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Electrodynamic Properties of Resonator Probes for Local Microwave Diagnostics of Nanoelectronic Objects

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The work focuses on detailing the distribution of the near evanescent field depending on the geometry of the aperture-forming region, the electrical properties of the objects under study, and assessing methods for scanning the properties of objects in depth. The results of a study of the electrodynamic properties of resonator probes with a coaxial aperture, developed for local microwave diagnostics of various objects, are presented. In particular, the influence of the size and shape of the tip and the tip-sample distance on the field distribution of a classical quarter-wave resonator measuring transducer is analyzed. Quantitative dependencies are presented that comprehensively characterize the probe-object system in terms of locality and sensitivity. Various options for changing the geometry of the probe aperture assembly are discussed to optimize the conversion characteristics of microwave sensors. The results of a study of the field distribution of a probe with tunable sensitivity by changing the position of the tip tip relative to the aperture plane are presented. The dependence of the field distribution on the tip displacement in such a probe has been established. Various variations of the operating modes of a probe with tunable sensitivity were studied: immersion of the tip into the probe aperture, extension of the tip into the interior of the object, extension of the probe tip from the aperture to the surface of the object.

Keywords: Resonator Probes, Quarter-Wave Resonator, Tip-Sample Distance Field Distribution, Nanoobjects, Electrodynamic Properties, Finite Element Method, Local Microwave Diagnostics, Tunable Sensitivity, Near-Field, Evanescent Electromagnetic Field.

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1. INTRODUCTION

The spatial distribution of the electromagnetic field of scanning probes plays a decisive role in the operational capabilities of Scanning Microwave Microscopy (SMM). In this area, the greatest practical success has been achieved using near-field resonator probes with a coaxial aperture [1, 2]. However, their capabilities have not yet been fully studied, especially in SMM functional devices of nanoelectronics, biophysics and nanophysics.

The main feature of local microwave diagnostics is the near-field nature of the interaction of the microwave sensor with an object or its fragment [1-3]. The determining factor in diagnosing the objects under study in nanotechnology is the resolution of the diagnostic tool themselve. The spatial resolution (SR) that can be obtained using microwave probes allows the SMM to occupy a leading position in this field. However, the electrodynamics of processes in nanosized structures has its own characteristics that must be taken into account [4].

The electromagnetic field that arises in the volume of the resonator and then exits through a subwavelength aperture is called evanescent in foreign literature [3]. This type of energy includes electromagnetic fields that quickly decay or decrease according to an exponential law. The study of the distribution of the electromagnetic field, as well as its changes under the influence of various factors, is the main task when analyzing the electrodynamic properties of resonator measuring transducers (RMT). The importance of solving this kind of problem is due to the fact that it is the electrodynamic properties of the RMT that determine the type of transformation characteristics of resonator probes (RP) [5]. The study of the distribution of the evanescent field is theoretical, since in practice we deal only with signals in their pure form, which are determined not only by the properties of the object, but also by the electrodynamic properties of the RMT. The first successful attempts to model the processes of interaction between a probe and an object using analytical models include works [6, 7]. However, it should be noted that the existing theoretical models, despite the cumbersomeness of their analytical description, as well as the complexity of calculations, are extremely inaccurate and idealized. Therefore, the distribution of the field in a quantitative representation has practically not been studied.

The purpose of the work is to study the electrodynamic properties of resonator probes by establishing theoretical dependencies of the field distribution in their aperture part.

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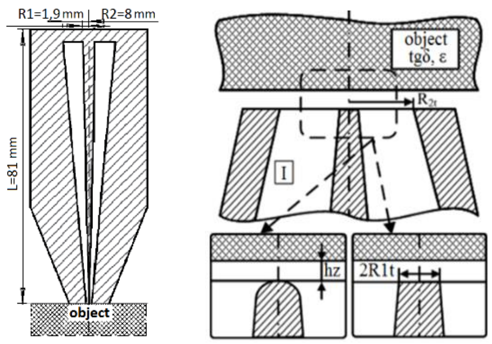
2. DESCRIPTION OF THE OBJECT AND RESEARCH METHODS

The studies are carried out for a fairly general probe structure, shown in Fig. 1.

