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NANOSTRUCTURE DEVICES

Graphite-Based Blade-Type Field Emission Cathodes

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Abstract—In this work, the blade-type field emission cathodes (BFECs) of original construction have been developed and produced. As the basis of the cathodes the (110)-cut silicon wafers were used. On the upper surface of Si substrate the parallel grooves of the 20 μm width and 50 μm depth of 1.7 mm in length were etched in a concentrated aqueous 44% KOH solution. As a result the parallel Si walls of the rectangular shape were created, which after imparting them a wedge shape form were used as a pedestals for supporting of emitting graphite blades, obtained by the electron beam evaporation of graphite. The blades were sharpened to the thickness not exceeding 10 nm. It was shown that our BFECs can operate at field emission current up to 6 mA, depending on the sharpness of a blade. It was found that the cathodes, which had previously worked on low currents, then showed high limiting currents, in comparison with the cathodes, which were initially forced to work on extreme emission currents.

Keywords: graphite blade emitters, Si pedestals, field emission, emission current

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1. INTRODUCTION

One of the new and rapidly developing areas in modern electronics is vacuum micro- and nanoelectronics. In connection with the rapid development of communication and information technologies electronics faces the task of creating active devices capable to operate at super-high frequencies. Unfortunately, the solution of these issues is difficult and in some cases nearly impossible because of a number of restricting physical effects in semiconductors. The development of field emission devices opens the prospects for the creation of devices that can be widely used in various fields of electronics: ultrafast microprocessors; memory with picosecond time access for computer machines; field emission displays with high brightness e.c. The key component of field emission vacuum devices is field-emission cathode (FECs). A number of specific requirements are imposed on FECs regardless of their field of application, such as low threshold and operating voltage, maximum possible uniformity, high density and stability of emission, good mechanical properties.

The prospects of using allotropic forms of carbon [1, 2] for these applications is due to their exclusive electrical, chemical, thermal and mechanical properties. Regardless of the field of FECs application, a number of requirements to their characteristics must be satisfied such as high emission efficiency, low threshold and operating voltages, high homogeneity, density and stability of electron emission. Moreover, FECs should have a firm construction providing a good electrical contact and adhesion of carbon materials to the cathode electrode, which, in turn, must allow electrical connection to the bonding pads and metal interconnections, and it should be compatible with the technology of microelectronics.

In previous our investigations [3–5] we studied application of carbon nanotubes (CNTs) for these purposes. Despite of the attractiveness of FECs based on CNTs the fabrication processes of controlled CNT arrays remain relatively complex and expensive. Furthermore, the problem of their fast degradation under operational conditions has not yet been solved. This drawback of the CNT-based technologies stimulates investigations of alternative forms of nanocarbon, such as nanodiamond, nanographitic, amorphous and composite films. This paper presents the results of development and investigation of FECs on the basis of graphite blades sharpened to nanographite—nanoscale blade-type FECs with a high-quality graphite structure.

2. FORMATION OF Si PEDESTALS

The construction of the developed graphite-based blade-type field emission cathodes (BFEC) is pre-

