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Dielectric Losses in Nanosized Ferroelectric and Diamond-Like Films on SHF

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Abstract. The article considers the issues of receiving nanosized $Ba_{0,8}Sr_{0,2}TiO_3$ ferroelectric films and diamond-like films in the range of 10–60 GHz with various thickness between 0.1–10 μm and their dielectric properties. Peculiarities of SHF dissipation measuring method in dielectric films are discussed. It shows the influence of structural perfection of films on the value of losses of SHF energy.

Introduction

Thin nanosized ferroelectric films are obtained by synthesis on a single-crystalline substrate both by a solution deposition method [1–4] and deposition from active gas phase of low vacuum [5]. Such film elements have unique ferroelectric properties which allow performing the broad operating functions in integrated devices of microelectronics, optoelectronics, SHF equipment and others. They have proven to be high-demand for the creation of electronically controlled component base, antennas with electronic scanning, the systems of video signal transfer between mobile objects, the systems of superfast information transfer, in security systems and others [6–8]. Ferroelectric controlled elements are of great importance in reconfigurable SHF devices.

Diamond and diamond-like films received from carbon plasma have unique properties [9-12]. The main physical properties of such diamond-like films are lack of the hysteresis phenomena of properties at abnormally high heat conductivity that is perspective for their use in high power SHF devices of gigahertz frequency range. The combined use of ferroelectric and diamond-like films in SHF devices will allow creating the highly effective controlled devices.

The main physical characteristic which strongly defines the application of ferroelectric and diamond-like materials in SHF technology is the value of dielectric losses. It is rather difficult to predict metrological parameters of SHF using thin-film diamond-like or a ferroelectric material without dissipation knowledge of SHF energy in films.

The article explores dielectric properties of nanosized ferroelectric and diamond-like films in the frequency range of 10–60 GHz with various film structure and thickness.

Samples and Research Methods

Ferroelectric films of composition $Ba_{0.8}Sr_{0.2}TiO_3$ and diamond-like films which are perspective for the development of SHF devices are chosen as a subject of researches [5].

Two single-crystal materials - MgO and Si oxide are chosen as a substrate. It is determined by the fact that the growth of ferroelectric and diamond-like films with crystal structure is possible only on a basic faultless perfect surface of a substrate. MgO substrate is isostructural to chrystallo-chemical parameters for ferroelectric ($Ba_{0,8}Sr_{0,2}TiO_3$) and diamond-like materials.

Ferroelectric films were formed by high-frequency method (HF) of reactive sputtering in an oxygen atmosphere [5, 8]. The main advantage of this method is the possibility of sputtering structural and perfect metal-oxide films with oxygen stoichiometry preservation. The method has broad opportunities regarding the change of growth modes (temperature, oxygen pressure, growth rate, geometry of substrate placement concerning the HF-electrode).

Receiving of Ferroelectric Films. The single-crystal substrate was fixed on the heater in the vacuum chamber. Pressure of working UHP oxygen gas in the camera was 60 Pa. Control of residual pressure was carried out by means of the system of RRG-3 gas regulator with an accuracy ± 0.1 Pa. Having reached necessary pressure the heater power supply was turned on. Control and temperature maintenance of a substrate was exercised automatically by means of TRM-101 microprocessor measuring instrument with an accuracy ± 5 °C. The substrate was heating up to 400–420 °C and was sustained within 5 min. Further process of a film layer deposition on a substrate from a gas phase of the sprayed substance of an initial target became involved. The HF power supply of the generator was turned on and HF plasma was lit in an oxygen atmosphere in operating volume between a target and a substrate. Substrate temperature in the process of sputtering can change in the range of 500–900 °C.

Process of film substance growth on a substrate passes two stages. At the first stage process of sputtering in oxygen within 2–10 min., depending on the specified film thickness is carried out. The second stage consists in the subsequent heat treatment of a film in an oxygen atmosphere. For this purpose samples with a film out of discharge HF plasma are sustained with oxygen pressure in the camera up to 103 Pa with the subsequent cooling to room temperature within 2 hours.

The morphology of ferroelectric films of composition $Ba_{0,8}Sr_{0,2}TiO_3$ which are grown up on MgO substrates depended on thickness of a film coating. At the thickness up to 100 nm films had single-crystal structure, and in film layers with thickness more than ~ 100 nm the structure was already polycrystalline.

