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CVD diamond structures with a $p-n$ junction — diodes and transistors

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The doping of diamond with boron and phosphorus in a plasma chemical reactor with a laminar gas flow was investigated. Diamond layers heavily doped with boron and phosphorus were obtained. The layers had low resistivity with high crystalline perfection. Structures for the formation of electronic devices on diamond have been created on the basis of such layers. Several types of diamond devices have been studied: Schottky diode, *pn*-Schottky diode, $p-i-n$-diode and field effect transistor. High values of breakdown fields and current densities in the studied devices have been obtained.

Keywords: CVD diamond, diamond structures, Schottky diode, $p-i-n$-diode, field effect transistor.

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Introduction

Currently diamond is a promising material to develop the next generation of powerful and high-frequency semiconductor devices [1,2]. Diamond has unique physical properties: high mobility of electrons $(1000\,\mathrm{cm^2/(V{\cdot}s)})$ [2,3] and holes $(2000\,\mathrm{cm^2/(V{\cdot}s)})$ [2,4] with low doping, high drift velocity of charge carriers in strong electric fields $(2.1 \cdot 10^7\,\mathrm{cm/s})$ [5], record thermal conductivity $(22\,\mathrm{W/(cm{\cdot}K)})$ [6] and high breakthrough field $(7-9\,\mathrm{MV/cm})$ [7]. By a combination of its physical properties the semiconductor diamond substantially exceeds other wide-band materials [8]. The main drawback of the diamond are deep energy levels of impurities — 0.38 eV [9] when diamond is doped with boron (*p*-type of conductance) and 0.57 eV [10] when diamond is doped with phosphorus (*n*-type of conductance). For such energy levels only a very small part of the doping impurity is ionized at room temperature. As the doping impurity concentration increases, the mobility of the charge carriers decreases due to drastically rising scattering in neutral and ionized impurities [11,12]. At high levels of doping the zonal type of conductance in the diamond first changes to the hopping type of conductance [13], and then to the metal type of conductance [14], which is observed only when the diamond is doped with boron. When the diamond is doped with phosphorus, it was not possible to obtain such a transition yet [15]. Therefore, comparison of the diamond characteristics at low level of doping with other semiconductor materials is not quite correct [16]. Indeed, at low level of doping the diamond layers have rather high specific resistance. To reduce the resistance, the doping level is increased. Besides, the mobility of the carriers and the breakthrough characteristics decrease. Paper [16] with account of these factors estimates the Schottky barrier diode parameters, necessary to obtain the low resistance of the diode and high breakthrough voltages. And the estimate results differ from the results obtained for the diamond characteristics at low level of doping.

When the electronic device is developed, it is necessary to grow a structure that contains several layer of the diamond with various doping levels. For this purpose, the plasma-chemical method of diamond deposition from the gas phase is most suitable — CVD (chemical vapor deposition) method [17], since this method, contrary to other methods, makes it possible to vary doping levels in a wide range in the lamellar diamond structure. Diamond is deposited in the plasma-chemical reactors based on microwave cavities excited at frequency of 2.45 GHz [18]. Inside the resonant cavity the plasma is developed in a gas mixture at pressure of $30-500$ Torr. The gas mixture consists of hydrogen with a small additive of methane. As a result of rather complicated sequence of both volume and surface chemical reactions, a CVD-diamond is deposited on the substrate. To produce a doped diamond, gases containing boron or phosphorus are added to the gas mixture.

This paper presents the results of the study on diamond doping with boron and phosphorus and creation of diamond structures that contain a sequence of such layers. The results are provided from the development and research of the prototypes of some electronic devices formed on the diamond structures: Schottky barrier diode, *pn*-Schottky barrier diode, $p-i-n$-diode and field transistor. The transport characteristics of these devices have been studied.

1. Experimental procedure

All epitaxial layers of the structures doped with boron and phosphorus were grown in a CVD-reactor developed in the Institute of Applied Physics of the Russian Academy of Sciences and described in detail in paper [19]. The reactor is a cylindrical microwave cavity with a quartz pipe installed on its axis, through which the working gas mixture is pumped. Inside the pipe a substrate holder is installed, above which plasma is generated by radiation of a magnetron at frequency of 2.45 GHz. The reactor design makes it possible to quickly (for the time of less than 10 s) change the composition of the gas mixture. The non-doped diamond was grown in the gas mixture $H_2 + CH_4$ (ratio $CH_4/H_2 = 0.1-1\,\%$). To grow the layers doped with boron and phosphorus, diborane (B_2H_6) or phosphine (PH_3) was added to the working gas mixture. The main advantage of the used reactor compared to other CVD-reactors is the fact that in it the plasma is maintained in the laminar vortex-free flow of gas, which promotes less contamination of the reactor with a doping impurity in process of deposition of heavily doped diamond layers.