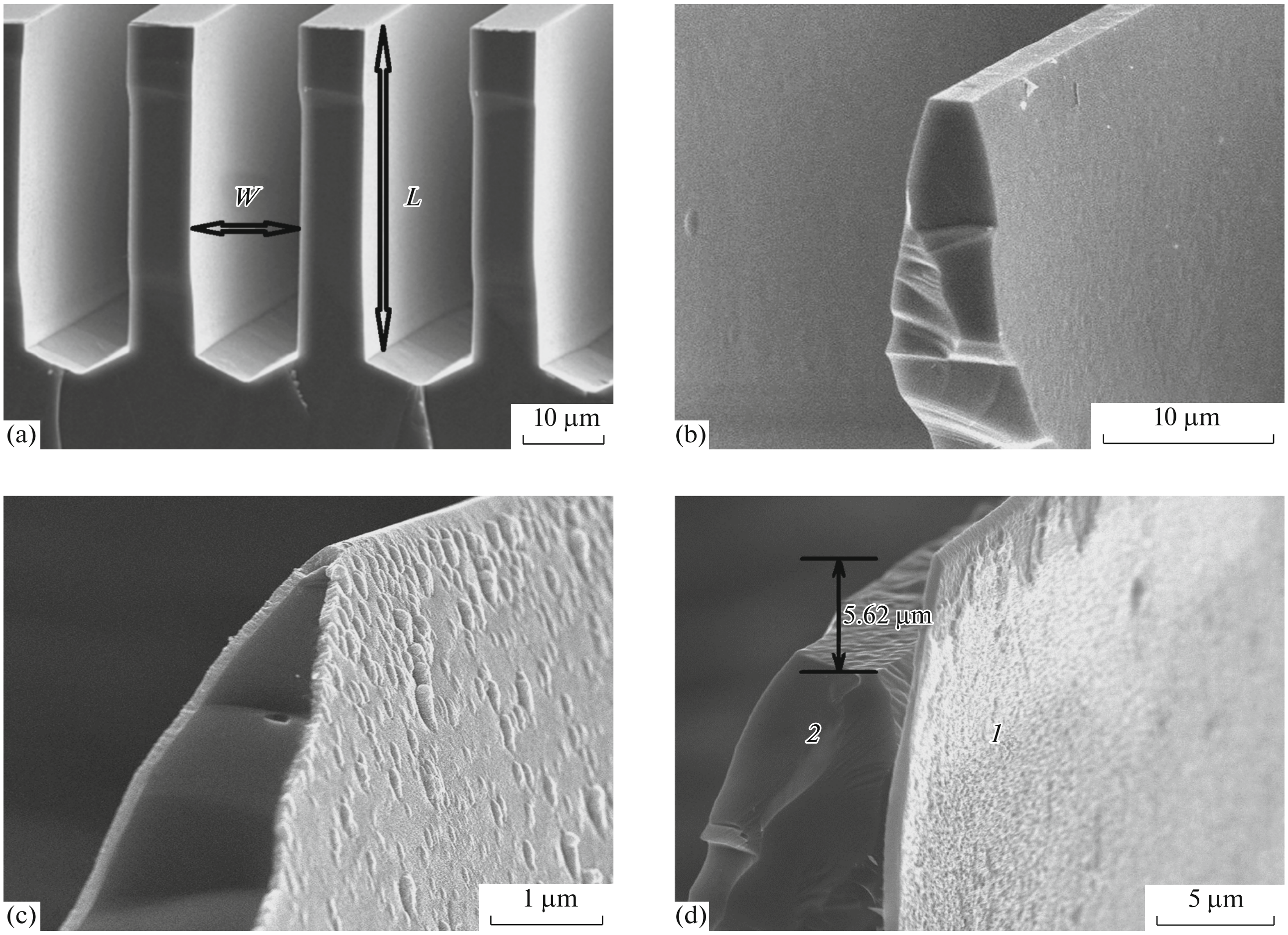

Fig. 1. (SEM) Graphite-based blade-type field emission cathode (BFEC): (a)Si pedestals of multi blade FEC, (b) Si pedestal of one blade FEC with imparted wedge shape, (c) wage shape Si pedestal covered by the layer of graphite, (d) graphite blade (1) supported by Si pedestal (2).

sented in Fig. 1. As the basis of the cathodes, the (110) silicon wafers were used. In general there might be produced multi blade BFECs. In this case on the upper surface of Si substrate the parallel grooves of the certain width (*W*) and depth (*L*) are formed by the anisotropic chemical etching of arsenic highly-doped (110) silicon (Fig. 1a) in a concentrated aqueous 44% KOH solution heated to 73°C. As a result the strictly vertical Si walls of the grooves are obtained. The created rectangular shape Si islands separated by the grooves are considered as the pedestals for supporting of the e-emitting graphite blades. It has been established that in the multi blade structures, under creation of pedestals, etching rate of Si strongly depends on the ratio of the depth L to the width W of the grooves. The optimum etching rate, with the pedestals height of 50 μm or more, is achieved when L/W ratio is close to unit.

