UDC 621.385.032

MODERN ELECTRON SOURCES FOR TWTS IN MILLIMETER AND SUBMILLIMETER RANGES

T. M. Krachkovskaya [1,2], G. V. Sahadji [2], S. D. Zhuravlev [1,2]

[1] Yuri Gagarin State Technical University of Saratov,

77 Polytechnicheskaya St., Saratov, 410054, Russia

[2] JSC "R&D enterprise "Almaz", 1 Panfilova St., Saratov, 410033, Russia

The paper is received on December 6, 2017

Abstract. The paper presents the state of development of electron sources used in traveling wave tubes (TWT). Main achievements in the field of manufacturing technology of metal porous cathodes, matrix field emission cathodes, scandium cathodes, metal-alloy cathodes are described. Modern level of emission parameters, reliability and durability of such cathodes are considered. Actual problems for developments of electron sources for TWTs in millimeter and submillimetric ranges are discussed. Moreover, traditional emissive materials and the newest cathode materials based on carbon nanoclusters are described. Conclusions are made about further ways of developing the technology for manufacturing metal porous cathodes used nanocarbon.

Keywords: metal porous cathodes, matrix field emission cathodes, scandium cathodes, metal-alloy cathodes, nanocarbon material.

1. Introduction

In recent years there has been a significant increase in the requirements for traveling wave tubes (TWT) which are used as broadband amplifiers in radio equipment applied in the systems of space communication and navigation [1].

These requirements include: the increase in operating frequency; increase of reliability and durability; reducing the weight and size dimensions; and the reduction of readiness time. This is particularly so with satellite TWT operating in the millimeter and submillimetric ranges [2].

However, while creating these devices there are a number of serious problems, and the most critical one is connected with the necessity of using electron beams with extremely small transverse size and, consequently, with a large current density at a cathode [3].

Since with the increase of current density at the cathode its service life decreases, one of the areas of cathodes improvement is the search for cathode materials, which provides:

1) decrease in operating temperature of the cathode;
2) increase in the emission current density J;
3) reduction of the degradation factor of the surface.
4) reduction in the spread of the work function ϕ on the surface.

The following types of thermoemission cathodes are considered as a possible emission sources while creating microwave devices with millimeter range: metal porous cathodes (MPC) are the cathodes with surface coating of platinum group metals or their composition (e.g., osmium or rhenium), which reduce the function work; chamber cathodes containing an increased supply of emissive material; scandium cathodes (Sc- cathodes), etc. [4]

At the same time, one should note the attempts to create cathodes on the basis of matrix field emission cathodes (MFEC) and field-radiating cathode systems containing carbon nanotubes and nanoclusters for miniature TWT in millimeter and submillimetric ranges.

Below we consider the main achievements in the development of these areas in relation to the development of TWT.

2. Dispenser cathodes

The analysis of patents, devoted to improvement of the cathode assemblies, revealed the following areas of improvement of the MPC (Fig.1).

The diagram shows that today the problems of improving durability, reliability and increasing the emission current density are the most relevant.

As it was noted above, decrease in operating temperature and degradation factor of the surface directly affect the durability of the cathode, and hence the durability of the whole device.

