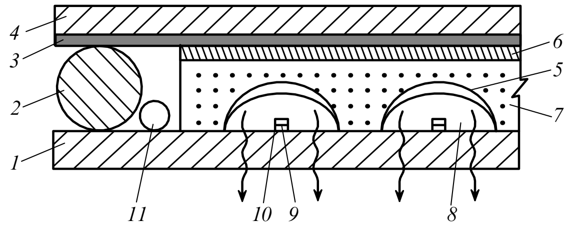

Figure 8. Flat field emission type illumination module with strip-shaped field emission cathodes using the light reflection effect: *1* — bottom glass plate for light extraction, *2* — sealant layer, *3* — transparent conductive layer (ITO), *4* — top glass substrate, *5* — fluorescent layer, *6* — black coating, *7* — aluminum anode, *8* — semicylindrical groove, *9* — strip-shaped cathode (silver paste), *10* — nanotubes, and *11* — getter.

Invention [128] (Fig. 8) comprises a field emission cathode from silver paste-strips on which nanotubes are regularly laid down parallel to one another to serve as the field emission cathode proper. Cathode strips are accommodated in the center of grooves shaped like semicylinders. The grooves themselves are cut parallel and at an equal distance from one another in an aluminum template that serves as the anode. The inner surfaces of the grooves are coated with phosphors of different colors.

Electrons emitted from field emission cathodes bombard the phosphor layer on the anode and excite it to luminesce light, which is reflected from the inner surface of the cathode grooves and passes through the bottom glass plate. The shape of the grooves facilitates scattering and re-reflection of light fluxes, which enhances the uniformity of luminescence emitted by the illumination module.

The field emission backlight device [129] comprises

- a first substrate and a second substrate separated from and roughly parallel to each other;
- a first anode electrode and a second anode electrode that face each other on inner surfaces of the first substrate and the second substrate;
- cathode electrodes separated from and roughly parallel to one another between the first substrate and the second substrate.

It may also include electron emission sources disposed on the cathode electrodes to emit electrons by an electric field and a phosphor layer on the first anode electrode or the second anode electrode.

The available large-area flat light sources are, as a rule, assembled from many smaller sources. For example, inventions [130, 131] relate to one- and two-sided combined field emission light sources (or display modules [132]) having no vacuum-insulated posts and consisting of many illumination modules. The field emission modules individually placed on the substrate are integrated into a single field emission light source. The fact that integral flat field emission light sources with a large area do not need vacuum-insulated posts resolves the problem of charge accumulation and maintenance of the proper vacuum level. According to the authors, this prolongs the lifetime of field emission light sources, enhances the uniformity of luminescence, and provides an opportunity for practical realization of large-area planar field-emission light sources.

The field emission light source of invention [133] includes a plurality of spacers, each connecting a substantially transparent substrate to a backing substrate. The device can also include many pixels, wherein each can include one or more first electrodes disposed over the substantially transparent substrate, a light emitting layer over each of the one or more first electrodes, and one or more second electrodes located over the backing substrate, wherein the one or more second electrodes and the one or more first electrodes are disposed at a predetermined gap in a low-pressure region. Each set of pixels can further include one or more nanocylinder electron emitter arrays disposed over each of the one or more second electrodes.

Reference [134] proposes an analogous surface field emission light source allowing us to maintain substantial light-emitting efficiency by forming the first and second construction sealants in the vacuum state.

The main difference between invention [135] and those described in preceding paragraphs concerns the number and arrangement of nanoscale electron emitters which can include a first electrode electrically connected to a first power supply and a second electrode electrically connected to a second power supply. The nanoscale electron emitter can also include

- a nanocylinder electron emitter array disposed over the second electrode, and
- a nanocylinder electron emitter array disposed in a dielectric matrix.

Each of the plurality of nanocylinder electron emitters can include a first end connected to the second electrode and a second end positioned to emit electrons, the first end being opposite to the second end.

The objective of study [136] was to improve the quality of light utilization from the front side of the flat panel of a field emission light source in which electron emitters in the form of metal film wires are accommodated in a large number of grooves.

The large and thin flat light source invented in Ref. [137] has a flat front panel resistant to strains caused by internal pressure.

The space between the plane front and back panels is vacuum-sealed. Deformation of the front panel under the effect of atmospheric pressure at the interface with the vacuum is prevented by reinforcement ribs in the vacuum cavity, between which two field emission structures in the form of metal film wires are incorporated. The anode interposed between these structures is also shaped like a phosphor-coated wire.

The authors of Ref. [138] elaborated a reproducible design of a device with high brightness and uniform light emission. It has a large and thin front panel resistant to strains caused by internal pressure, despite the absence of reinforcement ribs.

A dome-shaped front panel is positioned opposite the back one. An anode phosphor film is formed on the inner surface of the front panel and wire-shaped cathodes are placed on the inner surface of the back panel with a geometry that allows putting equal spacing between each cathode and anode.

A similar light source [139] also has a rear plate, a front plate formed with the anode layer, and a cathode interposed between them. The cathode includes many electrically conductive carriers and field emitters formed thereon. The field emitters are uniformly distributed on anode-facing surfaces of the conductive carriers. The anode layer includes a host of curving portions corresponding to the conductive carriers. Preferably, the field emitters extend radially outward from the corresponding conductive carriers. The conductive carriers are parallel to each other and are located substantially on a common plane. Each of the conductive carriers can be connected with a pulling device arranged on at least one end thereof; an example of a pulling device is a spring.

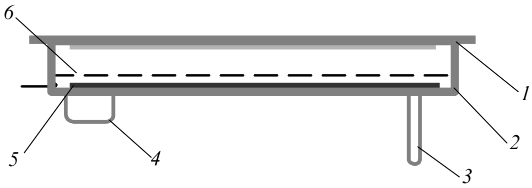

Figure 9. Triode construction of a flat light source: *1* — anode with a phosphor layer, *2* — glass spacer, *3* — exhaust tube, *4* — getter cavity, *5* — flat field emission cathode, and *6* — modulator(s).

A triode structure is preferred to design ultrabright light sources (Fig. 9).

The most popular embodiment includes a modulator placed between the cathode and the anode. For example, the authors of Ref. [140] proposed a design of the field emission lamp (FEL) reducing the drive cost and increasing the lifetime, while capable of electron emission at a lower voltage. This FEL includes cathode, gate, and anode electrodes inside a vacuum-sealed container. The cathode electrode is formed on the protruding or concave part of the substrate (a nanocarbon material).

Reference [141] describes a similar design of the field emission lamp containing a number of cathode electrodes formed above a first substrate, an anode electrode formed under a second substrate to face the cathode electrode, a fluorescent layer composed of red, green, and blue (RGB) patterns formed alternately on the anode electrode in an oblique direction, and many emitters formed on the cathode electrodes to correspond to the RGB patterns. According to this invention, a FEL having a fast response time is used as a backlight unit, and a color breaking phenomenon can be prevented by the color sequential driving method.