The tip of the probe is designed in the shape of a truncated cone and a sphere. In the main part of the research, it is the spherical model of the tip that is used, due to the more localized nature of the interaction with the object, as well as the more adequate physics of the model [8].



a b

Fig. 1 – Schematic representation of a quarter-wave RP (a); schematic representation of the probe aperture assembly (b)

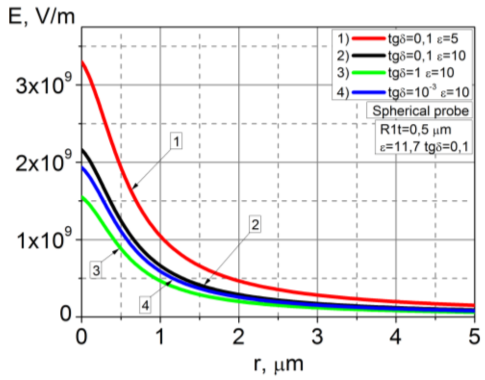
Attempts to theoretically study the probe model presented in Fig. 1 using a numerical-analytical method using [6, 7] convinced us that the approach is labor-intensive and not highly accurate. Earlier studies using the direct numerical method showed problems associated with the rather long process of solving modeling problems. In this work, high-performance packages similar to the latest versions of HFSS and Comsol were used. The effectiveness of their use is shown in the example of [9].

3. DESCRIPTION AND ANALYSIS OF THE RESULTS

Based on the results of many studies, we have come to the conclusion that it is the geometry of the aperture-forming region (I) that almost unambiguously determines the spatial distribution of the probing microwave field in the object, while the storage region of the resonator (II) has virtually no effect on the degree of sagging of the electromagnetic field. The electrodynamic properties and structure of the object affect the probing depth almost only within the limits of the existence of evanescent field distribution. This is clearly demonstrated by the dependencies presented in Fig. 2.

As practice has shown, the sensing depth is also affected by the presence of an air gap between the probe and the object [10]. Thus, we come to the conclusion that only the geometry of the aperture node affects the distribution of the evanescent field. And various changes in the geometry of the aperture node have a significant impact on the field distribution. Therefore, further we focus our attention on studying the geometry of the aperture-forming region of the probe.

In Fig. 3 shows the field distribution depending on the size and shape of the tip, obtained by solving Maxwell's system of equations using the finite element method (FEM). These solutions were found using standard packages based on the FEM [9]. All studies were carried out for an operating frequency of 10 GHz and an object with tgδ = 0.1, ε = 11.7.



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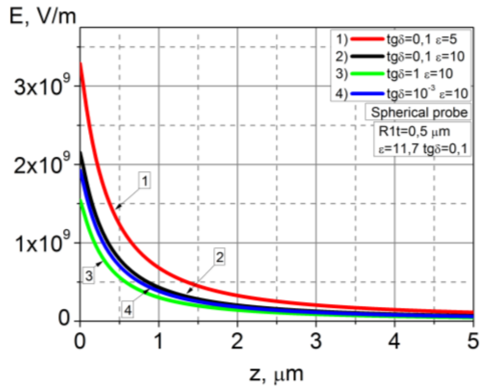
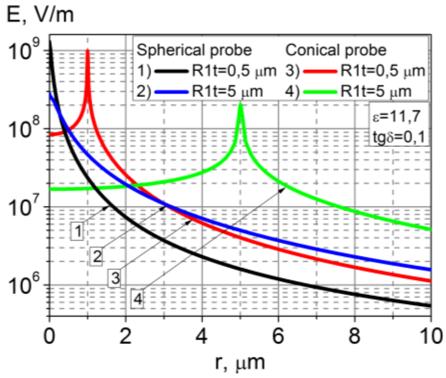


b

Fig. 2 – Field distribution over the surface (a) and depth (b) depending on the electrodynamic parameters of the object

From the given dependences it is clear that when using a spherical tip, the field strength is maximum under its center, and the nature of the dependence is quasi-Gaussian. The absolute opposite is the results obtained when using a truncated cone-shaped tip. As can be seen from the figure, there are two extrema, and their maxima are located on the periphery, the so-called tubularity of the field occurs. For both versions of the tip, it is characteristic that as the radius of the tip increases, the field strength decreases, the so-called lightning rod effect. However, upon a detailed examination of the presented dependences, one can see that as the radius of the tip increases, the steepness of the decline in field strength becomes less strong, and the nature of the decline smoothly passes from exponential to quasi-linear.

