Investigation of the Concept of a Miniature X-ray Source Based on Nanoscale Vacuum Field-emission Triode Controlled by Cut-off Grid Voltage

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***Abstract*—Nowadays, there is a revived interest in the field of vacuum nanoelectronics, which is due to the prospect of creating low-power, high-frequency, radiation-resistant and scalable electronic devices with nanosized vacuum channel. In particular, it provides good motivation for developing a miniature X-ray source using triode-type field-emission structures to generate an electron beam with diameter reduced down to nanometer scale by the grid electrode. In this paper we propose the concept of X-ray source based on vertical field-emission vacuum triode containing transmission-type beryllium target on a metal anode and nanoscale cathode, the cold emission from which is controlled by a negative cut-off grid voltage. The optimal geometric parameters of this triode are found, sufficient to obtain the maximum electric field on the cathode surface up to 10^7 V/cm. It is shown that for an optimal design of vacuum triode the diameter of the electron spot is narrowed to about 100 nm, while the cut-off grid bias varies in the range from -10 to -40 V for the anode potential closing to 2-2.5 kV, that is required for achieving maximum conversion of electron energy into soft X-ray radiation. The results obtained can be widely used in the development of X-ray sources for portable diagnostic systems, as well as medical and lithographic equipment [1-3].**

Keywords—X-ray source; X-ray wavelength; field electron emission; nanoscale vacuum triode; cut-off grid voltage; electric-field enhancement factor

I. Introduction

It is well known that in the modern world the use of X-ray radiation plays an important role in various fields of science and technology. For an example, X-rays are widely used to study the chemical composition and structure of materials, to measure the geometric parameters of objects, for carrying out non-destructive quality control of products, and also have good prospects of its industrial application in micro - and nanoelectronics for the fabrication of submicron structures that can be obtained by x-ray lithography [1]. Furthermore, x-ray methods of the analysis are actively used for performing medical diagnosis of diseases (traumatology, dentistry, radiotherapy) and in security systems of the airports, bus and railway stations [2,3]. As a rule, X-ray tube is used for the generation of X-rays, and it typically includes the electronic part for creating an electron beam (vacuum triode which is

presented as a field-emission cathode to produce the electrons extracted by the electric field from the control grid electrode and the anode) and the transmission-type X-ray target as a source of X-ray radiation (Fig. 1). X-rays are generated as a consequence of interaction process between the field-emitted electrons of given energy, transmitted by electric field from cathode to anode, and the material of X-ray target. The two main physical processes, Bremsstrahlung and fluorescence, are laid in the basis of the formation of the X-ray energy spectrum of characteristic lines [4]. The fabrication of miniature X-ray tube based on nanosized field-emission triode, as it is shown in Fig. 1, can be performed using modern CMOS technology [5].

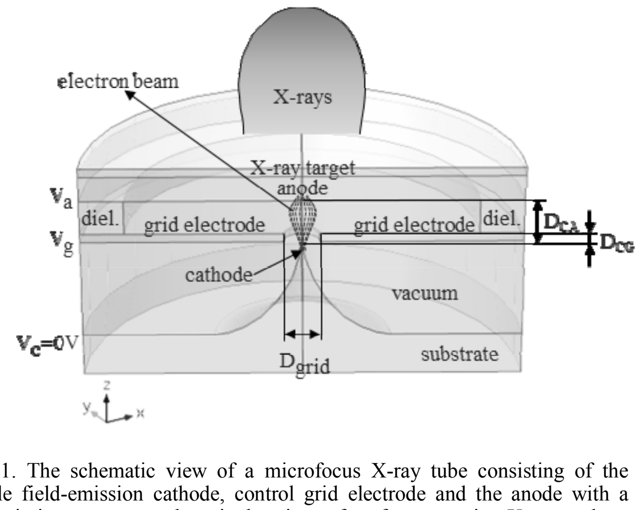

Fig. 1. The schematic view of a microfocus X-ray tube consisting of the needle field-emission cathode, control grid electrode and the anode with a transmission-type target deposited on its surface for generating X-rays, where R_c is the radius of the cathode tip, $D_{grid} = 2R_{grid}$ is the diameter of the circular aperture of grid electrode, D_{ca} (D_{cg}) is the inter-electrode distance between cathode and anode (cathode and grid), diel. is the dielectric spacer.

