Development of a Technology for the Creating of Diode and Triode Field-Emission Nanostructures for Signal Generating in the GHz Range

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***Abstract* — A process flow for the creating of diode and triode field-emission needle-type and blade-type nanostructures is proposed. The created experimental samples were studied using scanning and transmission electron microscopy. Current-voltage characteristics of the created experimental samples of silicon field-emission structures are obtained. The results of this paper can be used to create field-emission nanostructures for development of high-frequency electronics in the GHz range.**

Keywords—field emission; silicon field-emission cathodes; needle-type cathodes, blade-type cathodes; field emitter array; semiconductor nanostructures; GHz range; microwave electronics.

I. Introduction

Devices for generating and forming high-frequency signals are an integral part of any RF electronic system or technical complex. Either semiconductor devices with high electron mobility based on gallium arsenide (GaAs) or gallium nitride (GaN) or vacuum electronic devices with a dynamic method of electron flow control can be used in development of modern microwave electronic systems and devices [1].

The principle of operation of high-frequency electronic vacuum devices is based on the phenomenon of electron emission. Electronic emission is the process when solid or liquid body emits if they are given additional energy due to one or another external influence: due to electromagnetic radiation, heating, etc. Field electron emission, in turn, does not require additional external energy to initiate the emission process.

Microwave electronic devices can be created utilizing thermionic incandescent cathodes, which require heating, or utilizing “cold” field-emission cathodes. The latter have a number of important advantages: energy efficiency associated with the absence of necessity for constant heating of the cathode, resistance to temperature fluctuations and radiation dose effects, high transconductance of the current-voltage characteristics of field emission structures, due to the exponential dependence of the emission current on the applied collector voltage.

Previous publications devoted the studying of the possibilities of using field emission structures as the basis for development of microwave electronics devices were mainly focused on the use of metallic and carbon emission structures [2, 3]. In this paper, we consider the technological possibilities of creating field-emission nanoscale diode and triode structures based on silicon for signal generating in the GHz range.

II. Technology for the Creating of Field-Emission Nanostructures

Currently, field emission structures can be created utilizing metals or semiconductors [4, 5]; a large number of papers are devoted to the study of the prospects for using allotropes of carbon as a material for field emission structures [6, 7]. Silicon is a promising material for the creation of field-emission structures. This material possesses a high degree of reproducibility of the resulting structures, the achievement of which is a rather serious technological problem in the creation of homogeneous arrays of field emission structures based on metals or allotropes of carbon [8]. The use of silicon for the manufacture of field emission cathodes makes it possible to achieve very small radii of curvature of the cathode tips (within a few angstroms) [9], and, consequently, to obtain high current densities and narrow electron beams from small area of emission surfaces. The high reproducibility of the technology for creating of field-emission structures based on silicon also gives the possibility of creating emitter arrays with a strict periodicity, which is especially important when creating multi-beam devices for generating high-density electron beams.

This paper presents the results of the development of process flows for silicon needle- and blade-type field-emission structures.

The process flow for the formation of blade-type field-emission silicon cathodes with a nanoscale curvature radius of edge is described below (schematic images of the structures obtained at each stage are presented in Fig. 1 under the corresponding letters):

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a) oxidation of thinned n-type silicon 150 mm and orientation (100) wafers doped with phosphorus and deposition of a silicon nitride layer;

b) photolithography to form nitride-oxide masks (SiO_2 - Si_3N_4);

c) anisotropic etching of a silicon wafer in 10% KOH at 80 ° C to form V-shaped trenches;

d) oxidation of the front and back sides of the silicon wafer in a dry oxygen atmosphere;

e) deposition of silicon nitride on the front and back sides of the silicon wafer;

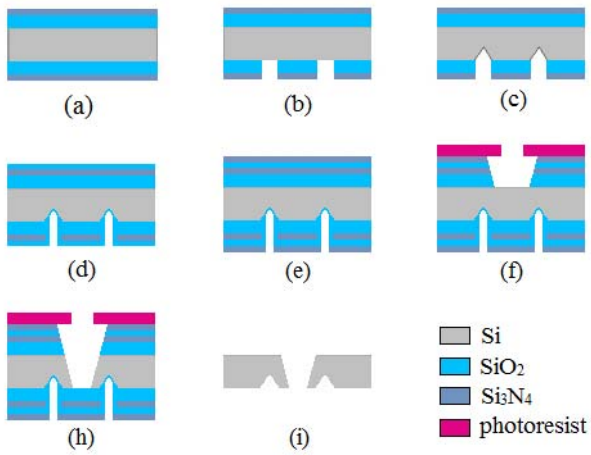

Fig. 1. Process flow for the formation of a silicon field-emission blade-type cathode.

f) photolithography and liquid chemical etching;

g) liquid chemical etching of the front side of the wafer to the entire depth along the (111) plane;

h) detaching the resulting samples of silicon blade-type cathodes.

