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CVD diamond with boron-doped delta-layers deposited by microwave plasma

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Introduction

The semiconductor single-crystal CVD diamond (obtained from the gas phase during homoepitaxial deposition) is a wide band gap semiconductor with a gap width of 5.5 eV. CVD diamond has unique characteristics – high mobility of charge carriers, high carrier saturation speed, high electric breakdown field, the greatest thermal conductivity, high radiation and chemical resistance. On a combination of properties the CVD diamond is superior to other wide band gap semiconductors and is considered a promising material for the creation of a new generation of high-power and high-frequency electronic devices. The main difficulty in realization of the potential of CVD diamond as an electronic material is the problem of creating charge carriers inside it. Compared with conventional semiconductors, dopants in diamond have deeper energy levels that significantly impede the activation of the dopant (the degree of ionization of the dopant at room temperature is less than 1%). Thus, in order to create an acceptable level of conductivity, it is necessary to increase the level of doping, but in case of boron doping this leads to a decrease of carriers (holes) mobility in diamond. To solve the problem of boron doping of CVD diamond, an approach based on delta-doping technology is known. A thin layer of diamond heavily doped with boron (having a thickness of 1–2 nm and concentration of boron atoms higher than 5×10^{20} cm^{-3}) is formed inside an undoped defect-free diamond of high quality. To achieve high electronic properties (obtaining high hole mobility and conductivity of the layer), it is necessary to realize sharp boundaries between the doped and undoped materials. Recently, this problem has been successfully solved [1, 2]. This report provides an overview of the results of studies on the growth of electronic-quality epitaxial layers of diamond, the production of heavily boron-doped layers and the study of their characteristics.

Experiments

The novel microwave plasma assisted CVD reactor for growth of nanometric boron delta-doped layers with ultra-sharp interfaces between doped/undoped materials was built in IAPRAS [1]. Fig. 1 shows a schematic of the reactor. The main features of the reactor are: 1) rapid gas switching; 2) laminar gas flow; 3) axial symmetric resonant mode – symmetric discharge; 4) slow growth of diamond 40–100 nm/h. We achieve rapid gas switching from one input gas to another by a home-made electronic switch. The residence time of the reactor is approximately 5 s.

In developed reactor the diamond deposition regimes in which one obtains thin doped delta layers with thickness of 1–2 nm with concentrations of boron about $5\cdot10^{20}$ cm^{-3} were found. Typical parameters of the delta layer under these conditions are given in Fig. 2 for the SS6-1 sample, in which the boron concentration is $4.8\cdot10^{20}$ cm^{-3} and thickness is 1 nm.

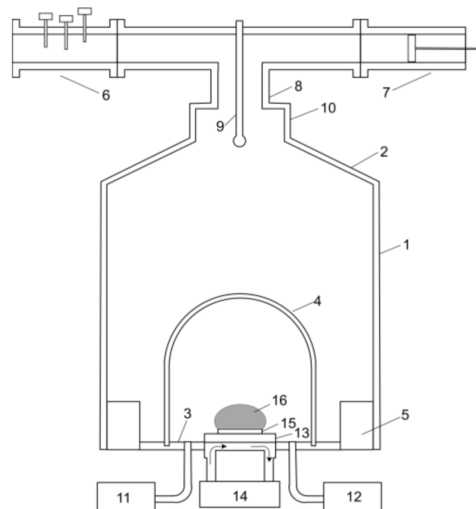

Fig. 1. Experimental setup: 1 – cylindrical cavity, 2 – circular cone, 3 – bottom cavity wall, 4 – quartz dome, 5 – step ledge, 6 – waveguide system, 7 – plunger, 8 – coaxial line, 9 – antenna, 10 – shorted cylindrical waveguide, 11 – gas supply system, 12 – gas evacuation system, 13 – substrate holder, 14 – substrate cooling system, 15 – substrate, 16 – microwave discharge

Measurement of the boron concentration in the grown samples was carried out by the secondary ion mass spectroscopy (SIMS) method using a time of flight SIMS setup (IONTOF TOF.SIMS-5). The depth of the etch craters for calculation of the analysis depth from the etching time was carried out using white light interference microscopes Talysurf CCI 2000 and Zygo NewView 7300. Sputtering was performed by Cs^+ ions with energy of 1 keV at angle of 45°. The probing was carried out by Bi^+ ions with energy of 25 keV. The output of the cluster ion C_2B^- was registered. Quantitative calibration of the mass spectrometer was performed using a test HPHT crystal implanted with boron ions with three different maximum concentrations (10^{18}, 10^{19} and 10^{20} cm^{-3}).

