

PAPER • OPEN ACCESS

Investigation of the emission properties of a silicon blade-type cathode

To cite this article: S V Filippov *et al* 2019 *J. Phys.: Conf. Ser.* **1400** 055011

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Investigation of the emission properties of a silicon blade-type cathode

S V Filippov¹, A G Kolosko¹, E O Popov¹, G D Demin², M A Makhboroda²,
N A Djuzhev², T A Gryazneva² and S Yu Korotkov²

¹Ioffe Institute, 26 Politekhnicheskaya, St Petersburg 194021, Russian Federation

²National Research University of Electronic Technology (MIET), Shokina Sq., 1, Zelenograd,
Moscow 124498, Russian Federation

E-mail: s.filippov@mail.ioffe.ru

Abstract. The present paper describes the properties of a silicon blade-type cathode with high technological reproducibility. The emission characteristics were obtained using a modern computerized method for studying field emission cathodes in a non-destructive pulsed mode with a flat anode. The technique includes an assessment of the emission current stability, an estimate of the magnitude of the effective parameters of the cathode (field enhancement and emission area) and the degree of their fluctuations over time. A numerical analysis of the glow patterns of the field emission projector was also performed, representing of the distribution of the current load along the edge of blade-type field emitter.

1. Introduction

Blade-type field emission cathodes are one of prospective type of free electron sources. Electron emission in these cathodes occurs from the area of elongated sharp edge that located perpendicular to flat anode. Latitude of edge area significantly increase emitting surface and consequently increase maximal current level, which can be obtained from such structures without vacuum discharges and breakdowns.

Importance of increasing of stable current level of field emission cathodes connect with perspective of replacement of bulky and inert thermo emission cathodes with field emission ones, which are widely used in modern vacuum electronics (X-ray devices, electron microscopes, lasers, broadband light sources and etc.) [1, 2]. Besides the problem of current level stability, there is a second problem associated with the technological reproducibility of field cathodes. Many scientists now actively study these two problems either on fundamental physical or on technological levels.

One of widely common blade-type cathodes are elongated blades with a triangle cross-section. Lee et al. developed and described in details a process of fabrication the blade-type field cathodes formed on the basis of a silicon wafer with (110) orientation [3]. Emitter was placed into SiO₂ hole covered with metal layer (as gate electrode), so that apex of blade was arranged on the same height with the gate electrode. The height of hole was about 6 μm and the blade width at the base was about several microns, while the edge radius of the blade was less than 250 Å.

Field emission from metallic blade-type cathodes, sputter-coated with a thin film of lanthanum hexaboride (LaB₆), was investigated in [4]. Based on experimental current-voltage characteristics (IVC) of the cathode plotted in Fowler-Nordheim (FN) coordinates, the effective field enhancement factor was found to be about 400. It was shown that the deposition of thin LaB₆ layer with a low work function on the cathode surface (with a thickness of less than 10 nm) results in an increase in the emission current.



Another type of blade-shape cathode is a thin film of well-emitting material, placed perpendicular to the flat anode [5]. In this work, vertically aligned freestanding graphene-based film field emitter with a length of emitting edge of 3 mm was investigated. The distance between the field emitter surface and the anode was adjusted to 0.5 mm. An electrical aging process was performed to achieve a uniform distribution of emission sites along the edge of the film, so that the most stable in time field emission current was reached. The field emission uniformity and distribution of emission sites over cathode surface was monitored using glow pattern registration in the field emission projector.

Third widespread type of blade cathodes that may be of interest is based on flat conductive nanosized particles, synthesized or deposited onto flat substrate. Shen et. al. showed that blade-shape emitters obey better field-emission characteristics than point emitters [6]. In particular, it was demonstrated that blade-shape emitter has a higher current density output and better field-emission performance than the pointed ones, when the same external electric field is applied to both of them.

In ref. [7] field emission performance of the "C-cork" planar and "line" emitters was studied. C-cork nanowalls with a thickness of 100-200 nm were produced by carbonization process of 1-2 μm cork cell walls. Because of the carbonization, the C-cork must be very regular, but images obtained by scanning electron microscope (SEM) showed cells having disordered shapes and different sizes. The "line" emitter demonstrated good field emission characteristics such as a maximum emission current density of 40 mA/cm^2 and low turn-on field about 0.93 $\text{V}/\mu\text{m}$. This excellent field emission performance is also attributed to the vertically-aligned thin graphite sheets with sharp edges and high aspect ratio of 133.

