Dielectric Loss at Millimeter Range and Temperatures 300–950 K, and Electrophysical Properties in Diamonds Grown by the Arc Plasma Jet Technology

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Abstract— The results of study of the dielectric loss at millimeter (MM) wavelengths range and temperatures 300–950 K in two different diamonds grown by the arc plasma jet (APJ) technology are presented. The electrophysical properties and parameters of point defects are also investigated. A comparison of results was made for these samples with the diamonds which have been grown by the technology of microwave plasma chemical vapor deposition (MPCVD).

It is revealed that both frequency and temperature loss dependences as well as the electrophysical properties and parameters of point defects in the APJ diamonds essentially differ from the MPCVD diamonds properties.

Also these properties in the studied APJ diamonds also essentially differ.

The dielectric loss mechanisms are discussed.

1. INTRODUCTION

Diamond films are a new kind of high quality dielectric material because they possess a combination of novel properties, i.e., low dielectric loss, extremely high thermal conductivity, high dielectric strength, etc..

Conventionally, high quality diamond films are prepared by using microwave plasma chemical vapor deposition (MPCVD) technique [1]. The dielectric and other properties of such diamonds were presented in [2–4]. However the deposition rate of high-quality diamond films by this technique is rather low (2–3 mkm/hour). Such material is rather expensive and its application is restricted.

During the last decade, a high power DC arc plasma jet (APJ) technique has been developed [5] which shows the advantages of higher deposition rate and lower material cost. Until now, there has been little report on dielectric properties of diamond films prepared by the APJ technique.

The first results on dielectric properties at MM range at the first time for the APJ diamonds were presented in [6] for one sample (K1). In [7] also the first data on electrophysical properties and parameters of point defects are investigated also by the charge-based deep level transient spectroscopy (Q-DLTS) technique. The metal (Ag) contacts were fabricated on diamond surface. However the Ag contacts provided only a qualitative data.

In this paper the results of investigation of the dielectric properties in two different APJ diamond samples are presented. The dielectric loss temperature dependences at the range $T = 300$–950 K are measured at the first time for the APJ diamonds. Also electrophysical properties and parameters of point defects are studied. A "strict" Ni and Ti contacts have been used that allowed to obtain quantitative data at the first time for the APJ diamonds.

A comparison with the MPCVD diamonds was made.

2. RESULTS AND DISCUSSION

In the present work the results of study of two APJ diamond samples are presented and discussed. The first sample "K1" is the disk of 18.2 mm in diameter and with the thick of 0.316 mm (the dielectric properties in it were studied earlier only at room temperature [6]. The second sample "K2" is the disk of 63 mm in diameter and with the thick of 0.401 mm. The samples were presented by the Beijing University of Science and Technology (BUST).

Earlier the dielectric loss tangent $\tan\delta$ was measured in the sample K1 at millimeter (MM) wavelengths range and room temperature [6]. At long MM range the measuring technique at the base of cylindrical cavity resonator was used. At short MM range the measuring technique at the base of high-Q open resonator was used [6]. It was found that $\tan\delta\sim 2\cdot 10^{-4}$ at frequency $f = 35\,\text{GHz}$, and $\tan\delta\sim 3\cdot 10^{-3}$ at $f = 201\,\text{GHz}$. The later measurement was made on "resonant" frequency of a disk at which the optical thickness of a disk is equal to a half wave ($t\cdot n = \lambda/2$) where t is the geometrical thickness of the sample, n is the refractive index of material, λ is the length of wave in vacuum. The refractive index in the sample K1 has been found on the specified resonant frequency. Its value $n = 2.354$ (± 0.002) essentially less than refractive index $n = 2.380$ (± 0.001) found in our previous measurements in various MPCVD diamonds in which the given value is close to the value for monocrystal diamond. The smaller value of the refractive index in the sample K1 in comparison with other diamonds means, that the given sample has smaller density.

From a comparison of the measurements data on different frequencies described above it follows, that in the APJ sample K1 an essential increase $\tan\delta$ with frequency ($\tan\delta\sim f$) in the MM a range is observed. It essentially differs from the frequency dependence of loss in other diamonds, in particular in MPCVD diamonds, where reduction of loss with frequency ($\tan\delta\sim 1/f$) in the given range was observed at $f < 200\,\text{GHz}$. In the MPCVD diamonds it caused by electric conductance in the intercrystalline (intergranular) areas [2, 8, 9].

From observable increase of loss with frequency in the investigated APJ diamond K1 follows, that the mechanism of loss in it is another compared to the MPCVD diamonds. As theoretical interpretation of the loss in the sample K1, the mechanism of the lattice loss induced by the lattice disorder can beoffered because it corresponds to dependence $\tan\delta\sim f$ [10]. It agrees also with smallerdensity (in comparison with MPCVD diamonds), corresponding to smaller value of the measured refractive index.

In the present work the dielectric loss and refraction index at the MM range was measured at another APJ diamond: sample K2.

The dielectric loss was measured at various temperatures $T = 300$–$950\,\text{K}$ (at the first time for the APJ diamonds). The temperature dependences were measured on two frequencies, 157 and 313 GHz. The results are presented in the Figure 1.