The authors of Ref. [142] reported a field emission device in which the metal gate substrate is enclosed between anode and cathode substrates to operate as a gate electrode inducing electron emission. The device has a simple design and is easy to manufacture. Also noteworthy is the current flows through a few electrically insulated cathodes, which opens up the possibility of local adjustment of brightness.

The authors of Ref. [143] described a field emission device in which the initial divergence angle of electrons emitted from the cathode is increased by deposition of an insulating layer onto the substrate.

Many parallel cathode electrodes are formed on the lower substrate. Of the many 3–10-μm high insulating layers in the form of parallel lines, one is localized on the substrate, while the remaining ones intersect many cathode electrodes. At least one of these electrodes carries an emitter from a field emission material sandwiched between insulating layers.

The objective of study [144] was to elaborate a field emission illuminating system resistant to external mechanical shocks that can alter the distance between the cathode mask and the gate electrode.

The proposed system includes an integrated structure of gate electrode incorporated into the insulator, a gate electrode proper, and a cathode mask that does not need to be positioned between the cathode mask and the gate electrode during assembling. Moreover, some of the components may be combined to save labor in manufacturing. Because the insulator is connected to both the gate electrode and the cathode mask, their relative position does not change, even if there is an external shock.

The authors of Ref. [145] proposed an illuminating system, peculiar in that its gate electrode is protected from the penetration of electrons emitted by the field emission cathode.

This object is attained by making the diaphragm at the open part of the gate electrode bigger than that at the open part of the insulator. The configuration at which the insulator projects above the open part through which electrons flow prevents collisions of field emission electrons with the gate electrode. In this way, the problem of electron collision with the gate electrode is solved.

The study reported in Ref. [146] aimed at developing a field emission type illuminating system with reduced nonuniformity of the emitted light.

The authors shifted the emittive portion of the cathode (using a mask) and the open part of the gate electrode in parallel directions in order to change electron trajectories. In this way, they made the electrons irradiate different parts of the anode and thereby reduced nonuniformity of the emitted light.

The authors of Ref. [147] proposed a triode type field emission device and manufacturing method suitable for use in the screen print process on a curved or planar substrate comprising the following steps:

- simultaneous formation of a cathode and a gate on the substrate spatially separated to avoid short circuit or interference by means of screen printing;
- deposition of a field-emitting layer on the cathodes;
- formation of a transparent conductive layer and a light emitting layer sequentially on the anode substrate;
- disposition of the cathode substrate and the anode substrate in parallel and spaced apart, packaging them into a triode type field emission device.

In this structure [147], bias of the cathode and gate can be controlled to achieve local adjustment of emitted light. Also, the gate may serve as an additional emitter to increase field emission efficiency and the operational life of the device.

A distinctive feature of the FEL proposed in patent [148] is that the control electrodes are disposed lower than the cathode emissive surface. The emission source rests on the cathode structure opposite the anode with the luminescent layer. The getter providing a predetermined vacuum level is located in the nonluminous area on the cathode plate or the anode plate. Protection shields prevent metal ions generated by the getter from entering the luminous area.

In the field emission lamp of Ref. [149], the gate and the cathode are at the same level and parallel to each other. The design comprises a conducting film laid on an inner surface of a flat front glass, a linear cathode conductor with a field emission film, and a linear gate electrode. In this configuration, a high potential is applied to the anode when the lamp is turned on, with the cathode and the gate electrode being grounded.

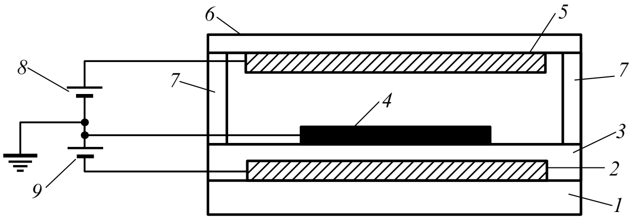

Figure 10. Field emission light-emitting element: *1* — cathode substrate, *2* — control electrode, *3* — insulating layer, *4* — emissive layer, *5* — conductive light-emitting layer, *6* — transparent substrate, *7* — support, *8* — anode power supply, and *9* — control electrode power supply.

This FEL is claimed to be suited for backlighting liquid crystal displays with low power consumption and high luminous efficiency in the absence of uneven emission.

Some field emission sources include a cathode inserted between the anode and the control electrode, as exemplified by Ref. [150] proposing a field emission element (Fig. 10) with a simplified structure of the gate electrode controling field emission current.

The control electrode formed on the substrate is surrounded by an insulating layer. The electron-emitting layer consists of carbon nanotubes located on the insulating layer. The conductive light-emitting layer lies opposite the electron-emitting layer. The gate electrode is placed beneath the electron emitter under the insulating layer. The gate electrode has a simple flat structure. The carbon nanotubes are built into a mesh film. The thickness of the carbon film cover is less than 1% of the base thickness.

Reference [151] proposes a surface field emission light source, including base and transparent substrates placed opposite each other. A number of insulator-coated gate electrodes and emitters are formed on the upper surface of the base substrate, while the luminescent layer is laid on the lower surface of the transparent substrate opposite the emitters.

A similar complicated structure for screen backlighting was considered in Ref. [152]. Uniform light emission was achieved by adding to the said structure a diffusion plate between the surface field emission light source and the display panel.

The authors of Ref. [153] considered a surface field emission light source and an information display device based on this structure. This source also contains two oppositely arranged substrates. One of them serves to place thereon control electrodes partly covered by an insulating layer with the deposited emissive layer. The design provides an electrical connection of electron emitters and gates. The phosphor layer is deposited on the second substrate, while the third electrode (anode) is located on the phosphor surface.

The authors of Ref. [154] proposed a field emission illuminating device (Fig. 11) with uniform brightness of the light-emitting surface. The device consists of a field emission electron source having a cathode electrode and a carbon nanotube (CNT) layer, an anode electrode, a gate electrode, and a closed insulating sheath sandwiched between the field emission source and the phosphor substrate. The cathode electrode is inserted between the gate electrode and the phosphor side facing the conductive substrate. An element electrostatically charged when hit by field emission electrons

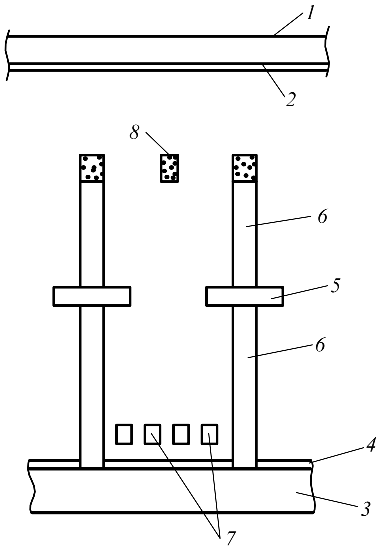

Figure 11. Field emission type light-emitting device: *1* — phosphor layer, *2* — anode electrode, *3* — cathode electrode, *4* — CNT layer, *5* — cathode electrode, *6* — insulator, *7* — gate electrode, and *8* — electrostatically charged element.

is placed at the same level. The totality of such elements (cells) make up the light-emitting device.

