Investigation of local ion-stimulated carbon deposition to create vacuum field emission diodes

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Abstract. This paper presents the results of experimental studies of the influence of the technological parameters of a focused ion beam (FIB) on the process of local ion-stimulated deposition of carbon and tungsten when creating elements of vacuum nanoelectronics. The dependences are obtained illustrating the influence of the time of the FIB exposure at a point on the geometric parameters of the structures. Experimental samples of vacuum field-emission diodes based on semiconductor-metal-dielectric structures were fabricated by ion-stimulated carbon deposition. A technological process for creating field-emission diodes has been developed. The prospects of applying the FIB method for creating structures of vacuum field emission nanoelectronics are demonstrated.

1. Introduction

One of the promising areas of development of modern electronics is the creation of miniature vacuum devices operating on the effect of field emission [1]. The development and creation of elements of vacuum field-emission nanoelectronics allows to achieve high speed, noise immunity and low power consumption. In elements with a nanometer interelectrode distance, threshold voltages are V units, which allows them to be used as the basis for creating energy efficient microelectronic devices that do not require complex heat removal systems [2]. Reducing the radius of curvature of the cathode tip and the interelectrode distance makes it possible to achieve significant advantages compared with analogues, but this leads to many technological difficulties. Modern technological processes based on the operations of optical lithography, liquid and plasma etching do not allow to achieve sufficient accuracy and high resolution in the formation of structures of field-emission nanoelectronics. The application of the method of focused ion beams (FIB) helps to overcome the main limitations of traditional methods and to expand the ranges of parameters of the structures obtained. The FIB method allows, under high vacuum conditions, to perform technological operations of local ion-beam etching with a Ga+ beam and ion-stimulated deposition of materials from the gas phase without the need for resists, masks and chemical etchants [3].

2. Study

In this work, experimental studies have been carried out to determine the effect of technological modes of local ion-induced deposition of carbon and tungsten on the parameters of the structures being formed, which can be used in the production of vacuum-emission nanoelectronics devices.
At the initial stage of the work, experimental studies of the effect of the time of FIB exposure on the process of local ion-induced deposition of carbon and tungsten in the formation of nanoscale conductors were carried out. Studies were performed using a scanning electron microscope with the FIB Nova NanoLab 600 system (FEI Company).

In the software for managing the FIB system, a graphic template was created, which is an array of lines, with each of them representing a sequence of points of individual exposure to the FIB located with a certain overlap.

The resulting number of points is determined by a combination of several technological parameters: the total line length, the diameter of each impact point and the overlap area. The length of the line and overlap are set by the operator, and the diameter of the point of exposure depends on the selected value of the FIB current. With an increase in the value of the current FIB, the diameter of a single point of exposure increases [4].

For experimental studies, a technique was developed according to which a raster graphic pattern was formed in the FIB system software in the form of a matrix of 8 lines 5 microns long. The distance between the lines was 1 µm.

The values of the technological parameters of the FIB used in the experiment are presented in table 1.

| Parameter                  | FIB current, pA | FIB overlap area, % | The number of passes FIB, pcs |
|----------------------------|-----------------|---------------------|------------------------------|
| Value                      | 1, 10, 30, 50, 100, 300, 500 | 0 | 10 000 |

After the operation of ion-stimulated precipitation according to a pattern, the substrate with the formed structures was studied by the SEM method. The research results are presented in Figure 1.

![SEM image of local ion-stimulated deposition of tungsten (a) and carbon (b) lines at a current of FIP of 30 pA.](image)

Processing and analysis of the experimental data showed that the time of exposure to FIB has a significant impact on the process of local ion-stimulated deposition of carbon and tungsten. With an increase in the FIB current, the local ion-induced deposition in the lines shifts towards a shorter exposure time of the FIB and vice versa [5]. This effect can be explained by the fact that, with a short exposure time to FIB (0.1–0.5 µs), the processes of ion-stimulated deposition predominate over the
processes of ion-beam etching due to exposure to Ga\textsuperscript{+} ions with a small dose. With an increase in the dose of Ga\textsuperscript{+} ions, due to an increase in the current of the FIB, as well as an increase in exposure time (1–5 µs), the processes of ion-beam etching predominate over ion-stimulated deposition.

Thus, it has been shown that the parameters determining the dynamics of the process of ion-induced deposition of carbon and tungsten are the ion current density [6] and the FIB dwell time.

Based on the analysis of the obtained experimental results, the dependences of the thickness of the formed carbon elements on the exposure time of the FIB, presented in Figure 2, were constructed.

![Figure 2](image)

**Figure 2.** The dependence of the thickness of the formed structures of platinum on the exposure time at the currents of FIB 3.6 pA (a) and 7.9 pA (b).

3. Experimental
At the next stage of work, the technology was developed and experimental samples of vacuum field-emission diodes with vertically oriented emitters created by the method of ion-stimulated carbon and tungsten deposition were created. Silicon with a silicon oxide layer 850 nm thick on its surface was used as a substrate. At the initial stage, a cylindrical cavity was formed by ion-beam etching, at the bottom of which an electrical contact was formed by the method of local deposition of tungsten. The use of FIB in this case made it possible to vary the diameter (300 nm to 2 µm) and the depth of the structures (1 µm to 3 µm) over a wide range.

![Figure 3](image)

**Figure 3.** SEM images of the FIB-fabricated hole.
After that, using ion-induced carbon deposition from the gas phase (C14H10), a vertical field emission cathode was formed with a tip radius of about 20-25 nm and a height of 1 μm (Figure 4, a). Ion-stimulated deposition was carried out at the following values of the FIB parameters: the beam exposure time was 100 μs, the FIB overlap area was 0%, the FIB passes number was 10,000, the beam current was 10 pA, and the accelerating beam voltage was 30 keV.

At the next stage, the formation of the upper contact (anode) was carried out. In the formed experimental structure, the anode was formed by the method of ion-stimulated carbon deposition according to proven technology using a specially developed package of raster templates. The shape of the anode was a hollow cone that covered the cell with a “dome”. As a result, an anode about 1 micron in height was formed (Figure 4, b). Parameters used in the deposition: beam current from 1 to 25 pA, beam accelerating voltage 30 keV. At the final stage, the operations of opening the windows were performed in order to provide access to the lower contact and the formation of metal wiring on the surface of the test crystal.

According to the developed technology, the method of magnetron sputtering is applied to form the lower contact, after which a layer of silicon nitride with a thickness of 0.8 - 1 micron is applied by plasma chemical deposition. After the formation of the anode, the current-voltage characteristics of each cell are studied, which will allow to control the electrical parameters and assess the directions for further optimization of the proposed design. The estimated value of the field emission threshold voltage in such structures is 1.8 V, while each cell provides emission current at a level of 10-9 A. To increase the emission current density, cells can be combined into matrices, and several cells can be created in each cell cathodes.

4. Conclusions
The high precision of the FIB method, combined with the high repeatability of the cell parameters, ensures low operating voltages of the elements, and the use of carbon and tungsten makes it possible to achieve high stability and durability of the field emission structures. The obtained dependences illustrating the influence of the time of the FIB dwell time on the geometric parameters of the structures. Vacuum field-emission diodes based on semiconductor-metal-dielectric structures were fabricated by ion-induced carbon deposition. A technological process for creating field-emission diodes has been developed.

Acknowledgments
This work was supported by The Grant of the President of the Russian Federation for State Support of Young Russian Scientists, Candidates of Sciences (project no. MK-1811.2019.8).

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