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RESEARCH ARTICLE

Optimal electrode design for microminiature electronic optics

Pavel S. Kuznetsov [1, @],
Anton O. Sinelnikov [2]

[1] *State Scientific Research Institute of Instrument Engineering, Moscow, 129226, Russia*
[2] *Peoples' Friendship University of Russia (RUDN University), Moscow, 117198 Russia*
[@] *Corresponding author, e-mail: ps_kuznetsov@mail.ru*

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Abstract
Objectives. The work set out to systematically analyze and optimize the overall design and technological characteristics of microminiature electron-optical systems for achieving maximum performance indicators. The study paid special attention to establishing relationships between the geometric parameters of the system and its functional characteristics.
Methods. The research is based on comprehensive mathematical modeling of electron dynamics in a complex five-electrode scheme that accurately reproduces the actual design of a compact electron-beam microcolumn. This approach was used to establish the quantitative dependencies of resolution and electron beam intensity critical system performance indicators on fundamental geometric parameters: interelectrode distances, diaphragm aperture configurations, and output angular size. The main efforts focused on determining the optimal parameter values while ensuring minimal focal spot size and simultaneously maximizing beam energy.
Results. The computer modeling revealed the determining influence of each component of the five-element electron-optical structure on the formation of qualitative electron flow characteristics. A pronounced minimum in electron beam diameter was established at a specific combination of geometric and electrical system parameters. The thus-obtained optimum was used to develop a new methodology for designing and calibrating compact electron-beam devices that ensures maximum resolution and high sensitivity with minimal power consumption. Detailed analysis demonstrated that the optimal electrode configuration reduces spherical aberration by 25% compared to traditional solutions.
Conclusions. The developed design approach for microcolumn electron-optical systems significantly enhances performance while expanding the functional capabilities of electron microscopes and related analytical instruments. The practical significance of the work is confirmed by the possibility of creating devices with record resolution indicators in compact sizes. An important achievement is the establishment of quantitative optimization criteria for enabling targeted improvement of electron-beam system characteristics.

Keywords: electron-beam microsystem, electrostatic optics, microcolumn, microlens, Schottky emitter, optimal design, mathematical modeling, multi-beam lithography

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НАУЧНАЯ СТАТЬЯ

Оптимальная конструкция электродов для микроминиатюрной электронной оптики

П.С. Кузнецов [1, @],
А.О. Синельников [2]

[1] *АО «Государственный научно-исследовательский институт приборостроения», Москва, 129226 Россия*
[2] *Российский университет дружбы народов, Москва, 117198 Россия*
[@] *Автор для переписки, e-mail: ps_kuznetsov@mail.ru*

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Резюме

Цели. Цель работы – систематический анализ и оптимизация основных конструкционно-технологических характеристик микроминиатюрных электронно-оптических систем для достижения максимальных показателей их работоспособности. В ходе исследования особое внимание уделялось установлению взаимосвязей между геометрическими параметрами системы и ее функциональными характеристиками.

Методы. В основе исследования лежит комплексное математическое моделирование динамики электронов в сложной пятиэлектродной схеме, достоверно воспроизводящей реальную конструкцию компактной электронно-лучевой микроколонны. Данный подход позволил установить количественные зависимости критических показателей производительности системы – разрешающей способности и интенсивности электронного пучка – от фундаментальных геометрических параметров: межэлектродных расстояний, конфигурации апертур диафрагм и углового размера выходного отверстия. Основные усилия были сосредоточены на определении оптимальных значений указанных параметров, обеспечивающих минимальный размер фокального пятна при одновременной максимизации энергии пучка.

Результаты. Проведенное компьютерное моделирование выявило определяющее влияние каждого компонента пятиэлементной электронно-оптической структуры на формирование качественных характеристик электронного потока. Установлено наличие выраженного минимума диаметра электронного пучка при определенной комбинации геометрических и электрических параметров системы. Обнаруженный оптимум позволил разработать новую методику проектирования и калибровки компактных электронно-лучевых приборов, обеспечивающую достижение максимального разрешения и высокой чувствительности при минимальном энергопотреблении. Детальный анализ продемонстрировал, что оптимальная конфигурация электродов позволяет снизить сферическую аберрацию на 25% по сравнению с традиционными решениями.