Diamond structures doped with boron and phosphorus were grown on the substrates from the diamond of type IIa with crystal-lattice orientation (001) and size $3.5 \times 3.5 \times 0.5$ mm, produced by HPHT (high pressure high temperature) method [20]. Prior to the growth process, the substrates were mechanically polished to the surface roughness of 0.2 nm, measured using white light interferometer Zygo NewView 7300 in the area of 0.22×0.22 mm. To eliminate defects introduced by polishing, a layer was etched off the substrate with thickness of $5\,\mu$m in the ICP (inductive coupled plasma) (Oxford Instruments, Plasmalab 80) [21]. As a result, to grow the epitaxial layers of the CVD-diamond, a defect-free substrate was used with the atomically smooth surface.

Measurement of boron and phosphorus concentration in the grown diamond structures was done using the SIMS method (secondary ion mass spectrometry) on TOF.SIMS-5 (IONTOF) device with separate functions of ion beams „sputtering“. Sputtering was done with ions Cs^+ having energy of 1 keV, probing Bi_3^+ having energy of 25 keV. Negative secondary ions were recorded. To determine the concentration of boron and phosphorus atoms, several lines were used that correspond to different ions of these elements, which made it possible to substantially increase the measurement accuracy. For quantitative calibration, test specimens were used from single-crystal diamond (100), implanted with boron and phosphorus ions. Depth of etching craters to recalculate the etching time into the analysis depth was measured on white light interferential microscopes Talysurf CCI 2000 and Zygo NewView 7300.

2. Diamond doping

To design the electronic devices on the diamond, it is necessary to grow a structure that consists of several layers with a different doping level. For the active layers, the required level of doping mixture concentration is in the range of $10^{15}-10^{17}\,\mathrm{cm}^{-3}$, and for the contact layers the layer of doping mixture concentration must exceed $10^{20}\,\mathrm{cm}^{-3}$. There are several methods of diamond doping: ion implantation, temperature gradient method at high pressure and temperature (HPHT), CVD-method of deposition in the hot-filament reactors and CVD-method of deposition in the reactors with microwave cavities. The ion implantation method may dope the diamond with boron only, and the specific resistance value is higher than for the layers obtained by the CVD-method, and when the threshold dose of implantation is exceeded, the diamond, by contrast with silicon, converts to graphite [1]. The high pressure and temperature method makes it possible to create the thick layers doped with boron and phosphorus [22,23], but it is not possible to obtain high values of doping impurity concentration in these layers. Thus, the boron doping leads to the maximum impurity concentration of $10^{19}-10^{20}\,\mathrm{cm}^{-3}$, and the minimum specific resistance is $10\,\Omega\cdot$cm [22]. Doped layers of the diamond with the least specific resistance may only be obtained by the CVD-method. In both types of the CVD-reactors (in the microwave one and with hot filaments) it is possible to obtain the layers doped with boron at concentration of $10^{21}\,\mathrm{cm}^{-3}$ with specific resistance of $10^{-3}\,\Omega\cdot$cm, and with phosphorus at concentration $10^{20}\,\mathrm{cm}^{-3}$ with specific resistance $70\,\Omega\cdot$cm [24]. Besides, the main disadvantage of the hot filament reactors is the high level of metal impurities, which may impact the characteristics of electronic devices.

2.1. Diamond doping with boron

Diamond doping with boron in process of CVD-synthesis is described in quite many papers [24–27]. Doping is accompanied with high incorporation of the impurity boron atom in the diamond crystalline lattice, which is related to the closeness of its covalent radius 82 pm to carbon radius 77 pm. High incorporation complicates the controlled doping of diamond with boron in the range of concentrations $10^{15}-10^{17}\,\mathrm{cm}^{-3}$ due to technical difficulties of controlling the small gas flows and the level of reactor contamination with boron in process of its use. With large gas flows of the doping impurity in the reactor, the doping level (concentration of the impurity boron in the crystalline lattice) is saturated. For the crystallographic surface (001) the saturation comes at the doping level $1 \cdot 10^{21}-3 \cdot 10^{21}\,\mathrm{cm}^{-3}$, and the number of the crystalline lattice defects increases in the doped layers, and they become unfit for development of instrumental structures on their basis.

We studied the diamond doping with boron at high doping levels. Special attention was then paid to obtaining high quality layers with the least surface roughness and small specific resistance. Diamond layers heavily doped with boron, having thickness of $3-4\,\mu$m were grown in the reactor at gas pressure of 60 Torr and methane content of around 1 % in the gas mixture. Fig. 1, *a* shows the dependence of boron concentration in the layers on the B/C ratio in the gas mixture obtained by SIMS method. Fig. 1, *b* shows the profile of the boron concentration in the

