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Stabilization of Field- and Photoemission of a Planar Structure with a Nanosized Diamond-Like Carbon Film

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Abstract—Effects that may provide an increase in the stability of field emission and tunneling photoemission of a planar blade structure using an emitter that is covered with nanosized dielectric diamond-like carbon (DLC) film are analyzed. A model of specific features of the distributed zone of the field localization on the DLC surface in the structure (zone with a smooth peak of electric field) is constructed and the corresponding theoretical analysis is performed. It is shown that the DLC film with a thickness of 20 nm on a molybdenum blade (Mo blade) provides an increase in the area of the emission region by a factor of 15 in comparison with the area corresponding to the Mo blade without coating. The working time of the emission structure with the DLC film is increased by a factor of greater than 50 (to 8700 h) for the regime of long pulses (320 μs) with a relative interpulse period of 10 and the mean current density of the field emission of no less than 30 mA/cm^2. An increase in the sensitivity of the structure with the DLC film is demonstrated.

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INTRODUCTION

The problem of reliability and long-time stability of field-emission structures with a relatively high current density is important for development of new generations of modern devices of vacuum electronics [1, 2] (microwave oscillators and amplifiers with a working frequency range extending to several terahertz). Tunneling transport of electrons from the material of field emitters to vacuum makes such devices promising for the development of broadband vacuum photosensors [3] with dynamic tuning of spectral sensitivity. Ballistic transport of electrons in the cathode–anode gap with extreme electric field strength and fast response to an optical signal may provide high working rates of the devices. Relatively low level of modulating potential and functioning under technical vacuum conditions (at a pressure of about 10^{-5} Pa) are also important for applications. In practice, the mass of power supplies and the price of vacuum electronic and photonic devices can substantially be decreased. The above requirements can hardly be satisfied simultaneously owing to contradictory character.

The analysis of the classical Fowler–Nordheim equation shows that an increase in the electric field strength leads to an exponential increase in the current density of the field-emission (FE) current. The inhomogeneity of the emitter surface (tips of the Spindt cathode, blades, arrays of nanotubes, etc. [1–6]) causes localization of the zones of efficient FE. In such zones, local heat liberation results from the Joule heating and/or Nottingham effect.

Several schemes can be used to construct unit cells for the FE arrays, and the preferred schemes provide FE mean current density J of no less than several tens of milliamperes per square centimeter. A structure of [4] consists of an emitter that represents a molybdenum spike with a height of 0.8–1.8 μm and a gate electrode with a diameter of 0.8 μm. The transverse size of a cell is 4 μm, the potential difference between the gate and emitter is $U_g = 300$ V, and the FE current from the tip amounts to 1 mA. In such a structure, the FE current is limited by the intrinsic resistance of the spike that additionally increases with temperature. The concept of current limitation has been further developed in the structure of [5], in which a column silicon struc-

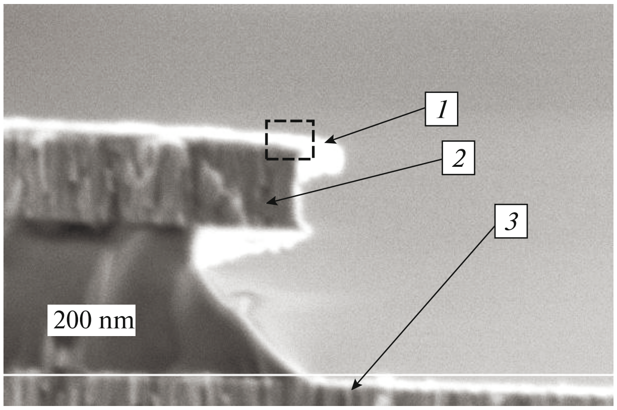

Fig. 1. Planar structure with the Mo blade coated with the DLC film: (*1*) DLC film, (*2*) molybdenum blade, (*3*) molybdenum gate electrode (electrodes *2* and *3* are insulated using a SiO_2 layer).