Выводы. Разработанный подход к проектированию электронно-оптических систем микроколонн существенно повышает производительность и расширяет функциональные возможности электронных микроскопов и родственных аналитических приборов. Практическая значимость работы подтверждается возможностью создания устройств с рекордными показателями разрешения при компактных размерах. Важным достижением является установление количественных критериев оптимизации, позволяющих целенаправленно улучшать характеристики электронно-лучевых систем.

Ключевые слова: электронно-лучевая микросистема, электростатическая оптика, микроколонна, микролинза, эмиттер Шоттки, оптимальное проектирование, математическое моделирование, многолучевая литография

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INTRODUCTION

The introduction of microtechnologies into electronic optics has led to a qualitative leap in the characteristics and utility of electron beam devices and equipment. The creation of electronic sources, lenses, and deflectors having dimensions reduced by an order of magnitude or more compared to conventional ones [1–4] has given impetus to the development of microcolumns for miniature electron microscopes [5, 6] and multi-beam lithography systems [7–9] offering new technical and economic capabilities. The transition to smaller scales has expanded the prospects for the application of electron beam systems in areas related to the storage, processing, and display of information [10–16], where they have been supplanted by semiconductor devices and devices based on liquid crystals, as well as other materials having pronounced sensory and electroluminescent properties.

For design, technological, and electronic-optical reasons, microcolumns are made completely electrostatic. The first such column, having a total length of about 3.5 mm, consisted of a thermoelectric electron source with a two-electrode cathode lens, an aperture diaphragm, an octupole deflector, and a three-electrode focusing lens [17, 18]. The lenses were comprised of stacks of silicon crystals separated by insulating spacers made of Pyrex glass, with membrane windows for the electrodes. Traditional electron beam lithography and reactive ion etching microelectronics technologies were used to form holes in the electrodes, while multilayer anodic welding was used to connect the silicon components. The microcolumn [17], which demonstrated very high performance in low-voltage mode (resolution of about 10 nm at an accelerating voltage of 1 kV and a beam current of ~1 nA), served as the prototype for all subsequent modifications, representing a kind of reference standard. Ongoing research aimed at expanding microcolumn functionality and simplifying their manufacture concerns the structure (composition and mutual arrangement) and operating parameters of functional elements. One noteworthy experimental variant consists in an integrated electron-optical system (microlens) having dimensions of 1 × 1 × 0.05 cm, which performs electron extraction, focusing, and beam deflection [19–21]. The positioning of the cathode at 1–2 mm away from the microlens reduces the requirements for its installation accuracy and makes it possible to use any type of source: cold field, thermionic, or thermofield (Schottky emitter). Another promising modification is a dual-lens microcolumn [22, 23], which, while maintaining optimal aperture conditions in the objective lens, ensuring minimum aberrations and sufficient resolution for sub-100-nm technologies (no worse than 20–50 nm per 1 kV), significantly increases the solid angle of reception and, accordingly, the beam current (up to 50 nA at a source angular brightness of 100 μA/cm²), albeit at the expense of a slight increase in the size of the system (~7 mm).

PROBLEM STATEMENT

The task of optimal design consists in determining the optimal parameters of the geometry and mode of the microlens to ensure the minimum diameter of the probe (focused beam in the object plane) for given source characteristics, focusing distance (working distance), accelerating voltage (determining the final energy of electrons), as well as physical and technological limitations. Unlike [2, 15], the optimization problem was solved with fewer variable geometric parameters (the diameters of the holes and the interelectrode distances were selected to be the same), but with a larger number of electrodes and corresponding variable potentials.