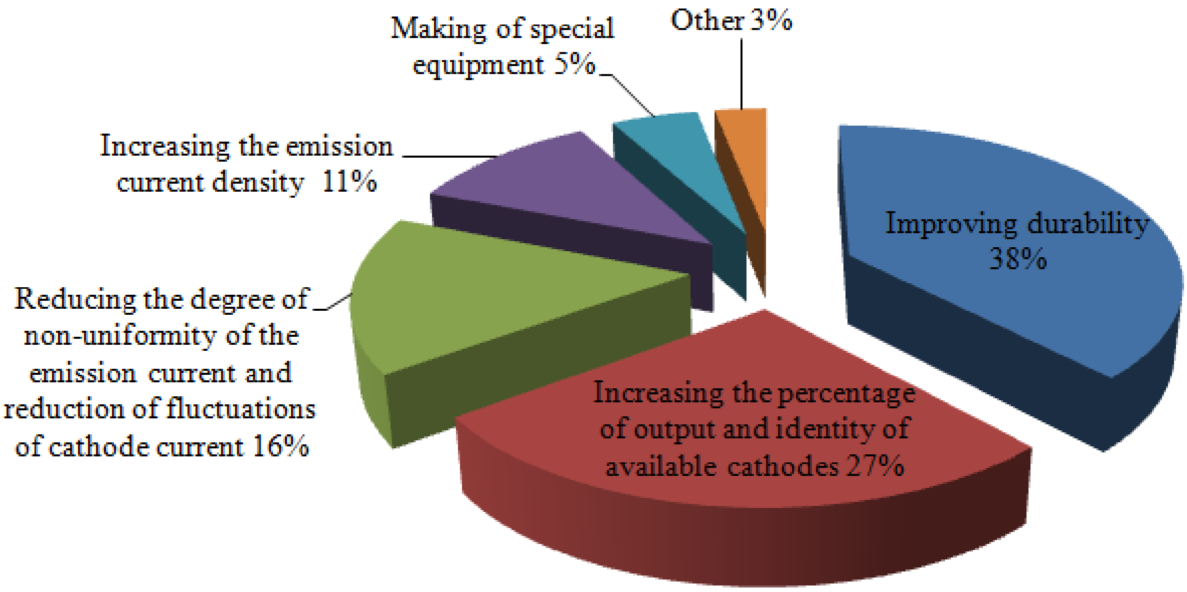

Fig.1 Major trends in the improvement of the MPC

Many scientists have been researching the problem of increasing the durability for many years. Authors of the paper [5] carried out a detailed study of the mechanism of the MPC "aging" which refers to a complex of physical-chemical processes occurring during long-term work inside and on the surface of the cathode and leading to a decrease in its emissive ability. The analysis of existing points of view on the mechanism of the MPC "aging", despite of their ambiguity, allowed to single out the following main areas of improving emission and durability of the MPC in the paper [5]:

1) increase in the supply of active material in the cathode and increase of its efficiency by optimizing the porosity of the sponge;

2) development of the composition of the active material with stable, increased emission properties and low evaporation rate;

3) application of the metals of sponge and coatings that reduces the intensity of solid-state reactions of the active material with the metal of sponge, coating and sponge metals; increases the lifetime of the activator on the surface of the active layer with an increased emission ability.

These problems are solved in several directions. The first one basically comes to the selection of materials for impregnating a refractory porous sponge, in particular, including various combinations of rare-earth metals, which must have a lower melting point in order to implement the impregnation of the tungsten matrix and have sufficient emissive properties. In addition, the compositions for impregnation are subjected to the special conditions of preparation, e.g. to oxidation in air or carbon dioxide at elevated temperature and reduction in hydrogen atmosphere at a temperature of about 1000-1300^{o}C.

The main materials used are: aluminate of barium-calcium with different ratios of oxides of Ba, Ca and Al and the aluminum silicate of barium-calcium.

The second direction aims at improving the refractory matrix of the MPC, in particular, papers [6,7] suggest adding Os, Ir, Ru, and Re to the tungsten powder.

The third direction is characterized by the selection of materials for coating refractory matrix, as, in addition to traditional MPC osmium-ruthenium coating, a number of other coatings, for example, Os+Ir, Os+Ir+Al etc. are used.

The fourth direction can be characterized by the selection of efficient designs of the dispenser cathodes. JSC "R&D enterprise "Almaz" created a method to improve the durability of the MPC by means of design changes of the metal sponge of the cathode [8]: the sponge has a porosity 20-22% in the zone adjacent to the working emitting surface, which reduces the evaporation rate of Ba from this zone; and the sponge has 1.5-2 times greater porosity beneath this zone (40-45%), which provides for the increase of the supply of active material in the volume of the cathode and, consequently, enhances the durability.

Due to this design of the sponge and the application of film with the composition of Os+Ir+Al in the cathode we obtained the durability of the cathode with continuous emission current of 2 A/cm^2 for more than 200,000 hours. Paper [9] reports on further prospects of development of the two-layer structures of the MPC, and it gives the theoretical calculations of durability of dispenser cathodes with a two-layer sponge, the working area of which is made of tungsten powders with nanograins (~0.07 μm).

In recent years in cathodic field, foreign specialists drew their attention to the double-layered MPC. In 2007 the Institute of electronics of Chinese Academy of Sciences conducted tests of a two-layer MPC, repeating the porosity of the layers specified above [8] the development of JSC "R&D enterprise "Almaz" of the 90s [10], however it differed by the sprayed to the cathode film. They used a two-layer film of Re with a thickness of 0.2 µm, on which there was deposited a Os+W film with a thickness of 0.3 µm. There was obtained the same durability of 191,000 hours under a continuous load of 2 A/cm^2.

In paper [11] the Chinese developers completely repeated our two-layer design of the MPC with developed at our enterprise film coating with the composition of Os+Ir+Al having the thickness of 0.5 µm and the same aluminate composition 6:2:1. In tests of the cathodes they obtained the durability of 190,000 hours at a current density of 1.5 A/cm^2.

To select the optimal conditions, which provide the increase of durability during the production of cathodes, calculation methods are used. For example, in [12] they calculate the average diameter of the powder particles D_p, based on values of the pressure of the air flow through the test pellet, then determine the condition of a minimum open pore channel in the sintered pellets of the optimal value interval for this production and determine the optimum compacting pressure of pellets.

The second direction with the largest number of patents deals with increasing the percentage of output and identity of available cathodes. Hence, one of the technological problems is mounting of the porous impregnated sponge in a refractory case. This process often uses powder solder, which is filled between the case and the disk and melts under the action of temperature, bonding given surface.

This technology has several drawbacks such as uneven filling of the bonding space, hollow spaces, escaping of excess powder, and cracks. In addition, high soldering temperature exceeding the temperature of the spraying of the active material leads to deterioration of the emission properties of the cathode and reduction of mechanical strength of the case, while large pressure of compacting the sponge with solder often leads to destruction of the case.

