Theoretical Model of the Stripline Measurement Cell for Doped Diamond Films

V V Vitko¹,², A V Kondrashov¹,², A A Nikitin¹,², P Y Belyavskiy¹, M A Cherkasskii¹, A B Ustinov¹ and J E Butler³

¹St. Petersburg Electrotechnical University, St. Petersburg, 197376 Russia
²Institute of Applied Physics of the Russian Academy of Science, Nizhny Novgorod, 603950 Russia
³Cubic Carbon Ceramics, Huntingtown, MD 20639, USA

E-mail: vitaliy.vitko@gmail.com

Abstract. A method for measurement of electrophysical properties of delta-doped diamond samples loaded into the measurement cell based on symmetrical stripline is demonstrated. The simulation of S-parameters of the measurement cell with doped diamond samples is carried out. The influence of the carrier density on the transmission characteristics of the symmetric stripline with doped diamond film is investigated. An increase of the carrier density in the doped diamond film from $5 \times 10^{19}$ m$^{-3}$ to $10^{22}$ m$^{-3}$ leads to frequency shift of transmission characteristic minimum from 15.85 GHz to 16 GHz and increasing of increment losses from -15 dB to -25 dB.

Recent years an interest to study microwave properties of artificial diamond films with doped layer is observed [1]. In order to use the diamond structures for microwave applications it is necessary to measure the carrier density and mobility. One of the non-destructive investigation technique is based on planar transmission lines. Main advantage of these lines is an absence of cut-off frequency that provides a wide frequency range of measurement [2, 3]. This paper is devoted to design and modeling of the measurement cell based on the symmetric stripline for study the microwave properties of the doped diamond samples.

The insertion losses introduced by the sample in a waveguide path are determined by the imaginary part of the complex dielectric permittivity and magnetic permeability. The method of calculation of the complex permittivity and permeability with the measured transmission coefficient $S_{21}$ and reflection coefficient $S_{11}$ is described in works [4, 5]. In this method, the complex dielectric permittivity can be determined using measured S-parameters of the structure as follows:

$$\varepsilon = \frac{i c/(\omega L)}{(1+\Gamma)/(1-\Gamma)},$$

where $c$ is the velocity of light and $\omega$ is an angular frequency, $L$ is a sample length, $z$ is a parameter expressed as $z = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21}) \Gamma}$, and $\Gamma$ is a reflection coefficient expressed as...
\[ \Gamma = \frac{1 - (S_{21} + S_{11})(S_{21} - S_{11})}{(S_{11} + S_{21}) - (S_{21} - S_{11})} \pm \sqrt{\frac{1 - (S_{21} + S_{11})(S_{21} - S_{11})}{(S_{11} + S_{21}) - (S_{21} - S_{11})}} - 1. \]  

(2)

The sign of the second term in equation (1) is defined by \(|\Gamma|<1\). A further specification of the complex dielectric permittivity is carried out in accordance with the Nicholson-Ross algorithm [5].

One of the Maxwell’s equation has the following form for the layer with free carriers:

\[ \text{rot} \mathbf{H} = i\omega \varepsilon_0 \left\{ \epsilon' - i \left[ \frac{\sigma}{\omega \varepsilon_0} \right] \right\} \mathbf{E} = i\omega \varepsilon_0 \epsilon_k \mathbf{E}, \]

where \( \mathbf{H}, \mathbf{E} \) are vectors of the magnetic and electric fields, respectively, and \( \varepsilon_0 \) is a dielectric permittivity of vacuum, \( \epsilon' \) is a real part of the complex dielectric permittivity

\[ \epsilon_k = \epsilon' - i \left[ \frac{\sigma}{\omega \varepsilon_0} \right] = \epsilon' - i \epsilon'^*, \]

and \( \epsilon'^* = \sigma/(\omega \varepsilon_0) \) is its imaginary part.

