Characterization of delta-doped diamond samples with a planar capacitor

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Abstract. The method for characterization of delta-doped diamonds is developed based on the measurement of a planar capacitor. Theoretical model for calculation of the product of carrier density and carrier mobility is obtained. Theoretical model verified by the experiment. The experimental value of the product of carrier density and carrier mobility was $6 \times 10^{14} \text{ cm}^2\text{s}^{-1}\text{V}^{-1}$.

One of the most common way to a non-destructive measurement of dielectric properties of artificial diamond films with delta-doped layer is measurement of impedance of a planar capacitor based on this film. RLC-meters are devices that measure the admittance and impedance of a capacitor with dielectric or semiconductor material filling. The planar capacitor based on the delta-doped diamond sample consists of three layers (Fig. 1): a High Temperature High Pressure (HTHP) diamond substrate, a chemical vapor deposited (CVD) diamond film with a delta-doped layer and planar electrodes.

![Figure 1. The planar capacitor based on a delta-doped diamond film.](image-url)
The impedance of the planar capacitor shown in Fig. 1 is formed by (1) the capacitance $C_3$ of the stray fields in an ambient space with dielectric constant $\varepsilon_3=1$, (2) the capacitance $C_2$ of the CVD diamond film with the delta-doped layer of thickness $h_2$ with dielectric constant $\varepsilon_2$, (3) the capacitance $C_1$ of the HTHP substrate of thickness $h_1$ with dielectric constant $\varepsilon_1$, (4) the conductivity $G$ of the delta-doped layer and (5) two shunt capacitances $C_s$ due to delta-doped layer conductivity. The equivalent circuit of the structure is shown in Fig. 2.

The RLC-meter measures resistance $R_\Sigma$ and capacitance $C_\Sigma$ of delta-doped diamond structure. One can see from Fig. 2 that the impedance of the investigated structure is determined by the sum of connected in parallel planar capacitances $C$, as well as connected in series shunt capacitances $C_s$ and conductivity $G$:

$$Z_\Sigma = R_\Sigma + \frac{1}{\frac{i\omega C_\Sigma}{2} + \frac{1}{G}} = \frac{2 + \frac{i\omega C_s}{G}}{i\omega(C_s + 2 + \frac{C_\Sigma C_s}{G})}. \quad (1)$$

Therefore, the conductivity is equal to

$$G = \frac{i\omega C_s + C_\Sigma^2 C_s Z_\Sigma}{i\omega C_s Z_\Sigma + 2i\omega C_\Sigma Z_\Sigma - 2}. \quad (2)$$

The shunt capacitance is

$$C_s = \frac{\varepsilon_0 \varepsilon_r S}{h}. \quad (3)$$

The calculation of planar capacitances was based on the partial capacitance method [1, 2]. We represent the composite layered capacitor (Fig. 1) as three simple planar capacitors with homogeneous filler (Fig. 3) connected in parallel, and seek its capacitance as the sum of the three partial capacitances

$$C = C_1 + C_2 + C_3, \quad (4)$$

where $C_1$, $C_2$, and $C_3$ are the capacitances of the component parts of the planar capacitor, which are the fringing field in air, the CVD diamond film with the delta-doped layer, and the HTHP substrate.
Here the dielectric constants of the media are decreased in accordance with the equalities

\[ \varepsilon_2^* = \varepsilon_2 - \varepsilon_1, \quad \varepsilon_1^* = \varepsilon_1 - \varepsilon_3. \]  

(5)

These changes in the values of the dielectric constants of the layers constitute the main idea of the partial capacitance method, in which each layer is screened from the other layers by a “magnetic wall” which does not transmit the normal components of the electric field vectors. The mutual influence of the various layers on the field distribution in each of them is taken into account by the changes in the values of the dielectric constant of each of the layers represented in the case under consideration by relations (5).

The distribution of the electric field in planar capacitors is nonuniform. To calculate the capacitance of a planar capacitor, it is customary to use conformal mapping based on the Christoffel–Schwarz transformation [3]. The capacitance of a sandwich capacitor without fringing fields is easily calculated:

\[ C = \varepsilon_0 \varepsilon_r \frac{K(k)}{2K(k')}, \quad k' = \sqrt{1 - k^2}, \]  

(6)

where \( K(k) \) is the total elliptic integral of the first kind, \( k \) is the modulus of the elliptic integral, \( \varepsilon_0 \) is the permittivity of free space, and \( \varepsilon_r \) is the dielectric constant of the medium in which the electric field is concentrated.