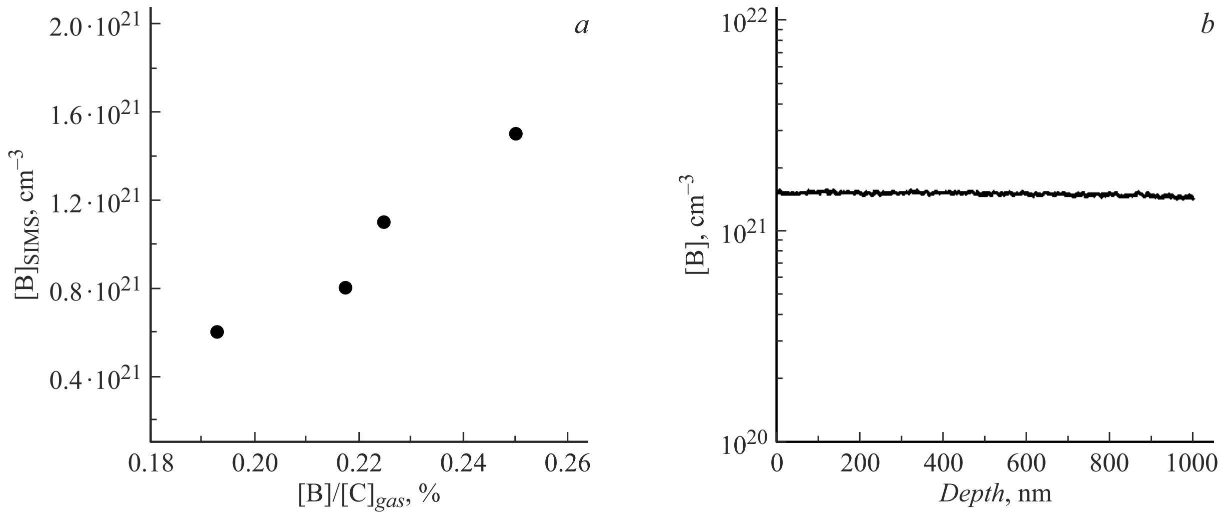

Figure 1. Dependence of boron concentration in epitaxial CVD-layers of diamond on boron content in gas mixture (*a*). SIMS profile of boron concentration in the doped layer (*b*).

layer obtained at B/C ratio in the gas mixture at 0.25 %. As the boron content increased further, the boron concentration practically did not change in the layer, and the speed of growth of the boron-doped diamond reduced substantially from $1-2$ to $0.1-0.2\,\mu$m/h, and the surface roughness increased greatly. For all layers shown in fig. 1, *a*, the electrophysical values were measured by the Hall method, and swing curves for reflection (004) of the diamond by method of X-ray diffractometry on Bruker D8 Discover device. The shift of the swing curve of the layer relative to the swing curve of the substrate determined the value of the „structural" impurity of boron, i.e. concentration of boron that substituted carbon in the lattice. The electrophysical measurements recorded *p*-type of conductance, the specific resistance decreased from $3 \cdot 10^{-3}$ to $10^{-3}\,\Omega$·cm with the growth of the boron content in the gas mixture. The conducted measurements of „nominal" (SIMS method), „structural" (X-ray diffractometry) and electrically-active (electrophysical measurements) boron concentrations in the grown specimens demonstrated their good match, i.e. in the used method of doped diamond growth practically all boron incorporated in the diamond was electrically active.

The surface roughness of the diamond layers was measured using white light interferometer Zygo in the area of 0.22×0.22 mm. The mean-square roughness of the surface in this area was 0.3 nm. The arithmetic-mean roughness of the surface measured along a random line in the area of measurement of the mean-square roughness was 0.085 nm. Therefore, in the found growth mode the diamond crystal growth was implemented in the form of serial filling of atom planes (step-flow) growth [28].

2.2. Diamond doping with phosphorus

Diamond doping with phosphorus in process of CVD-synthesis is a more complicated task compared to diamond doping with boron [29–31]. This is due to the large difference of covalent radii of phosphorus (106 pm) and carbon (77 pm). Currently the least value of the specific resistance obtained on the substrates with crystal-lattice orientation (111) [15], is $70\,\Omega$·cm at phosphorus concentration in the diamond 10^{20} cm^{-3}. It is not possible to obtain a noticeable level of conductance on the substrates with orientation (001) in the wide range of phosphorus impurity concentrations.

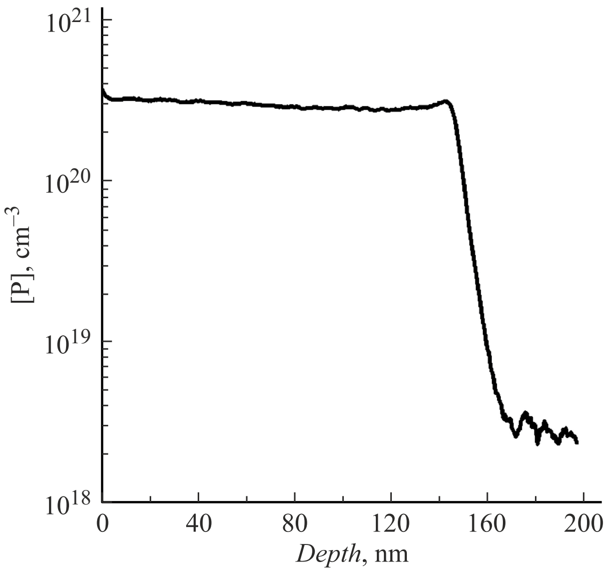

Figure 2. SIMS profile of phosphorus concentration in the doped layer.