In the ref. [8] the structure with doped polysilicon nanowires located on oxidized silicon substrate was considered, where the maximum field emission current of about 1 mA associated with presence of nanowire was obtained (for nanowires with a length of about 1 μm with the gap distance between them equal to 5 μm).

In this paper, we study the field emission properties of a silicon blade-type cathode produced by a technology with a high degree of reproducibility. The study was carried out using the methodology described in [9] in a pulsed mode as the most benign mode, in which the degree of emitter destruction is less than in a DC mode.

2. Experimental

The sample of silicon blade-type cathode was created using technologies of lithography and etching and, as a technological product, has a high reproducibility.

The cathode was formed from a highly doped silicon substrate (KEF4.5 brand) with a resistivity of 4-5 $\text{Ohms}\cdot\text{cm}$ with a crystallographic orientation (100), for which standard operations of silicon microelectronics technology were applied.

In the present work, blade was produced by deep anisotropic etching of Si in a KOH solution, where a soft etching mode was used (10% KOH, temperature — 800 ° C). As protection, a combined mask consisting of SiO_2 and Si_3N_4 layers was used. The selected mode ensures the safety of the protective mask during the entire time of etching. Using the method described above, micro-blades with well-reproducible geometry were formed. In this geometry, the angle at the tip of the blade is determined by the mutual arrangement of the crystallographic planes (111) and (100) of single-crystal Si, and in theory it is equal to 54.75°. When the front reaches the $\text{SiO}_2 / \text{Si}_3\text{N}_4$ 'stop layer', as a result, it is possible to form a wedge-shaped cutting edge of Si, on the edge of which only a few atomic layers remain. Figure 1a demonstrate SEM image of produced blade-type cathode fixed in an aluminum holder.

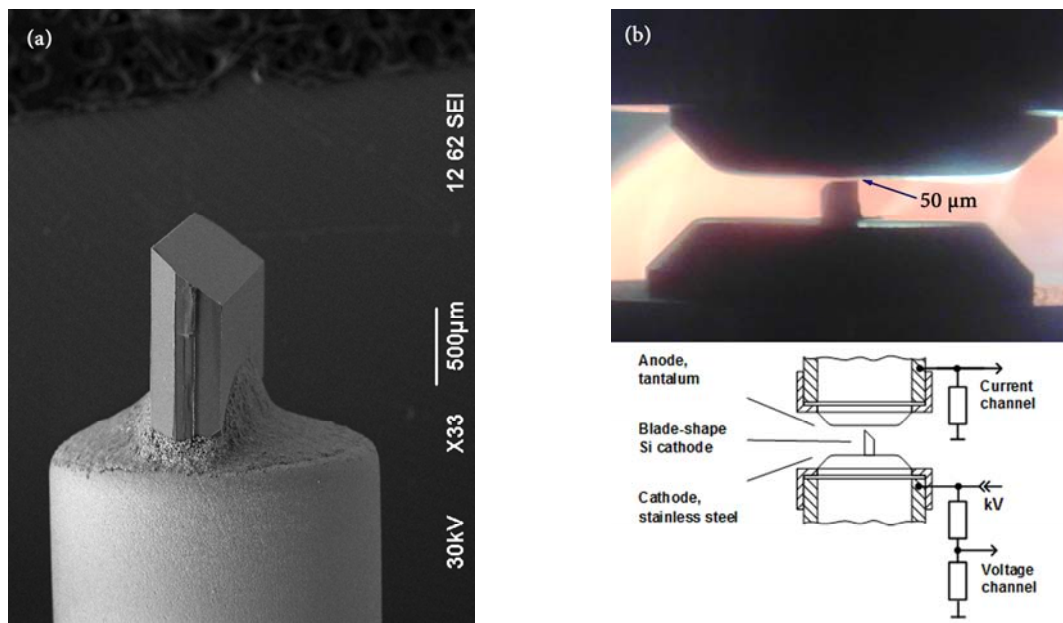


Figure 1. a) SEM image of the test sample. b) Photo and scheme of the cathode-anode system.

