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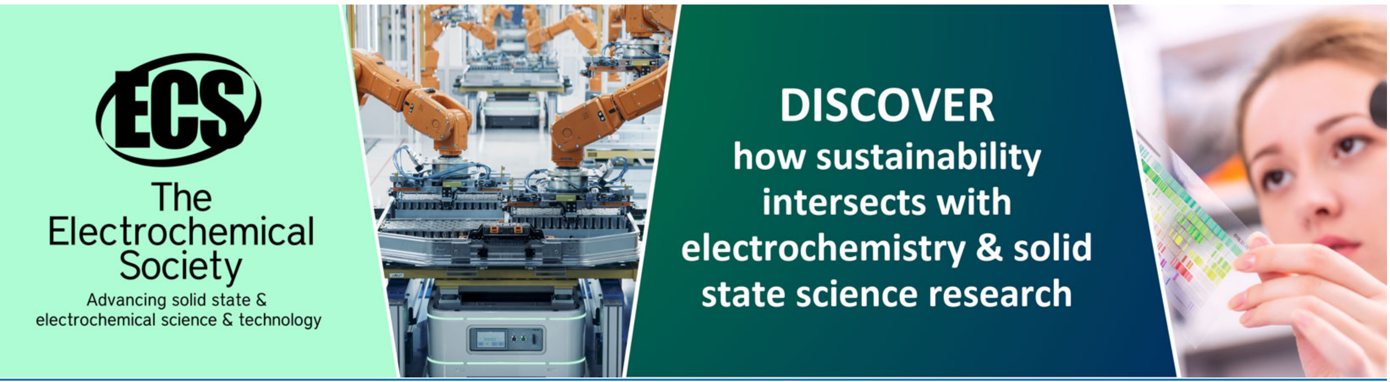

Field emission cell with a W-cathode formed by local ion-stimulated deposition

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Abstract. This article presents the results of a theoretical study of a field emission cell with a vertically oriented emitter. The field emission cell was formed based on a combination of etched methods with a Ga^{+} focused ion beam and local ion-stimulated tungsten deposition. The influence of the geometric parameters of the field emission cell on the electric field strength at the emitter top is estimated. It was found that a decrease in the rounding-off radius of the emitter top from 150 to 5 nm leads to an increase in the electric field strength by more than an order of magnitude from 1.28×10^6 to 16×10^6 V/cm. A decrease in the diameter of the field emission cell from 2.5 μm to 900 nm contributes to an increase in the electric field strength by 33.6 % from 3.04×10^6 to 4.58×10^6 V/cm.

1. Introduction

A promising direction in the development of modern electronics is the creation of miniature vacuum devices operating on the phenomenon of field emission, which are characterized by high performance and increased noise immunity [1, 2]. Field emission occurs when the electric field near the surface of the field emission cathode exceeds a threshold value. In this case, the electrons receive enough energy to overcome the potential barrier at the metal / vacuum interface. Reducing the geometric dimensions of field emission cells helps to reduce the threshold voltage. Nanoscale field emission cells are characterized by a low threshold voltage of less than 10 V [3-6].

The formation of field emission structures with nanometer resolution is accompanied by several technological difficulties. It`s associated with the fabrication of a nanometer interelectrode gap and reproducibility of geometric dimensions with nanometer accuracy. Another important task is the precision processing of materials, including refractory materials. The use of the focused ion beam method for the formation of nanoscale field emission cathodes allows under high vacuum conditions to carry out technological operations of local ion-beam etching and ion-stimulated deposition of materials from the gas phase without the need for resists, masks and liquid etchants. The application of the local ion-stimulated deposition of tungsten by focused ion beam and nanoscale profiling of heterogeneous multilayer materials helps to overcome the main limitations of traditional methods and expand the range of parameters of the obtained nanoscale structures [7-12].

The aim of this work is a theoretical study of the field emission cell with an emitter formed by the method of local ion-stimulated deposition of tungsten and revealing the relationship between the geometric parameters of the nanoscale field emission cell and the electric field strength at the emitter top.

2. Design and simulation

Traditionally, emitters were made based on refractory materials. In our study, tungsten was used as an emitter material. This is a material with a high melting point, which allows its use in systems with a high current density. The structure of the field emission cell consists of Si/Ni/SiO_2/Ni layers. A silicon wafer was used as a substrate. A conductive Ni-layer was formed on the Si-substrate. The anode Ni-layer is separated from the cathode by a dielectric (SiO_2). This dielectric has been selected for agreement with the standard technology processes used in the manufacture of nanoscale devices. The next step was the etching of the Si/Ni/SiO_2/Ni structure by the focused ion beam method. The anode Ni-layer and the SiO_2-layer were etched to the entire depth. Also, the cathode Ni-layer was slightly etched to a certain depth. It is important that the dielectric layer of SiO_2 does not remain on the cathode Ni-layer in the etching region. The emitter was formed on the surface of the conductive Ni-layer by the method of local ion-stimulated deposition of tungsten from the gas phase (Figure 1).

