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REGULAR ARTICLE

On Increasing the Sensitivity of a Resonator Probe with Axial Symmetry in Local Microwave Diagnostics of Nanoscale Objects

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The paper discusses the prospects for expanding the sensitivity range of local microwave sensors (resonator probes, RP) with axial symmetry in diagnostics of small-sized objects, including micro- and nanoelectronics objects. All the considered methods for increasing the sensitivity of RP with a coaxial measuring aperture (RPCMA) are based on changing the coefficient of inclusion of the analyzed object in the electromagnetic field of the resonator. Particular attention is paid to increasing the sensitivity of probes with a submicron tip size for studying objects with a resolution of the order of nanometers. Models of RP with different designs of the aperture region are presented. The results of a study of the influence of both the storage and aperture parts of the RP on the signals of measuring information in various probe designs are presented. It is shown that the achievable sensitivity in the probes is directly related to the volume of the storage part, which is due to a change in the unloaded Q-factor of the resonator. The results of a study of small-sized RPCMA are presented. The prospects of their use for diagnostics of objects with low dielectric losses are discussed.

Quantitative data are presented that characterize the operation of a sensor based on a resonator with tunable sensitivity, which is ensured by shifting the tip of the probe relative to the aperture. Various operating modes of such a sensor are studied in detail. The results obtained indicate the presence of high losses in this design when diagnosing solid objects with low values of the dielectric parameters ε and $tg\delta$. Also, very interesting results are presented from a study of the use of a sensor with tunable sensitivity for diagnostics of liquid or bulk objects with low dielectric parameters ε and $tg\delta$.

Keywords: Resonator measuring transducer, Microwave sensor, Tip-sample distance, Inclusion coefficient, Permittivity, Resonant frequency, Quality factor, Conversion characteristics, Retractable probe.

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1. INTRODUCTION

Local microwave diagnostics of materials appeared much earlier than scanning microwave microscopy (SMM) [1-4]. Historically, due to the achievements obtained in microwave dielectrometry, SMM not only emerged, but also began to develop intensively [5-8]. What unites these two areas is the possibility of applying their theory and tools to the study of small-sized objects or their fragments. However, the problems solved in them are sometimes of a different nature. In local microwave sensorics, it is necessary to obtain some integral information about the physical properties of objects. On the contrary, SMM seeks to increase the locality of the interaction of the probe sensor with the object. The choice of the locality of microwave sensorics primarily depends on the subject of diagnostics. The most common objects of local microwave diagnostics are physical structures, biological environments and samples, thin-film materials, layered structures of solid-state micro- and nanoelectronics. The range of measured values of ε and $tg\delta$ in the study of such structures can be relatively wide, which in turn requires the development of appropriate tools. For these purposes, it may be quite acceptable to use microwave sensors developed for SMM and already well-studied based on aperture resonator measuring transducers (RMT) with a coaxial output (tip) [9]. The aim of this work is to theoretically substantiate the possibility of increasing the sensitivity of near-field resonator probes (RP) with axial symmetry for diagnostics of dielectric materials with ultra-low ε and $tg\delta$ values.

2. DESCRIPTION OF THE OBJECT AND RESEARCH METHODS

To assess the sensitivity of the RP, their conversion characteristics are usually used [9-11]. The dependencies of the main signals of measurement information on the electrophysical parameters of the object, obtained in the presence of the tip-sample distance, show how suitable the sensor is in terms of metrological parameters for diagnosing certain objects.

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In turn, the sensitivity is determined by the coefficient of inclusion of the object in the microwave field of the resonator. Quantitatively, this coefficient is determined by the ratio:

$$K_{incl} = \frac{\int_{Vobject} (E(\mathrm{r}, \varphi, z, \varepsilon_S, \mathrm{tg}\,\delta_S))^2 \,\mathrm{rdrdzd}\,\varphi}{\int_{Vresonator} (E(\mathrm{r}, \varphi, z, \varepsilon_S, \mathrm{tg}\,\delta_S))^2 \,\mathrm{rdrdzd}\,\varphi} \qquad (1)$$

Integration in the numerator is performed over the entire volume of the object, and in the denominator – over the entire volume of the resonator.