An analysis of the field-emission properties of blade-type cathode was carried out using advanced computerized technique for field emission cathode investigation in non-breaking pulse mode of high voltage feeding [9]. Investigation of analogue sample in DC mode can be found in the ref. [10].

Photo of the system for measuring the field-emission current from blade-type cathode is shown in figure 1b. A half-sine pulse voltage was applied to the sample and the corresponding pulses of the emission current were recorded, where one IVC is obtained every 20 ms, which differs from the IVC obtained in DC supply mode by special smoothness and suitability for analysis. The distance between the flat metal anode and the apex of the tip was set to 50 μm . To obtain data on the distribution of emission sites over the cathode, the metal anode was replaced with glass with an ITO coating on which a phosphor layer was deposited. Registration of glow luminescent patterns was carried out by a long-focus USB microscope through a transparent window in a vacuum chamber.

3. Field emission properties and analysis

In addition to studying emission signals in a stable field emission mode, field emission analysis also includes so-called «sample conditioning» (activation of its surface with a high electric field with removal of adsorbates that deteriorate emission), as well as studying the emission sites distribution along the blade using a field emission projector. Experimental data were obtained sequentially in the emission test system developed for the LAFEs (large area field emitters) study.

The first stage of emission test was devoted to the assessment of the threshold voltage of the field emission with a current level exceeding the noise level of the signal recording system. Threshold voltage was $U_{thr} \sim 750$ V. Then the first IVC was obtained at the amplitude level of the emission current of 500 μA (see figure 2a).

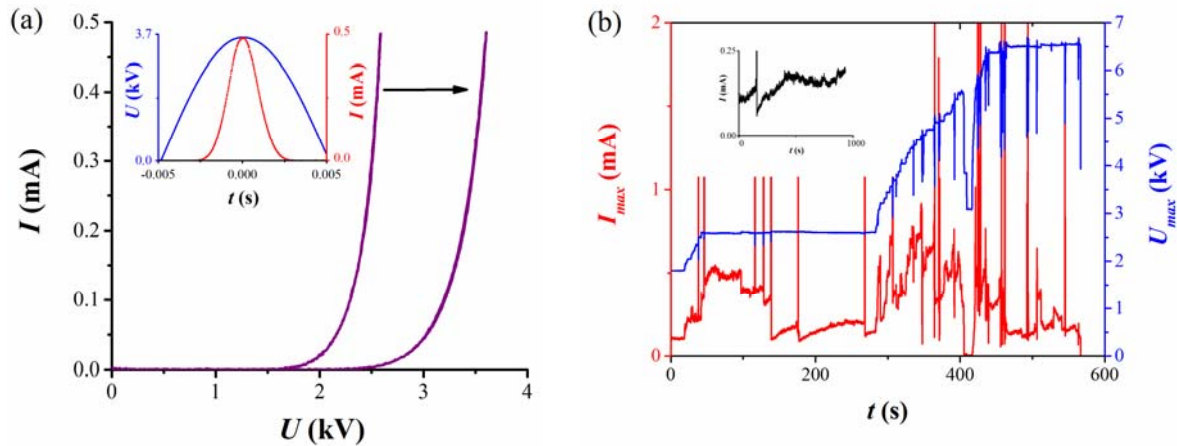


Figure 2. The emission characteristics of the blade-type cathode: a) the IVC obtained in the pulsed mode before and after conditioning with high voltage (the inset shows voltage and current pulses); b) the time dependence of the amplitude of the voltage pulses applied to the sample and the amplitude of the corresponding current pulses (the inset shows the stability of the field-emission current level of the sample at $U = 3400$ V).

During the subsequent conditioning of the sample, it was found out that the maximum current from its surface of about $900 \mu\text{A}$ at a voltage of 4600 V can be obtained. Figure 2b demonstrates the kinetics of the sample conditioning process.

After conditioning, IVC was recorded again at the amplitude of current pulse of $500 \mu\text{A}$ (see figure 2a). The offset of the IVC toward high voltages indicates a drop in the field enhancement factor, that is, the loss of blade sharpness due to a series of vacuum discharges (visible from the vertical lines in figure 2b). The minimum voltage of the onset of field emission after training was $U_{thr} \sim 900$ V.

Figure 3a shows the hysteresis of the IVC with a gradual increase and decrease in the amplitude of the applied voltage. This hysteresis is usually associated with adsorption-desorption processes on the cathode surface. In addition, there is a hypothesis [11] that the anode plays an active role in determining the concentration of adsorbates in the interelectrode gap.