Flat field emission light sources can be applied in creating highly specialized devices, such as an exposure light source for optical printer heads, described in patent [155]. The material of the electron emitter is provided by CNTs. This light source is cheap and can be employed in combination with a photosensitive drum.

The above data indicate that the characteristics of planar field emission light sources make them, especially after design optimization, serious competitors to analogous existing and projected devices. Their advantages include in addition the possibility of application in different technological fields.

5.3 Cylindrical light sources

The layout of a structure with an axial arrangement of constituent components is presented in Fig. 12. It can be realized using a cathode based on fibers, CNTs, and other field emission materials [156].

An important advantage of such cylindrical construction over a planar one is that the electric field E, having in cylindrical sources the form

$$E = \frac{U}{r} \ln \frac{R}{r} ,$$

is stronger than in planar devices, with the applied voltage being equal. Here, R and r are the anode and cathode radii, respectively, and U is the voltage applied to the anode–cathode gap. This offers the possibility of exploiting a diode structure in light sources that is much cheaper to produce than a triode one.

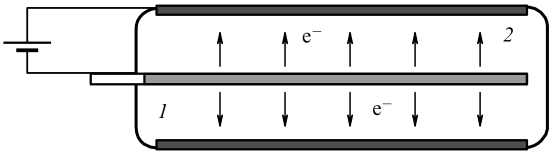

Figure 12. Construction of an axial light source: *1* — central part with the cathode structure, and *2* — cylindrical anode with luminescent cover.

A triode-based cylindrical light source with field emission cathodes made from a bundle of carbon fibers is described in Refs [157, 158].

Such a light source has an anode with the usual configuration, i.e., a cylindrical base glass sheet with the deposited conductive phosphor layer. The modulator is a cylinder made from either a metal mesh or an etched metal foil. The field emission cathode is fabricated from carbon fibers.

Two variants of cylindrical field emission cathodes have been proposed. In one of them, carbon fibers are secured between two or three twisted wires into a brush-like structure. It is very easy to produce but has a disadvantage of fiber deformation, resulting in their breakup and extraction from the cathode by the electric field. Moreover, it is very difficult to ensure the equidistant arrangement of the cathode and the modulator. In the second variant, carbon fibers are clamped between two disks from a conductive material using a conducting adhesive or soldering. The assembled modules are arranged sequentially along a bearing core of the proper length. Such a design ensures excellent mechanical strength and precise alignment of the field emission cathode and the modulator, the result being enhanced uniformity of field emission current over the field emission cathode surface and a reduced risk of a short-circuit between the cathode and the modulator.

A few publications [159–164] deal with the development of cylindrical diode structures that are simple and, therefore, cheap to produce. The field emission cathodes in such light sources are made from tungsten wire or metal rods up to 2 mm in diameter coated with nanotubes. In all the above-cited publications, the length of the structures varied from 3 to 10 cm, and the diameter from 15 to 30 mm. The nanotubes were deposited in tubular reactors made from quartz tubes at 680–850 °C for 10–30 min. The brightness amounted to 10,000 cd m^{-2} at an anode voltage of 5.4 kV [159].

The luminous efficiency was somewhat increased by a modification of the anode design [165, 166]. The main difference from earlier constructions was the use of a reflecting aluminum coating on which a phosphor layer was deposited. The cylindrical cathode, 1 mm in diameter, was placed co-axially in the interior of a glass tube 20 mm in diameter.

To increase the power of a light source and improve the phosphor thermal regime, external radiators dissipating excess heat by convection were utilized [167]. An essentially similar construction was proposed in Ref. [168].

It is possible to further increase the efficiency of a cylindrical light source by introducing an additional electrode in the anode circuit [169] for reducing the voltage drop along the tube length and, therefore, the probability of microdischarges resulting from electron accumulation; also, the additional electrode partly prevents local temperature changes in the phosphor coating.

Construction of the auxiliary electrode may vary in a wide range, from grid to spiral or a conductor parallel to the field emission cathode located at the cylinder generatrix.

A stronger field emission cathode coating [170, 171] consists of a mixture of nanotubes, conducting metal particles, and getter powder, which are dispersed inside a

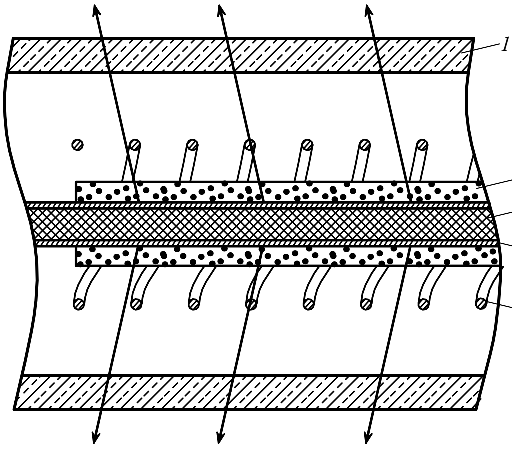

Figure 13. Cylindrical light source with an internal anode: *1* — glass bulb, *2* — phosphor, *3* — anode rod, *4* — specular layer, and *5* — field emission cathode.

glass matrix. This composition forms an even layer over the cathode rod and thereby ensures uniform emission from its surface.

The brightness (hence, the efficiency) of a field emission source can be enhanced by increasing the number of cathodes and anodes in one container. For example, a cylindrical cathodoluminescent light source in Ref. [172] contained five circumferentially arranged reflection-mode anode–cathode nodes. Anode structural elements assembled into a block were aligned along the lamp axis and secured by a holder. Field emission cathodes were placed in the focus of each anode element.

Brightness enhancement can be achieved by arranging field emission cathodes on a bearing rod as proposed in patent [173]. In this case, six field emission strips were circumferentially pressed at regular intervals around the bearing rod. The bending radius of the strips, *r*, was 10–20 times smaller than the bulb radius, with the emissive layer protruding one-half radius *r* over the rod surface.

The field emission coating can be made from carbon nanotubes and the bearing rod from nickel.

A cylindrical light source having a relatively small diameter is schematically depicted in Fig. 13 [174]. Its anode is placed inside the glass bulb *1*, and phosphor *2* is deposited on the central metal anode rod *3*. The luminous efficiency is enhanced by coating rod *3* with a reflecting layer *4*, e.g., from aluminum. The field emission cathode *5* was made from a metal spiral covered with CNTs.

Double light emission transformation was proposed in Ref. [175]. The main advantage of such a construction is the improved uniformity of luminescence in the visible spectral range.

The rod-shaped field emission cathode, covered either with carbon nanotubes or with ZnO nanocrystals, emits electrons exciting the UV-phosphor deposited onto the transparent conducting coating inside the sealed quartz bulb. UV radiation, in turn, excites the phosphor that emits light in the visible wavelength range.