The conductivity of the doped diamond sample was calculated as

\[ \sigma = \omega \varepsilon_0 \epsilon'^*. \]

(3)

Conductivity measurement allows to estimate the doping level of the doped layer in the diamond sample. It is well known that carrier mobility in the diamond achieves 4500 cm²/(V s) for electrons, and 3800 cm²/(V s) for holes [6]. The carrier density \( n \) inside the doped layer can be find as

\[ n = \sigma / \epsilon \mu, \]

(4)

where \( \epsilon \) is electron charge, \( \mu \) is carrier mobility.

In order to increase functionality of the measurement cell a symmetrical stripline is selected due to features of the field distribution. The symmetrical stripline shown in Fig. 1 consists of a metal strip placed inside a dielectric medium between two grounded metal plates. Stripline is usually filled with a homogeneous dielectric, but it also can be partial filling by different dielectrics. The lowest mode in such a line is a quasi-TEM wave, which is characterized by the absence of the cut-off frequency.

**Figure 1.** Symmetric stripline with a delta-doped diamond sample.

In order to estimate influence of the carrier density on the transmission characteristics a numerical simulation of S-parameters was carried out. The simulation had following conditions. Ideal metal plates were parallel to the diamond sample and were placed equidistant from the strip. The distance between the metal plates and the strip was equal to the thickness of the diamond sample. As soon as operating frequency range of symmetrical stripline is determined by its dimensions such as the metal strip width and the distance between metal plates [7]. In order to provide operating frequency range from 15.5 GHz to 16.5 GHz following parameters were chosen. A distance between metal plate and strip was about 500 µm. A characteristic impedance of the stripline was of 50 Ohm. The transmission characteristic of investigated measurement cell was calculated with varying carrier density in the doped layer.
Results of the transmission characteristic simulation are shown in Fig. 2. An increase in the carrier density of delta layer leads to a shift of frequency $f_{\text{min}}$ corresponding to a characteristic dip in the transmission characteristic. It is also leads to an increase in microwave losses in the sample at the frequency $f_{\text{min}}$. The dependences of frequency $f_{\text{min}}$ and transmission coefficient $S_{21}$ at this frequency from the carrier density of the doped layer are shown in Fig. 3 (a, b).

**Figure 2.** Transmission characteristic of symmetric stripline with a doped diamond sample.

**Figure 3.** The dependences of the frequency $f_{\text{min}}$ (a) and transmission coefficient $S_{21}$ at this frequency (b) from the carrier density in delta-doped layer.
One can see from Fig. 3(a, b) that $f_{\text{min}}$ is changed from 15.85 GHz to 16 GHz and insertion losses increase from -15 dB to -25 dB in the carrier density range about $5 \times 10^{19} - 10^{22}$ m$^{-3}$. Thus, the proposed method allows to determine the carrier density in the doped layer with the measurement the microwave characteristics of the diamond samples.

In conclusion, it was shown that the proposed method based on symmetrical stripline is useful for measurements of microwave parameters of doped diamond samples in a wide frequency range. The simulation of the measurement cell is carried out. It is found that the design of the cell fabricated with a symmetrical stripline has a high sensitivity to microwave parameters in the carrier density range about $5 \times 10^{19} - 10^{22}$ m$^{-3}$.

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References
[1] Gurbuz Y, Esame O, Tekin I et al 2005 Solid-state electronics 49 No 7 1005-1070
[2] Blackham D V, Pollard R D 1997 IEEE Trans. instrum. and meas. IM-46 No 5 1093-1099
[3] Baker-Jarvis J 1990. Transmission/reflection and short-circuit line permittivity measurements Colorado: National institute of standards and technology 151
[4] Domich P D, Baker-Jarvis J, Geyer R G 1991 J. res. nation. inst. stand. technol. 96 No 5 565–575
[5] Nicolson A M, Ross G F 1970 IEEE Trans. instrum. and meas. IM-19 No 4 377–382
[6] Isberg J, Hammersberg J, Johansson E et al 2002 Science 297 No 5587 1670–1672
[7] Cohn S B 1995 IRE Trans. 3 No 4 16–21