The inclusion coefficient contains information reflecting the influence of various design parameters of the RMT on its sensitivity. Also, as mentioned in [12-14], this parameter takes into account the influence of various interfering factors, such as the distance from the probe to the object, the shape of the object, the change in the radiation of the RMT field outside the object, etc. From the simplest physical considerations, it is obvious that there is a direct relationship between the inclusion coefficient of the object in the microwave field of the resonator and the sensitivity of the sensor. Using the conversion characteristics of such a coefficient makes it possible to obtain comprehensive information about the metrological properties of the sensor. Unlike the conversion characteristics of fundamental signals, it becomes possible to estimate not only various losses in the probe-object system, but also to directly compare the RP in the dynamics of change of the parameter under study. It is the use of numerical methods that makes it possible to obtain such characteristics with a very high convergence of the results [15]. Theoretical studies in the work were performed using a numerical method for the electrodynamic structure of the RP with axial symmetry, shown in Fig. 1 in different variations of the aperture unit design. The operating frequency of the quarter-wave RP was selected in the region of 10 GHz. The intrinsic quality factor of the RP, not loaded with an object, has a value of about 2100. Studies were also performed for a small-sized RP, the quality factor of which was no more than 1300.

The studies were carried out by finding the distribution of the electromagnetic field, the value of the resonant frequency and quality factor of the RP, interactive calculation of the inclusion factor according to formula (1) from the solution of Maxwell's equations by the finite element method [15, 16].

Fig. 1 shows the type of RP models calculated in a software package based on the finite element method and functionally similar to HFSS or COMSOL Multiphysics. For a comprehensive sensitivity analysis of the presented models, the following components of the RP design can be selected for modification: the resonator storage area, the aperture width, the connection of the storage and aperture areas, the tip shape, the degree of tip protrusion beyond the aperture plane, and also the shielding of the sample in the presence of radiation in the radial direction in the tip-sample distance.

Fig. 1 shows: a standard probe (the so-called conical) (a), a compact conical (b), a cylindrical (c), a version of a cylindrical probe with a movable tip system (d), and a version with a side screen for a sample with ultra-low dielectric losses (e).