Regardless of the optimization criterion (maximum resolution, i.e., the smallest possible size of the probe formed, the minimum size of the probe at a given current, or the minimum of individual aberrations), the optimal parameters are determined for a narrow range of electron energies, working distances, and source characteristics. For other conditions, the obtained parameters are nonoptimal. Therefore, lenses that are optimized to a greater extent by the selection of potentials rather than by geometry, which cannot be changed, appear to be more flexible in terms of utility. This, as well as the focus on simplifying the technology, which also includes the adjustment function, determines the formulation of the optimization problem with a minimum number of variable geometric parameters. To evaluate the electron-optical advantages and select the preferred option, the maximum calculated resolutions of optimized lenses consisting of three, four, and five identical silicon membrane electrodes were compared with each other and with those obtained under the same conditions by a three-electrode lens optimized for all geometric parameters [2].

MATHEMATICAL MODEL OF AN ELECTRONIC LENS

Studies [24–32] present the results of various numerical experiments aimed at structural and parametric optimization to evaluate the limiting focusing properties of micro-miniature diaphragm systems in a given range of geometric parameters. In this case, optimization is understood as a search—under conditions of sequential increase in the number of electrodes, hole diameters, distances between electrodes, and potentials applied to them—for the linear increase, accelerating voltage, and working segment that provide minimum axial aberration coefficients when varied within specified limits. In each of the cases presented, a direct optimization method is used with original algorithms that enable tracking and correction of the axial distribution of the potential. The electrostatic field is typically defined analytically as a superposition of the fields of individual diaphragms.

The practical optimization methods used, which provide the initial data for designing high-quality optics, are therefore entirely adequate for the task at hand. Moreover, the same programs can be used to obtain an approximate solution to the optimization problem, which is presented as a linear combination of a sufficiently large number of functions of the appropriate type [9]. This allows us to estimate how close we can get to the limiting values of aberration coefficients under given conditions. A similar approach was tested in the problem of optimal synthesis of magnetic focusing fields when compared with the solution obtained by the optimal control method [10].

With optimal design of the electrostatic microminiature optics of electron beams shown in Fig. 1, the following data becomes available for processing. The variable parameters will be the voltage U_i, interelectrode distances l_i, diaphragm diameters d_i, and angular aperture α_0. The initial data for optimization are the working length ($l_0 = 1$ mm) and source parameters (source radius $r_0 = 2$ nm and angular brightness 10 μA/cr, voltage variation range $\Delta U_0 = 0.2$ V, distance from the source to the first electrode $l_{\text{src}} = 50$–250 μm).

The objective of optimization is to achieve a minimum beam diameter equal to:

$$d = \sqrt{(Md_0)^2 + d_{\text{chr}}^2 + d_{\text{sf}}^2 + d_{\text{dif}}^2} = \min, \tag{1}$$

where M is the linear magnification of the lens; Md_0 is the diameter of the probe in the cross-sectional plane; d_{chr} is the diameter of the chromatic aberration spot; d_{sf} is the diameter of the spherical aberration spot; d_{dif} is the diameter of the electron beam cross-section formed as a result of diffraction.

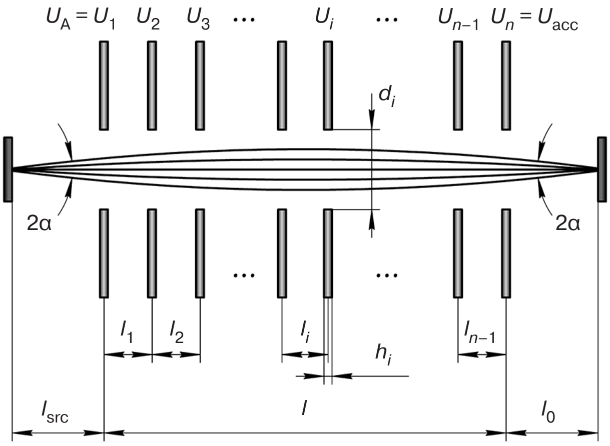


Fig. 1. Initial model of an electronic lens. U_A is the voltage at the starting point A of the lens, U_{acc} is the accelerating voltage

Given the existing limitations on electric field strength ($E \leq 10^4$ V/mm) and geometric parameters ($l_i = 100$–500 μm, $d_i = 20$–200 μm, hole diameter $h_i = 1$–3 μm) the following technical characteristics are expected: accelerating voltage of about 1–3 kV; beam current greater than 1 nA; probe diameter about 10 nm; column height about 5 mm.