Receiving of Diamond-Like Films. Diamond-like films growth was carried out in the vacuum chamber on heated silicon substrate by method of condensation of methane decomposition products (CH_4) in the film-forming gas mix CH_4 H_2 environment with more 90 % hydrogen (H_2) in discharge plasma with 0.2–0.5 Pa residual pressure in the camera. Such method of chemical vapor deposition (CVD) is widely used for filming with perfect structure. Deposition of a diamond-like film layer is conducted on a heated substrate at 700–900 ºC. Time of sputtering is defined according to the specified thickness of the deposited film which made 50–120 min.

Ferroelectric and diamond-like films which are grown up on Si represented polycrystalline structure with a grain size of 1–5 µm. The value of relative dielectric permittivity of ferroelectric films was 800±10 and 5.7 for diamond-like ones.

Measurement Procedure of Films Parameters on SHF. To estimate energy SHF loss in films the resonant measurement method of losses in the condenser was used [13-16]. Measurement of dielectric losses in films was taken in the frequency range of 10–60 GHz. The measurement technique included determination of Q-factor (Q) in a co-planar microstrip transmission line (MTL) without loading (Q_0) and with the planar condenser (Q_k) which is switched on in the line. Q-factor is a parameter which characterizes irreversible conversion of electromagnetic energy into lines and condenser. Figure 1 shows the structured diagram of measuring stand of dielectric characteristics of thin-film specimen.

Specimens for dielectric losses research were carried out in the form of planar condensers by capacity ~ 0.1 pF with comb-shaped electrodes. Metal electrodes of condensers were formed by a planar and group method directly on a surface of ferroelectric and diamond-like films. For prevention of losses in MTL electrodes and the condenser their thickness considerably exceeds skin-effect value at a higher frequency of measurements.

Energy dissipation of an electromagnetic wave in dielectric of the measured condenser without losses in MTL and electrodes of the condenser can be defined as a loss angle tangent $tg\delta$:

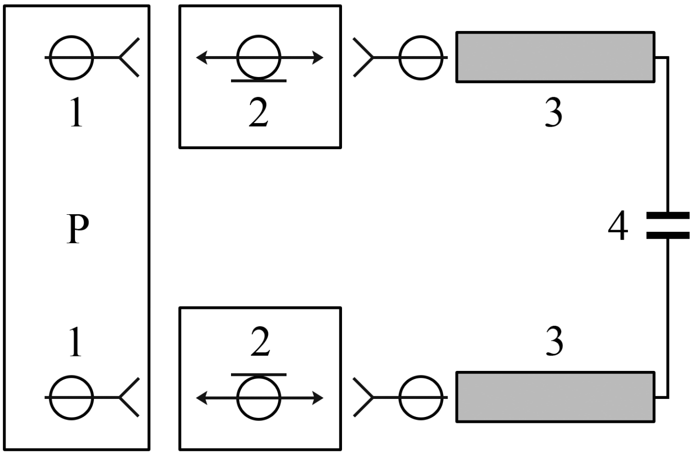

Figure 1. Measurement stand of dielectric losses in ferroelectric and diamond-like films on SHF. 1 – vector circuit analyzer N5234A, 2 – low frequency filter; 3 – co-planar microstrip transmission line: 4 – planar condenser – test item

$$tg\delta = \frac{1}{\xi}\cdot\left(\frac{1}{Q}-\frac{1}{Q_o}\right), \text{где } \xi = -2\cdot\frac{C_o}{f_o}\cdot\frac{df}{dC}. \quad (1)$$

Here ξ is a coefficient of including the condenser into transmission line which connects frequency $df = f_0 - f$ and capacity $dC = C - C_0$ changes of the measuring line components. f_0 и f are resonance frequencies corresponding to C_0 and C line capacities without loading and with the switched-on measured condenser.

Direct measuring method [10] was conducted by definition of resonance characteristics of a wave guide of the resonator which contains a ceramics test specimen acting as a load.

Results and Discussion

Measurements of value losses of SHF energy in diamond-like and ferroelectric films were carried out at fixed frequency of 20 GHz according to the registration scheme of condenser capacity value with a sample (Fig. 1).

Figure 2 presents schedules of dependence of loss angle tangent *tg*δ value on *h* thickness of ferroelectric structure $Ba_{0,8}Sr_{0,2}TiO_3$ which is grown up on MgO and Si single-crystal substrates, as well as on the diamond-like film deposited on a silicon substrate by a plasma chemistry method. Energy loss rate is marked by the dashed line in specimens of ceramics of homogeneous ferroelectric ceramics $Ba_{0,8}Sr_{0,2}TiO_3$.