Various constructive changes are proposed in order to solve this problem. Thus patents [13-14] offer mounting without solder. Moreover, the solders and their compositions are being improved. Paper [15] proposes a solder made of platinum and boron, the soldering temperature of which is substantially lower than the above mentioned materials and is 1050-1100°C. This significantly reduces the risk of embrittlement of the soldered materials.

In the last decade there has appeared works aimed at reducing the degree of non-uniformity of the emission current [16]. Reduction of the dispersion of the work function of electrons ϕ on the surface, and, as a consequence, reduction of fluctuations of cathode current are provided by different constructive solutions, using various physical methods of processing emitting surface. For example, the controlled porosity dispenser or CPD-cathodes [17-18].

When modifying the MPC by laser radiation, providing the packing density of the holes of $2.7 \cdot 10^3$ mm^{-2} with a diameter of 15±2 μm and a depth of 18±5 μm (Fig.2), one can reduce fluctuations of the emission current and noise of TWT by 4 ... 5 dB due to the alignment of emission current density over the entire surface of the dispenser cathode [19].

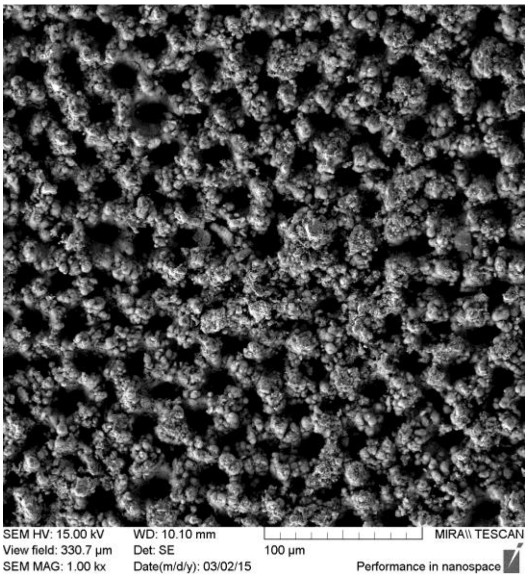

Fig.2 SEM image of a tungsten disk treated with laser radiation

The mode of evaporation of the MPC surface during the processing with solid-state laser with a wavelength of 1.06 μm is provided with power pulses of 2.25...3 W, duration of 60 ns and porosity of 10^3 [20].

Currently one of the most promising objects of research and development in the field of high emissions is scandium cathodes of various modifications.

2. Scandium cathodes

There are many constructive and technological variants of scandium dispenser cathodes. The main types of cathodes are: 1) introduction of a scandium oxide or its compounds in a matrix of tungsten or a mixture with rhenium; 2) addition of the scandium oxide in the Ba-Ca aluminates; 3) coating the surface of standard aluminate cathodes with thin films based on scandium oxides mixed with W, Re, and other metals or oxides, and with multilayered coatings with the inclusion of scandium or its oxide and other elements.

There are also available combined variants of the listed types. From the point of view of maximum emission current, the most striking results were obtained by Philips. Using the technology of laser ablation deposition (LAD), G. Gartner et al. describe the process of obtaining emission current density of 400 A/cm^2 at the temperature of the cathode 965°C (brightness) and a service life of 2500 hours in the mode of current limitation by space charge.

A "top layer" of a mixture of W/Re+Sc_2O_3 with the thickness of 0.1-0.5 μm was created in this cathode on the surface of a standard MPC with a tungsten sponge impregnated with aluminate of a composition 4:1:1 using the LAD method [21-22]. These works do not give an explanation of the unique results, they only claimed that such technology provides uniform emission, which gives hope for a better resistance of this cathode to ion bombardment in an imperfect vacuum. One of the authors of the previous two works G. Gartner made an attempt to explain the mechanism of obtaining high densities of emission current of the Sc-cathode, obtained with the help of the LAD technology. He indicates that the emitting surface of the cathode consists of a complex Ba-Sc-O with a uniform distribution of Sc_2O_3 in the surface layer of the cathode due to the laser evaporation.

It is noted that scandium oxide has a very low mobility, hence it should be uniformly distributed to overcome short diffusion lengths of Ba to Sc. This is achieved by means of ultrafine uniform distribution of nanoparticles containing Sc and Re, by laser evaporation. It is also noted that Sc-cathodes exhibit low evaporation rate, so that these cathodes can have long life (more than 10 thousand hours) when emission current is more than 100 A/cm^2. The authors of the work [23] explain sensitivity of the Sc-cathodes to ion bombardment by a smaller diffusion length of Sc compared to Ba (~0.1 μm in 1300K) and a limited number of Sc. Uniform distribution of the Sc by laser evaporation provides a more rapid recovery of emission of the cathodes after ion bombardment.