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The tip of the needle-shaped cathode has a radius of up to several nm, which causes the concentration of a strong electric field on its surface in the case of non-zero potential at the electrodes, leading to the emission of electrons when the amplitude of electric field exceeds a threshold value of the order of 10^7 V/cm [6]. The cut-off voltage variation at the grid electrode controls the diameter of the electron beam passing through the circular grid aperture into vacuum towards the anode covered by the thin metal film of the transmission-type target which allows operating the area of initialization of X-ray photons. Progress in the development of X-ray sources is mainly associated with a reduction in the diameter of electron spot and technological transition to the nanoscale vacuum channel to improve the localization of radiation with reduced energy consumption and small X-ray tube dimensions. This opens the way to the development of portable diagnostic devices for 3D computed tomography and high-precision tools of medical therapy allowing the local treatment of malignant tumors [7], as well as the equipment for carrying out a maskless X-ray lithography with the design rules of up to 20 nm to form elements with an extremely small spatial resolution [8].

The vacuum field-emission triode controlling the electron beam is a key element of the X-ray source, since the radius of cathode tip R_C, diameter of the aperture of grid electrode D_{grid}, the distance of inter-electrode space («cathode-anode» D_{CA} and «cathode-grid» D_{CG}) significantly affect the field-emission current and, therefore, the spatial resolution of radiation. In this regard, it becomes important to choose the optimal geometric design of the vacuum triode to obtain the maximum efficiency of field-emission process and minimum diameter of an electron beam at low level of energy consumption, which requires finding new ideas to solve this issue. The concept proposed here is based on the field-emission nanosized vacuum triode with X-ray target on the anode surface, which can be fabricated using the standard CMOS process technology (Fig. 1). The blocking voltage on the grid electrode makes it possible to control the focusing parameters and the cut-off voltage needed to achieve the surface electric field at the tip of needle cathode sufficient to turn on the field-emission current. In turn, for given values of the field-emission current, X-ray photons are generated in the transmission-type X-ray target during «electron-phonon» and «electron-electron» interactions in it, which occur after the electron beam hits the anode in such type of X-ray source [9]. In the case of X-ray therapy, the increase in the amplitude of grid potential enhances the radiation localization, while in the case of X-ray lithography this approach avoids accidental errors in formation of the desired pattern that is created on the X-ray resist by feeding the negative potential to the columns and rows of grid electrodes in the matrix of X-ray tubes [10]. In addition, for the X-ray lithography, the selection of the target material taking the account its conversion efficiency (the ratio between the electron and X-ray photon energy) is required, which is necessary to obtain the optimal exposure dose of X-rays on the sensitive resist. In this work, beryllium was chosen as the target material that due to its wavelength of 11.4 nm for obtaining soft characteristic X-ray radiation, well adsorbed by X-ray resist. The analysis of optimum geometric parameters of the vacuum triode within the considered concept of X-ray source was carried out in the case when the anode potential is in the range from 2 to 2.5 keV where the maximal conversion coefficient is observed which is shown below.

