Laser formation of tip emitting structures with high aspect ratio on glass-carbon field-emission cathodes

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Abstract. Paper describes the method of creating the sharp emitting tips on the surface of a field-emission cathode. The needle-shaped structures with a high aspect ratio on the glass-carbon plate are produced by means of nanosecond laser micromachining. The operations of laser scribing, milling and cleaning were applied for fabrication of the single- and multi-tip field-emission cathode. The special technique of laser rough and fine milling provided high tips with sharp and smooth apexes. As a result we obtained the tips with aspect ratio up to 600. The tests of cathodes showed that high density of current emission and a shorter technological route of production to be reached.

1. Introduction

Field-emission cathodes (FEC) are an attractive alternative to mainstream thermionic cathodes in microelectronics [1], which are power hungry and require high vacuum and high temperature to operate. One of the promising material for FEC is glass-carbon. The unique properties of this material make it suitable for manufacturing of FEC of different configurations [2,3].

With a number of advantages over thermionic cathodes (lack of energy costs for heating the cathode, microsecond time availability), nevertheless, FEC of carbon materials have a low value of the field-emission current density divided by the square of the cathode disk. The maximum value of the electron beam current density in triode electron gun with spike-shaped FEC made of glass-carbon is about 1.5 A/cm², which is approximately 30 times lower than for modern metal porous cathodes. This is due to lack of planarity of the emitting surface of the cathode, and is determined by the method of tips forming, namely thin-film technology. For modern vacuum electronic devices the cathode current density of 30 A/cm² and above is required.

It was found out that the emission area of the tip and the effective field on the tip apex are key design parameters of an optimized tip structure and depends mainly on the apex radius and tip height. Since the effective field on the tip surface has been proven to have an intimate relation with the ratio of tip height to apex radius (aspect ratio), many research groups over the world have long devoted huge efforts to developing emitter tips with longer lengths but smaller radii for lower voltage operation [4]. For example, carbon nanotubes were considered appropriate emitter structure due to their extremely high aspect ratio (up to 270 [5]) of length in micrometer to radius in nanometer [6]. But such cathodes based on nanotubes with a small radius often show distinct emission instability and fast and nonhomogeneous...
destruction [5]. So, the requirements of stability demanded less fragile structures to be applied, such as needle-shaped tips with sharp apexes of micrometer dimensions.

A method of glass-carbon microtip FEC producing by plasma chemical etching [7] is time-consuming and includes several different processes (metallization, creating a mask, etching, removing the mask, thermochemical sharpening) that require complex and expensive equipment. Samples, obtained with traditional methods, contain inclusions of the catalysts (Fe, Ni), and the structures themselves have many sources of secondary emissions that negatively affect at work of devices based on them (rapid destruction of the emitting structure, poor performance of the electron beam). In addition, the aspect ratio is low (about 3). It weakens the current emission. Thus, we faced with the task of creating the emitting structure of glass-carbon using a complex of laser processes.

2. Method
Fabrication of the glass-carbon field-emission cathode by laser radiation comprised the operations of laser scribing, milling, cutting and cleaning. The operations were carried out with D-Mark laser commercial installation with parameters: Q-switched Nd:YAG diode-pumped laser, $\lambda=1.06 \mu m$, mean power $P=6.7$ W, pulse duration 70 ns. Visual investigation was carried out with MIRA/TESCAN electron microscope. Research on the plate surface cleanliness was carried out by laser induced breakdown spectroscopy (LIBS).

As the most developers of field-emission cathodes, we chose the commercial brand of glass-carbon SU-2000. This material is treated well by laser radiation. It has excellent absorption capacity at 1064 nm wavelength, which is the most characteristic of the process equipment.

Fabrication of FEC includes several stages, each of which used a separate driving computer program (figure 1). The first operation (figure 1a) is scribing and subsequent fracture of the glass-carbon preform of the needed dimensions. (This operation can be implemented by any suitable method, as it is preliminary). Then the array of pillars with flat tops, or one pillar in the case of the single-tip cathode, was formed by laser milling (figure 1b). At the next stage the tips were sharpened to a needle-shape form (figure 1c and 1d) by laser milling with other parameters. After that the technological ledge was formed (figure 1e) and the cathode disc itself was cut (figure 1f). Finally, the laser cleaning of the cathode and the tips took place.