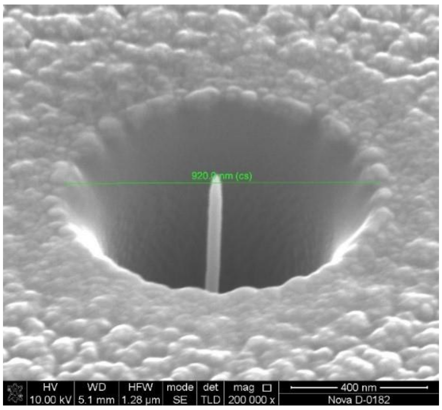


Figure 1. SEM-image of the W-emitter

Simulation of field emission cells with various geometric parameters allows optimization of their design to reduce threshold voltage, increase emission uniformity and durability of field emission cathode [13-19]. The distribution of the electric field strength in the interelectrode space was studied. A theoretical study of field emission cells was carried out using the finite element method in COMSOL Multiphysics software. General view of the studied field emission cell with the main geometric parameters is presented in Figure 2.

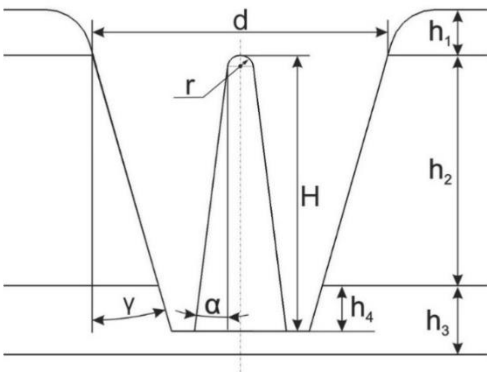


Figure 2. General view of a field emission cell with a vertical emitter

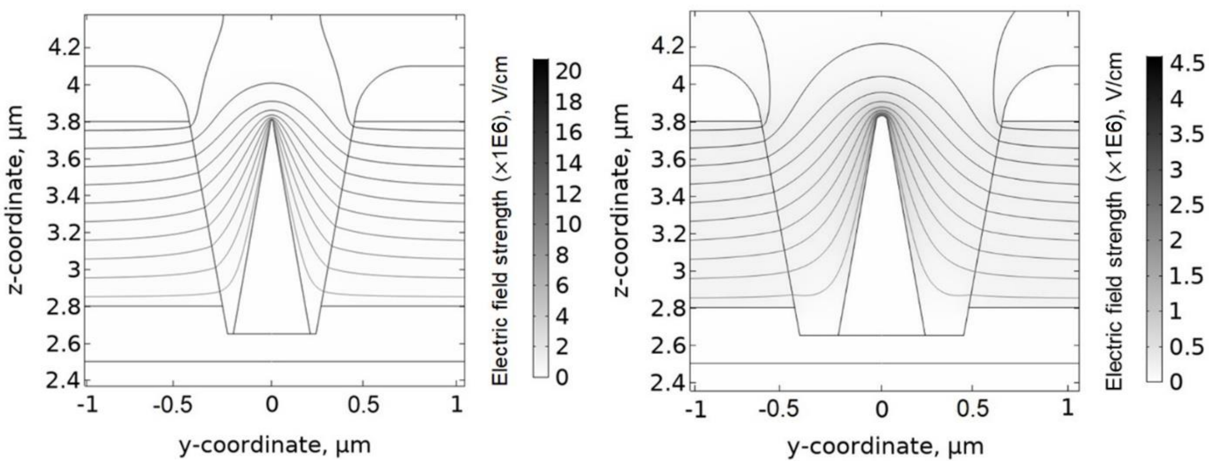
The simulation parameters are presented in Table 1 and based on the geometric dimensions of the experimental samples formed using the local ion-stimulated FIB deposition method [20, 21]. The parameters of the interelectrode distance and the rounding-off radius of the emitter top have the greatest effect on the distribution of the electric field strength in the field emission cell. The lateral dimensions of the field emission cell depend on its diameter. In turn, the diameter of the field emission cell affects the interelectrode distance. It was found that it is possible to reproducibly form experimental samples of field emission cells with the diameter of 1.3 μm and the rounding-off radius of the emitter top of 30 nm. Therefore, theoretical dependences are presented for a field emission cell with such parameters. In our study, the applied voltage was 20 V to evaluate the electric field strength at the emitting surface.

Table 1. Simulation parameters.