II. THE ELECTRIC-FIELD ENHANCEMENT FACTORS AND CUT-OFF GRID VOLTAGE

Initially, it was assumed that the geometric parameters of the vertical vacuum triode are as follows: $R_{grid} = D_{grid}/2 = 100nm$, $D_{CA} = 500nm$, $D_{CG} = 0nm$, where D_{CA} (D_{CG}) corresponds to the distance from the cathode tip to the bottom surface of the anode (grid) electrode. For the design of the vacuum triode, presented in Fig. 1, the cathode tip is supposed to have a nearly semispherical shape of radius $R_C = 5nm$, the cathode is at ground potential, while the cut-off voltage $V_{grid} \le 0$ is applied to the grid electrode to control the beginning of field-electron emission from the cathode. The anode potential ($V_{anode} \ge 0$) is considered to be constant for extracting electrons to the metal film of X-ray target deposited on the back side of the anode layer. Since optimization of the design of the X-ray tube requires the maximum amplitude of the electric field on the surface of cathode tip for given geometric parameters, we first consider the electric-field enhancement factors β_{grid} (β_{anode}) induced by the potential of the grid (anode) electrode separately, similar to our previous analysis of scaling of various configurations of the triode with the nanoscale vacuum channel [11]. These factors determine the average electric field on the cathode-tip surface $\vec{\varepsilon}_C^{avg}$ that is given by the formula:

$$\vec{\varepsilon}_C^{avg} = \varepsilon_C^{avg}\vec{e}_C^{avg} = \beta_{grid}V_{grid}\vec{e}_{Cg}^{avg} + \beta_{anode}V_{anode}\vec{e}_{Ca}^{avg}, \quad (1)$$

where the unit vector $\vec{e}_C^{avg}$ defines the direction of the total electric field $\vec{\varepsilon}_C^{avg} = \vec{\varepsilon}_{grid}^{avg} + \vec{\varepsilon}_{anode}^{avg}$, $\vec{e}_{Cg}^{avg}$ ($\vec{e}_{Ca}^{avg}$) is the unit vector which shows the direction of the field $\vec{\varepsilon}_{grid}^{avg}$ ($\vec{\varepsilon}_{anode}^{avg}$), generated by the potential of the grid (anode) electrode separately, $\varepsilon_C^{avg} = \left|\vec{\varepsilon}_C^{avg}\right| = \int \varepsilon_C dS_{CT}/S_{CT}$, ε_C is the amplitude of electric field at each point of the surface of the cathode tip, S_{CT} is the cathode-tip surface area. In this case, the electric-field enhancement factor β_{grid} (β_{anode}) can be determined as:

$$\beta_{grid} = \frac{\partial \varepsilon_C^{avg}}{\partial V_{grid}}, \; \beta_{anode} = \frac{\partial \varepsilon_C^{avg}}{\partial V_{anode}} \quad (2)$$

In our model we use the Comsol MultiPhysics software [12] to obtain the full three-dimensional electric field distribution in the inter-electrode space of the vacuum triode presented in Fig. 1 at nonzero electrode potentials. It helps to calculate the factors β_{grid} (β_{anode}) and corresponding trajectories of emitting electrodes determining the electron spot size on the surface of anode. To perform this task, the parameters R_{grid}, D_{CA}, D_{CG} were varied, where the change in the grid position relative to the cathode tip was taken into account by the parameter $k_{cg} = D_{CG} / D_{CA}$. For the consideration of the individual field enhancement factors, the potential V_{anode} (V_{grid}) was taken equal to zero to neglect the influence of the grid (anode) potential on the form-factors β_{grid} (β_{anode}). Fig. 2 presents the dependencies of values β_{grid} (β_{anode}) on the radius of the grid aperture R_{grid} at different parameters k_{cg}, when the anode (grid) potential is zero. From Fig. 2a it is easy to see that for a given distance $D_{CA} = 500 nm$ the effect of the aperture size R_{grid} on the parameter β_{grid} is weakened, and the dependence $\beta_{grid}(R_{grid})$ becomes practically linear, where the maximum factor β_{grid} is reached when $k_{cg} = 0$.