Laser shaping and cleaning of emitting structures is possible in a single process, using a single laser facility. The milling of pillars is considered to be a stage of “rough” milling. The height and diameter of the created straight cylinder was up 700 $\mu m$ and about 200 $\mu m$ respectively. Repeatable results were obtained with the following, found empirically, parameters: focal length of the lens 50 mm, radiation power 3.9 W, speed of the laser beam 343 mm/s, pulse repetition rate 30 kHz.

After the formation of pillars, the process of “fine” milling started for the individual forming of each needle-shaped tip. According to the developed algorithm, the laser beam moved radially from the periphery of each pillar towards its center. Each subsequent movement of the beam was carried out at an angle 30’ to the previous. The complete number of lines was 720. The movement of the laser beam for each pillar carried out in such a way that the final point of the movement of the center of the laser beam was on circle $D=5 \mu m$, centered on the axis of the pillar. Since the energy of the laser radiation is distributed by the Gauss law, the removal of material in the center of the pillar was minimal. As a result, in the center of the pillar an intact spot of 2-5 $\mu m$ diameter appeared. At each subsequent azimuth
moving the value $D$ became 5 $\mu$m more. Thus, after each full turn, the needle-shaped tip was formed with an increasing diameter to its base. The programmable image of the laser beam movement during a single tip formation is shown on Figure 2.

![Figure 2. Image of paths of movement of the laser beam on one of the tip.](image)

The following parameters were applied for fine milling: the focal length of the lens 50 mm, radiation power 1.15 W, speed of the laser beam 171 mm/s, pulse repetition rate 8 kHz.

After both milling processes, the FEC surface was cleaned with the following parameters: radiation power 1.3 W, speed of the laser beam 1150 mm/s, pulse repetition rate 30 kHz. Cleaning the surface of the needle-shaped tips is analogical to fine milling with some changes: radiation power 0.65 W, speed of the laser beam 630 mm/s, pulse repetition rate 8 kHz.

3. Results and discussion

Figure 3-5 represents the FEC and, separately, one tip and its apex. The diameter of the cathode is 3.1 mm. 19 needle-shaped tips are located on two concentric circles: 6 tips on the 1.25 mm diameter circle and 12 tips on 2.5 mm diameter circle. One tip is located in the center. The height of the tips on some samples of cathodes reached 700 $\mu$m. For each cathode, the tops of all tips are supposed to be lying on the same plane. The radii of curvature of the apexes on some cathode samples were 0.8-3 $\mu$m. The aspect ratio of the geometric dimensions of the tips was 500-600.

![Figure 3. Image of paths of movement of the laser beam on one of the tip.](image)

![Figure 4. Image of paths of movement of the laser beam on one of the tip.](image)

![Figure 5. Image of paths of movement of the laser beam on one of the tip.](image)
The figures 6 and 7 show the tips before and after cleaning respectively. As seen from the photos the surface of tips is smooth. As glass-carbon consists of volume cavities (50 nm globules), divided by 5 nm partitions [7], obtaining such a surface indicates the presence of the liquid phase under the influence of laser radiation, which is consistent with observations [8].

Figure 6. The apex before laser cleaning.  
Figure 7. The apex after laser cleaning.

As the structure is cut from a single piece, the resulting matrix has a high strength against degradation by ponderomotive force. The manufacture time of one tip out of the forth-mentioned preform (disc diameter 3.1 mm, thickness 1.3 mm) did not exceed 35 minutes.

4. Conclusions
The laser processing technique including scribing, milling and cleaning on the same laser set-up allows the glass-carbon FEC with high, more than 500, aspect ratio to be created. Due to the special technique of rough and fine laser milling with programmable azimuth movement the tips have a needle-shape. The surface of the tips is smooth, which is a prerequisite for stability in time of field-emission.

The advantage of this technology is its high performance. The manufacture of a 19-tip cathode wastes about 45 minutes. Laser manufacturing, unlike the other methods, performed on the same equipment and the same production site. The technological process is ecologically clean, requires minimal energy and labor costs.

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