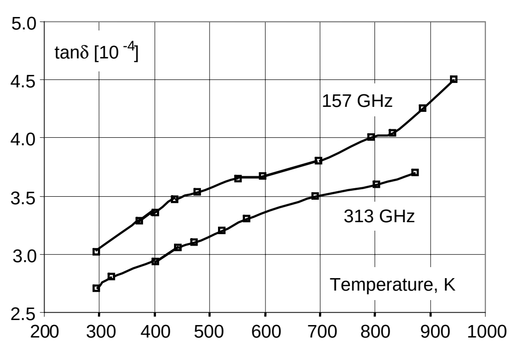

Figure 1. Temperature dependences of the dielectric loss tangent $\tan\delta$ in the APJ diamond sample K2 on two frequencies, 157 and 313 GHz.

The APJ sample K2 essentially differs on the loss temperature and frequency dependences from the MPCVD diamonds. In particular, the loss weakly depends on temperature not only at the "low" temperatures ($T\sim 300\,\text{K}$), but also at the "high" temperatures ($T\sim 900\,\text{K}$). Whereas in the MPCVD diamonds a sharp increase of loss is observed at $T\sim 500$–$900\,\text{K}$ [2, 3]. The decrease of loss at the increase of frequency in the sample K2 is observed as well as in the MPCVD diamonds. However it is much weaker compared to the dependence $\tan\delta\sim 1/f$ that is observed in the MPCVD diamonds at $f < 300\,\text{GHz}$ [2, 3] and is due to the electric conductance in the intercrystalline areas [2, 8, 9].

The APJ sample K2 also essentially differs on the loss frequency dependence from the APJ sample K1. In the sample K2 a decrease of loss with frequency is observed. Whereas in the sample K1 an increase with frequency is observed [6, 7]. It is possible to explain these frequency and temperature dependences in the sample K2 by the combination of contributions of two loss mechanisms: a) lattice loss induced by the lattice disorder which do not depend on temperature [10] (and can predominate at rather low temperatures; b) the loss caused by electric conductance in the intercrystalline areas [2, 8, 9]. The received results, including much lower losses in the sample 2 show, that in this sample the concentration of lattice disorder much low, than in the APJ diamond K1.

As it had shown in the previous our researches, the defects of various nature are characteristic for artificial diamond materials. And they can render essential influence on value of dielectric loss. However the mechanisms and character of influence of defects, in particular point defects, are not sufficiently studied.

In the present work the electric conductivity σ and its activation energy of E_a were obtained for the samples K1 and K2 from the volt-ampere characteristics measured at various temperatures (290–520 K).

The defect concentrations N_t, were determined by the Charge-based Deep Level Transient Spectroscopy [8]. The Q-DLTS spectrum is the charge $\Delta Q = Q(t_2) - Q(t_1)$, which is measured as a function of the "time of rate window" $\tau_m = (t_2 - t_1)/\ln(t_2/t_1)$, where t_1 and t_2 are the times from the beginning of the defect discharge, upon applying a voltage pulse to the sample. The ratio $t_2/t_1 = 2$ was kept constant while the Q-DLTS spectra were obtained. The amplitudes of ΔQ peaks (which are directly proportional to the defect concentration) are used to determine the N_t values as described in [8].

The results were compared with the data for typical MPCVD diamond sample "D1" that we researched earlier.

In the Table 1 some data obtained are presented: electric conductivities σ (at $T = 520\,\mathrm{K}$), its activation energies E_a, and point defect concentrations N_t.

Table 1.

Sample	σ , $\mathrm{Ohm}^{-1}\cdot\mathrm{cm}^{-1}$	E_a, eV	N_t, cm^{-3}
D1	$3.8 \cdot 10^{12}$	1.43	$\sim 4 \cdot 10^{10}$
K1	10^{12}	0.33 at $T < 450\,\mathrm{K}$ 0.89 at $T > 480\,\mathrm{K}$	$\sim 8 \cdot 10^{10}$
K2	$6 \cdot 10^{12}$	0.63	$\sim 7 \cdot 10^{10}$

In the sample K1 two different activation energies are observed: 0.33 eV at $T < 450\,\mathrm{K}$ and 0.89 eV at $T > 480\,\mathrm{K}$. It indicates that there are two deep levels in the forbidden gap. Their contributions dominate in the thermal excitation of the free char carries and in the electric conductivities at $T < 450\,\mathrm{K}$ and $T > 480\,\mathrm{K}$ respectively. The activation energy of levels corresponding to the room temperatures is the most in the sample D1 (1.43 eV) and the least in the sample K1 (0.33 eV). So at the room temperatures the dielectric loss in the sample D1 is significantly lower compared to the sample K2, and in the sample K1 it is significantly above.

3. CONCLUSION

The studied samples of APJ diamonds essentially differ from the MPCVD diamonds studied earlier. In particular:

1. The observed both frequency and temperature dependences of dielectric loss essentially differ from the dependences in the MPCVD diamonds. Also the frequency dependences in the studied samples of APJ diamonds essentially differ.
2. It follows from the results obtained that the loss natures in these three diamonds are different among all them.
3. The dielectric loss at the short MM wavelengths region in the subsequent APJ sample K2 is significantly lower compared to the sample K1. So a progress in the further reduction of loss in the APJ diamonds can be proposed.

The APJ diamonds are perspective material in applications for the flats and layers in the high power electronics at MM and THz ranges as a material combining very low dielectric loss, extremely high thermal conductivity (5 times higher compared to the copper), electric insulating properties, high dielectric strength, and rather low cost (compared to the MPCVD diamonds).

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