ture (Si structure) with a relatively high aspect ratio (diameter, 200 nm and height, 10 μm) is introduced into a dielectric matrix (the diameter of the gate aperture is 350 nm, the transverse size of the cell is decreased to 1 μm, the emitter–gate potential difference is 80 V, and current of a single Si-tip of a nanowire amounts to 1 μm). In the cell of [6], an array of carbon nanotubes (CNTs) is bound to a single column of crystalline silicon that serves as a nonlinear ballast resistor. The transverse size of such a cell is 15 μm, the working voltage is 20 V, and the current of the CNT cluster on the column is 5.6 μA. A similar structure with a pyramid-shaped nanodiamond tip on top of the ballast 140-kΩ resistor (Si rod) has been proposed in [7]. The method of [8] makes it possible to grow a nanosized silicon resistor on top of an emitting tip with greater size that provides stable operation of the emitter at an FE current density of 24.9 mA/cm^2 and a voltage of 94 V. Significant limiting effect in such structures is related to a nonlinear increase in the liberated thermal power in the ballast resistors with an increase in the FE current density.

For simplicity, an individual gate electrode of a single cluster is changed by a single extraction electrode with potential U in the structures of [9, 10]. Such an approach makes it possible to use blades with an increased size that may amount to several tens of micrometers. Note a simultaneous increase in voltage U to several or, even, several tens of kilovolts: voltage reaches a level of 6 kV in the structure of [9] and 55 kV in the needle-type carbon structure of [10]. The latter provides stable operation of the emitter over an interval of 1080 h at an FE current density of 102 mA/cm^2. However, permanent evacuation is needed to implement the needed vacuum conditions. An advantage of the above structures is related to weak requirements on the spread of the sizes of blades.

1. PHYSICAL FORMULATION OF THE PROBLEM

Specific features of the planar structure with the gate electrode (Fig. 1) [11, 12] are as follows.

(i) The composite blade emitter is formed as a relatively massive molybdenum base with high thermal conductivity and a thickness of 300–400 nm. Hydrogenated DLC film with a thickness of 20 nm is deposited on the emitter with the aid of PECVD (objects *1* and *2* in Fig. 1).

(ii) Gate electrode *3* is fabricated is such a way that the plane of its surface is located at a distance of 600–700 nm from the plane of the DLC film and provides relatively low control voltage (150–250 V).

(iii) The distribution of electrostatic field in the interelectrode space of the planar structure provides protection of the emitter blade against ion bombardment [11] as distinct from conventional structures (e.g., Spindt cathode) with coaxial gate electrode and tip of emitter.

The results of [13] show photosensitivity of the proposed planar structure with respect to irradiation with low-energy photons at energies that are significantly less than the long-wavelength threshold of classical photoelectric effect for the materials under study. Advanced theory of the tunneling photoelectric effect for the structures under study [14] makes it possible to interpret the dependence of photocurrent on the electric field on the emitting surface and radiation wavelength and intensity. The resulting regularities prove possibility of broadband photosensors with dynamic tuning of spectral sensitivity based on variation in the working voltage.

However, insufficient data on the effect of dielectric film on the FE stabilization are available [15] for the above planar structure with the DLC-coated emitter blade. The purpose of this work is to assess possible differences of the parameters of localization of electrostatic field in the nanostructure in the presence and absence of the DLC film that determine both FE current and photocurrent.

2. NUMERICAL SIMULATION, EXPERIMENTAL STUDY, AND DISCUSSION

To solve the formulated problem of the effect of the DLC film on the conditions for carrier tunneling, we calculate variations in the field of potentials in the planar structure after deposition of the dielectric coating. For this purpose, we construct a finite-element model of two variants of the planar nanostructure: with the dielectric DLC film with a thickness of 20 nm and without film. Potentials on metal surfaces (blade emitter, gate, and anode) serve as the boundary conditions in the calculations. We also take into account dielectric properties of the DLC film. Figure 2a shows the calculated distribution of potentials in the structure with the DLC dielectric film in the vicinity of the edge of the blade (region that is bounded with dashed line in Fig. 1) as a grey-scale topogram and equipotential lines. It is seen that the equipotential lines concentrate in the vicinity of the edge of the Mo blade (region of field localization) and cross the dielectric film.