Another approach to the creation of cylindrical light sources was proposed in Refs [176, 177]. One of them was a glass tube 20–30 cm in length and 15–20 mm in diameter covered inside with a cathodophosphor. Pins bearing cathode-modulating nodes (like those in finger lamps) are welded into both ends of the tube. A lead-in wire (anode) is soldered to the middle of the tube, to which an accelerating voltage of 10–15 kV is applied. Electrons emitted by field emission cathodes knock out secondary electrons as they travel toward the anode. In this way, they markedly increase both uniformity of emission and the efficiency of the lamp.

An experimental prototype showed a luminous efficiency in excess of 20 lm W^{-1}, and a start-up time of less than 0.1 ms.

5.4 Spherical and quasispherical light sources

Illuminating devices with a spherical or quasispherical shape (spherical, semispherical, pyriform, or any other standard shape of the incandescent lamp) of the bulb make up a special group of field emission sources of visible light. They have axial symmetry of the emitting surface, with the axis of symmetry passing, as a rule, through the base of the lamp [178–188].

An example of such light sources is presented in Fig. 14. They are usually used to provide light emission patterns with high angular uniformity and large angular width, sometimes much more than 180°.

As a rule, the construction of such field emission light sources includes an electron-emitting cathode in the center of the closed quasispherical transparent surface with the transparent conducting anode and phosphor layers laid down on it [178–181].

The characteristics of spherical and quasispherical field emission light sources depend in the first place on their design and electron emitter material. Variants of such constructions are described in numerous patent publications. Specifically, the electron emitter may be a structure containing a metal conductor covered with an electron-emitting layer of CNTs [178]; a layer containing getter particles, a nanomaterial,

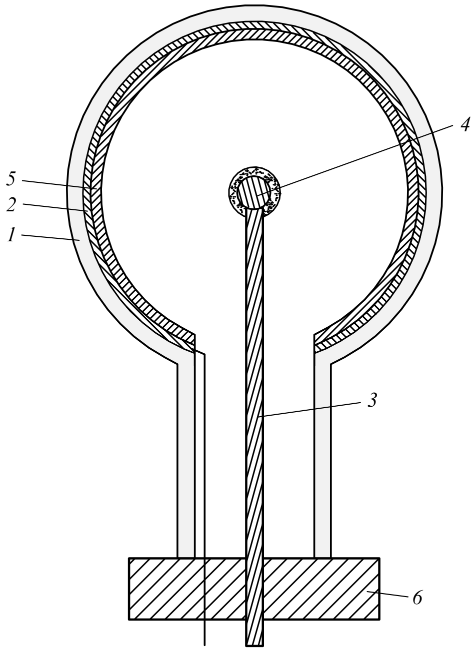

Figure 14. Schematic of a field emission light source: *1* — transparent envelope, *2* — anode, *3* — support element, *4* — cathode, *5* — phosphor layer, and *6* — base body from an insulating material (glass, ceramics, and the like).

conducting metal particles, and glass [180]; a substrate coated with a conductive layer [179]; or a filamentary field emission cathode made of a conducting wire with a multitude of electron-emitting centers on the surface (the conducting wire can be any curved piece of wire, viz. saw-like, wave-like, or twisted) [181]. Nanotubes, nanowires, or nanorods, especially those fabricated from CNTs, may function as electron-emitting centers.

The cathode can be designed as a small conducting metal ball covered with numerous tiny emitting structures, e.g., CNTs [182].

Also, the role of the emitting field emission cathode can be played by a cathode composed of at least one base body having an intricate 3D emissive structure (stepped, wavy, serrated), the emitting surface of which is covered at least partly with a special field emission layer of a nanostructured material [183]. The base may consist of a porous carbon material with the uniform pore size distribution.

The most important characteristics of quasispherical field emission light sources are the shape, structure, material, and arrangement of the anode and emitting surfaces. Patents describing constructions of field emission light sources offer a variety of structures and variants of the mutual disposition of the cathode and anode. The entire transparent lamp surface or only part of it may be coated with a transparent conductive anode layer and covered by the phosphor on the side facing the electron-emitting cathode [178–180, 183, 184]. The anode can be structured as a separate element inside a transparent outer shell opposite the field emission cathode in the presence or the absence of additional control (focusing, accelerating) grids [181, 183].

Moreover, the anode layer is not necessarily a transparent (e.g., reflecting) layer covered with the phosphor on the side facing the field emission cathode. In the presence of such an anode layer, luminescence outputs through the transparent inner surface of the outer shell where none of the anode portions is formed thereon [185], possibly through the focusing lens unit formed on the inner or outer surface of the shell. In certain structures, the phosphor-covered anode is an intricately shaped element accommodated inside the shell without contacting it [187].

Reference [188] considers a useful model of a field emission luminescent lamp comprising a metal lamp holder, a light-transmitting lamp shade, a driving power supply, a concave aluminum specular reflection element, and a field emission light source proper, e.g., based on zinc oxide.

A peculiar feature of the base of a transparent anode may be special ceramics used as the material for the outer shell and/or the anode base [179]. Such materials include Y_2SiO_5:Tb, Y_2O_3:Eu, Gd_2O_2S:Tb, $LaAlO_3$:Tm, and $LaGaO_3$:Tm. It has also been proposed to use thin ITO films as transparent anode layers [179].

Some patents describe field emission sources along with procedures for depositing cathode-emitting layers, e.g., the regimes and atmosphere of sintering the carbon base of the emitting surface and forming the surface nanostructure [178, 179].

Certain patents deal with various design features, technological schemes, and sequence of actions for producing anode and cathode conductive layers, their combination with driving power supplies, and other construction elements of the lamps, including such operations [179] as the fabrication of anodes, cathodes, and support elements, and assembling and vacuum pumping emission devices.

6. Specific features of power sources for field emission lamps

Field emission devices in general and light sources in particular operate under a rather high voltage (5–30 kV) even though a power as low as a few dozen watts is sometimes sufficient to keep them working. The majority of the promising power sources operate as high-frequency pulsed transformers [189–192].

A typical scheme of such a transformation procedure is presented in Fig. 15. The power line filter *1* protects the circuit from interference pulses of the power network, while the diode bridge rectifier *2* converts alternating current into direct current. The resulting voltage is converted into pulsed voltage, usually with a frequency of 20–100 Hz, by the high-frequency master generator *8* and power keys (usually transistors) *3*. Pulsed voltage is modified to an intermediate value by the transformer *4* and thereafter to the final value by the multiplier (usually a diode-capacitor type) *5*.

The capacitor filter *6* is installed in the output cascade if appropriate. The feedback circuit *7* is needed to stabilize output voltage. Such power sources are able to deliver the required voltage to cathodoluminescent light sources. However, field emission properties dictate rather specific requirements for power supply characteristics, first and foremost the exponential dependence of the emission current and its low value, besides relatively high voltage. This implies a specific approach to the creation of light sources with field emission cathodes. Some pertinent technical solutions are considered below.