The process flow described above makes it possible to create blade-type silicon field-emission cathodes with a high degree of reproducibility, since the angle at the apex of the cathode edge, in theory equal to 54.75 °, is determined by the mutual arrangement of crystallographic 111 and 100 planes of single-crystal silicon. The developed process flow can be implemented on most technological lines specializing in the manufacture of MEMS / IC with technological nodes from 0.8 to 0.35 microns. The results of studying of the experimental samples of blade-type field-emission cathodes by transmission electron microscopy demonstrate that the apex of the edge of the blade-type cathode consists of several atomic layers and has a nanoscale radius of curvature.

To obtain an array of nanoscale needle-type silicon cathodes, the following process flow was used (schematic images of the structures obtained at each stage are shown in Fig. 2 under the corresponding letters):

a) deep reactive-ion etching of thinned n-type silicon 150 mm and orientation (100) wafers doped with phosphorus, oxidation and filling of trenches with polysilicon for the shallow trench isolation;

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b) forming of cylindrical oxide masks (SiO_2) by plasma-chemical etching of polysilicon, photolithography and plasma-chemical etching of silicon oxide;

c) plasma-chemical etching of silicon in a mixture of SF_6 and O_2 to form a curved silicon pillars;

d) formation of a vertical "pedestal" of silicon columns by ion bombardment;

e) removal of the remains of the oxide mask and protruding oxidized walls of the shallow trench isolation, oxidation of silicon pillars to form nanoscale tips;

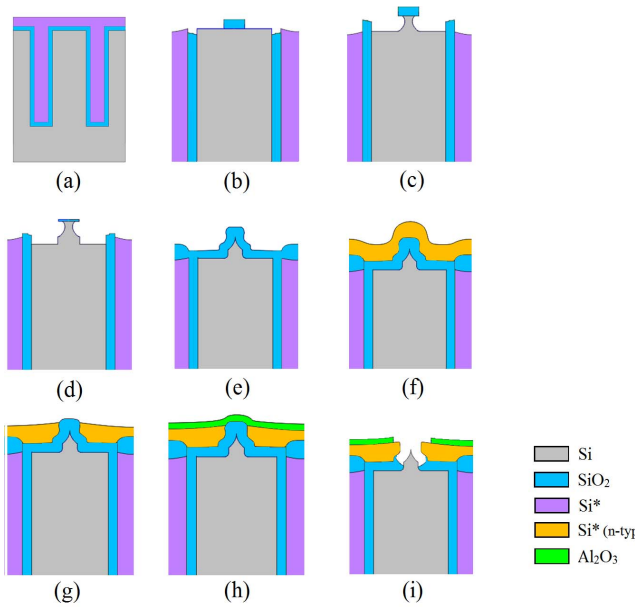

Fig. 2. Process flow for the formation of a silicon field-emission needle-type cathodes.

f) deposition of polysilicon layer and implantation of phosphorus into the deposited layer;

g) chemical-mechanical polishing of polysilicon layer to the underlying silicon oxide;

h) deposition of aluminum oxide passivation layer;

i) photolithography, chemical and plasma etching of remaining layers to open silicon tips.

The described process flow allows obtaining arrays of silicon field-emission structures of the tip type with a nanoscale radius of curvature (4–5 nm) at the apex of the cathode. As part of the research, arrays of 300 × 300 field-emission cathode-gate structures were created using this process flow.

III. Results

The surface and structure of an experimental sample of a silicon field-emission blade-type cathode was investigated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Fig. 3 shows the image and geometric dimensions of the silicon structure obtained as a result of a liquid chemical etching. Fig. 4 demonstrate an image of an experimental sample of a blade-type silicon field-emission cathode and the atomic structure of the cathode edge (inset). Fig. 3 shows that the value of the angle

at the apex of the cathode edge is 53 °, which is very close to the theoretical value. As can be seen from Fig. 4, the apex of the edge of the blade-type cathode consists of several atomic layers of silicon, and the its radius of curvature is no more than 2 nm.

Figure 5 shows a SEM image of a single field emission cathode with a grid electrode as part of an array of silicon cathode-grid nodes. The image clearly demonstrates that the radius of curvature of the field emission cathode is approximately 4.5 nm.

Experimental current-voltage characteristics were obtained for the fabricated samples of silicon field-emission

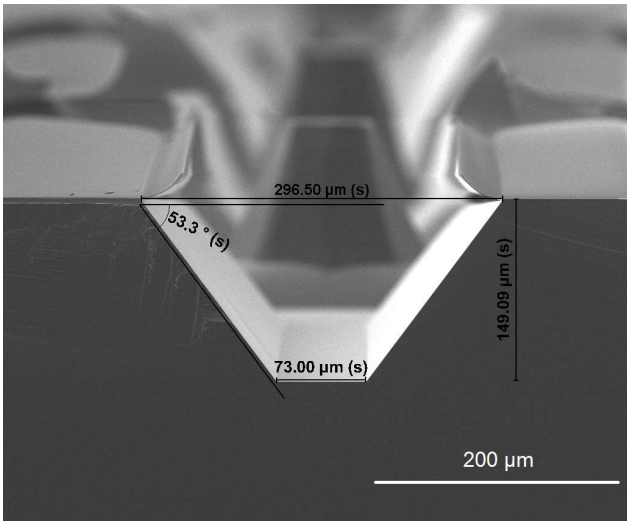

Fig. 3. SEM image of the silicon structure after liquid chemical etching.