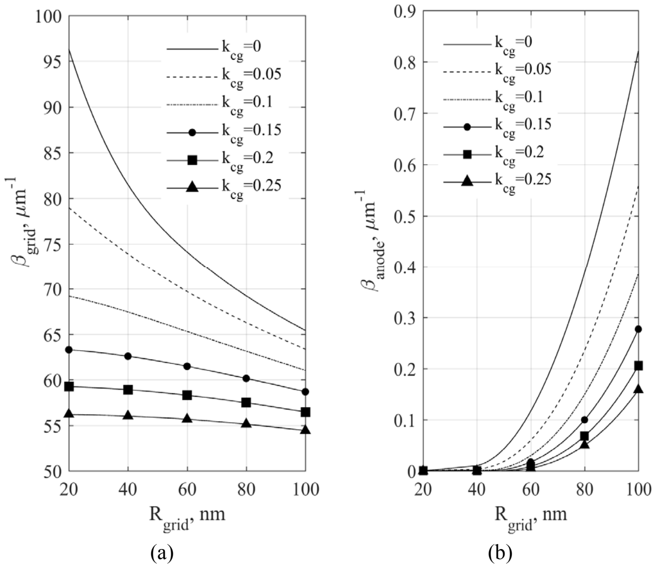


Fig. 2. The dependence of the electric-field enhancement factors (a) β_{grid} ($V_{grid} = 0V$) and (b) β_{anode} ($V_{anode} = 0V$) on the radius R_{grid} of grid aperture for varied values of the parameter k_{cg}, where $k_{cg} = D_{CG} / D_{CA}$, $R_C = 5nm$, $D_{CA} = 500nm$.

At the same time the dependence β_{anode} on the radius of grid aperture R_{grid} becomes noticeable only when $R_{grid} > 40nm$, which is due to the screening of the electric field $\vec{\varepsilon}^{avg}_{anode}$ by the grid layer in the case of small radius of aperture. As the aperture radius R_{grid} decreases, the growth of factor β_{grid} occurs and the influence of grid electrode on the cathode electric field is predominant. Fig. 3 shows the dependence of the field-enhancement factor β_{grid} (β_{anode}) on the distance D_{CA} when the parameter k_{cg} is varied. It is interesting to note that the dependence of parameter β_{grid} on the distance D_{CA} changes its behaviour from growth to fall during the transition from zero to nonzero values of the parameter k_{cg}. As the distance D_{CA} is growing up, the factor β_{grid} decreases, which is due to corresponding increase in the distance between the grid electrode and the cathode tip for values of k_{cg} varied from 0.05 to 0.25. In the case, when $k_{cg} = 0$, the grid position is fixed, and the field enhancement factor β_{grid} monotonically increases with the displacement of the anode position with respect to grid. In turn, the factor β_{anode} reduces with the distance D_{CA} over the full range of the parameter k_{cg}.

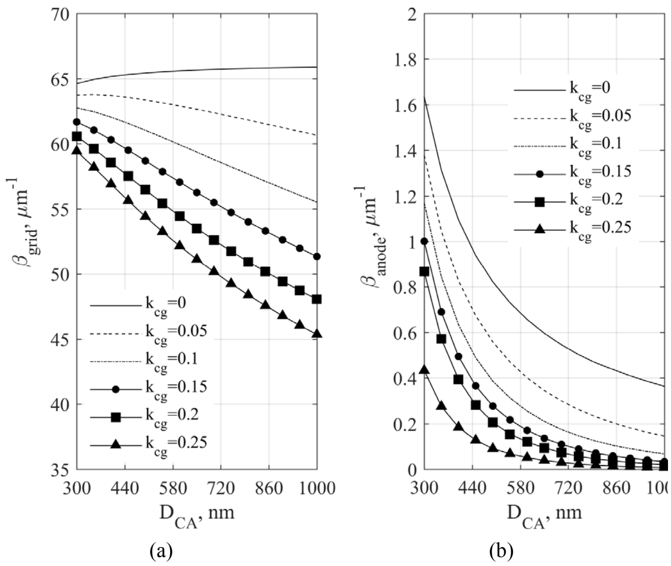
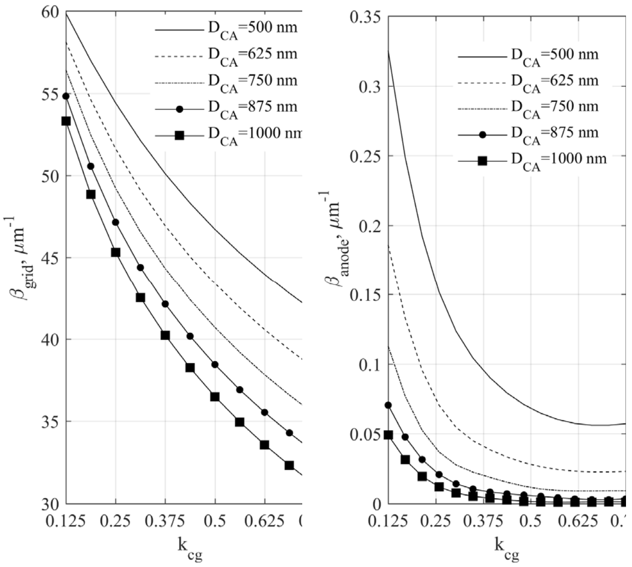