According to the selected mathematical model, we obtain the following characteristics:

- minimizable beam radius:

$$r = \sqrt{r_G^2 + \left(r_{\text{dif}}\right)^2 + \left(r_{\text{sf}}\right)^2 + \left(r_{\text{chr}}\right)^2}, \tag{2}$$

where $r_G = Mr_0$ is the radius of the Gaussian image, $r_{\text{dif}} = \dfrac{0.75M}{\alpha_0\sqrt{U_0}}$ is the radius of the diffraction blur, $r_{\text{sf}} = MC_{\text{sf}}\alpha_0^3$ is the radius of the spherical aberration discs, $r_{\text{chr}} = MC_{\text{chr}}\alpha_0\dfrac{\Delta U_0}{U_0}$ is the radius of the chromatic aberration discs;

- axial distribution of potential:

$$E(z) = \frac{2}{\pi}\sum_{i=1}^{n}\tilde{E}_i\left[\operatorname{arctg}\left(\frac{2(z-z_i)}{h_i}\right) + \frac{\dfrac{2(z-z_i)}{h_i}}{1+\left(\dfrac{2(z-z_i)}{h_i}\right)^2}\right], \tag{3}$$

where $$\tilde{E}_i = \frac{E_i - E_{i-1}}{2},\ E_i = \frac{U_i - U_{i+1}}{l_i},\ i = \overline{1, n-1},$$

$E_0 = E_n = 0$; z is the axial position of the source, z_i is the axial coordinate of the ith electrode.

- spherical and chromatic aberration coefficients:

$$C_{\text{sf}} = \frac{1}{32}\int\limits_{z_0}^{z_i}\sqrt{\frac{U}{U_0}}r^4 \times$$
$$\times\left\{\left(\frac{U'}{U}\right)^2\left[\frac{r'}{r}+\frac{5}{6}\cdot\frac{U'}{U}\right]^2+\frac{3}{2}\left(\frac{U''}{U}+\frac{U'}{U}\cdot\frac{r'}{r}-\left(\frac{U'}{U}\right)^2\right)^2+\right.$$
$$+\left(\frac{U'}{U}\right)^2\left(\frac{r'}{r}+\frac{5}{6}\cdot\frac{U'}{U}\right)^2+ \tag{4}$$
$$\left.+\frac{1}{36}\left(\frac{U'}{U}\right)^4+\left[\left(\frac{U''}{U}+\frac{U'}{U}\cdot\frac{r'}{r}\right)-\frac{5}{4}\left(\frac{U'}{U}\right)^2\right]^2\right\}dz,$$

$$C_{\text{chr}} = \frac{3}{8}\int\limits_{z_0}^{z_i}\sqrt{\frac{U_0}{U}}r^2\left(\frac{U'}{U}\right)^2 dz. \tag{5}$$

RESULTS AND DISCUSSION

The results of modeling and optimization of the five-electrode lens are shown in Figs. 2–4. Figure 2 shows the dependence of the minimum radius of the electron lens on the angular aperture, which has a characteristic minimum at $\alpha_0 = 4$ mrad. It can be seen that at first the lens radius decreases rapidly with increasing aperture to reach its minimum value, after which it begins to increase gradually with further growth of the angular aperture.

As can be seen from the graphs shown in Fig. 3, the maximum focus and corresponding beam aperture decrease almost linearly with increasing length of the five-electrode lens under consideration.