One of the first power sources was proposed in Ref. [193] (Fig. 16). It includes a high-voltage rectifier *1*, load (field emission lamp) *2*, control block *3*, feedback resistor *4*, direct current amplifier (DCA) *5*, and alternating voltage source *6*.

The voltage from the high-voltage rectifier *1* is fed directly to the field emission lamp *2*. The current passing through the lamp causes a drop in voltage on the feedback resistor *4*, which becomes equal to the set voltage from the

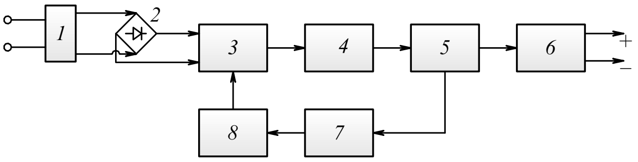

Figure 15. Schematic structure of a standard high-frequency pulsed converter fed from an AC main: *1* — filter, *2* — rectifier bridge, *3* — power keys, *4* — high-voltage pulse transformer, *5* — voltage multiplier, *6* — filter, *7* — feedback circuit, and *8* — high-frequency master generator.

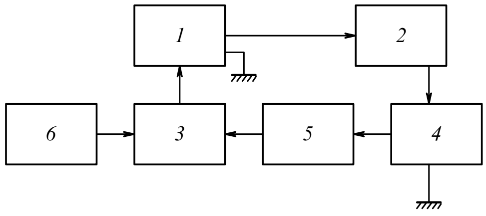

Figure 16. Field emission current stabilizer: *1* — high-voltage rectifier, *2* — field emission lamp, *3* — control block, *4* — feedback resistor, *5* — DC amplifier, and *6* — additional voltage supply.

DC amplifier (DCA) *5*. The difference signal is amplified and sent to the control block *3* simultaneously with the voltage from the source *6* (e.g., network transformer winding). Alternating voltage amplified by the control block *3* is fed to the step-up transformer of the high-voltage rectifier *1*. This voltage depends on the strength of the signal from the DCA.

The most frequently proposed efficient scheme to control field emission light sources is transistor control of field emission cathode current [194, 195]. A light source contains an input lead soldered to the outer shell, a luminescent screen, and a modulator-field emission cathode node attached to the input lead. The light source has a block to control the emission current, composed of a resistor and a high-voltage transistor with the grounded emitter.

To operate the light source, a direct voltage of 5–6 kV and 1.8–2.0 kV is applied to the screen and the modulator, respectively. The current is controlled by feeding driving voltages to the transistor base. At the above parameters of the light source and the control block, the device is turned on and completely switched off at a driving voltage of 0.5–1.0 V across the transistor base. The lowering of the driving voltages permit improving the operational characteristics and cost efficiency of devices based on electrovacuum light sources.

Control may be effected by both direct and pulsed [196] voltages. The latter regime is preferred because it allows phosphor heating to be decreased and, therefore, increases the luminous efficiency of the light source, reduces energy consumption, and prolongs the life of the lamp.

Further improvement in the power supply for field emission light sources is described in Ref. [197]. In the proposed construction, the network rectifier produces a direct voltage of around 300 V that is converted into a direct voltage of 3 kV through generation of a roughly 100-kHz voltage in the transformer. Then, the resonant inverter converts this direct voltage into alternating voltage with a frequency of over 800 Hz. The resonant inverter is controlled by pulse-width modulated voltage.

The voltage is increased to 10–25 kV by a high-voltage multiplier and applied to the field emission light source. The ceramic capacitor serves to filter voltage supplied from the converter. The power block is controlled by a microprocessor that keeps output voltage at the proper level by maintaining the necessary operational parameters of the converter and the inverter. The feedback between the output voltage and the control block is realized through a voltage divider of the high-voltage multiplier.

In addition, the microprocessor can monitor the illuminance of the lamp and adapt it to ambient light intensity. The control block may include an interface to receive an external control signal.

Reference [198] presents a resonant power source with an inductor having a predetermined inductance and connected either in series or in parallel with the anode and the cathode to create a resonant circuit.

A transistor-free power source for field emission lamps was proposed in Ref. [199]. It includes several transformers, besides such standard elements as a rectifier and an inverter. Alternating voltage is fed from the inverter to the primary coils of the transformers connected in parallel.

The sequentially connected secondary coils generate the high voltage needed to maintain operation of the field emission lamp. The number of the transformers depends on the operating voltage of a given field emission light source.

However, such systems are cumbersome, even if simple, and can be used largely in light panels for public places, such as railway terminals, airports, and stock markets.

Some modification of power sources to maintain operation of several lamps at a time, e.g., in ceiling or wall-mounted lights, is described in Ref. [200]. The authors used the same modern technique to control modulator potential for simultaneous switching on of several lamps.

Naturally, the possible schemes and methods for addressing the problem of the optimal feeding field emission cathodoluminescent lamps are not limited to those considered in this review.

One more variant of resonant power supply to cathodoluminescent lamps using field emission cathodes combined with a one-wire circuit was presented recently in Ref. [201].

Line voltage is supplied to the filter input and then, through capacitors, to the low-voltage coil of the high-frequency step-down resonant transformer. The low-potential terminal of the high-voltage coil is grounded via a capacitor. The high-voltage lead of the high-voltage coil of the high-frequency resonant transformer is connected, through a single-wire circuit, to a light source having natural capacitance. Such a design provides feeding of the electric energy to the light source.

This electric illumination system operates as follows. The electric energy from the source of alternating current passing through a supply-line filter is amplified in terms of voltage by a high-frequency resonant transformer; the frequency of excited current and voltage resonant oscillations in the primary and secondary coils and the single-wire circuit (1–100 kHz) is equal to that of the alternating current at the frequency converter output.

Because the single-wire circuit is open with respect to the coil, there is a phase shift of 90° between current and voltage; the current leads the voltage by 90° and recharges the single-wire circuit, the light source, and its own capacitances.

The electromagnetic energy in the form of a current and voltage wave flow travels from the high-potential terminal along the circuit through the loads toward intrinsic lower-potential capacitances, defined as the result of division of the line potential in the relation

$$\varphi_{11} = \varphi_9 \, \frac{C_{\mathrm{a-c}}}{C_{11} + C_{\mathrm{a-c}}} \, ,$$

where φ_{11} is the potential of the isolated conducting body having natural capacitance with respect to Earth in volts, φ_9 is the potential of the single-wire circuit of the illuminating system in volts, $C_{\mathrm{a-c}}$ is the interelectrode capacitance (anode–cathode transfer capacitance) of the luminescence emitter in farads, and C_{11} is the electrical capacitance of the isolated conducting body with respect to Earth in farads.

The lamps described in Section 5.4 are exploited in lighting devices.