Fig. 3. The dependence of the electric-field enhancement factors (a) β_{grid} ($V_{grid} = 0V$) and (b) β_{anode} ($V_{anode} = 0V$) on the distance D_{CA} between the cathode tip and anode for varied values of the parameter k_{cg}, where $k_{cg} = D_{CG} / D_{CA}$, $R_C = 5nm$, $R_{grid} = 100nm$.

In Fig.4 the dependencies of the factors β_{grid} (β_{anode}) on the parameter k_{cg} varied from 0.125 to 0.75 are presented, which characterizes the local position of the cathode, anode and grid relative to each other for different distances D_{CA}.



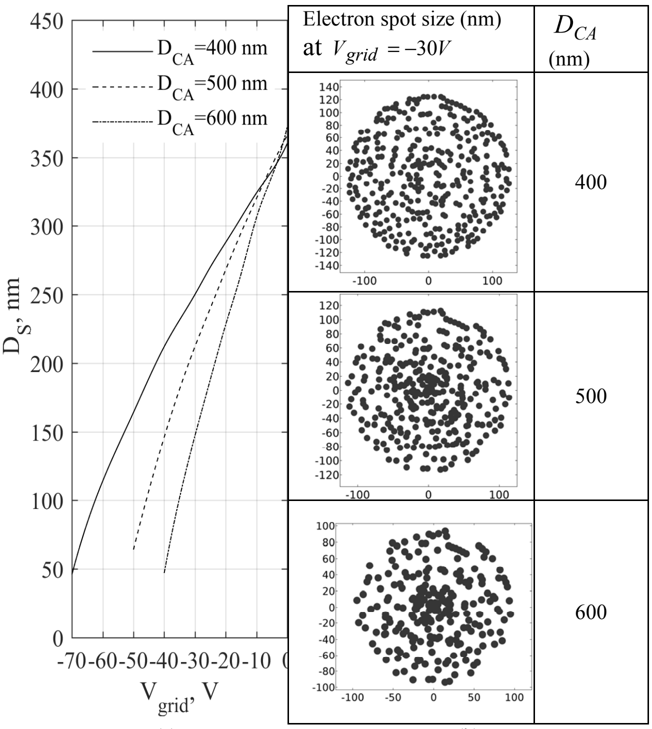
(a) (б)

Fig. 4. The dependence of the electric-field enhancement factors (a) β_{grid} ($V_{grid} = 0V$) and (b) β_{anode} ($V_{anode} = 0V$) on the parameter k_{cg} for varied values of the distance D_{CA}, where $k_{cg} = D_{CG} / D_{CA}$, $R_C = 5nm$, $R_{grid} = 100nm$.

It was obtained that β_{grid} strongly falls down with increasing the parameter k_{cg}, while the factor β_{anode} decreases to zero when the distance D_{CA} reaches 1000 nm.