We studied the diamond doping with phosphorus on the substrates with crystal-lattice orientation (111). As a result, it was possible to find the mode where the maximum phosphorus concentration in the diamond was achieved.

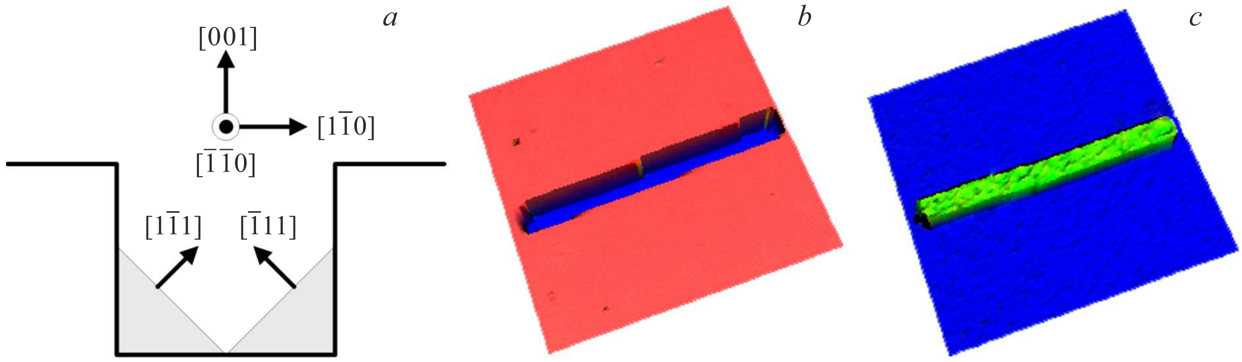

Figure 3. Cross section of groove etched in diamond. The arrows indicate the direction of diamond growth in the groove (*a*). The profile of the diamond surface with the etched groove with width of 9 μm, depth of 250 nm and length of 100 μm (*b*). The diamond surface profile with the groove filled with diamond heavily doped phosphorus (*c*).

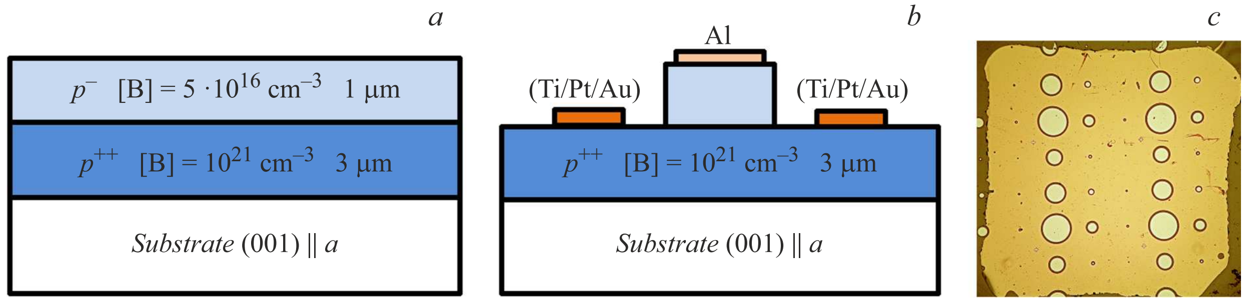

Figure 4. Scheme of diamond structure made of layers with different level of doping (*a*). Scheme of Schottky barrier diode in pseudovertical geometry (*b*). Photograph of diamond surface with the manufactured Schottky barrier diodes (*c*).

Fig. 2 shows the phosphorus concentration profile in the grown layer, obtained at P/C in the gas mixture at 50 %, pressure of 75 Torr and methane content in the gas mixture 0.1 %. Phosphorus concentration in the diamond reached $3 \cdot 10^{20}\,\mathrm{cm}^{-3}$. Electrophysical measurements by Hall method demonstrated the presence of the n-type of conductance in the grown layer at the specific resistance of 5–7 Ω·cm.

Paper [32] proposed the method to develop the areas heavily doped with phosphorus on the surface with crystal-lattice orientation (001). A groove of rectangular shape is etched on the diamond surface with width of several microns and depth of several hundreds of nanometers (fig. 3, *a*). Then the groove was covered with growth of the layer heavily doped with phosphorus in the growth mode, when the diamond grows only in direction [111], the growth speed in direction [001] in this mode was close to zero. As a result, the area is developed in the groove, which is heavily doped with phosphorus with the conductance level that is same as in the layers heavily doped with phosphorus on the surface with orientation (111). We implemented this technology [33]. Fig. 3, *b* showed the profile of the diamond surface with the etched groove with width 9 μm, depth 250 nm and length 100 μm, and in fig. 3, *c* the surface profile after its covering with growth in the growth mode for the surface (111).