In [24] the authors generalize the results obtained by the staff of the Beijing University of technology and BVERJ about the development of Sc-cathodes with Sc alloyed W-matrix. For a number of years (since 2000) they conducted a complex of works on creation of the method of producing a material for Sc-cathode, in which Sc was evenly distributed in the W powder, and the grain size of Sc to be at the level of nanometers. They created the following methods for alloying of W powder with Sc:

1) liquid and solid fraction, a mixture of Sc_2O_3;
2) liquid and solid fraction, a mixture of Sc_2O_3+Re;
3) the liquid fractions, the mixture of Sc_2O_3 (sol-gel method);
4) the spray drying method.

Sc-cathodes developed with the help of this technology have already been applied in the practical development of TWT. Thus, collaborative work of employees of BVERJ and the University of California (USA) [25] shows the results of the development of Sc-cathode for TWT with miniature ribbon beam of the range 220 GHz, made within the American military program HiFJVE. The developed nano- and microcomposites of scandium dispenser cathodes used W powder with addition of Sc_2O_3, made by sol-gel method. Scandium was present in the powder in the form of nanoparticles. Adjustment of the size of the powder particles was carried out by changing parameters of the sol-gel mechanism.

The matrix made from this powder had a uniform distribution of Sc and open pores, thus ensuring uniform distribution of Ba, Sc and O on the emitting surface, improving the uniformity of emission and lowering function work. It is established that this cathode with uniformly distributed dispersed Sc can resist ion bombardment better. Powder W contained 5% of Sc_2O_3 (wt.). The powder particles had a size of 300-500 nm. Cathodes tests showed the possibility of achieving a durability of more 1000 h at a current density of the cathode 40 A/cm^2 in a continuous mode. This current density corresponds to the working mode in the TWT with ribbon beam of the range 220 GHz. The BVERJ experts reported on the application of the Sc-cathodes of different modifications at the conference IVEC-2015 [26]. In particular, ellipsoidal Sc-cathode with a size of 1.5 mm by 0.6 mm is used in TWT (SBTWTs) in the range of 220 GHz. There were tested two modifications of Sc-cathodes – impregnated Sc-cathode with Sc_2O_3 in the aluminate and Sc-cathode made with the help of nanocomposite alloying of tungsten powder with Sc. Both types of cathodes during the tests showed the possibility of obtaining the density of the emission current over 100 A/cm^2.

Sc-cathodes are being developed in other countries. Thus, experts from India have found [27] that the rate of evaporation of the active material from an W-Ir cathodes is less than that of the W cathode due to the formation of ε-fraction on their surface, which improves the interaction of Ba-Sc-O layers with the cathode surface. W-Ir cathodes are resistant to ion bombardment. It is noted that this property can be enhanced by coating the cathodes with rhenium. The samples of the cathodes have demonstrated a service life of more than 9000 hours at testing.

In Russia in recent years, there has also appeared a lot of works devoted to the study of the Sc-cathodes [28-33].

These works attempt to describe the operating principle of the Sc-cathodes, in particular, paper [31, 32] refers to a possible thermal-field emission principle of the Sc-cathodes.

Paper [28] also notes that during the ion bombardment of the MPC surface the rate of replenishment of surface with oxygen affects the rate of destruction of the active layer, as the formation of the Ba-O film, which protects the cathode surface from the ion impact, and the protection factor, to a first approximation, is proportional to the thickness of the film. The degree of protection of the MPC surface from the ion impact is a critical parameter for the Sc-cathode. The author of the work [28] proposes to increase the protective properties of the Sc-cathode by increasing the rate of the surface replenishment with oxygen so that Sc, located on the cathode surface, is protected from direct ion bombardment. The problem of an increase in the intensity of replenishment of surface with oxygen is still being unsolved.

3. Matrix field-emission cathodes

In the beginning of the article we noted that in addition to the most used thermionic emitters in TWT, there are attempts to create TWT on the matrix field emission cathodes (MFEC) which can provide almost instant readiness of the devices, and that is very important for a number of cases of their use.

In [34] the current density of the Spindt cathode matrix with molybdenum cathodes with a diameter of 1 mm in TWT of C-band was approximately 100 A/cm^2 under the maximum current from the cathode 121 mA. However, this construction of TWT, as well as the other constructions of these devices with MFEC, developed in the subsequent years, failed to provide the service life of this type of emission source more than 150 hours. Therefore, in recent years there has significantly increased the interest in the creation of MFEC with the use of carbon materials.

Papers [35-37] note the utility of application of a millimeter and terahertz ranges of cathode systems in the miniature TWT, which are based on MFEC and contain carbon nanotubes and nanoclusters. The work [36] is dedicated to creating a field emission cathode-grid structures with low-voltage grid-controlled electronic flows of high density based on carbon nanotube.

Currently, JSC "R&D enterprise "Almaz" continues the work on development of laser technology of MFEC manufacturing based on glass carbon [38-42].