With allowance for the calculated field distribution, electron transport can be described in the following way. Concentration of the equipotential lines at the interface of the Mo blade and DLC film (an increase in the field strength) provides injection of electrons from molybdenum to the dielectric film. (Note that the concentration of injected electrons is less than the concentration of electrons in metal by several orders of magnitude.) This circumstance leads to limitation of electric transport through the insulator that is possible due to an increase in the field strength (e.g., in accordance with the Poole–Frenkel effect [16]). The intensity of the FE from the surface of the dielectric film to vacuum substantially depends on the field strength and specific properties of the DLC film.

Initial interest in the DLC films has been driven by unexpectedly high level of photoresponse to irradiation with low-energy photons and low FE threshold that do not correspond to the work functions of diamond and graphite. Not also the absence of clear reasons for a high form factor. Such properties are related to the presence and interaction of electronic structures of diamond nanoclusters (Sp^3-phase) and thin boundary sheaths of graphite (Sp^2-phase). The study of, hypotheses on, and substantiation of the effect of electron injection from graphite to diamond granules with negative electron affinity and the subsequent tunneling to vacuum can be found in [17]. It has been shown that hydrogenation and doping of nanocrystalline diamond with sodium, gold, platinum, etc. ions provide an additional decrease in the electron work function [18]. A total decrease in the work function may amount to 2–2.5 eV. Therefore, the field emission from the film surface may take place at a relatively low orthogonal (with respect to the surface) component of the field vector under conditions for sufficient electron transport through the film with a nanoscale thickness. The distribution of quantity $|E_y|$ (Fig. 2b) exhibits smooth peak. The width of the region at a level of no less than 90% of the maximum $|E_y|$ in which the main FE current is emitted is 30 nm.

The results of similar calculations for the above structure in the absence of the DLC film (Fig. 3) show significant redistribution of the equipotential lines

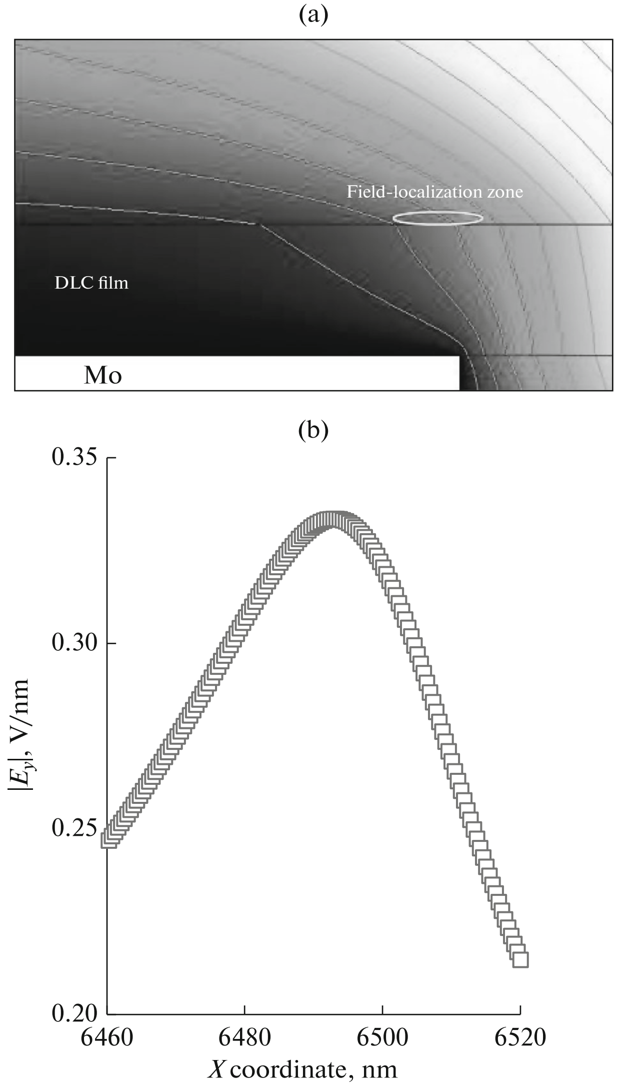

Fig. 2. Results of simulation of electrostatic field in the planar structure with the DLC film: (a) topogram of the potential distribution (the difference between the equipotential lines is 1 V) and (b) distribution of normal component of the field strength E_y on the surface of the DLC film.