3. Doped diamond structures

3.1. Schottky barrier diode

One of the most studied electronic devices on the diamond is a Schottky barrier diode [8,34–36]. The diode is made in two types of geometries: in the vertical and pseudovertical ones. When the diode is made in vertical geometry, an HPHT-substrate is used which is doped with boron. When the diode is made in pseudovertical geometry, a heavily-doped diamond layer is grown in the non-doped HPHT-substrate. As it was noted already, in the boron doped HPHT-substrates it is not possible to obtain high levels of concentrations and low values of specific resistance [22]. Besides, in the boron-doped HPHT-substrates a large density of dislocations is observed — around $10^6\,\mathrm{cm}^{-2}$ [37]. Therefore, it seems promising to develop the Schottky barrier diodes in the pseudovertical geometry using the thick heavily doped diamond layers of high crystalline perfection grown with the CVD-method.

The structure grown by us on the non-conducting HPHT-substrate is shown in fig. 4, *a*. The structure contained two layers: a layer heavily doped with boron of thickness 3 μm and concentration $10^{21}\,\mathrm{cm}^{-3}$ and a layer lightly doped with boron of thickness 1 μm and boron concentration of $5 \cdot 10^{16}\,\mathrm{cm}^{-3}$. To develop the Schottky barrier diode, in the oxygen-containing ICP-plasma via a metal mask a

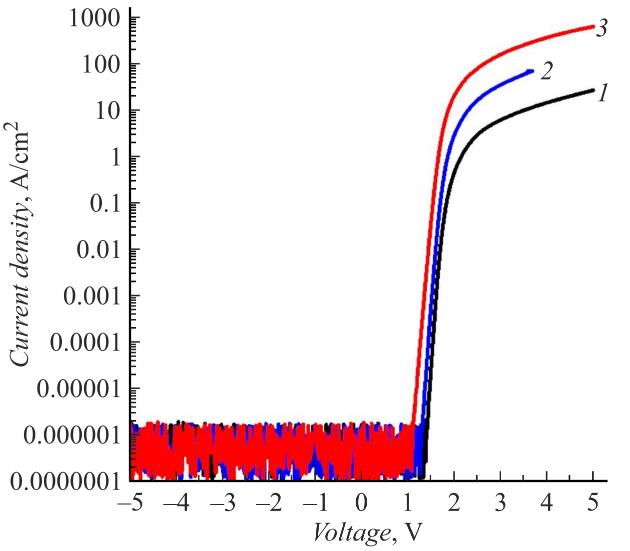

Figure 5. CVC of Schottky barrier diode with diameter of $300\,\mu$m at various temperatures of the specimen: *1* — 21, *2* — 51, *3* — $110\,^{\circ}$C.

mesastructure was etched for access to a layer heavily doped with boron, onto which the ohmic contacts Ti/Pt/Au were applied (fig. 4, *b*). Aluminum was used as a Schottky contact. Fig. 4, *c* shows a photograph of the diamond surface with the manufactured Schottky barrier diodes.

Current-voltage curve (CVC) of the diode taken at different temperatures of the specimen is shown in fig. 5. At 5 V voltage the current density in the forward direction in the diode with diameter of $300\,\mu$m achieved $30\,\mathrm{A/cm^2}$ at room temperature, as the temperature increases to $110\,^{\circ}$C the current density increased $640\,\mathrm{A/cm^2}$ due to strengthening of the thermal activation of the boron impurity in the lightly doped layer. Using the given CVCs, the Schottky barrier value and the diode ideality factor were assessed. The Schottky barrier value was $1.8-1.9$ eV, and ideality factor — 1.1. When the diode was connected in the backward direction, the breakthrough voltage value was 300 V, which corresponds to the breakthrough field of 3 MV/cm. The diode rectification coefficient at voltage of ± 5 V exceeded 10^7. It should be noted that when the diode was connected in the backward direction, the obtained current density $7 \cdot 10^{-7}\,\mathrm{A/cm^{-2}}$ $(5 \cdot 10^{-10}\,\mathrm{A})$ matched the sensitivity limit of the measurement device. The conducted additional measurements using a more sensitive device demonstrated that the backward current density was substantially lower and amounted to around $10^{-11}-10^{-10}\,\mathrm{A/cm^{-2}}$ $(10^{-14}-10^{-13}\,\mathrm{A})$. Such low current density at diode connection in the backward direction makes the developed Schottky diode promising in development of the supersensitive sensors of ionizing radiation, where this current determines the value of the dark current of the sensor. Reduction of the dark current causes increased signal-to-noise ratio of the ionizing radiation sensor.

3.2. *pn*-Schottky barrier diode

Another unipolar diode on the diamond is *pn*-Schottky-pn diode [38–40]. Its primary difference from a regular Schottky barrier diode consists in the fact that the active layer is doped instead of boron with phosphorus at low concentration. The thickness of the active layer and the doping level are chosen so that phosphorus in the active layer is fully depleted, and conductance electrons do not participate in the transport of charge carriers. The primary advantage of the *pn*-Schottky barrier diode — in high values of breakthrough fields with the preserved high density of current at diode connection in the forward direction [39].