III. THE PARAMETERS OF X-RAY SOURCE BASED ON OPTIMAL DESIGN OF THE FIELD-EMISSION TRIODE

Since the factors β_{grid} and β_{anode} take part in the formation of the total electric field ε_C^{avg} on the cathode tip, it is necessary to take into account the combined effect of the electric-field enhancement factors on the field-emission process for choosing the optimal design of the vacuum triode as an electronic part of the miniature X-ray source. Thus, firstly we obtained that the radius of grid aperture $R_{grid} = 50nm$ is the most optimal for the effective field-emission generation in the vertical vacuum triode considered here, where the screening effect of the grid on the electric field from the anode $\vec{\varepsilon}_{anode}^{avg}$ begins to decrease. According to results obtained in Fig. 3a, we should consider $k_{cg} \neq 0$. In according with the calculated factors β_{grid} (β_{anode}), we should choose the parameter k_{cg} close to zero (for example, $k_{cg} = 0.05$) for achieving the maximum electric field ε_C^{avg}.To determine the most effective distance D_{CA} for the generation of electron beam which controls the spatial resolution of the microfocus X-ray tube, we also conducted the analysis of the variation of the diameter of electron spot on the X-ray target, depending on the cut-off grid voltage $V_{grid} \leq 0$ when the anode voltage $V_{anode} = 500V$. The particle tracing module of Comsol MultiPhysics software was used for this purpose. Fig. 5 illustrates the dependence of the diameter D_S of electron spot on the cut-off grid voltage V_{grid} for different distances D_{CA}. It can be seen from the graph that with increasing V_{grid} the electron beam begins to narrow, which causes variation of the spot diameter in the range from 370 nm to about 50 nm. However it is worth noticing that a decrease in the distance D_{CA} from 600 nm to 400 nm increases the cut-off grid voltage V_{grid} necessary to obtain a focusing with the diameter of electron beam of the order of 100-225 nm, which is optimal from the point of view of generating X-rays in the transmission-type beryllium target [8]. From this it follows that the distance $D_{CA} = 600nm$ is the most effective, since in this case the electric field enhancement factors slightly decrease, while the energy consumption for obtaining the high resolution of X-ray generation area markedly decreases.



(a) (b)

Fig. 5. (a) The dependence of the diameter D_S of electron spot on the X-ray target on the cut-off grid voltage $V_{grid} \leq 0$ at various distances D_{CA} for the optimal design of the vertical vacuum triode, where $V_{anode} = 500V$. (b) The size of electron spots on the anode surface for the grid voltage $V_{grid} = -30V$, depending on the distance D_{CA}.

Since the grid electrode has the predominant influence in the vacuum triode, with an increasing the voltage V_{anode} to 2-2.5 kV, which is necessary for the maximum conversion of the electron energy to X-rays in the transmission-type beryllium target [8], the spot diameter will slightly change, and its dependence on the cut-off grid voltage will have a similar character as shown in Fig. 5, where the most optimal values V_{grid} are in the range from -45 V to -25 V.

IV. CONCLUSION

Thus, the dependence of the electric-field enhancement factors β_{grid} and β_{anode} on the geometric parameters of the vertical triode with a nanoscale vacuum channel has been studied. As a result, its optimal design was chosen to obtain the high spatial resolution and reduce the energy consumption of the X-ray source, for which the maximum efficiency of the conversion of electron energy to soft X-ray radiation in a thin beryllium target is reached. It also was found that for the radius of cathode tip $R_C = 5nm$, the radius of grid aperture R_{grid}, the distance D_{CA} and the ratio k_{cg} should be chosen equal to 50 nm, 600 nm and 0.05, respectively. In this case, the cut-off grid voltage V_{grid} is varied from -45 V to -25 V, when the anode voltage V_{anode} is in the range 2-2.5 kV to obtain the optimal resolution with maximum conversion factor and the diameter of electron spot of about 100-225 nm. The obtained results can be used in the development of an electronic system based on the vertical vacuum triodes with field-emission silicon nanocathode [13] for the new generation of the portable and miniature X-ray sources [14].

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