Research of FIB local milling processes for creation of nanosized field emission structures

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Abstract. The paper presents the results of experimental studies of the influence of the main parameters of a focused ion beam (FIB) during surface profiling on the accuracy of transfer of a pattern to a silicon substrate to create nanoscale field emission structures. In this work, the optimal FIB currents are determined, introducing a minimum amount of distortions during the formation of structures of various sizes. The possibilities of the method of local ion-beam etching of structures in a wide range from 0.1 to 2 μm are shown. The prospects of using this technology for the creation of field emission structures have been demonstrated. It is determined the current-voltage characteristic of the fabricated field-emission cells with a threshold voltage of the onset of emission of ~2.5 V and a maximum current of 300 nA at 30 V.

1. Introduction
One of the urgent and important tasks in the development of modern electronics is the creation of miniature vacuum devices operating on the effect of field emission. The development and formation of elements of vacuum field emission nanoelectronics allows achieving high performance, noise immunity and low power consumption in finished devices [1]. To obtain the most advanced devices with improved output parameters and characteristics, it is necessary to use ever smaller mass and size parameters of the structural elements of the device down to nano sizes when creating devices. Also, this approach allows you to increase the density of the placement of elements on a single chip (substrate). For example, a decrease in the interelectrode distance makes it possible to sharply decrease the threshold voltage of the emission start. However, when providing the necessary parameters of the elementary component base, a number of technological difficulties arise. Modern production processes based on the operation of optical lithography, liquid and plasma etching do not allow achieving sufficient accuracy and resolution in the formation of structures of field emission nanoelectronics. The application of the focused ion beam (FIB) method helps to overcome the main limitations of traditional methods and expand the ranges of parameters of the resulting structures.

The FIB method allows performing technological operations of local milling and deposition of materials from the gas phase under high vacuum conditions without the need for the use of resists, masks, and chemical etchants [2]. The main advantage of this method is the possibility of profiling the substrate surface with nanometer accuracy and in a strictly specified area. By creating various templates in the FIB control software, it is possible to achieve almost any shape of the structure.
The aim of this work is experimentally studying the main parameters of FIB during surface profiling, to determine their optimal values during the formation of structures of given sizes, as well as to create nanoscale field emission cells and study their parameters.

2. Surface profiling by FIB method

The work was carried out on a Nova Nanolab 600 electron microscope equipped with a FIB system. One of the main parameters of the FIB, which has the greatest effect on the profile of the final structure during ion-beam milling of the surface, is the ion beam current. It also determines the milling rate and has a great influence on the degree of deviation of the obtained object sizes from those specified in the pattern. At this stage of the work, experimental studies of the accuracy of transfer of the pattern to the silicon substrate during local ion-beam milling for various FIB currents were carried out. For this, a pattern was generated in the software for controlling the ion beam, consisting of 20 circles with different diameters varying in the range from 0.1 μm (left upper structure) to 2 μm (right lower structure) with a step of 100 nm. The main parameters of the FIB: accelerating voltage 30 kV, beam current 0.1-0.5 nA, beam dwell time (Dt) 1 μs and beam overlap (OL) 50%. SEM images of the structures are shown in Figure 1.

![SEM images of an array of structures after milling with a FIB current of 0.1 nA (a), 0.3 nA (b), and 0.5 nA (c) at an angle of 0 ° and 52 °, respectively.](image-url)
From the analysis of SEM images, it can be seen that the experimentally obtained structures have a surface raster near the circle, which is most noticeable in the image at an angle, and the angle of the lateral surface of the recesses is different from 90°. This is due to the fact that the FIB has a rather complex beam shape, which can be described by the law of normal distribution or the Gaussian function. Figure 2 shows the simulated beam shape. In this regard, the milling profile of the substrate is very different from that specified in the template and has the indicated inaccuracies when transferring the pattern of the template to the substrate.

Figure 2. Ion beam shape described in terms of the Gaussian function.

In this regard, to assess the degree of influence of the FIB current on the resulting nanoscale structures, the dependences of the deviation of the specified values in the pattern from the experimentally obtained values were plotted. The measurement of the inner circumference obtained at the bottom of the milled object will be used as the measured value for the diameter of the structure. The use of this plane is justified by the fact that it is this plane that is the “useful” area on which the field-emission cathode will be grown in the future. Thus, the dependences of the deviation of the given value from the practically obtained for the inner diameter of the circle were plotted, presented in Figure 3.