The dependencies of the minimum radius of the electron lens on the aperture diameter (Fig. 4) at values of α_0, equal to 4 and 6 mrad, is distinctly nonlinear and is graphically described by a U-shaped curve with a local minimum. This means that as the aperture diameter increases, the minimum radius value first decreases smoothly, passing through the point of extremum (minimum value). After passing the minimum point, a further increase in the aperture diameter causes a gradual increase in the radius.

Thus, there is an optimal aperture diameter at which the minimum focus radius of the electron beam is achieved. At the minimum point, the electron lens has the following parameters:

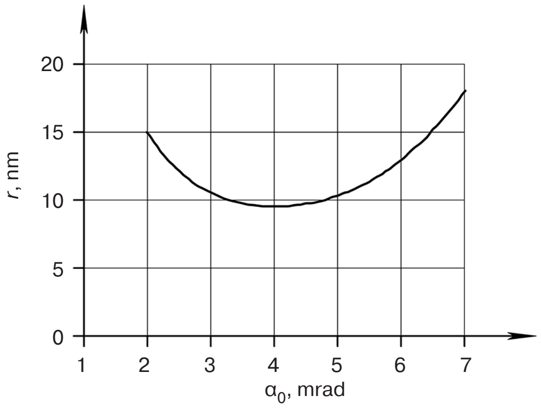
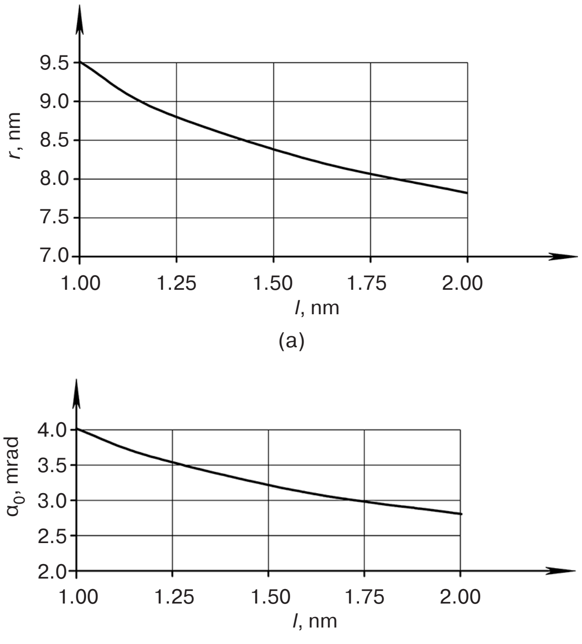


Fig. 2. Dependence of the minimum radius on the angular aperture



(b)

Fig. 3. Maximum focus (a) and corresponding optimal beam aperture (b) depending on the length of the five-electrode lens, $d_i = 1/4$

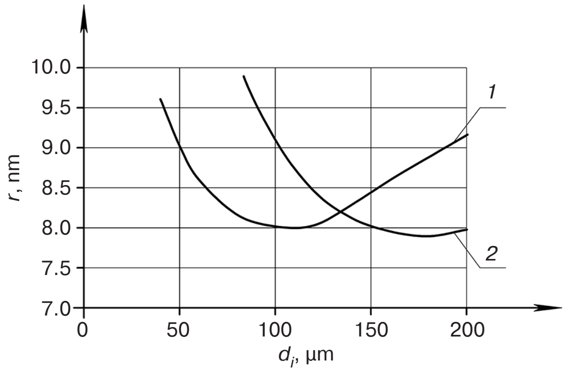


Fig. 4. Dependence of the minimum radius of the electron lens on the diameter of the diaphragm: (*1*) $\alpha_0 = 4$ mrad, (*2*) $\alpha_0 = 6$ mrad; $l_0 = 0.25$, $l_{\text{src}} = 1$, $U_0 = 1$ kV

1. Electro-optical characteristics: C_{chr} = 1.65 mm, C_{sf} = 51.42 mm, M = 1.34, r_G = 2.64 nm, r_{chr} = 1.76 nm, r_{sf} = 4.33 nm, r_{dif} = 7.83 nm.
2. Mode parameters: U_1 = 0.62 kV, U_2 = 1.17 kV, U_3 = 3.5 kV, $U_A = U_{acc}$ = 1 kV, l_{src} = 250 µm, l_i = 250 µm, d_i = 50 µm, l_0 = 1 mm.