Parameter	Symbol	Value
Thickness of the anode layer	h_1	300 nm
Thickness of the insulator layer	h_2	1 μm
Thickness of the cathode layer	h_3	300 nm
Hollow in the cathode layer	h_4	150 nm
Height of the field emission cathode	H	1.15 μm
Inclination angle of the side surface of the emitter	α	10°
Inclination angle of the side surface of the emission cell	γ	10°
Diameter of the field emission cell	d	900 nm – 2.5 μm
Rounding-off radius of the emitter top	r	5 – 150 nm
Potential difference	U	20 V

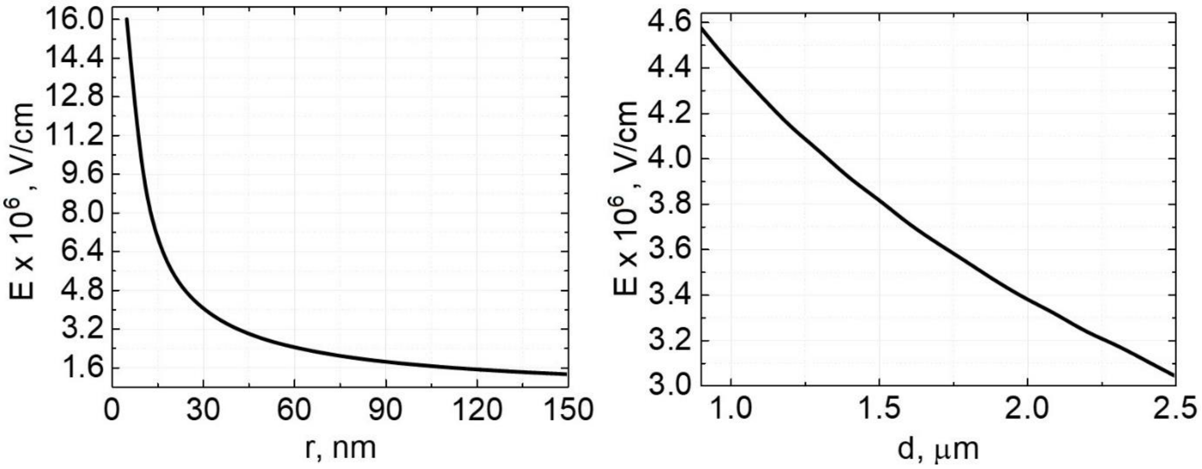
3. Results

The distribution of electric field strength in the interelectrode space of the field emission cell were obtained from theoretical studies. The results of simulation the distribution of the electric field strength in the interelectrode space are presented in Figure 3. The dependences of the electric field strength at the top of the field emission cathode on the rounding-off radius of the emitter top and the diameter of the field emission cell were obtained based on the simulation results (Figure 4).



a) b)

Figure 3. The distribution of the electric field strength in the interelectrode space of the emission cell when: (a) r = 5 nm, d = 900 nm; (b) r = 30 nm, d = 1300 nm



a) b)

Figure 4. The dependences of the electric field strength on: (a) the rounding-off radius of the emitter top at *d* = 1300 nm; (b) the diameter of the field emission cell at *r* = 30 nm

It was found that a decrease in the rounding-off radius of the emitter top from 150 to 5 nm leads to an increase in the electric field strength by more than an order of magnitude from 1.28×10^6 to 16×10^6 V/cm. A decrease in the diameter of the field emission cell from 2.5 μm to 900 nm contributes to an increase in the electric field strength by 33.6 % from 3.04×10^6 to 4.58×10^6 V/cm.

4. Conclusion

Thus, the importance of miniaturization of field emission cells is shown in the work. In this case, the technology of manufacturing vacuum field emission cells with emitters formed by etching by a focused ion beam and local ion-stimulated deposition of tungsten from the gas phase becomes relevant. The theoretical dependences obtained from the simulation results correlate well with the known theoretical and experimental studies of nanoscale field emission cathodes [22-28]. However, studies of a nanoscale field emission cell showed the possibility of reducing the threshold voltage by more than an order of magnitude. It is necessary to take into account the obtained dependencies and use the recommended geometric parameters to optimize the field emission cell. The highest values of the electric field strength were obtained at the lowest values of the studied geometric parameters. It is important to note that it is possible to decrease the interelectrode distance by local ion-stimulated deposition of the metal on the anode after the formation of the field emission cathode to reduce the cell opening.

Thus, the use of the recommended parameters of field emission cells will reduce the time and, as a result, the economic costs of manufacturing. Further theoretical and experimental study of the considered nanoscale field emission cells will help to optimize their geometric parameters and reduce the threshold and operating voltage.

Acknowledgments

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