Figure 3. Dependences of the deviation of a given diameter of structures from the experimentally obtained at a FIB current of 0.1 nA (a), 0.3 nA (b), 0.5 nA (c).
From the obtained dependences it follows that, in general, the percentage of deviations has not too large values and their spread. Exponential dependence is caused by the presence of extreme points, such as 100 nm, which slightly distort the real picture and cause some inaccuracies when transferring the pattern to the substrate. The increase in the percentage of deviations for structures with a given diameter of less than 500 nm is associated with the difficulty of obtaining the minimum diameter of the ion beam, due to the Coulomb interaction of like-charged particles. Thus, for the formation of structures with sizes less than 500 nm, it is preferable to use a FIB current of 0.1 nA, since in this region it provides the most accurate transfer of the pattern to the substrate surface. For the formation of structures with dimensions greater than 500 nm, the FIB current of 0.5 nA is optimal, since, with a similar spread in the percentage of deviation with the data obtained in the graph for a current of 0.3 nA, it provides a shorter milling time.

3. Fabrication of a field emission cathode

The obtained experimental results can be used in the formation of nanoscale field emission cells with a combination of methods of local FIB milling and deposition of material from the gas phase. Next, one of the possible options for the technology of cell formation will be presented.

The process of creating a field-emission cell with an emitter grown at the bottom of a depression was carried out in two stages. First, the depression itself was obtained by the method of local ion-beam milling of the FIB, and then an cathode was grown using ion- and electron-stimulated (as a comparison) deposition at the bottom of the structure [3]. The cell was formed on the basis of the data obtained at the previous stage for the parameters of the pattern and FIB. SEM images of fabricated field emission cells are shown in Figure 4.

So, when forming a depression for the deposition W of the FIB emitter (Figure 4, a), the minimum possible cell diameter is 1.5 μm, which, in accordance with the dependence shown in Figure 3, makes it possible to find the diameter at the bottom of the cell equal to ~ 1 microns. The formation of structures with a smaller value of the cell diameter is impossible, since this is due to the complete overgrowing of the depression with the deposition material, caused by a different physics of distribution and interaction of chemically active gases with an ion beam in submicron objects. For an cathode made of C (Figure 4, b) and W (Figure 4, c) formed by FIB and an electron beam, respectively, it was possible to achieve a cell diameter of 930 nm, which is ~ 500 nm at the bottom of the structure. The height of the resulting emitter, as well as the height of the cell for all cases, was about 1.3 μm. The settling time of the points from the W and C FIB is, respectively, 84 s. and 28 s., and an electron beam 45 s. The tip radius of the field emission cathode for the structures in Figure 4 is 65 nm, 75 nm, and 5 nm, in accordance with the captions to the SEM images. It is also seen that during the deposition of an cathode from carbon, a negative factor is found associated with the redeposition of the material on the cell walls, which leads to the shunting of the electrodes and the absence of the field effect.

It is also worth noting that a further decrease in the radius of the tip of the emitter tip by “sharpening” it by ion milling according to a special pattern is impossible, since the material sputtered by the ion beam in such a closed volume will be re-deposited on the cell walls, which will inevitably lead to a short circuit of the entire structure.

The current-voltage characteristics of the vacuum field emission cell were measured on an Analytical Submicron Prober EM-6040A setup using a KEITHLEY 4200-SCS semiconductor parameter measurement system.
Figure 4. SEM images of the formed field emission cells by the FIB method with a vertically oriented emitter from W (a) and C (b), as well as an electron beam with an cathode from W (c).

One probe, which was at a positive potential, was placed on the upper Ni layer, the other on the contact area obtained by ion-beam milling of the FIB on the lower nickel layer, to which a negative bias was applied. The I - V characteristic was measured in the range from 0 to 30 V. The results of measuring one of the formed structures are shown in Figure 5.
Figure 5. I-V characteristic of a field emission cell with a vertically oriented emitter.

It follows from the analysis of the curve that this field emission cell demonstrates an exponential increase in the anode current depending on the applied voltage, which indicates the presence of a pronounced field effect. The threshold voltage of the onset of emission for this type of construction and cell formation technology is about 2.5 V. At an interelectrode voltage of 30 V, the field emission current is 300 nA.

4. Conclusions
Thus, from the results of experimental studies, the optimal FIB current was determined for the formation of structures with sizes less than 500 nm, equal to 0.1 nA, and for structures larger than 500 nm, equal to 0.5 nA, at which the minimum amount of distortions is introduced into the formed structures and the most accurate transfer is provided. drawing the template onto the surface. To reduce the deviation in the range of values less than 500 nm, it is necessary to additionally investigate such FIB parameters as beam dwell time and the overlap. Based on the data obtained, field emission cells with a vertically oriented emitter were formed. Measurements of the current-voltage characteristic of the obtained cell have been carried out, from the graph of which it follows that the threshold voltage of the onset of emission is about 2.5 V, and the field current at a voltage of 30 V is 300 nA. The prospects of using this technology for the creation of field emission structures have been demonstrated.

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