4. Nanocarbon material for emitters

Special attention in all countries of the world has recently been given to the study of cathode systems based on nanomaterials. Most of them are now occupied by carbon nanoclusters, opened in 1991 [43]. A large number of patents in the Russian Federation describe the technology of obtaining the various forms of carbon nanoparticles, such as nanotubes [44], polyhedral multilayer carbon nanostructures of the fulleroid type [45], multi-layered carbon nanoparticles of the fulleroid type with toroidal shape [46] (Fig.3).

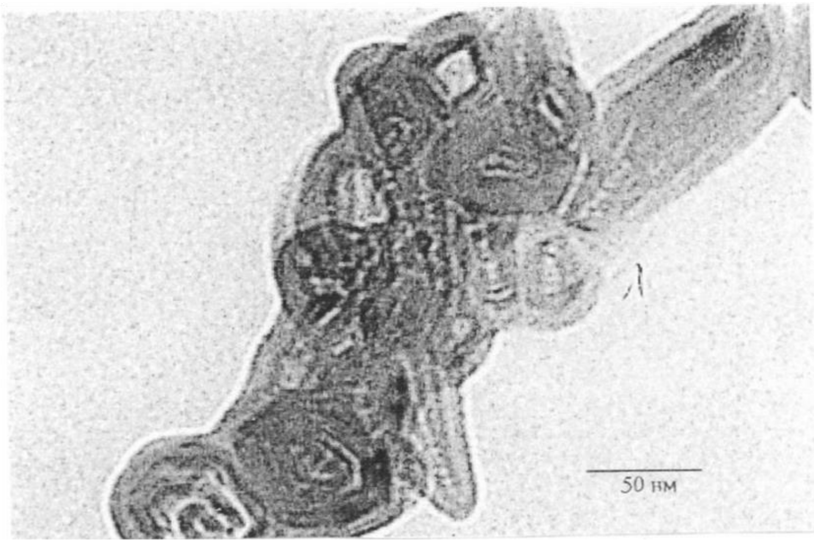

Fig. 3 TEM image of multi-layered carbon nanoparticles of the fulleroid type agglomerated as a bundle of torus

They also consider graphene [47] and various coatings based on diamond [48-50]. These nanoparticles are of special interest for emission electronics, due to the possibility of obtaining high durability and superior emissive properties of cathode systems [51-54].

A review of patent literature shows that to date the nanocarbon material is the most promising for use in MFEC [55-60]. It should be noted that for the MPC manufacturing nanocarbon material has not been applied yet, although it can be assumed that its implementation in the MPC matrix can change the mechanism and rate of occurrence of three-phase reactions of formation of active elements and oxygen and, thereby, improve its emission properties.

Therefore, a relevant task for future research can be the development of new technologies of implementation of the nanocarbon particles in the MPC composition and the study of physical and chemical processes of the conglomerate system and its emission properties.

References

1. Booske J. H., Whaley D. R., Menninger W. L., Hollister R. S., and Armstrong C. M. Traveling-wave tubes. *Modern Microwave and Millimeter-Wave Power Electronics,* 2005, No. 4, pp. 171–245.
2. Chong C.K. and Menninger W.L. Latest advancements in high- power millimeter-wave helix TWTs. *IEEE Transactions on Plasma Science*, 2010, Vol. 38, No. 6, pp. 1227–1238.
3. Longo R.T. Physics of thermionic dispenser cathode aging. *J. Appl. Phys.*, 2003, Vol. 94, No. 10, pp. 6966–6975.
4. Dubua B.Ch. Modern efficient cathodes. *Radio.* [Radio], 1999, No. 4, pp. 55. (In Russian)
5. Kozlov V.I. Emission properties and durability of the metal porous cathodes for microwave devices: Overview of Electronic Engineering. *Elektronnaya tekhnika, ser.1 SVCh-tekhnika.* [Electronic equipment. Ser. 1 Microwave Technology], 1983, Vol. 8 (541), pp. 54. (In Russian)
6. Virin J.L., Dubua B.Ch. The emission properties of the metal porous cathodes based on osmium. *Izvestiya AN SSSR, Ser. Fizicheskaya*. [Bulletin of the Russian Academy of Sciences: Physics], 1979, Vol.43, no.3, pp. 662. (In Russian)
7. Reznev V.A., Gurkov Y., Kiselev A.B. *Sposob izgotovleniya metalloporistogo katoda.* [A method of manufacturing metal porous cathode]. Patent 2064204 (RU), 1996. (In Russian)
8. Barantseva O.S., Kozlov V.I., Osipov V.A. *Sposob izgptovleniya metalloporistogo katoda s dvukhsloinoi gubkoi.* [A method of manufacturing a two-layer cathode metal porous sponge]. Patent 1621771 (RU), 1990. (In Russian)
9. Dubua B.Ch., Kultashev D.C., Polivnikova O.V. Emission electronics, nanotechnology, Synergetics (the history of ideas in the cathode technology). *Elektronnaya tekhnika, ser.1 SVCh-tekhnika*. [Electronic equipment. Ser. 1 Microwave Technology], 2008, No. 4 (497), pp. 3-22. (In Russian)
10. New dispenser cathodes Chinese developers. *Novosti SVCh tekhniki*. [News of microwave technology], 2007, No. 3, pp.19-22. (In Russian)