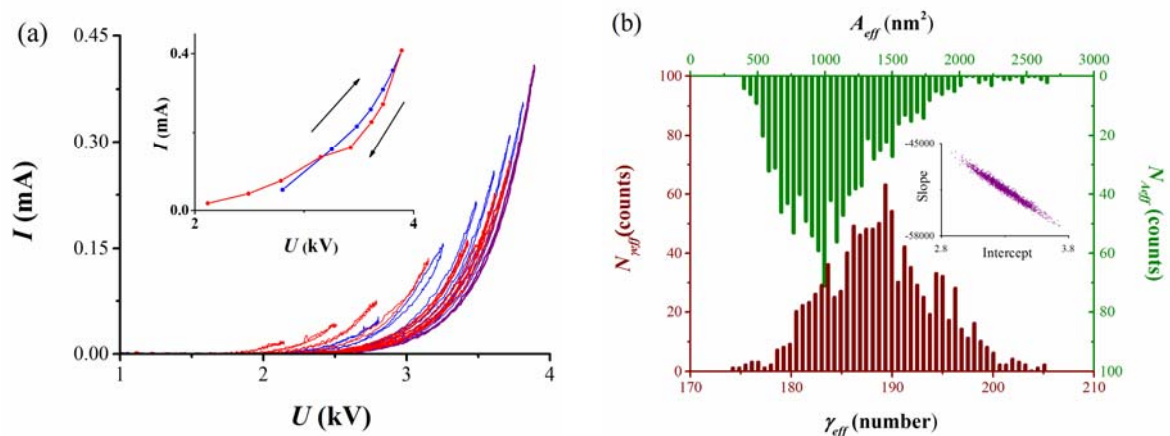


Figure 3. Dynamic and stochastic analysis of the field-emission characteristics: a) IVC hysteresis with a cyclic variation of the amplitude of applied voltage pulses (the inset shows the change in the coordinates of the vertices of IVCs); b) histograms of stochastic fluctuations of the effective parameters of the cathode at a current level of $100 \mu\text{A}$ (SK-diagram of the IVC fluctuations is shown on the inset).

The hysteresis has an eight-shaped form (see inset in figure 3a), which indicates the competition of two physical processes: the adsorption-desorption processes on the surface of the emitter and desorption of adparticles from the anode surface as a result of electron impact.

According to the shape of the IVC in the quasi-stable emission mode with the amplitude of current pulses of 100 μA , numerical estimates of the variation in the magnitude of the effective parameters of the cathode were made. We obtained that the emission area $A_{\text{eff}} \sim 1000 \text{ nm}^2$ and the field enhancement factor on the blade $\gamma_{\text{eff}} \sim 190$. Figure 3b illustrates stochastic histograms of fluctuations of these effective parameters.

To determine the validity of the application of field emission formulas, the Forbes test was used to calculate the effective parameters of the blade-type cathode taken from the measured IVC after sample conditioning [12]. The f_{low} and f_{up} parameters (where $f = F/F_R$ – dimensionless field [12]) turned out to be ~ 0.4 and 0.55 , respectively, which is close to the limiting values. This means that the emitter works with fields close to the limit, in which the destruction of the material and the occurrence of a vacuum discharge is possible.

Using a computerized field emission projector with a flat anode (the anode was located at a distance of 200 μm), the distribution of the total emission current of the studied cathode was analyzed from the distribution of separate emission sites on its blade. According to the glow pattern, emission sites do not cover the entire edge line of the blade. Figure 4a presents a histogram of the current load distribution on the emission sites registered in the pattern. The number of detected emission sites was equal to 16. Figure 4b demonstrates the SEM image of the cathode after conditioning. There is a significant change in the profile of the blade. One can see the changed edge of the blade with protrusions that could be emission sites.