Due to electric energy consumption in the resonant mode and the application of cathodoluminescence as the light-emitting mechanism of cathode electron beam generation, the utilization of an energy-efficient mechanism (electron tunneling through the potential barrier at the emitter surface), and energy transfer to an illuminating device along a single-wire circuit with insignificant losses in the conductor, the operating performance of the electric illumination system amounts to 80–90%. Moreover, feeding a lighting device through the single-wire circuit rules out the risk of short circuit, due to the absence of conductors with a potential difference between them, in contrast to conductors present in the conventional electric power network.

7. Special cathodoluminescent light sources

7.1 Color light sources

Developments in two areas of colored light source application are currently in progress. These are backlighting of liquid crystal screens and multiuser information display devices.

Liquid crystal (LC) display screens find wide application to present information in TV sets, computer monitors, and so forth. LC screens are backlit by linear or point light sources, such as gas-discharge fluorescent lamps or light-emitting diodes. However, LC screens suffer from serious drawbacks, such as complicated structure and manufacturing technology and high production costs and energy consumption. Moreover, it is difficult to ensure uniform brightness of large LC screens.

Hence, there is increasing importance on developing environmentally friendly field emission light sources with lowered energy consumption, improved uniformity of screen brightness, a short turn-on time, and different output power in various embodiments (butt type, flat, spherical, etc.) [202].

In what follows, several avenues of investigations are considered in which elaboration of cathodoluminescent lamps with field emission cathodes proceeds based on carbon materials. Some of them hold for flat light sources.

The operating principles of a conventional LC screen have been demonstrated in Refs [203, 204]. The main component of such a device is a passive LC gate matrix with a polaroid. The matrix is integrated with a light filter separating red (R), blue (B), and green (G) colors. The LC matrix is lit by a white light lamp in the continuous regime.

To enhance light output of the screen, it is proposed to remove the light filter and use a multicolor lamp allowing the synchronous turn-on and turn-off of color elements. The same matrix and polaroid as in Refs [203, 204] are employed. However, the white illuminating lamp is replaced by a three-color lamp allowing independent control of each color element. The main requirement for a multicolor lamp is uniform illumination of the matrix for each color. The size of the color element does not necessarily coincide with the pixel size in the matrix. With a given criterion for lighting nonuniformity, the choice of the size of a color element determines the distance between the illuminating lamp and the LC matrix.

Each color element turns on after an image corresponding to a given color is downloaded on the LC matrix. In this case, the effective resolution of the screen is three times that in Refs [203, 204], because each pixel of the matrix is employed.

Red, green, and blue lamps turn on sequentially. LC matrix elements are switched on synchronously with them in a proper configuration with the video picture.

Because the size of color elements should not necessarily coincide with that of LC matrix elements, one of the first devices for dynamic illumination consisted of a set of finger type light sources of three colors [204]. The sources of each color were turned on sequentially with a frame rate of 100 Hz.

Cathodoluminescent lamps must have a switch speed of less than 1 ms. The switch-over time depends in the first place on the phosphor rise time and afterglow period. Available lamps meet this condition.

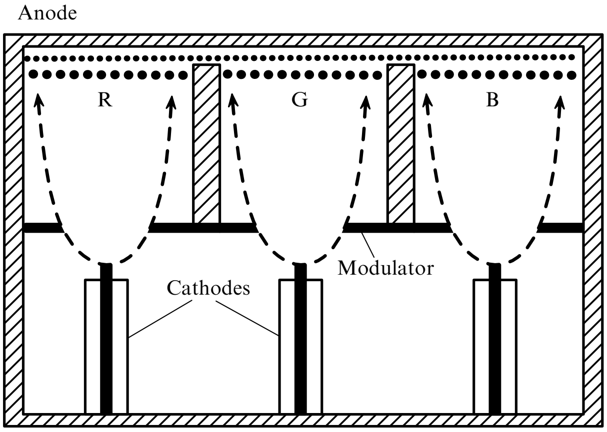

Figure 17. Three-color module with field emission cathodes from carbon fibers schematically represented as a low-resolution display screen.

The power consumption of a video screen module in the dynamic regime is below 20 W or 100 mW cm^{-2}, and the duration ratio for each color is 3. When the brightness of an individual source is 10^4 cd m^{-2} and their packaging density in the module is $2/5$, the brightness of the white light module reaches 1.3×10^3 cd m^{-2} in the dynamic regime, with the image brightness on the LC screen being 300 cd m^{-2}.

Another promising approach to the construction of colored lamps for dynamic illumination is the development of low-resolution display screens with pixels a few millimeters in size [205, 206]. Figure 17 depicts a three-color module based on carbon fiber field emission cathodes.

The anode of the conventional configuration is divided into 10×10-mm sections covered with phosphors of three different colors. The sections are separated by insulating partitions to prevent overlap of electron fluxes.

A single modulator with proper apertures forms electron beams for all cathodes that are governed by the control system via cathode circuits.

Sometimes, the employment of holographic diffusors is appropriate for improving the uniformity of screen illumination [207]. The holographic diffusor is a surface relief hologram allowing control of the angular light distribution (up to 100°) more efficiently and with a higher transmission factor (over 85%) than by traditional methods, e.g., with ground glass.

One of the promising applications of light sources is the production of large low-resolution screens [208], like remote projection screens performing a variety of functions, such as TV broadcasting or luminous advertising.

Modules of different sizes have been manufactured, one of them based on lamps with carbon fiber bunch field emission cathodes [209]. Its characteristics are presented in Table 2. Each light-emitting element of the module is governed by a control unit.

Integrable modules are needed to make full-color video screens. Such modules should be able to display at least one symbol (letter or numeral) and have built-in feeding and control systems in order to simplify electrical interconnection and control of the screen as a whole. The modules are fed only from the network and controlled by a computer. One of the modules is depicted in Fig. 18 [211].

Figure 18. Exterior view of a full-color video module: 8 × 8 pixels (192 lamps).

Table 2. Module characteristics of a large LC screen [210].

Characteristic	Value
Number of lamps	36
Power consumption	up to 40 W
Lighting efficiency	18 lm W^{-1}
Brightness	up to 12,000 cd m^{-2}
Viewing angle	180°
Pixel size	40 × 40 mm^2 (RGB)
Contrast	200 : 1

The module contains $8 \times 8 = 64$ full-color pixels, each composed of three (red, blue, and green) color lamps. The colors are mixed up by pulse-width modulation of emission current. There are a total of 192 lamps. The block is designed so as to enable them to be integrated into a panel of any size without loss of screen resolution. The nominal power of the block, with all the lamps operating simultaneously, is around 200 W. The remaining parameters of the module are analogous to those listed in Table 2.

The key problem of the field emission electron sources, namely the identity of their emissive characteristics in a large-scale manufacture, was successfully solved when designing and producing a given module [209].

The above structures can be applied in the further development of artificial light sources for growth stimulation of cultivated plants by electromagnetic waves, facilitating photosynthesis. Sources of phytoactive illumination are used in the absence of natural daylight or in situations of its deficit.