11. The dispenser cathode with a projected lifetime of more than 20 years. *Novosti SVCh tekhniki*. [News of microwave technology], 2015, No. 6, pp.22-27. (In Russian)

12. Usanov D.A., Melnikova I.P., Mullin V.V., Semenov V.K., Kazakov V.K., Naydenov G.P. *Sposob izgotovleniya metalloporistogo katoda iz vol'framovogo poroshka.* [A method of manufacturing metal porous cathodes of tungsten powder]. Patent 2297068 (RU), 2007. (In Russian)

13. Reznev V.A *Metalloporistyi katod*. [Metal porous cathode]. Patent 46605 (RU), 2005. (In Russian)

14. V.A. Reznev. Sposob izgotovleniya metalloporistogo katoda [A method for manufacturing mechanical metal porous cathode]. Patent 1415973 (RU). 1995. (In Russian)

15. Polivnikova O.V. *Pripoi dlya soedineniya elementov katodno-podogrevatel'nogo uzla.* [Solder for connecting elements of cathode preheating unit]. Patent 2278010 (RU), 2006. (In Russian)

16. Maslennikov O.Y., Ushakov A.B. *Effektivnye termokatody (konstruktsii i tekhnologii)*. [Effective thermionic cathodes (design and technology)], part 2. Moscow, MIPT Publ., 2003, 129 p. (In Russian)

17. Singh A.K., Ravi M., Bisht M.S., Barik R.K., Shukla S.K., Prajesh R., Singh T.P., Saini S.K., Ashish Kumar, Rajesh Kumar, and Raju R.S. Active sintered controlled porosity dispenser (CPD) cathode. *IVESC-ICEE*, Saint-Petersburg, 2014, pp. 253-254.

18. Cathodes with controlled porosity. *Novosti SVCh tekhniki*. [News of microwave technology], 2006, No.9, pp. 16-20. (In Russian)

19. Sakhadzhi G.V., Konyushin A.V., Odintsova Y.A, Popov I.A. *Sposob izgotovleniya emissionnoi poverkhnosti metalloporistogo katoda*. [A method of processing metal porous cathode emitting surface]. Patent 2459306 (RU), 2014. (In Russian)

20. Sakhadzhi G.V., Konyushin A.V., Odintsova Y.A., Popov I.A. *Metalloporistyi katod i sposob ego izgotovleniya*. [Metal porous cathode and a method of its manufacturing]. Patent 2459305 (RU), 2012. (In Russian)

21. Gartner G., Geittner P., Lydtin H., Ritz A. Emission properties of top-layer scandate cathodes prepared by LAD. *App.Surf.Sc*., 1997, No. 111, pp. 11-17.

22. Gaertner G., Geittner P., Raasch D., Wiechert D. Scandate-Vorratskathode. Patent 19961672B4 (DE), 2009.

23. Gaertner G., Barratt D. Life-limiting mechanisms in Ba-oxide, Ba-dispenser and Ba-Scandate cathodes. *App.Surf.Sc*., 2005, No. 251, pp. 73-79.

24. Liu W., Zhang K., Wang Y., Pan K., Gu X., Wang J., Li J., Zhou M. Operating model for scandia doped matrix scandate cathodes. *App.Surf.Sc*., 2005, No. 251, pp. 80-88.

25. The cathodes with high current density in the report of the International Conference EVP 2012 IEEE IVEC. *Novosti SVCh tekhniki*. [News of microwave technology], 2013, No. 1, pp.11-25. (In Russian)

26. Li J., Wang H., Yu Z., Li N., Wang P., Shao W., Zhang K. Scandate cathodes work at BVERJ. *IVEC*, Beijing, 2015.

27. Skandate metal porous cathodes with a large current density. *Novosti SVCh tekhniki*. [News of microwave technology], 2006, No. 11, pp.16-21. (In Russian)

28. Markin S.N. Poverkhnostnye protsessy v sovremennykh termoemissionnykh katodakh: diss. kandidata fiz.- mat. n. [Superficial processes in modern thermionic cathodes: Dr. Sci. (phys.-math.) dissertation]. Moscow, 2006, 163 p. (In Russian)

29. Li I.P., Kapustin V.I.et al. Physical and chemical properties "skandate" cathode materials *Naukoemkie tekhnologii.* [High technologies], 2014, Vol.15, No. 11, pp.40-50. (In Russian)

30. Kapustin V.I., Lee I.P. Skandate cathodes microwave devices. *Elektronika. Nauka. Tekhnologiya. Biznes*. [Electronics. The science. Technology. Business], 2015, No.2 (06142), pp.129-136. (In Russian)

31. Makarov A.P. Emission properties, microstructure and surface composition scandium impregnated cathode tungsten and tungsten-rhenium matrix. *IVESC*. St. Peterburg, 2014, pp.164-165.