that leads to changes of the field distribution in the zone of electron tunneling to vacuum from the surface of the Mo blade. It is seen, that, in the absence of the DLC film, maximum $|E_y|$ on the Mo base increases and the width of the localization region at a level of 90% of the maximum value decreases and becomes less than 2 nm.

Such changes of the degree of localization indicate that the same level of the FE current in the structure without the DLC film can be reached only due to an increase in the local current density by a factor of greater than 15 in comparison with the structure with the DLC film. However, an increase in the current density in any FE structure leads to a higher sensitivity

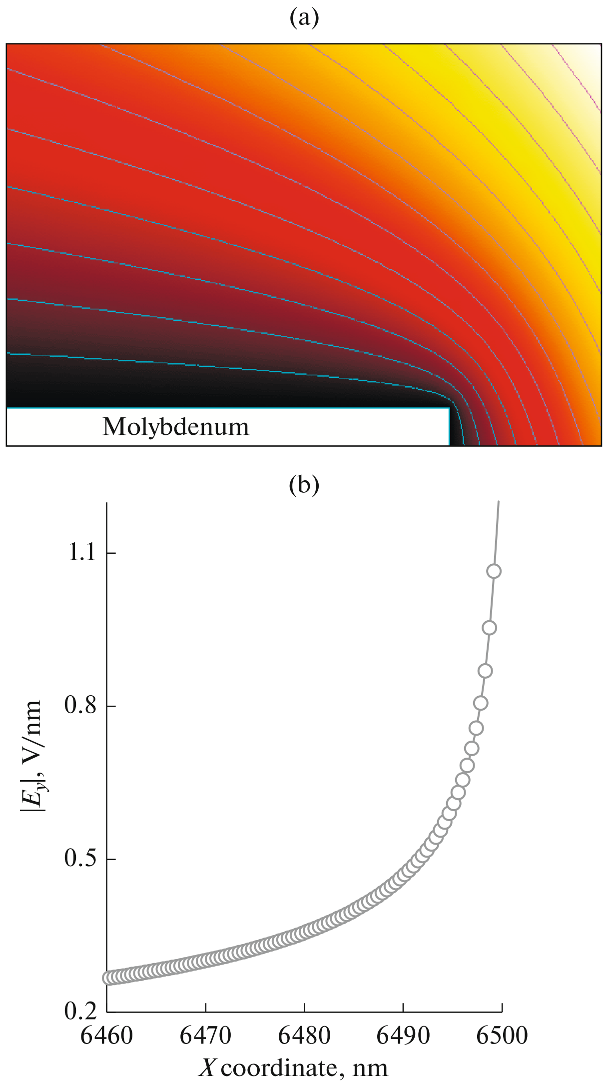

Fig. 3. Results of simulation of electrostatic field in the planar structure in the absence of the DLC film: (a) topogram of the potential distribution (the difference between the equipotential lines is 1 V) and (b) distribution of normal component of the field strength E_y on the surface of the Mo blade.

with respect to fluctuations of control potentials, lower stability of the Fe cathode, and higher probability of irreversible destructive processes. A decrease in the FE current density also inevitably leads a decrease in the local power of heat liberation in the region of electron tunneling to vacuum.

A significant decrease in the needed local current density in the structure with the DLC film that follows from the analysis of the calculated data on the level and distribution of the field strength that is obtained in the two variants is in agreement with the results of lifetime tests of the structure. The experimental study of the planar structures shows that the presence of the DLC film leads to an increase in the working time in the regime of long pulses with a relative interpulse interval of 10 and a mean FE current density of no less than 30 mA/cm^2 by a factor of greater than 50 (to 8700 h). The effect of a several-fold increase in the width of the zone with enhanced field due to deposition of the nanosized dielectric DLC film can be interpreted as the formation of the distributed zone of field localization.