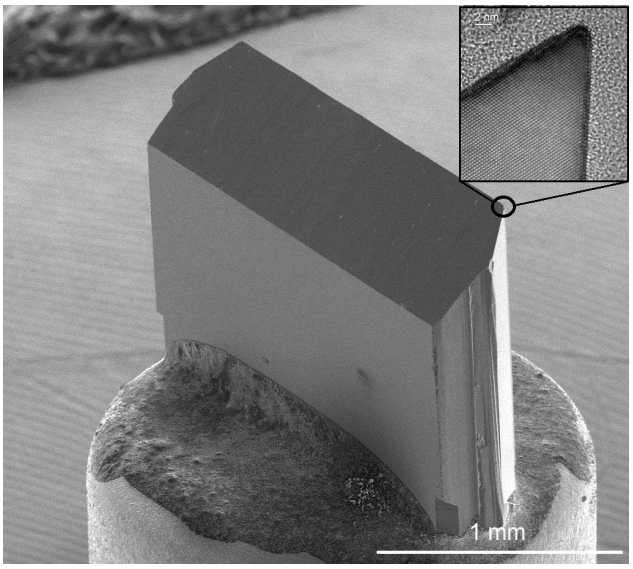

Fig. 4. SEM image of the sample of silicon field-emission blade-type cathode on metallic cylinder. The inset shows atomic structure of the edge apex of cathode.

cathodes. Figure 6a shows the current-voltage characteristics of the current-voltage characteristics of the array of field-emission cathode-grid nodes obtained at a cathode-anode distance of 30 microns, operating in the diode mode, i.e. with ground potential on grid electrodes and anode voltage variation from 0 to 3.3 kV. Figure 6b shows the current voltage-characteristics of a field emission blade-type cathode obtained at a cathode-anode distance of 40 microns with anode voltage variation from 0 to 2 kV.

IV. Conclusions

Process flows for the manufacture of a blade-type silicon field-emission cathode and an array of field-emission cathode-grid nodes with needle-type cathodes were developed in the course of this study. The surface of the obtained experimental samples of field emission structures was investigated by scanning and transmission electron microscopy.

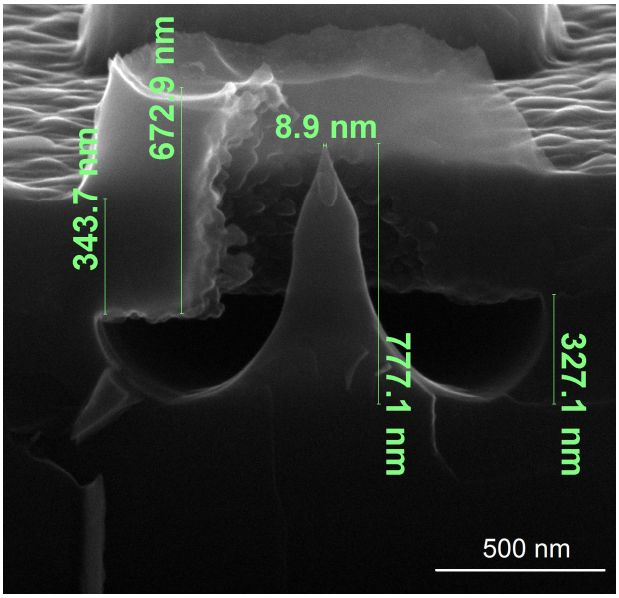

Fig. 5. SEM image of single silicon field-emission cathode-grid node.

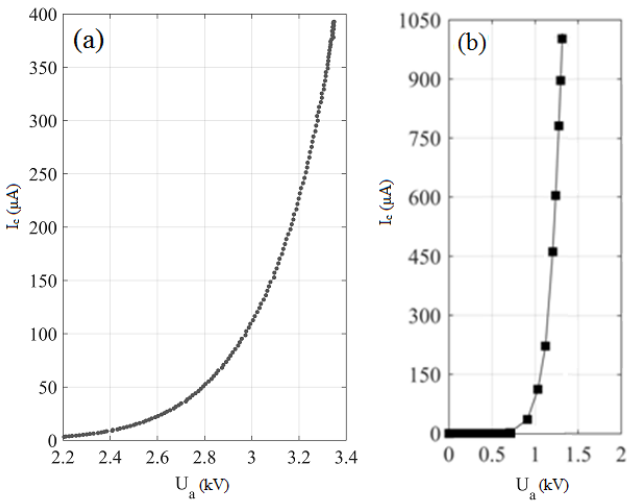

Fig. 6. Current-voltage characteristics of: a) silicon field-emission cathode-grid node; b) silicon field-emission blade-type cathode.

The current-voltage characteristics of the fabricated samples of field-emission structures were obtained as a result of experimental studies of the emission properties of the samples on a micrometer scale. The results of the study can

be used in the development of the electronic systems and devices for signal generating in the GHz range.

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