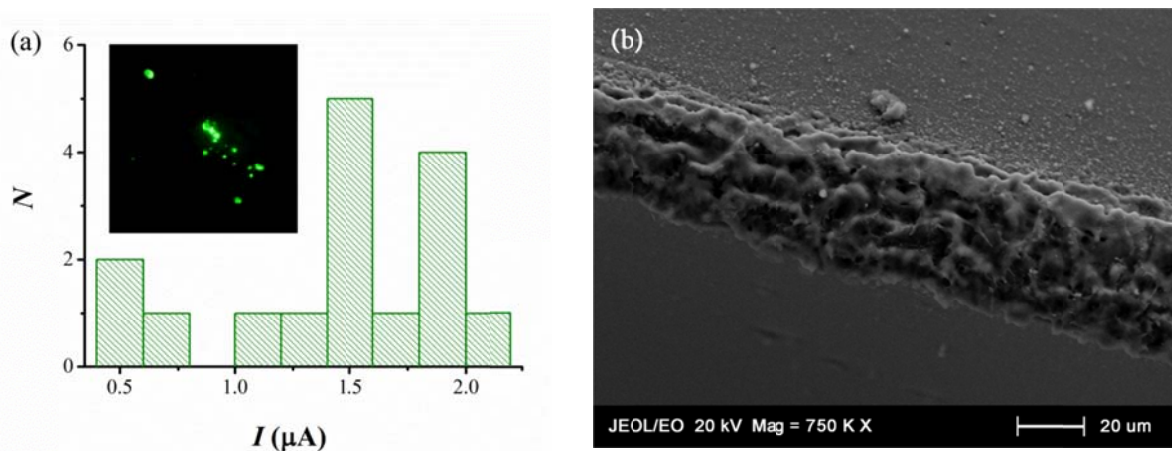


Figure 4. Analysis of emission site on the surface of a conditioned sample: a) a histogram of the current load distribution of emission sites (the glow pattern of the cathode is on the inset); b) SEM image of the edge of the blade after field emission experiment.

Conclusion

A technology has been developed for creating a microscopic blade cathode with good repeatability of a shape. A comprehensive study of the emission properties of this silicon blade-type cathode is presented. Because of such conditioning at a high voltage, it is shown that the edge of the blade is deformed and separate protrusions appear on its surface.

Studies have shown insufficient stability of the emission characteristics of the silicon sample, which is associated with the falling values of the applied emission fields in the region close to the limit values established for the classical field emission [12]. The possible solution is to increase the conductivity of the sample, as well as growing additional nanostructures on the surface of the blade emitter.

References

- [1] Fielden J 2018 *Technical Digest 31th International Vacuum Nanoelectronics Conf.* (Kyoto) Japan pp 2-3
- [2] Collins C M, Parmee R J, Milne W I and Cole M T 2015 *Advanced Sci.* 1500318
- [3] Lee B, Barasch E F, Mazumdar T, McIntyre P M, Pang Y and Trost H-J 1993 *Appl. Surf. Sci.* **67** 66-72
- [4] Kirley M P, Novakovic B, Sule N, Weber M J, Knezevic I and Booske J H 2012 *J. Appl. Phys.* **111** 063717-1-6
- [5] Baek I-K, Bhattacharya R, Lee J S, Kim S, Hong D, Sattorov M A, Min S-H, Kim Y H and Park G-S 2017 *J. of Electromagnetic Waves and Applications* **31 (18)** 2064-2073
- [6] Shen Y, Xu N, Ye P, Zhang Y, Liu F, Chen J, She J and Deng S 2017 *Advanced Electronic Materials* **3** 1700295-1-11
- [7] Lee J S, Lee H J, Yoo J M, Kim T and Kim Y H 2017 *ACS Applied Materials & Interfaces* **9** 43959-43965
- [8] Mazellier J-P, Perlemoine P, Berrazouane R, Friedl M, Fontcuberta A and Ponard P 2018 *Technical Digest 31th International Vacuum Nanoelectronics Conf.* (Kyoto) Japan p 202
- [9] Popov E O, Kolosko A G, Filippov S V and Romanov P A 2018 *Materials Today: Proceedings* **5** 13800-13806
- [10] Demin G D, Djuzhev N A, Filippov N A, Glagolev P Yu, Evsikov I. D and Patyukov N N 2019 *J. Vac. Sci. Technol. B* **37** 022903
- [11] Popov E O, Kolosko A G, Filippov S V, Romanov P A, Terukov E I, Shchegolkov A V and Tkachev A G 2017 *Appl. Surf. Sci.* **424** 239
- [12] Kolosko A G, Filippov S V, Romanov P A, Popov E O and Forbes R G 2016 *J. Vac. Sci. Technol. B* **34** 041802