32. Makarov A.P., Bersneva E.Yu., Zemchikhin E.M., Chistova G.I., Zakurdaev A.D., Ivanov V.V., Urazov M.N., Hrustov V.R. Scandate cathodes with high current

density for application in microwave devices. *Elektronnaya tekhnika, ser.1 SVCh-tekhnika.* [Electronic equipment. Ser. 1 Microwave Technology], No. 4(531), 2016, pp. 15-23. (In Russian)

33. Sakhadzhi G.V., Krachkovskaya T.M., Storublev A.V., Bogachev R.Y. Investigation metal porous cathode with the addition of scandium to the active substance. *Tezisy dokladoв XXII nauchno-tekhnicheskoi konferentsii s uchastiem zarubezhnykh spetsialistov "Vakuumnaya nauka i tekhnika".* [Theses of the report of the XXII scientific and technical conference with participation of foreign specialists "Vacuum science and technology"]. Feodosiya, 2015, pp. 217-219. (In Russian)

34. Whaley D.R. 100W Operation of a Cold Cathode TWT. *IEEE Trans. On Electron Dev.*, Vol.56, No.5, 2009, pp.896-905.

35. Gulyaev Y.V., Zhukov N.D., Bushuyev N.A. Carbon nanotubes and nanoclusters for the construction of new micro- and nanoelectronics devices. *Elektronnyye pribory i ustroystva SVCH: materialy nauchno-tekhnicheskoy konferentsii, posvyashchennoy 50-letiyu FGUPP "NPP "Almaz".* [Electronic devices and microwave devices: proceedings of the scientific and technical conference dedicated to the 50th anniversary of the Federal State Unitary Enterprise "NPP "Almaz"]. Saratov, SSU, 2007, pp.3-13. (In Russian)

36. Apin M.P., Bushuyev N.A., Burtsev A.A. and other. Technology field emission cathodes based on carbon nanotubes with high density power amplifiers terahertz. *Elektronnyye pribory i ustroystva SVCH: materialy nauchno-tekhnicheskoy konferentsii, posvyashchennoy 55-letiyu "NPP "Almaz".* [Electronic devices and microwave devices: proceedings of the scientific and technical conference dedicated to the 55th anniversary "NPP "Almaz"]. Saratov, SSU, 2012, pp.61-63. (In Russian)

37. Kim H.J., Choi J.J., Han J.-H., Park J.H., Yoo J.-B. Design and Field Emission Test of Carbon Nanotube Pasted cathodes for Traveling-Wave Tube Applications. *IEEE Trans. On Electron Dev.*, Vol.53, No.11, 2006, pp.26-74.

38. Shesterkin V.I. etc. Improved field emission properties of the cell glassy carbon high aspektivnym for acute. *Tezisy dokladov nauchno-tekhnicheskoy konferentsii AO "NPP "Istok": SVCH-elektronika.* [Theses of reports of the scientific

and technical conference of JSC "SPE "Istok": Microwave electronics]. Fryazino, 2016, pp.30-31. (In Russian)

39. Shesterkin V.I. et al. Multilayer needle cathodes with a high aspect ratio of the glassy. *Tezisy dokladov nauchno-tekhnicheskoy konferentsii AO "NPP "Istok": SVCH-elektronika*. [Theses of reports of the scientific and technical conference of JSC "SPE "Istok ": Microwave electronics]. Fryazino, 2016, pp.32-33. (In Russian)

40. Shesterkin V.I. et al. Autoissue cell with a dielectric gap cathode-grid and prospects of their use in electronic devices. *Doklady mezhdunarodnoy nauchno-tekhnicheskoy konferentsii "Aktual'nyye problemy eletronnogo priborostroyeniya"*. [Reports of the International Scientific and Technical Conference "Actual Problems of Electronic Instrumentation"]. Saratov, SSTU, 2016, pp. 161-165. (In Russian)

41. Benedik A.I., Krachkovskaya T.M., Shesterkin V.I. Microdischarges in diodes with small gaps and field emission cathodes of glassy. *Technical Physics*, Vol.60, No.10, 2015, pp.122-126.

42. Bushuyev N.A. and others. The emission characteristics of a multi-beam electron gun with a field emission cathodes of glassy. *Technical Physics*, Vol.86, No. 2, 2016, pp.134-139.

43. Eletskii A.V., Smirnov B.M. Cluster C60-a new form of carbon. *Uspekhi Fizicheskikh Nauk* [Physics - Uspekhi], 1991. Vol.161. No. 7, pp. 173-192.