Fig. 6, *a* shows the structure grown by us on a non-conducting HPHT-substrate. The structure contained three layers: heavily doped with boron with thickness of 250 nm and concentration of $10^{21}\,\mathrm{cm^{-3}}$, doped with boron with thickness of $1\,\mu$m and concentration of $10^{20}\,\mathrm{cm^{-3}}$, and a layer lightly doped with phosphorus having thickness of 150 nm and concentration of phosphorus $2 \cdot 10^{17}\,\mathrm{cm^{-3}}$. To develop the *pn*-Schottky barrier diode, a mesastructure was etched for access to a layer heavily doped with boron, onto which the ohmic contacts Ti/Mo/Au were applied (fig. 6, *b*). A compound Ti/Mo/Au was applied on the surface of the lightly doped layer, which at such low phosphorus concentrations forms a Schottky contact on the diamond surface. Fig. 6, *c* shows a photograph of the diamond surface with the manufactured *pn*-Schottky barrier diodes.

Fig. 7 shows the diode CVC. At voltage of 20 V in the forward direction the current density in the diode reached $1\,\mathrm{kA/cm^2}$ at the room temperature. Using the given CVCs, the Schottky barrier value and the diode ideality factor were assessed. The Schottky barrier value was $1.1-1.2$ eV, and ideality factor — 8. When the diode was connected in the backward direction, the breakthrough voltage value was 90 V, which corresponds to the breakthrough field of 6 MV/cm. The diode rectification coefficient at voltage of± 20 V exceeded 10^7.

3.3. *p–i–n*-diode

In diamond *p–i–n*-diodes the highest values of the current density were achieved in manufacturing of the diodes on the substrates with crystal-lattice orientation (111) [41,42] due to the ability of heavy doping of the diamond with phosphorus for this surface. At the same time it is not possible to achieve the high values of reverse voltages due to multiple defects of the layers grown with crystal-lattice orientation (111). We proposed the method to develop a *p–i–n*-diode on surface (001), where *n*-area presents a groove of rectangular shape, where the diamond is grown selectively in the growth mode for the surface (111) [33]. Previously such grooves were used only to reduce the contact resistance to the layers doped with phosphorus grown on the surface (001) [43]. One of the promising applications of the *p–i–n*-diode on the diamond it is use as a source of single photons [44].

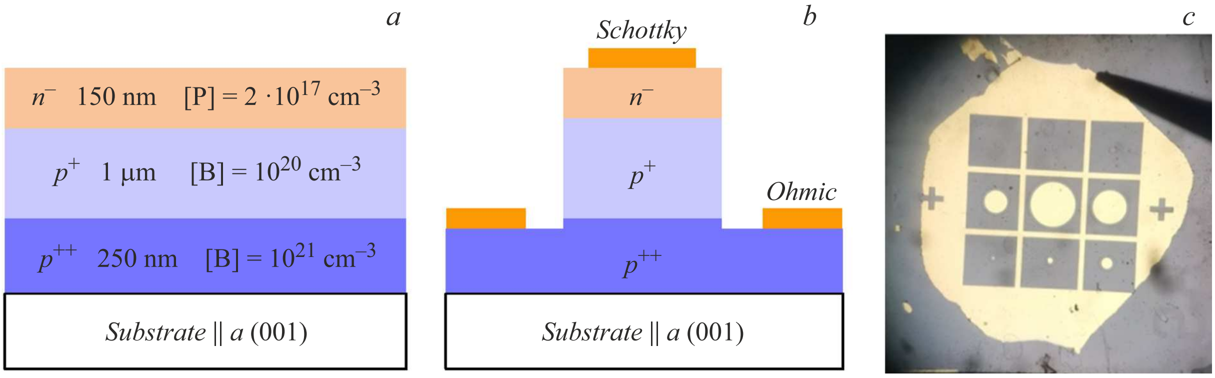

Figure 6. Scheme of diamond structure made of layers doped with boron and phosphorus (*a*). Scheme of *pn*-Schottky barrier diode in pseudovertical geometry (*b*). Photograph of diamond surface with the manufactured *pn*-Schottky barrier diodes (*c*).

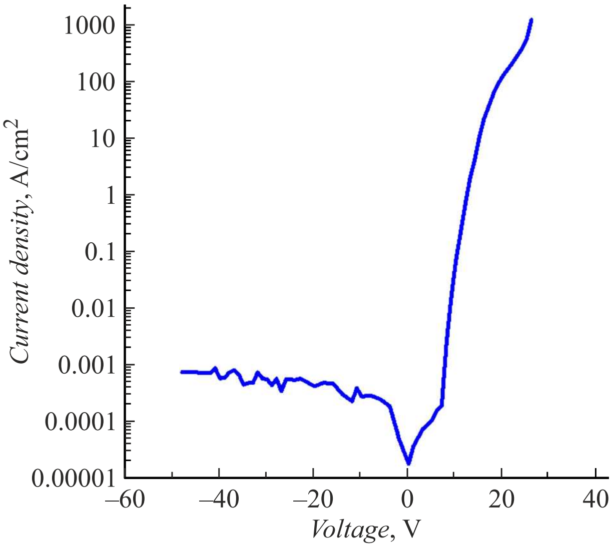

Figure 7. CVC of *pn*-Schottky barrier diode.