Also, factors influencing the geometry of the aperture unit include the tip-sample distance. The influence of the distance between the tip and the object on the response of measuring signals has been shown in many works on SMM [11-13]. However, the influence of the tip-sample distance on the field distribution was not fully considered, but only fragmentarily in a few works [6, 7]. Fig. 4 shows the field distribution of an aperture coaxial probe with a spherical tip depending on the tip-sample distance.



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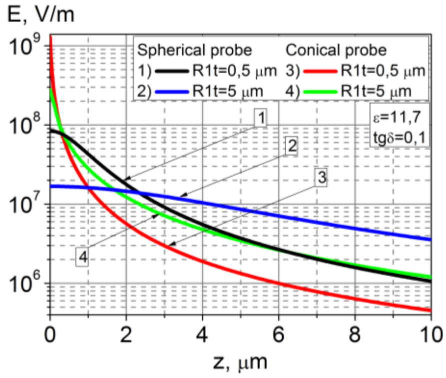


b

Fig. 3 – Field distribution over the surface (a) and depth (b) at different R1t for spherical and conical tip shapes

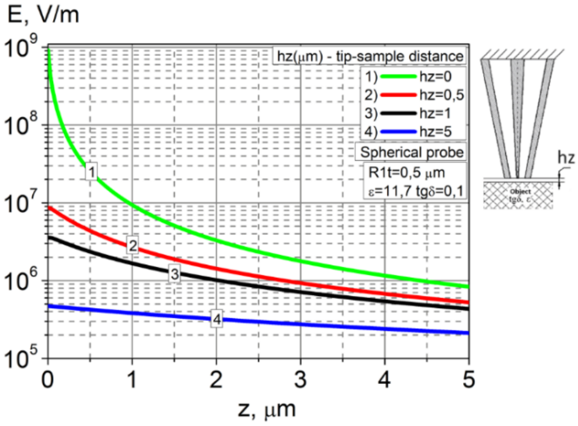
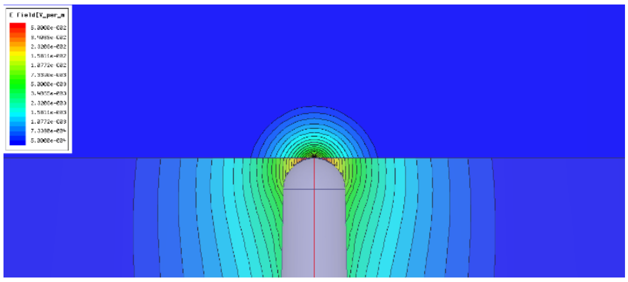


Fig. 4 – Field distribution over depth at different values of the tip-sample distance

From the presented dependencies, it is first of all clear that the presence of the tip-sample air distance significantly reduces the magnitude of the field strength in the object. This leads to a decrease in the sensitivity of the sensor and a decrease in the amplitude of the measurement information signals. As mentioned in our work [14], the tip-sample distance can be used as a tool for changing the sensitivity of the sensor. But, since its value is often determined by fairly approximate methods, the results obtained turn out to be very poorly reproducible. It should also be noted the phenomenon of delocalization of the electromagnetic field with increasing tip-sample distance, the results are shown in Fig. 5 [2].



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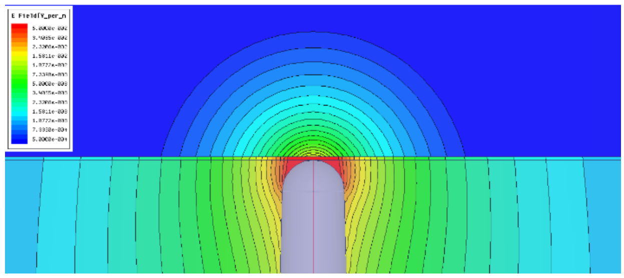
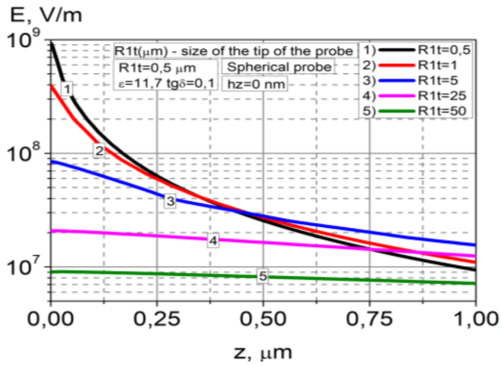


