Measuring the distribution of the charge carrier concentration in delta-doped layers based on diamond

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Abstract. Properties of single crystal diamond with four delta-doped layers are studied. The goal of this research is to measure the charge carrier concentration profile. Admittance spectroscopy was used as the principal method to measure the properties of samples at different temperatures and applied biases. The measurements showed that only the first (shallow located) δ-layer was confidently registered, especially at elevated temperatures (350–450 K). In addition, the concentration profiles included a weak response from the second delta layer, significantly shifted from its true location. A general conclusion is made concerning the observed charge carrier distribution. Further study is needed to determine the responses from the deeper delta-doped layers.

1. Introduction
The search for more advanced materials and research of the methods for their application is a relevant task in microwave electronics, power electronics, radioelectronics and photoelectronics, etc. A very promising material for such applications is diamond. It has a relatively high carrier mobility and an exceptionally high thermal conductivity among all semiconductors. The activation energies of impurities in diamond are very high, which leads to a small degree of ionization at room temperature. However, with increasing dopant concentration, the activation energy reduces. On the other hand, an increasing amount of ionized atoms leads to a decreasing carrier mobility which prevents using the bulk-doped diamond as a material for super-high frequency applications. The solution to this problem is doping with a very high concentration of impurities (~10^{20} cm^{-3}) in a few atomic layers, so-called delta-doping. Since the electron wave functions are localized in a wider area than the thickness of a delta layer, the charge carriers move into the undoped region, so the scattering by ionized atoms is reduced. In the future, delta-doped layers may become the main technology for obtaining super high-frequency devices based on semiconductor diamond.

2. Experiment details
Current-voltage and capacitance-voltage characteristics were measured using a computer-controlled setup of admittance spectroscopy. The setup consists of an Agilent E4980A LCR meter, a LakeShore 331S temperature controller and a Janis CCS400/204N probe station with a helium closed cycle cryostat [1]. The equipment allows carrying out measurements in the temperature range from 15 to 450 K and the frequency range 100 Hz ... 2 MHz.

High pressure high temperature (HPHT) (100)-oriented diamond crystals were used as a substrate at which a CVD single-crystal diamond layer with O-terminated surface was grown [2, 3]. The CVD
layer contains four delta layers doped by a boron impurity. The distance from the top of the sample and between the delta layers is 60 nm (figure 1). According to the SIMS data, the widths of the δ-layers were about 2.5 nm and the achieved peak intensity of an impurity in the delta layers is more than $10^{20} \text{cm}^{-3}$. The impurity concentration outside the delta layers was about $10^{16} \text{cm}^{-3}$.

For the current and capacitance measurements, the platinum Ohmic and Schottky contacts were sputtered on the top of a CVD-layer.

![Layer sequence for the investigated sample](image)

**Figure 1.** Layer sequence for the investigated sample

### 3. Results and discussion

We have studied the capacitance and conductance response of the sample in the temperature range 150...450 K. The sample behaves like a dielectric below 230 K, so the capacitance measurements were beyond the capabilities of the equipment used. Further, due to the incomplete impurity ionization in diamond in a wide interval of temperatures, including room temperatures, the total carrier charge under the rectifying barrier is collected from different depths at different temperatures (according to the Gauss theorem). At $T = 300$ K, particularly, the depletion region fully overlapped the delta-doped layers even at zero bias, and the measurements have shown that the concentration fluctuated around $2\times10^{16} \text{cm}^{-3}$.

As the temperature rises, the depletion region does narrow, so that the distribution of charge carriers in the delta layer region can be registered by capacitance-voltage ($C-V$) measurements. Figure 2 presents the specific capacitance response of the sample at 340 K and the resulting concentration profile manifesting the right-hand edge of the first delta-doped layer.

![C-V characteristics and concentration profiles](image)

**Figure 2.** $C-V$ characteristics (left) and concentration profiles (right) in a diamond sample with delta-doped layers ($T = 340$ K).

The data about the delta layer can be obtained at temperatures above 430 K, since the cap layer becomes more ionized and the depletion region is narrower (figure 3).
The concentration peak position obtained from the C-V measurements (62.7 nm) corresponds fairly well to the technologically specified position, if the hardware error of the C-V method is taken into account. The peak amplitude reaches $3.4 \times 10^{20}$ cm$^{-3}$. Two specific features can be seen in the concentration profiles. Firstly, they demonstrate some apparent “shift” of the delta layer’s peak position with temperature. The reason is the different locations of the space charge region (SCR) edge and the true layer position in the structures with heavy doped quantum confined layers. In addition, the profiles also include the weak responses from the deeper delta-doped layers, since in the lateral geometry of the capacitance measurements the smeared edge of SCR can simultaneously test several delta layers located near each other. These phenomena need further investigation.

To support the data obtained in the experiment, we performed preliminary numerical simulations aimed at a self-consistent solution of the Schrödinger and Poisson equations.

Figure 3. C-V characteristics (left) and concentration profiles (right) in a diamond sample with delta-doped layers ($T= 430$ K).

Conclusions
In this study, unique measurements were performed on a multi-delta-doped single-crystal CVD diamond by means of the capacitance-voltage technique in a wide temperature range. As a result, we obtained the distribution of charge carrier concentration in the vicinity of delta-doped layers. The most noticeable feature of this measurement was getting a response from deeper layers. However, there are also some arguable features that need additional investigation. The object of further research will be the detailed simulation of concentration profiles by the self-consistent solution of the Schrödinger and Poisson equations, which represents a separate task due to the complexity of the diamond band structure (namely, a small spin-orbit splitting in the valence band).

References
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