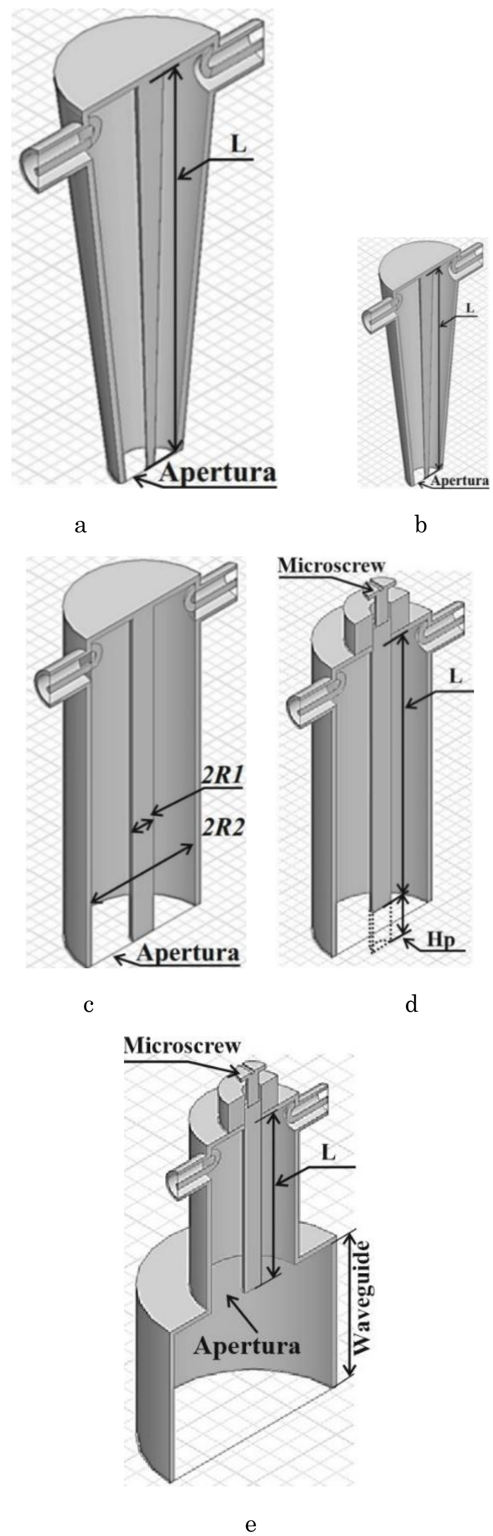


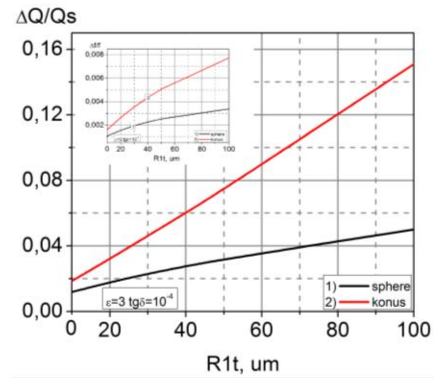
Fig. 1 – Schematic images of RMT with coaxial aperture [14]

Version (a) is characterized by an acceptable quality factor and very high measurement sensitivity. Version (b) is a compact version of version (a), distinguished by smaller dimensions but, consequently, a low quality factor. Version (c) also has a low quality factor but presumably should have high sensitivity due to the fully implemented connection between the storage region and the aperture in such a design. Version (d) is designed to operate in a wide range of sensitivities; the cylindrical design allows for a several times increase in efficiency when using it for diagnosing ultra-low values of ε and $tg\delta$. Option (e) is a modification of option (d), aimed at reducing radiation losses through the sample and in the radial direction in the tip-sample distance with the aim of significantly improving the metrological properties of the sensor.

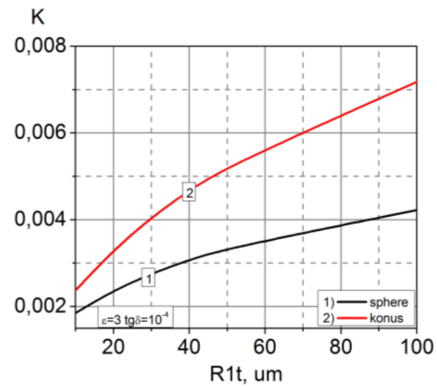
3. DESCRIPTION AND ANALYSIS OF THE RESULTS

As shown in [12-14, 17], some of the parameters affecting the sensitivity of measurements are the shape and radius of the probe tip. The field distribution under a spherical tip is characterized by a quasi-Gaussian character, and for a tip in the shape of a truncated cone, the effect of field tubularity is observed. The field extremes for a conical tip are not under its center, but on the periphery, as a result, the interaction with the object becomes much more effective than with a spherical tip. Fig. 2 shows the characteristics of the transformation of the fundamental signals of the RMT, as well as the coefficient of inclusion of the object in the resonator field depending on the shape and radius of the tip. To study objects with a resolution of the order of nanometers, the radius of the tip at the initial point of the characteristics takes submicron values. The characteristics of the transformation of the fundamental signal of the resonant frequency shift are shown in the inset of Fig. 2, (a); since they completely repeat the type of the signal of the change in the quality factor, individually they are of no interest for the problem under consideration.