44. Zharikova E.F., Zyuzin V.V., Shishagin V.V., Zorin E.N., Nikiforov M.E., Sidorov A.A., Novotortsev V.M., Eremenko I.L. *Sposob izgotovleniya uglerodnykh nanotrubok*. [A method for producing carbon nanotubes]. Patent 2431600 (RU), 2011. (In Russian)

45. Ponomarev A.N., Nikitin V.A. *Poliedral'nye mnogosloinye uglerodnye nanostruktury fulleroidnogo tipa*. [Polyhedral multilayer carbon nanostructures fulleroid type]. Patent 2196731 (RU), 2003. (In Russian)

46. Ponomarev A.N., Yudovich M.E. *Mnogosloinye uglerodnye nanostruktury fulleroidnogo tipa toroidal'noi formy*. [Multilayer carbon nanostructuresof fulleroid type and toroidal shape]. Patent 2397950 (RU), 2010. (In Russian)

47. Elshina L.A. *Elektrokhimicheskii metod polucheniya grafena.* [An electrochemical method for graphene production]. Patent 2500615 (RU), 2013. (In Russian)

48. Rakhimov A.T., Suetin N.V., Timofeev M.A., Tugarov V.A., Rezunenko V.I. *Sposob polucheniya almaznykh plenok metodom gazofaznogo sinteza*. [A method for production of diamond films by chemical vapor deposition]. Patent 2158036 (RU), 2000. (In Russian)

49. Rakhimov A.T., Samorodov V.A., Suetin N.V., Pochinkin V.V. *Sposob polucheniya almaznykh plenok metodom gazofaznogo sinteza.* [A method for production of diamond films by chemical vapor deposition]. Patent 2158037 (RU), 2000. (In Russian)

50. Semenov A.P., Semenov I.A. *Sposob polucheniya nanorazmernykh sloev ugleroda so svoistvami almaza*. [A process for preparing nanoscale carbon layers with the diamond properties]. Patent 2532749 (RU), 2014. (In Russian)

51. Kharlamova M.V. The electronic properties of single-walled nanotubes and their derivatives. *Phys. Usp.*, Vol. 56, pp. 1047–1073 (2013). Doi: 10.3367/UFNr.0183.201311a.1145.

52. Brozdnichenko A. N., Ponomarev A. N., Pronin V. P., and Rybalko V.V. Magnetic Properties of Multiwall Carbon Nanotubes and Astralenes in Strong Electric Fields. *Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques*, 2007, Vol. 1, No. 1, pp. 110–112. Doi: 10.1134/S1027451007010223.

53. Shames A.I., Katz E.A., Panich A.M., Mogilyansky D., Mogilko E., Grinblat J., Belousov V.P., Belousova I.M., Ponomarev A.N. Structural and magnetic resonance study of astralen nanoparticles. *Diamond & Related Materials*, 2009, Vol. 18, Issues 2-3, pp.505-510. Doi.org/10.1016/j.diamond.2008.10.056.

54. Shames A. I., Felner I., Osipov Yu. V., Katz E. A., Mogilko E., Grinblat J., Panich A. M., Belousov V. P., Belousova I. M., and Ponomarev A. N. Closed π-Electron Network in Large Polyhedral Multi-Shell Carbon Nanoparticles. *Nanoscience and Nanotechnology Letters*, 2011, Vol.3, pp. 41–48. Doi:10.1166/nnl.2011.1117.

55. Baht D.V., Blank V.D., Bug S.G., Kulnitsky B.A., Polyakov E.V, Beng-Joo Kwon Yang-Du Li. *Sposob polucheniya nanovolokonnogo materiala dlya kholodnykh katodov*. [Method for producing nanofiber material for cold cathodes]. Patent 2288890 (RU), 2006. (In Russian)

56. Alshevsky Y.L., Baht D.V., Blank V.D., Bormashov V.S., Buga S.G., Sheshin E.P. *Sposob izgotovleniya kholodnogo katoda s emissionnym sloem iz nanovolokonnogo materiala na osnove ugleroda.* [A method of manufacturing a cold cathode emission nanofiber layer of carbon-based material]. Patent 2331573 (RU), 2008. (In Russian)

57. Koroteev V.O., Okotrub A.V., Guselnikov A.V., Bulusheva L.G. *Sposob polucheniya materiala dlya avtoemissionnogo katoda.* [The process for production of the material for the field emission cathode]. Patent 2463253 (RU), 2012. (In Russian)

58. Rakhimov A.T. "Autoemission cathodes (cold emitters) on nanocrystalline carbon and nanodiamond films: physics, technology, applications". *Phys. Usp.* Vol. 43, pp. 926–929 (2000). DOI: 10.1070/PU2000v043n09ABEH000808

59. Eletskii A.V. Carbon nanotubes and their emission properties. *Phys. Usp*. Vol. 45, pp. 369–402 (2002). DOI: 10.1070/PU2002v045n04ABEH001033

60. Eletskii A.V. Cold field emitters based on carbon nanotubes. *Phys. Usp.*, Vol. 53, pp. 863–892 (2010). Doi: 10.3367/UFNr.0180.201009a.0897.

For citation:
T. M. Krachkovskaya, G. V. Sahadji, S. D. Zhuravlev. Modern electron sources for TWTs in millimeter and submillimeter ranges. *Zhurnal Radioelektroniki - Journal of Radio Electronics*. 2017. No. 12. Available at http://jre.cplire.ru/jre/dec17/5/text.pdf.