Development of technology for the formation of vacuum field emission cells using focused ion beams

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Abstract. The article presents the results of the development of technology for the formation of vacuum field emission structures. Experimental studies of local ion-stimulated deposition of W and C and ion-beam etching were carried out and their effects on the formation of final structures were studied. The technological process of manufacturing nanoscale field emission structures was developed, and experimental samples were fabricated. It is shown that the use of the method of focused ion beams (FIB) demonstrates its advantages compared with other methods.

1. Introduction
Present days, the use of vacuum field emission nanoscale structures is a promising direction of the development of micro- and nanoelectronics. The use of such structures in nanoelectronics allows us to achieve a high degree of noise immunity, low power consumption, high switching speed and, consequently, high frequencies of operation of such devices. The main difficulty in the development of electronics in this direction is the provision of vacuum in nanoscale structures. The currently used methods do not allow to create and maintain a high level of vacuum in elements of this size. The method of focused ion beam (FIB) solves the main problems associated with the creation of elements of vacuum-emission nanoelectronics [1-3]. The FIB method allows, under high vacuum conditions, to perform technological operations of local ion beam etching and ion-induced deposition of materials from the gas phase without the need for resists, masks and chemical etchants. When chemically active gases are supplied to the FIB exposure zone, their molecules dissociate, as a result of which one of the gas components is deposited on the surface, and the volatile reaction products are removed by a vacuum system [4, 5]. The wide nomenclature of materials deposited by this method allows the use of FIB in the formation of nanoscale structures for electronics (quantum dots, field emitters, point contacts) and nanodiagnostics (probe tips, calibration gratings of the nanometer range for scanning probe microscopy (SPM)) [1].

2. Theory and methods
In this paper, studies were performed on a Nova NanoLab 600 raster electron microscope (FEI Company) equipped with a FIB system. At the beginning of the work, a theoretical analysis was carried out of the physicochemical processes occurring when the flow of accelerated ions interacts with the silicon-gold-silicon oxide substrate, both under vacuum conditions and in the presence of the process gas W(CO)₆. As a result of the analysis, it was established that the main factor determining the kinetics of ion-stimulated deposition W is the coefficient of adsorption of carrier gases and the deposited material on the substrate under study [6]. Thus, during ion-stimulated deposition, at the first stage, the gas molecules supplied to the ion beam are adsorbed on the substrate surface, then under the action of gallium ions with an energy of 30 keV, the molecules decompose, the volatile organometallic compounds are removed by a vacuum system, and the components of the deposited substance (in this
case, W) remain on the surface of the material. By specifying the trajectories of the ion beam with the help of control electronics, it is possible to form three-dimensional nanoscale structures of a complex profile [7]. By adjusting the ion beam current, it becomes possible to precisely control the deposition rate and the minimum size of the structures.

3. Experimental
To study the rate of local ion-stimulated tungsten deposition, a graphic template was formed in the FIB module control program in the form of a matrix consisting of 16 elements 2×2 μm in size, the diagram of which with indicating time of the local ion-stimulated deposition (in seconds) of each element is shown in figure 1.

|   | 1  | 2  | 3  | 4  | 5  |
|---|----|----|----|----|----|
| 10| 15 | 20 | 25 | 30 |
| 35| 40 | 45 | 50 | 55 |
| 60|    |    |    |    |

**Figure 1.** The scheme of pattern

After local ion-stimulated deposition, the substrate was examined using a scanning electron microscope (SEM), as shown in figure 2a. After that, the substrate was investigated using an atomic force microscope (AFM) in a semicontact mode, as shown in figure 2b.

**Figure 2.** SEM image of a deposited tungsten structures (a); AFM profile of an array of tungsten structures (b).
Analysis of the obtained AFM images showed that with an increase in FIB current from 1 to 500 pA, the thickness tungsten structures from 0.545 to 969 nm with an increase in the time of ion-induced deposition.

Based on the analysis of the experimental results obtained, the dependences of the thickness of the formed elements on the time of ion-stimulated deposition were plotted, as shown in figure 3a. The analysis of the obtained dependences shows the uniformity of the process of local ion-induced deposition of carbon and tungsten during the entire time of deposition. The difference in the thicknesses of the carbon and tungsten elements can be explained by the different physicochemical properties of the chemically active gases used in ion-stimulated deposition.

Based on the processing and analysis of the obtained data, the dependences of the rate of ion-induced deposition of tungsten were obtained, as shown in figure 3b.

![Figure 3](image)

**Figure 3.** The dependence of the thickness of the formed elements of tungsten on the time of FIB deposition(a); The dependence of the rate of ion-induced deposition of tungsten on the time of deposition(b).

The analysis of the obtained dependences allows us to estimate the trends in the rate of ion-stimulated deposition of tungsten on the deposition time. With an increase in FIB current, the rate of ion-stimulated deposition increases. Uniform rate of ion-stimulated tungsten deposition is observed at FIB currents of 300 pA and 500 pA, which is associated with the physicochemical properties of a reactive gas that interacts with FIB.

The dependences obtained will allow us to further predict the thickness of the deposited materials.

4. Technology

![Figure 4](image)

**Figure 4.** Layout of the field-emission structure
Scheme of the field-emission structure is shown in figure 4. At the initial stage of creating the field-emission structure, a silicon-gold-silicon oxide substrate was used. The first step was the formation of a hole 1 μm deep and 400 nm in diameter. To do this, an appropriate template was set and using the ion-beam etching a hole with the required parameters was obtained (Figure 5).

In the next step, the formed hole was filled with tungsten. After this, a gas containing tungsten was supplied and, under the action of the FIB, ion-stimulated material deposition from the gas phase was carried out (Figure 6a). Then, using a raster pattern, which is a circle with an outer radius of 500 nm and an inner 200 nm using ion-beam etching, a tip was formed, which is a cathode, isolated from the side edges of the hole (Figure 6b).

The final stage is the formation of the anode contact, which is a “Cover” that provides isolation of the vacuum obtained under it from the external environment. The anode was created using the method of ion-induced deposition of tungsten from the gas phase and templates with decreasing diameters, obtained using specialized software [8] (Figure 7).
Due to the fact that all operations were carried out in high vacuum conditions, the resulting cell was vacuum.

When studying a similar structure using an Ntegra Vita atomic force microscope, we obtained the current-voltage characteristic shown in figure 8.

Analysis of the current-voltage characteristics showed that emission starts from about 1 volt, which will significantly reduce the power consumption of the circuits in which such emitters will be used.

5. Conclusions

Thus, the technology of creating an field-emission cell was demonstrated, which, thanks to the conditions of creation, turned out to be high-vacuum. This technology can be used to create vacuum integrated circuits that do not require additional vacuuming or circuits where it is not possible to use lamp electronics because of their large size. The capabilities of the FIB method and its advantages in creating vacuum field emission elements of nanoelectronics were demonstrated.
Acknowledgments
This work was supported by the Russian Science Foundation Grant No. 18-79-00175.

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