As it can be seen from the data presented in Fig. 2, the measurement information signals also increase with increasing the tip radius. However, when using a conical tip, we obtain more clearly expressed signals. The explanation of this phenomenon is presented in Fig. 2, (b). When a RP with a conical tip interacts with an object, the coefficient of inclusion of the object under study in the resonator field is significantly higher. This, as mentioned above, is explained by the features of the field distribution for such a probe. Thus, we see that to study materials with low dielectric losses, a design option based on a tip in the form of a truncated cone is necessary. Further studies are related to modeling RP based on just this tip. Also, one of the factors directly affecting the sensitivity of measurements is the volume of the storage part of the resonator. The standard conical resonator was reduced in our studies by 4 times, while keeping the "quarter-wave" property and geometric proportions (to avoid significant changes in the structure under study). The distributions of the electromagnetic field in such a probe (a) compared to a full-size one (b) for a frequency of 10 GHz are shown in Fig. 3.



a



b

Fig. 2 – Characteristics of the transformation of fundamental signals of the RMT (a) and the coefficient of inclusion of the object in the resonator field (b) depending on the shape and radius of the tip

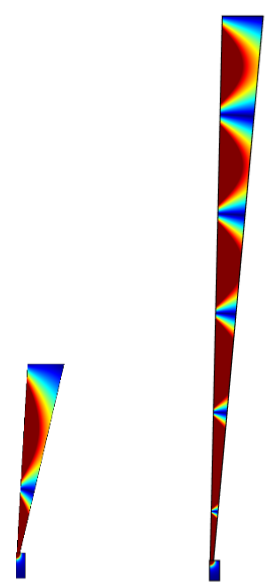
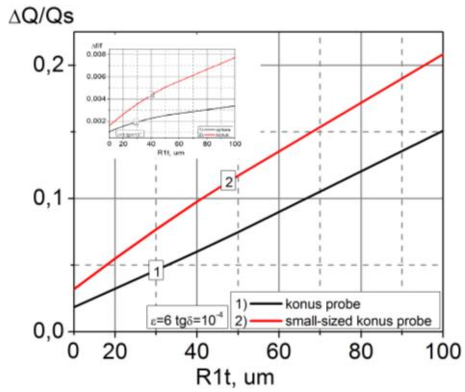


Fig. 3 – Electromagnetic field diagrams in cone resonators: (a) – small-sized resonator; (b) – standard resonator

Fig. 4, (a) shows the characteristics of the fundamental signal transformation of a conical and small-sized conical resonator. Fig. 4, (b) shows the characteristics of the inclusion coefficient transformation of these resonators depending on the change in the tip radius.



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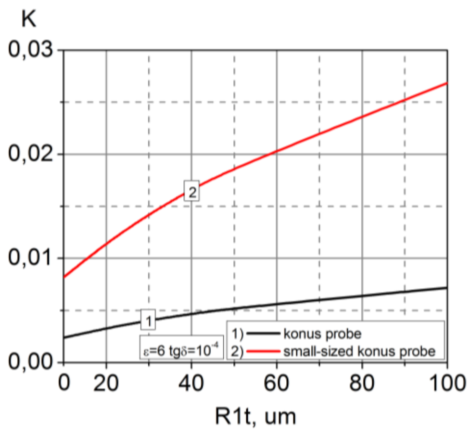
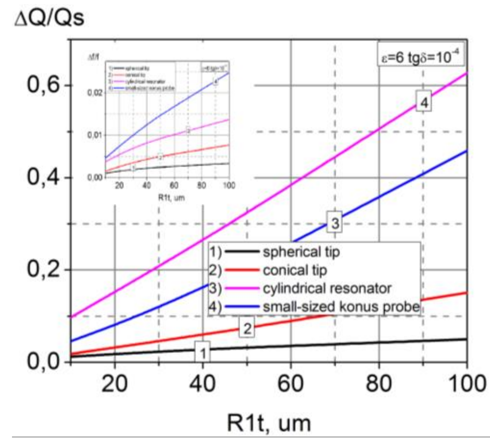


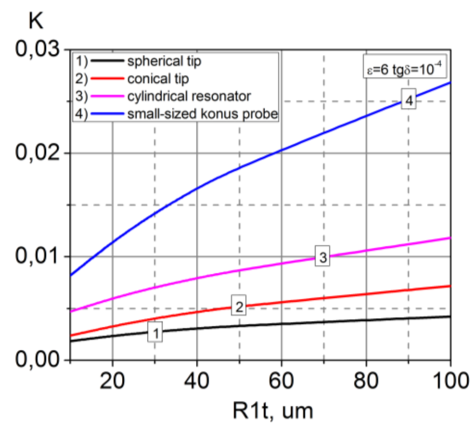
b

Fig. 4 – Characteristics of fundamental signal transformation of conical and small-sized conical resonators