Artificial light must have a spectral composition beneficial for plant growth. The favorable growth conditions are created not only by choosing the optimal color temperature and spectral characteristics of light but also by varying lighting intensity of used lamps. Different plant species and growth phases require different spectral characteristics, light output, and color temperature, as well as a light–dark interchange consistent with natural biorhythms. To meet these requirements, an illuminating system must be equipped with a control unit allowing it to be periodically switched on and off.

At present, incandescent, luminescent, gas-discharge, and electrodeless lamps, as well as light-emitting diodes, are used as light sources for such illuminating systems. Metal-halide lamps emitting a sufficient amount of blue light have until recently been used to accelerate green mass production during the first (vegetative) growth phase. High-pressure sodium lamps were employed in the second (reproductive) phase, because they emit reddish light promoting flowering and fruit ripening. However, luminescent lamps are finding increasingly wider application due to their higher luminous efficiency and economic viability.

Diode type phytoactive light sources have recently entered the market. A combination of such devices emitting light of different colors provides illuminating systems effectively stimulating plant growth at both the vegetative and reproductive stages. The National Aeronautics and Space Administration (NASA) of the USA has carried out successful experiments on food plant growth in outer space with the use of light-emitting light sources [210].

The authors of Ref. [211] recommend the following combination of light-emitting diodes as beneficial for plant growth and health: 12 red (660 nm), 6 orange (612 nm), and 1 blue (470 nm).

Wider emission spectra and color temperature ranges, as well as higher light output, of field emission lamps than those of other light sources render it possible to use them for cultivating various plant species with due regard for growth phases.

To sum up, the advantages and technical characteristics of field emission lamps provide a basis for creating modern light sources with a power of tens and hundreds of watts, which makes them a suitable alternative to other types of lighting devices meeting the requirements of both industry and individual users.

7.2 Ultraviolet lamps

Global environmental safety issues have recently accentuated the necessity of replacing the mercury-containing UV lamps widely employed in medicine, air clearing at different offices, in dye polymerization facilities, and other fields. Eximer and deuterium lamps are likewise far from perfect from the standpoint of environmental safety.

The first attempts to create cathodoluminescent UV lamps inspire optimism as regards the prospects for solving this important problem.

The following additional peculiarities of UV lamps are worth mentioning:

(1) practically zero time to turn on (10^{-8} s);

(2) operation in both analog and pulsed modes;

(3) wide operating temperature range;

(4) generation of UV radiation within virtually any fixed range owing to the dependence of the emission spectrum on the phosphor composition alone;

(5) possibility of producing lamps with a wide range of output powers in various embodiments (butt type, flat, spherical, etc.);

(6) environmental safety at all stages of production, operation, and disposal due to the absence of mercury and other noxious components;

(7) possibility of delivering power into lamps from any line (220, 380 V) or on-board (12, 24 V) voltage, storage cells and batteries.

The development of novel efficient UV cathodoluminescent lamps depends first and foremost on the availability of wide bandgap cathodophosphor materials.

Mixtures of oxides (BeO or MgZnO) have a wide bandgap [212–216]. However, BeO is highly toxic, while MgZnO production creates considerable difficulties due to the difference between ZnO and MgO structures.

Fluorides are very promising UV cathodoluminescent materials by virtue of a very wide bandgap [217–219]. Such fluorides as $KMgF_3$ and $KCaF_3$ [220] have emissions in a wavelength range from 140 to 220 nm. $KMgF_3$ possesses a cubic structure and does not need to be doped with rare-earth elements.

The construction of a flat UV lamp with a $KMgF_3$ phosphor is described in Refs [221, 222]. An oriented MgF_2 crystal on which a $KMgF_3$ layer is deposited by laser evaporation serves as the exit window with an area of 64 mm^2. The evaporation target is prepared by melting $KMgF_3$ ($KF:MgF_2 = 1:1$) in an atmosphere of $Ar:CF_4$ (95 : 5) at 1220 °C. The resulting structure is cooled to 900 °C for 1 h and further to room temperature during the next 48 hours.

The anode and the extraction electrode are made from copper mesh with 0.1-mm cells; the fluoroplastic spacers are 0.3 and 1 mm thick.

Cone-shaped nanostructured carbon field emission cathodes are grown on a glass–carbon substrate by Ar^+ ion bombardment at room temperature [223, 224]. The density, length, and diameter of the resulting microtips are roughly 5×10^8 cm^{-2}, 0.3–2.0 μm, and 20 nm, respectively. The operating pressure in the chamber is 5×10^{-6} Torr. The parameters of the system are: extraction voltage of 800 V, accelerating voltage of 1800 V, current of 0.32 μA, and UV radiation power of 2 mW. The $KMgF_3$ emission spectrum has a maximum at a wavelength of 180 nm; in a system with an MgF_2 substrate, the spectrum has two peaks, at 150 and 180 nm.

For UV radiation with longer wavelengths, it is far more practicable to use readily available and technologically simple materials for exit windows, e.g., quartz or uviol glasses. Reference [225] proposes a simple design for a UV lamp with emissions in a wavelength range from 220 to 350 nm (see Fig. 19).

The use of field emission cathodes from a nanostructured carbon material permits decreasing the threshold electric field strength for emission current (1–5 V μm^{-1}), increasing the operational life of the field emission cathode to 50,000 h and thereby prolonging the lifespan of the lamp as a whole. The start-up time of a vacuum UV lamp is less than 10^{-8} s, which means that light is emitted immediately after the power is turned on. The emission spectrum of luminescent UV lamps depends on the phosphor chemical composition, which allows choosing the optimal spectrum for a concrete application by varying the phosphor composition, e.g., using KL-UV-315 and KL-UV-300 cathode phosphors with emissions at wavelengths below 350 nm. The aluminum layer deposited onto the phosphor serves to increase luminous efficiency, because the angular spread of radiation from phosphor grains is 360 degrees and the aluminum layer plays the role of a mirror reflecting light into the exterior part of the lamp.