The initial etching profile on the Si wafer was created using the photoresist method. For photolithography, a special protective mask of high-temperature SiO_2 and thickness of 560 nm coated with a photoresist was formed on the Si wafer surface. A laser beam lithography was used to obtain a system of stripes with a step of 20 – 100 μm. The orientation of the stripes on the silicon wafer relative to the crystallographic axes is very important. To get vertical slots on a plate in a specified direction, the window in the mask should be strictly oriented at an angle of 70.53° relative to the base cut: deviation by a couple of degrees leads to a strong lateral raster. Mask thickness of 560 nm allows one to get grooves with a depth of up to 180 μm. The lateral raster of the slit with a depth of 100 μm did not exceed 5 microns.

In the present work the one blade FEC is investigated, what gives possibilities to easier interpret the mechanism and peculiarities of the emission process of the BFECs. In this case from the multi pedestal Si substrate one pedestal section was cutting.

As the next step, by using additional isotropic etching method, the obtained silicon pedestal was sharpened. The sharpening effect of a silicon blade was observed both with and without the SiO_2 masking coating. The effect is due to steric hindrances of the penetration of the solution to the lower boundary (base) of the pedestals. This, in turn, impairs mass transfer, which ensures the release of reaction products into solution. All this in a complex creates a difference in etching speeds in the upper part and at the base of the pedestals.

Under the realization of this process the wedge shape is imparted to this pedestal (Fig. 1b). The best etchant in this case was the aqueous solution of hydrofluoric and nitric acids with the addition of glacial acetic acid and ammonium fluoride. By changing the ratio of the components of the etching solution, a composition was found that provided the best etching mode from the point of view of obtaining a theoretically grounded cathode profile that meets the requirements of the formed structure.

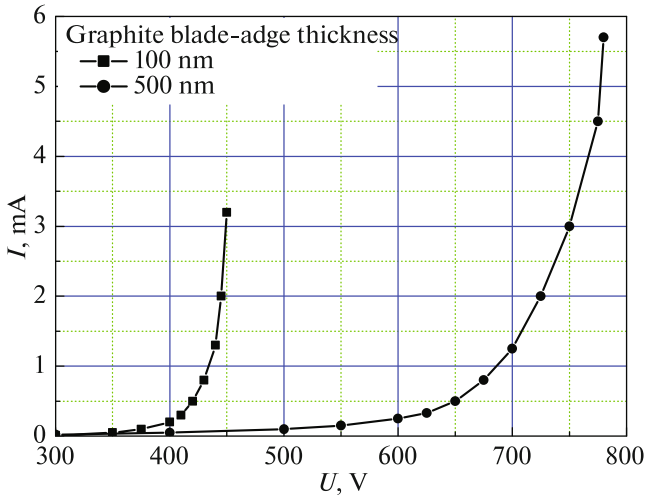

Fig. 2. Emission current–voltage (I–V) characteristics of a graphite FECs blade-type with thickness of 100 and 500 nm; anode-cathode distance is 10 μm.

3. GRAPHITE BLADE FORMATION

After Si pedestals formation, the carbon films of thickness 10–100 nm are deposited on the surface of Si pedestal by the electron beam evaporation of bulk graphite or RF magnetron sputtering (Fig. 1c). The deposited films were subsequently subjected to high-temperature annealing in an inert atmosphere of (Ar, N_2) or vacuum at a temperature up to $T = 1200°C$ during 1 h (graphitization). With increasing temperature and annealing time, the solidity of graphite films increased and electrical properties improved. In particular, electrical conductivity increased by more than three orders of magnitude.

It was found that films obtained using the electron beam had an order of magnitude less resistance than carbon films obtained by RF magnetron sputtering. Based on this, in the future we used only electron-beam evaporation, which allows one to obtain better carbon films. At last, a thicker layer of carbon (from 200 to 500 nm) is re-deposited onto the graphitized carbon layer by electron beam evaporation.

The most responsible operation in the production of efficient BFEC is creation the graphite blade on the basis of the obtained graphite film. A special technique was developed for this reason. Argon ion beam in vacuum chamber is used, which is directed at certain angle to the structure (Fig. 1c) creating the shadow effect. As a result of the etching process, the structure presented in Fig. 1d consisting of Si pedestal (1) and graphite blade (2), was obtained. Because of the different rate of Si and graphite etching the graphite blade automatically juts out of the surface of Si pedestal. In the structure of Fig. 1d, Si plays role not only a pedestal but as efficient heat sink. The process of cathode formation is completed by repeated high-temperature annealing in an inert medium or vacuum at $T = 1200°C$, 1 h. Re-annealing is necessary to recrystallize the deposited second thicker layer of carbon.