As can be seen from the data presented in Fig. 4, the decrease in the volume of the storage part of the conical resonator entailed a significant decrease in the initial quality factor. However, in this case, it is possible to observe several times increased signals of measurement information, as well as a higher achievable inclusion factor than in a full-volume resonator. A similar design was studied in [18], but the results obtained were not compared with the classical quarter-wave RP. Thus, we see that a change in the volume of the storage part of the resonator affects the magnitude of the signals from the sensor, but this change is of a behavior opposite to what should be expected. The reason is apparently associated with the degree of inclusion of the object in the resonator field. The smaller the volume of the storage part of the resonator, the greater the influence of the object and, consequently, the greater the shift in the resonant frequency and the signal response of the sensor, as shown in Fig. 4, (b). A cylindrical resonator, despite its low attainable quality factor, can also be quite effective in solving problems of this kind, and is expected to be better than a conical one due to the use of a larger tip size, a larger aperture, and a much better connection between the storage and aperture parts of the resonator. The results of the study of such a probe are shown in Fig. 5.



a

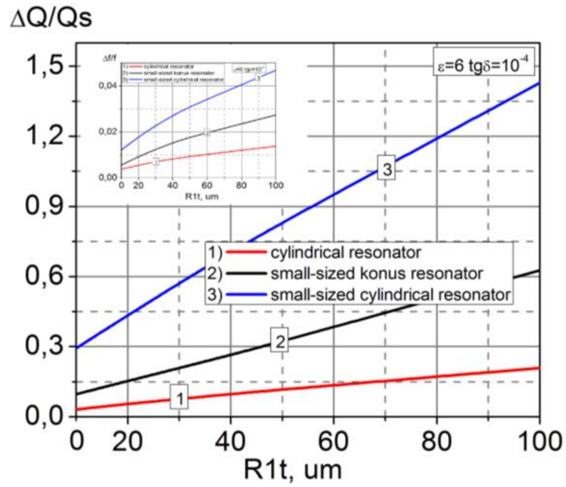


b

Fig. 5 – Characteristics of the transformation of fundamental signals of various resonators

As it can be seen, the reduced cylindrical resonator surpasses the full-size resonator in signal response. Thus, we can conclude that the volume of the storage part of the RP has a rather strong effect on the sensitivity of the RMT and, therefore, on the measurement information signals. However, this approach, apparently, can only be applied to diagnostics of materials with low dielectric losses because of the very low initial quality factor of the resonator.

A universal sensitivity control technique for all the RPCMA considered above can be the use of an aperture-forming region design with a movable tip. This technique is implemented using a system that shifts the tip relative to the aperture plane. Technical details on this probe with a description of the main operating modes are given in [10].



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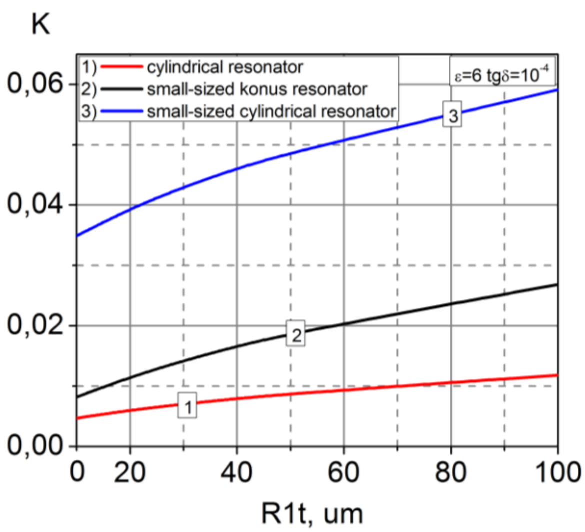
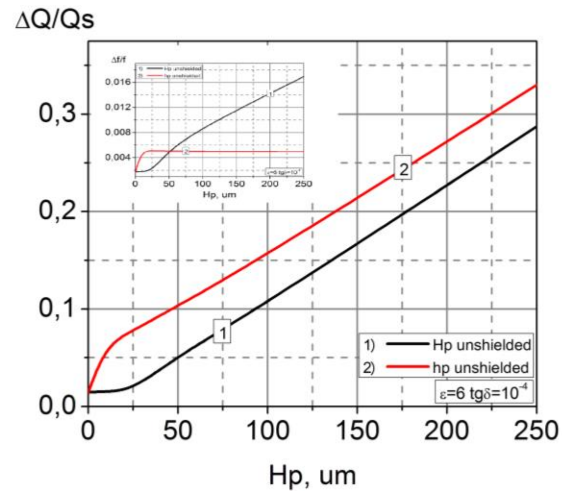