For the structures shown in Fig. 3 (a, b, c) we have

\[ k_3 = \frac{s}{l}. \]  

(7)
The ratio \( K(k')/K(k) \) can be represented by the following approximate form [4]:

\[
F(k) = \frac{K(k')}{K(k)} = \begin{cases} 
\pi^{-1} \ln\left( \frac{1 + (1 - k^2)^{0.25}}{1 - (1 - k^2)^{0.25}} \right) & \text{for } k^2 \leq 0.5, \\
\pi / \ln\left( \frac{1 + k^{0.5}}{1 - k^{0.5}} \right) & \text{for } k^2 \geq 0.5.
\end{cases}
\]  

(10)

The error of this approximate form does not exceed \( 10^{-5} \) [4]. Note that the above formulas give the capacitance of planar structures per unit length in the direction perpendicular to the plane of the figure.

Taking into account (6) each capacitance is calculated separately. The capacitance of the air gap on Fig. 3(a) is

\[ C_1 = \varepsilon_0 w F(k_1). \]

(11)

The capacitance of the CVD diamond with delta-doped layer bounded by the “magnetic wall” on Fig.3(b) is

\[ C_2 = \frac{\varepsilon_0 w (k_2 - \varepsilon_1)}{2} F(k_2). \]

(12)

The capacitance of the HTHP substrate bounded from below by the “magnetic wall” on Fig.3(c) is

\[ C_3 = \frac{\varepsilon_0 w (\varepsilon_1 - 1)}{2} F(k_3). \]

(13)

Substituting these capacitance in (2) allows to calculate the conductivity of delta-doped diamond layer.

The described method does not allow to investigate the carrier density and carrier mobility of the sample separately. However the CVD diamond fabrication process assumed that the doping rate level is desired value. In this case the carrier mobility can be easily estimated.

As reference we provide an information about desirable mobility for delta-doped CVD diamond samples. It achieves 4500 cm\(^2\)/(V s) for electrons, and 3800 cm\(^2\)/(V s) for holes [5]. The carrier density \( n \) inside the delta-doped layer can be find as \( n = \sigma / e \mu \), where \( e \) is electron charge, \( \mu \) is carrier mobility.

The impedance of investigated structures was measured by RLC-meter. The capacitance of delta-doped diamond structure \( C_z \) was 0.64 pF and resistance \( R_z \) was 7783 Ohm. The thickness of HTHP diamond substrate \( h_1 \) was 500 \( \mu \)m, the dielectric permittivity \( \varepsilon_1 \) was 5.7, the thickness of the CVD diamond film was 100 \( \mu \)m with 10 nm delta-doped layer inside and dielectric permittivity \( \varepsilon_2 \) was 3.5. The conductivity of delta-doped layer calculated by above described algorithm was 96 \( \mu \)S. Thus the product of carrier density and carrier mobility was \( 2 \cdot 10^{15} 1/(V \cdot s \cdot cm) \). Therefore the carrier density was \( 5.3 \cdot 10^{11} 1/cm^3 \) assuming that the mobility was 3800 cm\(^2\)/(V s). Obtained conductivity is two orders lower than reported in the paper [6]. In the same time the value of carrier density is also two orders lower than in another paper [7]. Due to the difference by the same amount of calculated values and results reported in papers, one can assume that the model allows to estimate properties of delta-doped diamond samples. However, the investigated diamond samples had delta layer with low doping rate level.
In summary, this paper reports the non-destructive method of investigation of the dielectric properties of delta-doped diamond. Experimental measurements allow to obtain the product of carrier density and carrier mobility through the conductivity in the delta-doped layer. Thus, in the present sample, it was $2 \cdot 10^{15} \, 1/(V \cdot s \cdot cm)$. Therefore in case of known doping rate the described method allows to estimate the carrier mobility.

The work was supported in part by the Russian Foundation for Basic Research, Ministry of Education and Science of Russian Federation (Project "Goszadanie"), a grant of the President of the Russian Federation, and by Act 220 of the Russian Government (Agreement No. 14.B25.31.0021 with host institution IAP RAS).

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