Optical radiation in such source is formed as a result of electroluminescence of the color center placed in the i-area of the $p{-}i{-}n$-diode. We performed the studies of the electroluminescence of the nitrogen–vacancy (NV-center) color centers in the diamond $p{-}i{-}n$-diode [33], and the silicon–vacancy (SiV-center) color center in the combined diode [45], representing parallel connection of the Schottky barrier diode and $p{-}i{-}n$-diode [46].

Fig. 8, *a* shows the scheme of $p{-}i{-}n$-diode. The diode was formed from the structure made of the layer heavily doped with boron — p-area of the diode and the layer doped with silicon — i-area of the diode (silicon in the diamond is not an electrically-active impurity). Doping with silicon was done to create SiV-color centers in the internal area of the diode. To isolate the upper part of the structure from the metal contact, ZrO_2 dielectric is applied on it. Fig. 8, *b* shows photographs of $p{-}i{-}n$-diode in absence of current and current of 1 mA, made with the optic microscope at the substrate side. Light rectangular frame *2* — ohmic contact to p^{++}-layer *1*. Rectangular area *3* — ohmic contact applied on the mesastructure. Band in the center *4* — this is n^+-area of the diode. When current of 1 mA flows in the diode (the right photograph), the bright luminescent band — is the area between the n^+-area and the p^{++}-layer, where electroluminescence of SiV-centers occurs. Fig. 8, *c* shows CVC of $p{-}i{-}n$-diode. The diode opened at voltage of 5 V. At voltage of 30 V in the forward direction the current in the diode reached 2 mA, which at groove width 4 μm and length 100 μm corresponds to current density 500 A/cm^2. As we know from the literature, in $p{-}i{-}n$-diode made on substrates with orientation (001), such high current densities were not achieved yet. Achievement of high current densities in $p{-}i{-}n$-diode made it possible to substantially increase the intensity of radiation in the SiV-centers.

3.4. Field transistor

Currently the best characteristics are obtained for field effect transistor on diamond, using a surface hydrogenated (H-terminated) layer as a conducting channel [47]. However, the parameters of such transistors deteriorate with time and degrade at higher temperatures [48]. Transistors with volume conducting channel are stable in time, may operate at high temperatures, but their output characteristics are still inferior to transistors on H-terminated layer.

Fig. 9, *a* shows the structure grown by us on a non-conducting HPHT-substrate. The structure contained two layers: a layer lightly doped with boron with thickness of 500 nm with boron concentration $4 \cdot 10^{17}\,cm^{-3}$ and a layer heavily doped with boron with thickness of 10 nm and concentration of $10^{21}\,cm^{-3}$. The heavily-doped layer was used to reduce the contact resistance to the lightly-doped layer. Ohmic contacts (Ti/Pt/Au) were applied on them. In the gate area the heavily-doped layer was etched in the oxygen-containing plasma. Then a gate of aluminum was applied on the surface (fig. 9, *b*). Fig. 9, *c* shows a photograph of the diamond surface with the manufactured field effect transistor.

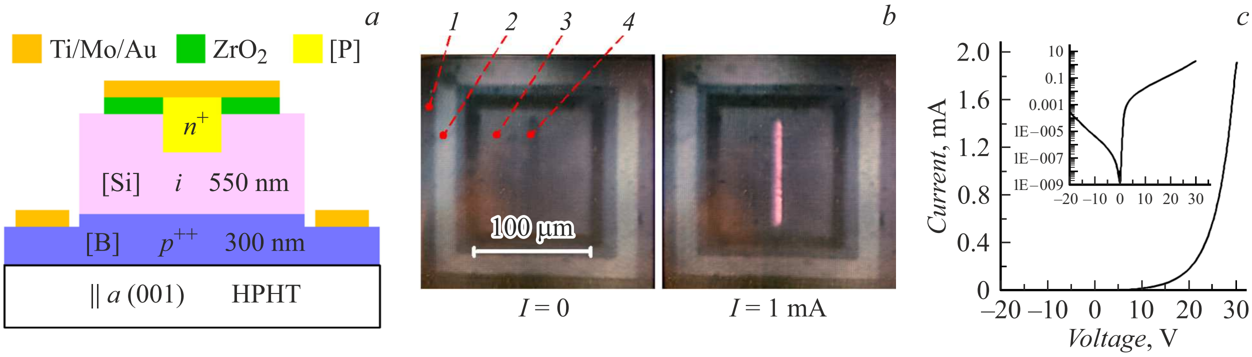

Figure 8. Scheme of $p-i-n$-diode (a). Photographs of $p-i-n$-diode at the absence of current and current of 1 mA, made with the help of optical microscope at the side of the substrate: *1* — p^{++}-layer, *2* — ohmic contract Ti/Mo/Au to p^{++}-layer, *3* — ohmic contact Ti/Mo/Au, applied on the mesastructure, *4* — n^+-area of the diode (b), CVC of $p-i-n$-diode (c). The figure was taken from paper [46].