Capacitance–voltage measurements were performed on sample Tr06 with two ‘delta layers’ and an underlying heavily doped layer. Mesa structures of diameters 25 to 400 μm were formed by lithographic masking and etching down to the heavily boron doped layer. Ohmic contacts were formed after etching on the heavily doped layer p^{++} layer by deposition of Ti/Mo/Au metallization and annealing. Schottky contacts were formed on the top of the mesas with Cr/Al metallization. The profiles of

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holes concentration and boron concentration in the Tr06 structure are shown in Fig. 3. For the investigated boron delta layer in diamond, the activation energy was determined to be ~ 60 meV, which is less than the activation energy of boron in diamond (370 meV) and corresponds to a high boron concentration, which according to SIMS data exceeds $3\cdot10^{20}$ cm^{-3}.

For another sample, Tr12, with higher boron concentration and less thickness of delta layer the hole profile is changed. The profiles of holes concentration and boron concentration in the Tr12 structure are shown in Fig. 4. It is seen that the portion of holes outside of the delta layer sufficiently increased then it was for Tr06 sample.

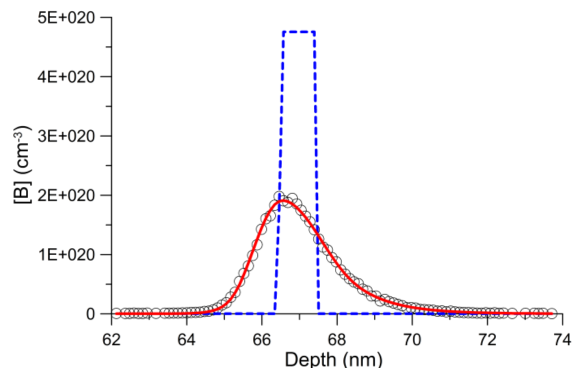

Fig. 2. Boron concentration profiles determined by SIMS (circles); boron concentration profiles recovered using depth resolution function (dashed line); convolution of recovered profile and depth resolution function

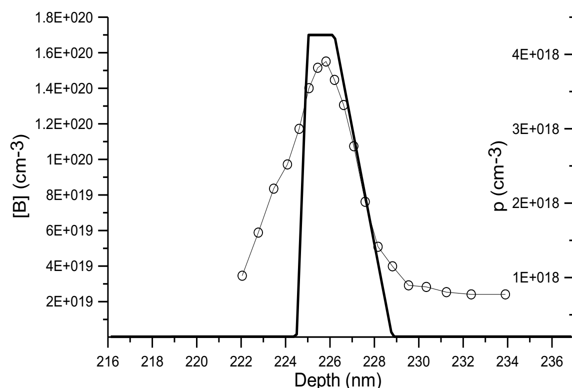

Fig. 3. Comparison of boron concentration profile recovered using analytical depth resolution function (solid line) and hole profiles extracted from C-V analysis measured at room temperature (circles), Tr06 sample

Measurements of the holes mobility in various samples were made by the Van der Pau method, and the maximum hole mobility was determined to be 300 $V^2/cm\cdot s$. Because of the spatial separation of holes and dopant boron atoms, the measured holes mobility consists of an integral value from different regions of diamond – doped with low mobility and undoped with high mobility. This is confirmed by the study of the dependence of the mobility and concentration of holes on the temperature of the sample. Thus, for the first time in the epitaxial diamond films with delta layers, the effect of increase of mobility of holes was observed due to the separation with the doping boron atoms. This proves the high quality of the fabricated structures – sharpness of transitions in the doping profile, the high quality of undoped epitaxial layers, and the high concentration of boron atoms in the delta layer.

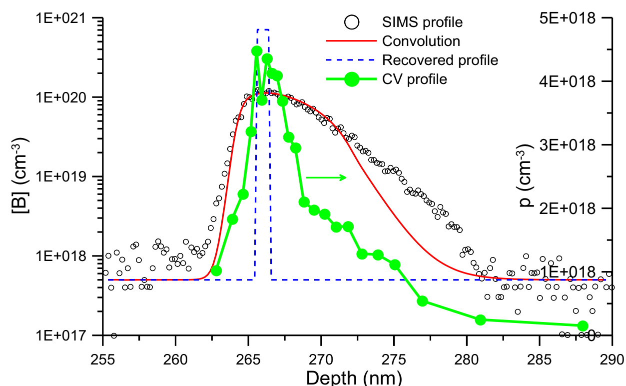

Fig. 4. Comparison of boron concentration profile recovered using analytical depth resolution function (dashed line) and hole profiles extracted from C-V analysis measured at room temperature (circles), Tr12 sample

Acknowledgments

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