High-current field-emission cathodes are advantageous to thermionic cathodes not only in making possible a significant reduction in dimensions of vacuum devices and systems, but also in significantly expanding the frequency range of their effective operation, increasing the degree of monochromaticity of emitted electrons, and improving the energy efficiency of devices. However, despite considerable effort of many research groups, fast field-emission cathodes for high-current vacuum diodes and triodes characterized by an acceptable stable operation lifetime have not been created until now [1–3]. For this reason, high-current cathodes for vacuum diodes and triodes are still fabricated with thermionic cathodes.

There were hopes to obtain effective field-emission cathodes based on carbon nanostructures grown by plasma-enhanced chemical vapor deposition (PECVD) from the gas phase, which were related to the unique electrical and mechanical properties of these structures, including high hardness (~1 TPa), strength (~45 GPa), electric conductivity (~12.9 kΩ−1), thermal conductivity (~2000 W/(m K)), elastic modulus (~1 TPa), and yield stress (~2 GPa), but all attempts have been unsuccessful so far. The main factor that hinders the use of these carbon nanostructures is an impermissibly large dispersion of lateral dimensions of the catalytic droplets, which serve as nanoreactors for the growth of carbon nanostructures and constitute a base of every nanoobject in their arrays obtained by PECVD. As a result, threshold conditions for the field electron emission from cathodes based on carbon nanostructures can only be provided for a small fraction of nanoobjects in the entire array. This circumstance accounts for the fact that, while a single carbon nanostructure can provide for a current of ~1 μA, a total current greater than 0.1 mA can rarely be obtained from an area of ~1 mm2, although it may contain several hundred thousand of these emitters. As a result, field emitters operating in a dc regime can reliably provide current densities not exceeding ~0.1 A/cm2. This factor, together with low yield stress of catalytic droplets, hinders the creation of high-current field-emission cathodes. Indeed, attempts at increasing the group of effectively emitting carbon nanostructures with dominating aspect ratios by including other nanoobjects due to increasing inter-electrode potential difference fail because this leads to fracture of catalytic bases the operating emitter groups. Attempts to form arrays of uniform nanostructures in solid films [4] allowed the dispersion of emitter point diameters to be significantly decreased, but the scatter of nanoobject aspect ratios in the array (related to a significant spread of lengths) still remains unacceptably large.

This Letter describes new field-emission cathodes for solid-state field-emission diodes, with the active surface containing nanostructures grown by plasma-enhanced chemical vapor deposition (PECVD) from the gas phase, which were related to the unique electrical and mechanical properties of these structures, including high hardness (~1 TPa), strength (~45 GPa), electric conductivity (~12.9 kΩ−1), thermal conductivity (~2000 W/(m K)), elastic modulus (~1 TPa), and yield stress (~2 GPa), but all attempts have been unsuccessful so far. The main factor that hinders the use of these carbon nanostructures is an impermissibly large dispersion of lateral dimensions of the catalytic droplets, which serve as nanoreactors for the growth of carbon nanostructures and constitute a base of every nanoobject in their arrays obtained by PECVD. As a result, threshold conditions for the field electron emission from cathodes based on carbon nanostructures can only be provided for a small fraction of nanoobjects in the entire array. This circumstance accounts for the fact that, while a single carbon nanostructure can provide for a current of ~1 μA, a total current greater than 0.1 mA can rarely be obtained from an area of ~1 mm2, although it may contain several hundred thousand of these emitters. As a result, field emitters operating in a dc regime can reliably provide current densities not exceeding ~0.1 A/cm2. This factor, together with low yield stress of catalytic droplets, hinders the creation of high-current field-emission cathodes. Indeed, attempts at increasing the group of effectively emitting carbon nanostructures with dominating aspect ratios by including other nanoobjects due to increasing inter-electrode potential difference fail because this leads to fracture of catalytic bases the operating emitter groups. Attempts to form arrays of uniform nanostructures in solid films [4] allowed the dispersion of emitter point diameters to be significantly decreased, but the scatter of nanoobject aspect ratios in the array (related to a significant spread of lengths) still remains unacceptably large.

This Letter describes new field-emission cathodes for solid-state field-emission diodes, with the active surface containing nanoobjects occurring under identical conditions with respect to the field electron emission, irrespective of their heights. The proposed approach is illustrated by the results of experimental investigations of the characteristics of solid-state field-emission diodes, which were created for the first time using silicon/diamond heterostructures with nanostructured hetero-boundaries containing arrays of nanostructured semiconductor objects.

Figure 1 shows typical SEM micrographs of an array of semiconductor nanostructures (Fig. 1a) and transverse cleavage of the heterostructure of a solid-state field-emission diode (Fig. 1b). Advantageous features of the formation of an array of nanosized emitter points (e.g., cones) are related to the possibility of significantly enhancing the electric field in the vicinity of their vertices, which increases probability of the under-barrier transport of charge carriers via metallurgical boundary of the heterojunction. This regime of emitter operation can be implemented not only for silicon points, but also for those made of some other semiconductors (e.g., Ge, SiC, GaAs). The use of a polycrystalline diamond film weakly doped with acceptors as a collector layer of the solid-state field-
emission diode provides identical threshold conditions that ensure participation of a large fraction of nanoobjects of the array in the field emission process.

Comparative investigations of the current–voltage ($I–U$) characteristics of electron emission into vacuum from (i) arrays of nanostructures formed on silicon substrates and (ii) solid-state diodes based on silicon/diamond heterostructures with the same surface density of nanoobjects on a polycrystalline diamond substrate showed that the latter diode currents exceed those emitted from the silicon-based nanostructure array (for the same specific area) by approximately three orders of magnitude. For example, the field emission into vacuum from silicon-based nanostructure arrays gave a current not exceeding 50–70 $\mu$A from an area of 1 mm$^2$. At the same time, for a solid-state diode with the same density of nanoobjects on the heteroboundary, the current emitted from a 1 mm$^2$ area reached about 50 mA. Note also that the threshold fields for the emission into vacuum from the array of nanostructures on silicon amount to $\sim$5–7 V/µm, while the threshold fields in a solid-state diode, the direct branch of the $I–U$ curve of which has a Fowler’s character, are about 0.2 V/µm.

Figures 2 and 3 show the typical $I–U$ curves and the temperature dependences of current for solid-state diodes. As can be seen, the $I–U$ curve has a diode character and its direct branch beginning with $U \sim 0.35$ V is indicative of electron emission according to the Fowler–Nordheim mechanism. Thus, it can be suggested that the $p–n$ heterojunction directly biased to 0.35 V provides conditions for the effective field emission of electrons from nanostructured silicon/diamond heteroboundary, which is evidenced by the Fowler’s character of the dependence of current on the voltage. Processing of the direct branch of the $I–U$ curve of the solid-state diode with allowance for the known diameters of cones ($\sim$20 nm, Fig. 1a) allowed us to evaluate the barrier at the silicon/diamond heteroboundary as $q\phi_k \approx 0.1$ eV and determine...