b

Fig. 6 – Characteristics of the transformation of fundamental signals of various resonators

Traditionally, the tip surface is coplanar with the aperture limited by the outer conductor of the coaxial. The sensitivity of the RP is interrelated with locality. For separate control of these two most important diagnostic characteristics, the specified coplanarity can be abandoned. Fig. 7 shows the results of modeling the interaction of such a sensor with an object in two possible variants, when the consistency of the object allows the tip to be inserted into the structure, or does not allow it, and the tip must simply be extended to the surface of the object.

As can be seen from Fig. 7, (a), the signals of the measurement information are not different quantitatively for the considered configurations. However, we can observe a completely different picture in Fig. 7, (b). It is evident that the inclusion coefficient for the case when the tip is immersed inside a liquid or bulk object is significantly higher, and the higher the deeper this immersion, in contrast to the option of the external location of the tip. Thus, we can conclude that there are significant radiation losses in such a configuration. The data presented in Fig. 7, (b) are quite unexpected, since previously published works (for example, [17]) claimed an increase in sensitivity with an external location of the tip relative to the diagnostic object. Thus, it is evident that the external location of the tip is very ineffective. According to general physical considerations, this problem could be solved by shielding the sample, like as it was studied in [12]. Fig. 8 shows the results of the study of the design with shielding. When diagnosing objects are of solid consistency, this version of the aperture region should significantly improve the characteristics of the RMT.



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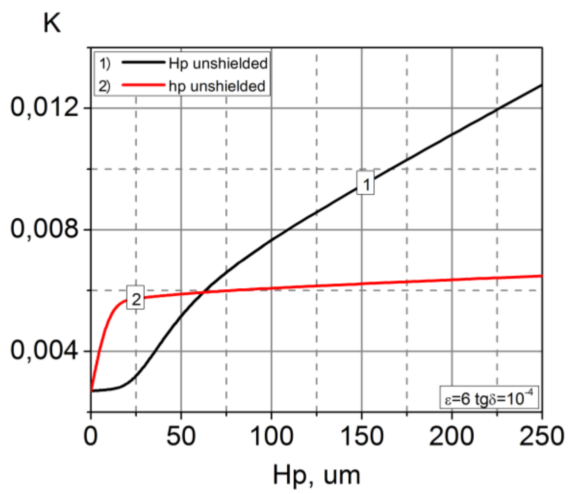
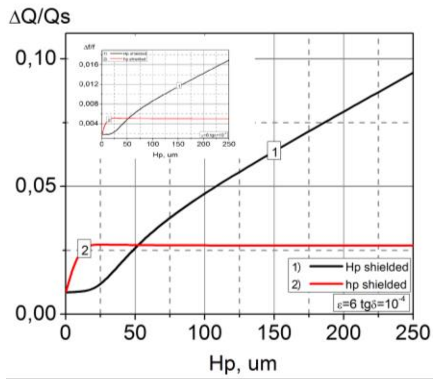


b

Fig. 7 – Transformation characteristics of the RMT with a shifting tip: signal of Q-factor changes (a) and inclusion coefficient (b)