The efficiency of the current emission of blade depends on its sharpness. A special operation of sharpening the blade was used by the ion beam etching. In our experiment we reached the smallest thickness of the blade-edge did not exceed 10 nm.

To achieve high emission currents, it is necessary to increase the thickness of the base of the graphite knife-edge, which in turn worsens the aspect ratio and increases the electric field strength at which the emission takes place. It was established experimentally that the optimum ratio of the height of the graphite proceed above the Si pedestal to its thickness is 20:1. During the operation of the cathode, the tip of the sharpened graphite proceed heats up rather strongly, but a graphite film about 500 nm thick allows heat to be quite effectively removed from the emitting zone to the Si substrate. The blade length of the obtained emission cathodes was 1.7 mm. In this case, an emission current of up to 5–6 mA was achieved, depending on the thickness of the base of the blade. Current-voltage characteristics shown in Fig. 2 were measured in sinusoidal signal mode at frequency of 50 Hz for two different basis thickness graphite blades. The thicker the base of the graphite blade, the greater the current density they can work.

It was found that during the operation of the FEC, the emission current increases with time. The typical time dependence of the current is shown in Fig. 3. This effect is due to two reasons. Firstly, during operation, the cathode is warming up significantly and a thermionic component is added to the field emission component of the current. In this case, an additional high-temperature annealing of the graphite blade occurs, as a result of which the material recrystallizes and its properties improve. This is the second important factor in increasing the emission current. An interesting consequence of cathode heating is the practically important effect of improving the operational proper-

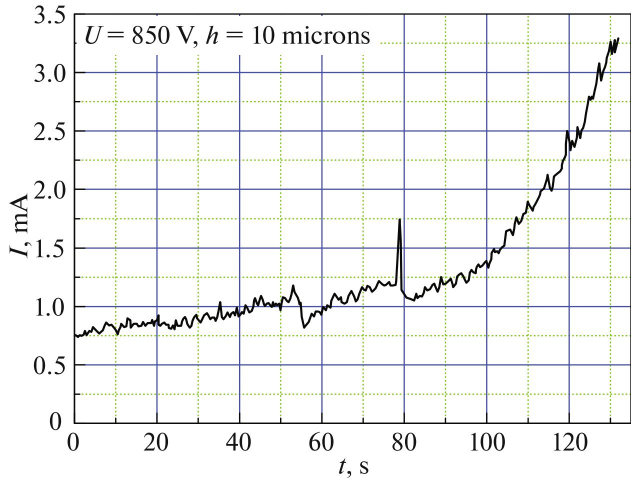

Fig. 3. Time dependence of the emission current from the entire blade at $h = 10$ µm, the voltage at the anode of 850 V and the anode-cathode gap of 10 µm.

ties of the cathode. Note that during the creation of the cathode, annealing is limited by the melting temperature of silicon (1414°C), while during the operation of the cathode the temperature of the blade tip can significantly exceed this temperature and approach 3000°C. As a result, it turns out that the samples, which worked for some time at low currents, then showed high limiting currents than the samples, which were immediately forced to work on the limiting emission currents.

4. CONCLUSIONS

Thus, by means of isotropic and anisotropic etching, heat-removing silicon pedestals are formed on which graphite blades are obtained. The undoubted advantage of a blade-type cathode based on a combination of nanographite structures and wedge-shaped silicon pedestals is the minimum dispersion of emitters in height and distance over a large surface area (technology on a silicon wafer is of 14 class of surface cleanliness and topological size of operations is up to 1 µm). In addition, this well-established silicon-based microelectronics technology enables the formation the required wedge-shaped profile along the height of the cathode, with high electrical and thermal conductivity, good mechanical, electrical and thermal contact with the substrate. It offers the best opportunity for the reproducible manufacture of a wedge-shaped profile along the height of the cathode and to distance the emitting blades relative to each other at the required distance. According to their characteristics, the obtained field emission cathodes correspond to analogues fabricated by other methods on amorphous [1, 6], CNT fibers [7] or nanocrystalline graphite [8–10].

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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