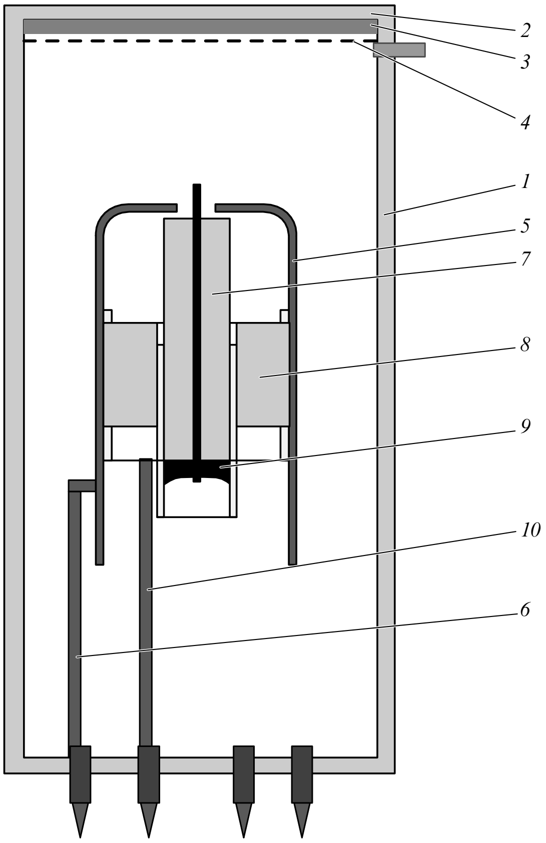

Figure 19. Finger type UV lamp: *1* — evacuated envelope from UV-permeable dielectric, *2* — anode, *3* — UV phosphor, *4* — aluminum layer, *5* — modulator, *6* — terminal lead, *7* — field emission cathode from a nanostructured carbon material, *8* — alignment disk, *9* — contact node, and *10* — field emission cathode terminal leads.

The UV lamp is a cylindrical evacuated enclosure from a light-permeable dielectric material with a field emission cathode made of a nanostructured carbon material, a modulator with a hole for passing electron beams, a luminescent screen, an anode, and terminal leads. Coaxiality is achieved by placing the field emission cathode in the hole of an alignment disk oriented coaxially with the modulator aperture. To enlarge the contact surface, the terminal of the field emission cathode can be made of an electrically conductive material, e.g., aquadag, deposited on the end of the field emission cathode and a rim adjoining its side surface with which the cathode terminal is rigidly connected. The luminescent screen of a field emission UV lamp is covered with a UV phosphor layer and aluminum to increase the light output from the phosphor.

The technical result, namely, efficient conversion of the electrical energy into UV radiation, is attained by using special materials for the field emission cathode and a phosphor capable of producing efficient UV radiation when combined. The lamp is characterized by high energy efficiency (at least 15%), a long operational time (50,000 h), almost zero time to turn on, a high resistance to mechanical vibrations and voltage fluctuations, and the absence of polluting substances.

Phosphors of various chemical compositions may be utilized, depending on the necessary UV radiation wavelength [226–230]. For example, high-performance $Bi_nY_mAl_3(BO_3)_4$ compositions are suitable for the purpose at a wavelength of 300 nm. The radiation spectrum of a UV lamp with one such phosphor is presented in Fig. 20. The efficiency of these phosphors is high enough for practical

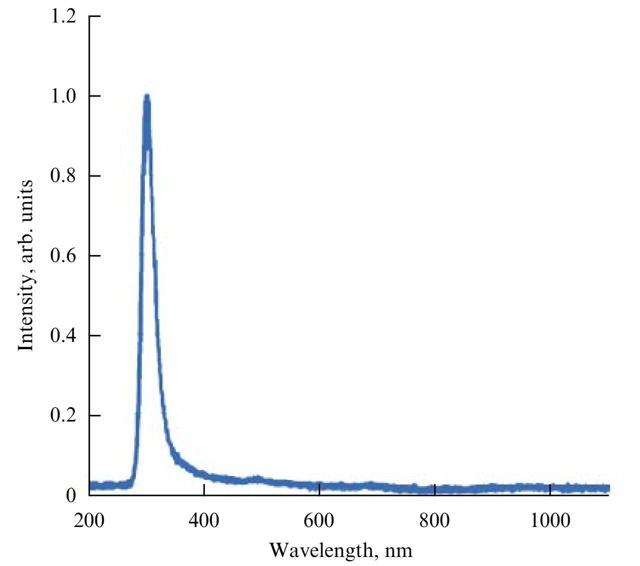

Figure 20. UV lamp radiation spectrum.

applications (27 mW at an overall power of 900 mW; $U = 8$ kV, $J = 112$ μA). Phosphors of a different composition, e.g., $ZnAl_2O_4$, are needed if the wavelength is to be decreased to 245 – 260 nm [229, 230].

Only the first steps have been taken to design vacuum luminescent lamps using field emission cathodes and to search for the optimal chemical compositions of phosphors. Therefore, considerable effort to continue development of this technology can be expected in the near future.

8. Conclusions

The rapid development of field emission cathode technologies gives hope that cathodoluminescent light sources with field emission cathodes will soon find applications as wide as illuminating systems operating on other principles.

To begin with, their production, operation, and disposal create no serious threats to the environment. Moreover, their manufacturing technologies are rather simple and based on readily available materials. They are economically viable devices and can be produced at existing traditional electric bulb factories. These lamps match very closely the spectrum of natural sunlight.

Recent progress in the elaboration of novel types of cathodoluminescent light sources has proceeded along several lines, of which the following ones are worthy of special mention:

- the search for new materials and the development of technologies for their production (including nanomaterials and carbon-based nanotechnologies), the construction of modern efficient field emission cathodes [61, 63, 64, 231, 232];
- the search for and the investigation of efficient phosphors, including elucidation of mechanisms of energy transfer and induction of luminescence by electron beams for their use in modern light sources with different spectral characteristics [62, 65, 68, 69, 231–237]; specifically, Ref. [234] reports the achievement of light output of 55 lm W^{-1}, 10 lm W^{-1}, and 13 lm W^{-1} from green, blue, and red phosphors, respectively;
- the development of modern (including miniature) variants of high-efficiency cathodoluminescent light sources for different applications based on new materials and technologies [54, 60, 232, 238]. For example, a light output of more than 60 lm W^{-1} was attained in Ref. [232] for miniature flat sources of green light using nanostructured carbon field emission cathodes based on single-walled carbon nanotubes (SWCNTs).

It is worthwhile to note that the development of traditional technologies aimed to promote production of phosphor-coated field emission cathodes and anodes, including the search for new materials and the employment of nanotechnologies for their manufacturing, goes on side by side with the solution of such crucial problems as extension of the lifetime and improvement of operation consistency of field emission light sources by special treatment of cathode and anode surfaces, formation of the spatiotemporal structure of their electromagnetic fields to increase the uniformity of electron fluxes, enhancement of focusing precision and intensity of electron beams impacting the phosphor, and the reduction of field emission cathode irradiation by positively charged particles resulting from electron bombardment of a phosphor-coated anode. These issues are of primary importance for the practical work on designing field emission cathodes and their application in various electronic devices.

A breakthrough in field emission cathode technologies, specifically in the creation of cathodoluminescent light sources, is possible only through a combination of novel materials and techniques based on the improvement of traditional physical methods and in-depth studies of the mechanisms of field emission and cathodoluminescence.

We assign an important role in the further development of field emission and cathodoluminescent technologies to research on the influence of the structure, composition, methods of production, and treatment of field emission and cathodoluminescent surfaces for the improvement of stability of field emission and cathodoluminescent characteristics of cathodes and anodes at different intensities and surface densities of electron beam generation at the cathode and illumination of the phosphor at the anode.

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