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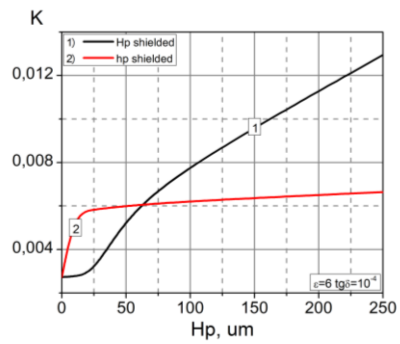

b

Fig. 8 – Transformation characteristics of the RMT with a shifting tip: signal of Q-factor changes (a) and inclusion coefficient when the sample is shielded (b)

As it can be seen from Fig. 8, the presence of a side screen has a favorable effect on reducing losses in the radial direction from the probe-sample gap. With complete screening, the difference between the external and internal location of the tip is not so great, and a significant part of the losses can be eliminated. It follows from the above that there are many ways to increase the sensitivity of the RPCMA and they are quite universal. Combining all of them in one design gives the most effective result.

4. CONCLUSION

The results of the research presented in this article quantitatively describe the influence of the RMT geometry on the sensitivity of the RP with axial symmetry in local microwave diagnostics of nanosized objects. It follows from those that by choosing the radius and shape of the tip, as well as its position on the axis of the coaxial probe, it is possible to significantly adapt the metrological parameters of the RP for diagnostics of objects with ultra-low dielectric parameters. The characteristics of the transformation of the coefficient of inclusion of the object in the resonator field obtained for the first time allow establishing several previously unknown facts:

– When the tip is inserted directly into the object, the inclusion coefficient is significantly greater than when it is extended out of the hole in the presence of an air gap at the tip-sample distance.

– The integral of the squared field over the resonator is greater if the tip is located outside the object.

– The integral of the squared field over the object is greater if the tip is located inside the object.

Thus, the interaction of the resonator with the object is more effective when the tip is extended into the object (at $tg\delta < 1$). At small shifts from the aperture plane, for both diagnostic options, the inclusion coefficients and the processes occurring in the probe-sample system are comparable.

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Про підвищення чутливості резонаторного зонда з осьовою симетрією в локальній мікрохвильовій діагностиці нанорозмірних об'єктів

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У статті розглядаються перспективи розширення діапазону чутливості локальних мікрохвильових сенсорів (резонаторних зондів, РЗ) з осьовою симетрією в діагностиці малорозмірних об'єктів, включаючи об'єкти мікро- та наноелектроніки. Усі розглянуті методи підвищення чутливості РЗ з коаксіальною вимірювальною апертурою (РЗКВА) базуються на зміні коефіцієнта включення аналізованого об'єкта в електромагнітне поле резонатора. Особлива увага приділяється підвищенню чутливості зондів з субмікронним розміром кінчика для дослідження об'єктів з роздільною здатністю порядку нанометрів. Представлено моделі РЗ з різними конструкціями області апертури. Представлено результати дослідження впливу як запам'ятовуючої, так і апертурної частин РЗ на сигнали вимірювальної інформації в різних конструкціях зондів. Показано, що досяжна чутливість у зондах безпосередньо пов'язана з об'ємом запам'ятовуючої частини, що зумовлено зміною ненавантаженої добротності резонатора. Представлено результати дослідження малорозмірного РЗКВА. Обговорюються перспективи їх використання для діагностики об'єктів з низькими діелектричними втратами.

Наведено кількісні дані, що характеризують роботу датчика на основі резонатора з настроюваною чутливістю, яка забезпечується зміщенням кінчика зонда відносно апертури. Детально досліджено різні режими роботи такого датчика. Отримані результати вказують на наявність високих втрат у цій конструкції при діагностиці твердих об'єктів з низькими значеннями діелектричних параметрів ε та tgδ. Також представлені дуже цікаві результати дослідження використання датчика з настроюваною чутливістю для діагностики рідких або сипучих об'єктів з низькими діелектричними параметрами ε та tgδ.

Ключові слова: Резонаторний вимірювальний перетворювач, Мікрохвильовий датчик, Відстань між вістрям та зразком, Коефіцієнт включення, Діелектрична проникність, Резонансна частота, Коефіцієнт якості, Характеристики перетворення, Висувний зонд.