Figure 2 shows that the value of dielectric losses depends on their structural perfection in $Ba_{0,8}Sr_{0,2}TiO_3$ ferroelectric films. So in single-crystal nanosized film layers with *h* thickness ~ 100÷200 nm having grown up on Si single-crystal substrates *tg*δ value is about $\sim 10^{-3}$. In films with thickness more than 200 nm monotonous increase of *tg*δ is observed. It is caused by decrease in structural perfection of films. In films with thickness more than 1.0 microns *tg*δ value is comparable with dielectric losses in a volume specimen of ferroelectric ceramics of the similar structure. For diamond-like films received by CVD method, the value of losses is $tg\delta \approx 10^{-4}$ and practically does not depend on their thickness, i.e. is commensurable with natural diamond-like losses.

Figure 3 presents the frequency dependence of loss angle tangent *tg*δ in a nanosized single-crystal film of $Ba_{0,8}Sr_{0,2}TiO_3$ ferroelectric with *h* thickness ~ 150±10 nm and a diamond-like film with *h* thickness ~ 1±0.1 μm.

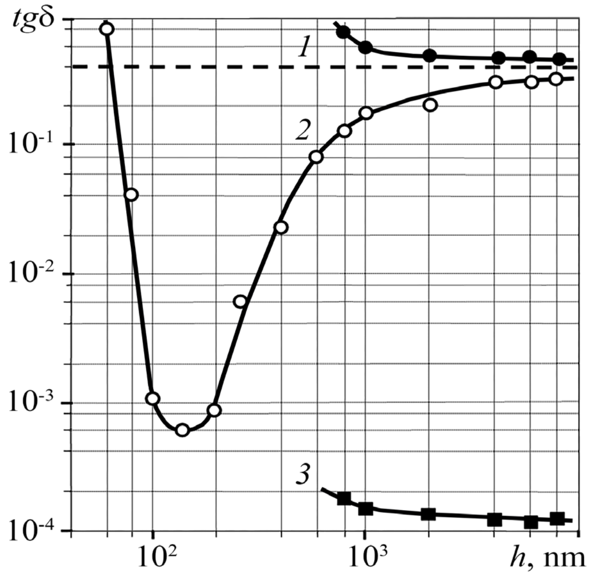

Figure 2. Diagram of dependence of *tg*δ value on *h* thickness of ferroelectric (1 and 2) and diamond-like (3) films on MgO single-crystal substrate (1 and 3) and Si (2) at the frequency of 20 GHz. The dashed line is *tg*δ value for $Ba_{0,8}Sr_{0,2}TiO_3$ ceramics

Figure 3 shows that the value *tg*δ of a diamond-like film makes ~ 10^{-4} at the frequency of 10 GHz, and about ~ 10^{-3} at the frequency of 60 GHz. The value of ferroelectric film *tg*δ at the frequencies of 10 and 60 GHz is 10^{-3} and ~ 1.0 correspondingly. Thus, the film element of a ferroelectric in SHF wave guide becomes an energy field absorber with increase in frequency.

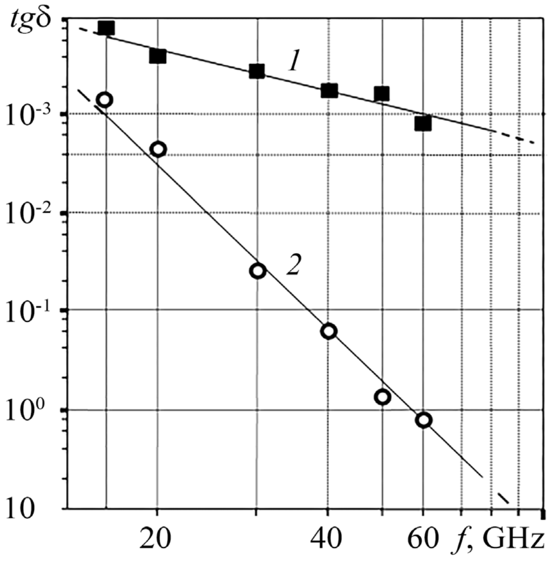

Figure 3. Dependence curve of dielectric losses *tg*δ for diamond-like (1) and ferroelectric (2) films on electrical field frequency *f*

Conclusion

The results of the conducted researches show the value change of dielectric losses in diamond-like and ferroelectric materials from thickness of a film and signal frequency. With the growth of their thickness and signal frequency the increase of *tg*δ is observed in films. The dependence of dielectric losses *tg*δ on film thickness and frequency of the impinging electric field is mostly defined for a ferroelectric film than for a diamond-like one. Collaborative use of properties of ferroelectric and diamond-like films is perspective for the development and creation of electronic reconfigurable component base and SHF micro devices of low and average power.

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