Based on the beam current value I = 1 nA and the angular aperture α_0 = 6 mrad, we obtain the following values for the minimum beam diameter: d_{min} = 26 nm (at ΔU_0 = 0.2 V), d_{min} = 54 nm (at ΔU_0 = 2 V).

Based on the results of the study, it can be concluded that the most appropriate configuration is a five-electrode electronic lens having evenly spaced electrodes, which reduces aberrations by approximately 10% by increasing the number of electrodes and varying the inter-electrode distances while maintaining the overall length. Maximum efficiency is achieved with an increased lens length, which is associated with an increase in the number of potential focusing areas and improved interaction of voltage fields with electrons. In addition, the optimal ratio between lens length, beam diameter, and aperture diameter was determined to minimize energy losses and scattering effects.

CONCLUSIONS

The methods of numerical, analytical modeling and software-support tools for optimizing computational experiments developed over the course of the research were aimed at finding optimal configurations and operating modes of low-voltage electrostatic optics for electron beam microcolumns in accordance with the formulated criteria. A detailed study of the electron-optical properties of microminiature diaphragm lenses implemented on the basis of microtechnologies was carried out.

The obtained estimates of the minimum probe size formed by an optimized five-electrode lens under different source parameters and aperture conditions showed that thermoemissive cathodes can be used to produce optimized five-electrode lenses having a length of 2.5 mm, which can form a probe having a diameter of 4 to 10 nm at distances of ~1 mm depending on the angular aperture (and, accordingly, the current in the probe). Such distances are sufficient for manipulating the object and placing special miniaturized secondary radiation detectors.

Authors’ contribution

Both authors contributed equally to the conceptualization, methodology, investigation, and writing of this work. All authors have read and agreed to the published version of the manuscript.

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About the Authors

Pavel S. Kuznetsov, Cand. Sci. (Eng.), Deputy Head of the Experimental Complex of Microelectronics and Micromechanical Systems, State Scientific Research Institute of Instrument Engineering (GosNIIP) (125, Mira pr., Moscow, 129226 Russia). E-mail: ps_kuznetsov@mail.ru. Scopus Author ID 58513707600, RSCI SPIN-code 6564-9540, https://orcid.org/0000-0001-5459-7883

Anton O. Sinelnikov, Cand. Sci. (Eng.), Associated Professor, Basic Department “Nanotechnology and Microsystem Technology,” RUDN University (6, Miklukho-Maklaya ul., Moscow, 117198 Russia). E-mail: mr.sinelnikov.a@mail.ru. Scopus Author ID 55382453500, ResearcherID AAC-2606-2022, RSCI SPIN-code 2442-7507, https://orcid.org/0000-0002-5579-3509

Об авторах

Кузнецов Павел Сергеевич, к.т.н., заместитель начальника экспериментального комплекса микроэлектроники и микромеханических систем, Акционерное общество «Государственный научно-исследовательский институт приборостроения» (АО «ГосНИИП») (129226, Россия, Москва, пр-т Мира, д. 125). E-mail: ps_kuznetsov@mail.ru. Scopus Author ID 58513707600, SPIN-код РИНЦ 6564-9540, https://orcid.org/0000-0001-5459-7883

Синельников Антон Олегович, к.т.н., доцент, кафедра «Нанотехнологии и микросистемная техника», ФГАОУ ВО «Российский университет дружбы народов имени Патриса Лумумбы» (РУДН) (117198, Россия, Москва, ул. Миклухо-Маклая, д. 6). E-mail: mr.sinelnikov.a@mail.ru. Scopus Author ID 55382453500, ResearcherID AAC-2606-2022, SPIN-код РИНЦ 2442-7507, https://orcid.org/0000-0002-5579-3509

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