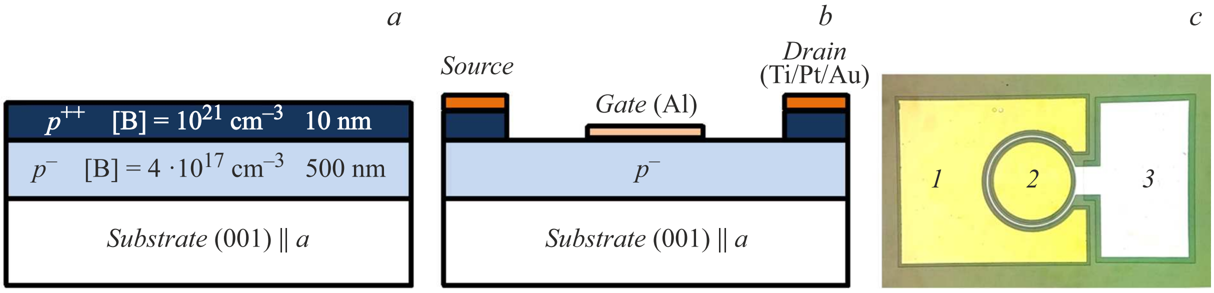

Figure 9. a — scheme of the diamond structure; b — scheme of field effect transistor; c — photograph of diamond surface with the manufactured transistor: *1* — source, *2* — drain, *3* — gate.

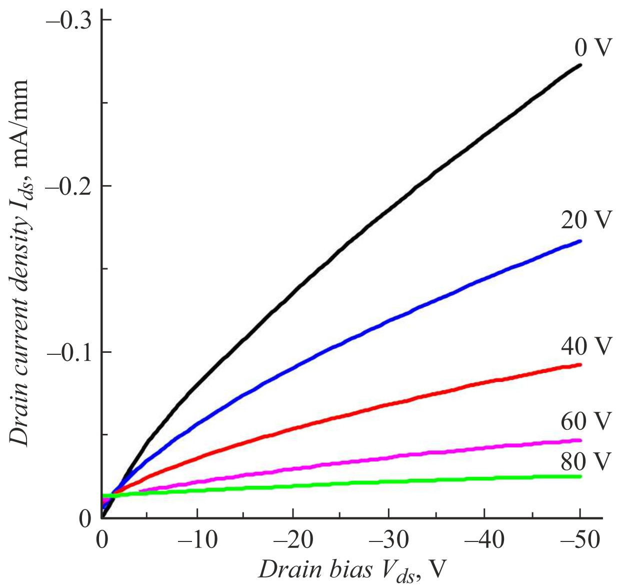

Figure 10. Output characteristic of transistor.

Fig. 10 shows the output characteristic of the transistor. At zero voltage on the gate (the transistor is fully opened) the current density reached the value of 0.27 mA/mm, which is comparable to the best current densities obtained for the field effect transistor on the diamond with the volume conductance channel [49]. As the voltage increases on the gate, the current in the transistor channel reduces, but the transistor is not fully closed. This is related to the leaks in the transistor gate.

Conclusion

Studies of the diamond doping with boron and phosphorus were carried out in the plasma-chemical reactor with a laminar gas flow. The layers were obtained, which were heavily doped with boron having concentration of $6 \cdot 10^{20} - 1.5 \cdot 10^{21}$ cm^{-3}, and low specific resistance from $3 \cdot 10^{-3}$ to 10^{-3} Ω·cm on substrates with crystal-lattice orientation (001). The conducted measurements of „nominal“ (SIMS method), „structural“ (X-ray diffractometry) and electrically-active (electrophysical measurements) boron concentrations in the grown specimens demonstrated their good match. The layers were obtained, which were heavily doped with phosphorus having concentration of $3 \cdot 10^{20}$ cm^{-3}, and low specific resistance 5–7 Ω·cm on substrates with crystal-lattice orientation (111). Based on these layers, the structures were grown to form diamond instruments: Schottky barrier diode, *pn*-Schottky barrier diode, $p-i-n$-diode and field effect transistor. The high values of breakthrough fields were obtained up to 6 MV/cm, and current densities up to 1 kA/cm^2 in such devices.

The electronic devices on diamond that we studied already have the characteristics that make them potentially in demand for various applications. Thus, Schottky barrier diodes had high current densities, which makes them promising for us in the power electronics assemblies. In the Schottky barrier diode made in pseudovertical geometry it was possible to obtain low current densities — less than 10^{-11} A/cm^{-2} when the diode is connected in backward direction, which makes it promising in development of supersensitive sensors of ionizing radiation. Production of the layers heavily doped with phosphorus made it possible to implement $p-i-n$-diodes with high density of current made on the surface of the diamond with crystal-lattice orientation (001). The conducted study of electroluminescence of NV- and SiV-color centers in the developed diodes demonstrated the promising outlook of their use to develop the sources of single photons based on these color centers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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