The presence of the DLC coating also leads to an increase in the photosensitivity of the structure (Fig. 4). It is seen that the dark current of the molybdenum sensor is greater than the dark current of the structure with the DLC film in almost entire range of variations in the field strength. The ratio of the dark currents is several units in the range of low and medium field strengths. Irradiation of the photosensors using a source of coherent radiation with a wavelength of 532 nm (the photon energy is less than the

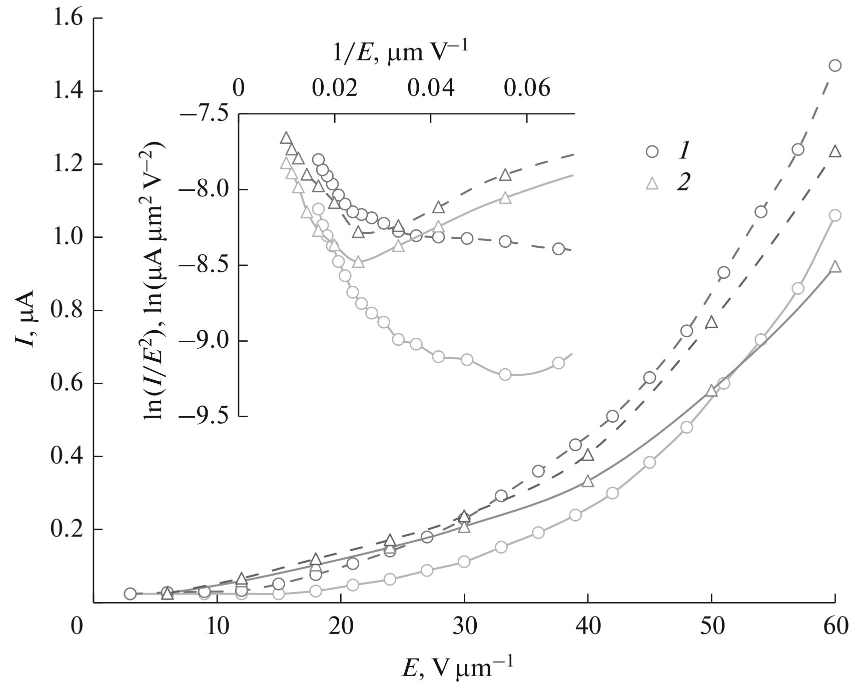

Fig. 4. *I*–*V* characteristics (curves of current vs. field strength) for the photosensors (*1*) with and (*2*) without DLC film obtained (solid lines) in the absence of irradiation and (dashed lines) under irradiation using a source of coherent radiation with a wavelength of 532 nm. The inset shows the curves on the Fowler–Nordheim coordinates.

long-wavelength threshold of the classical photoelectric effect for molybdenum, diamond, and graphite) causes photocurrent in both structures (with and without DLC film). Such a result is a consequence of tunneling of nonequilibrium photoelectrons in the zone of the field localization at the emitter–vacuum interface. The level of the photocurrent is determined by the difference of the resulting and dark currents. The analysis of the results of Fig. 4 shows that the photocurrent monotonically increases with an increase in the field strength. However, the photosensitivity of the structure with the DLC film is always higher than the photosensitivity of the structure with the molybdenum emitter: in particular, the former is greater than the latter by a factor of 5 at a field strength of about 30 V/μm.

CONCLUSIONS

The simulated results can be used to theoretically substantiate the concept in accordance with which a distributed zone of the localization of electrostatic field is formed and the multiplicative effect is implemented owing to the presence of the dielectric DLC film.

The presence of the distributed zone of localization of the electrostatic field provides an increase in the mean density of the field emission and tunneling photoemission accompanied with a decrease in the levels of specific local density of emission and specific power of heat liberation and an increase in the stability under low-voltage control.

The experimental results prove the correctness of the proposed model concepts.

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