b

Fig. 5 – Diagrams of field distribution in the absence of a tip-sample distance (a) and with a tip-sample distance of 1 μm (b)

The greatest influence of the air gap between the tip of the probe and the sample is achieved when using probes with submicron tip sizes. The research results are shown in Fig. 6.



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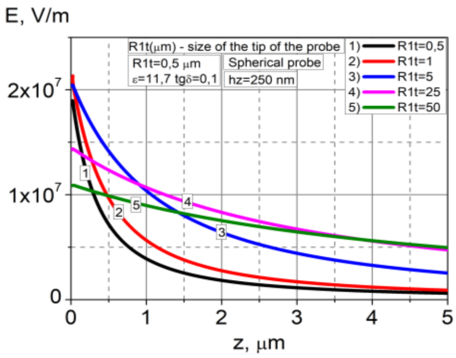

b

Fig. 6 – Field distribution in depth for different values of the tip radius without tip-sample distance a) and b) with small tip-sample distance

As you can see, in the contact mode the so-called lightning rod effect. With a small air gap, for probes of small radii, this effect ceases to occur. In practice, this can create serious difficulties in diagnosing nano-sized structures, since the tip of the probe is submicron in size. A solution to this problem can be the use of probes with R1t > 10 μm or the use of proven schemes for controlling the cantilever-sample distance for AFM and STM [15, 16].

An alternative to the tip-sample distance, as a tool for expanding the sensitivity of the probe, as shown in our works, can be a resonator with a displaced tip relative to the aperture plane [14, 17]. The range of measurement of electrophysical parameters of objects of classical quarter-wave RMT is within the limits ε: 1-15, tgδ: 0.001-0.1. The use of a RP with a retractable probe-forming central conductor makes it possible to measure ε in the range of 1-60, and tgδ from 0.001 to 2. A schematic representation of such a probe with possible operating modes is shown in Fig. 8. As shown in our works [14, 17, 18], the most effective range of change in the position of the tip tip is limited primarily by the sensitivity of the sensor and is of the order of several values of the tip radius both when extending from the resonator and when immersed in it. However, as shown in [19], when the tip of the probe extends beyond the aperture plane by an amount exceeding ten times or more the value of R1t, the sensor begins to radiate and switches to the monopole antenna mode. Diagrams of this phenomenon were obtained during modeling of the probe-object system using the FEM and are presented in Fig. 7.

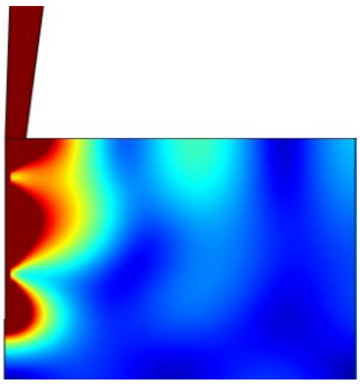

Fig. 7 – Diagrams of field distribution when the tip of the probe is immersed in an object to a depth Hp >> R1t

Fig. 9 shows the field distribution over the depth of such a probe at different positions of the tip relative to the aperture.

From the presented dependencies it is clear that the maximum achievable field strength for a spherical tip is maintained under the center and strongly depends on the position of the tip. As expected, when the tip extends into the object under study, the field strength increases, and when immersed in the resonator it decreases. However, as you can see, the field strength for the classical coplanar location of the tip is still higher than for other displacement variations, but only on the surface of the object. A similar picture is observed when the radius of the probe tip decreases. Apparently, the evanescence of the field deteriorates not only with increasing tip radius, but also with departure from coplanarity in such a probe.

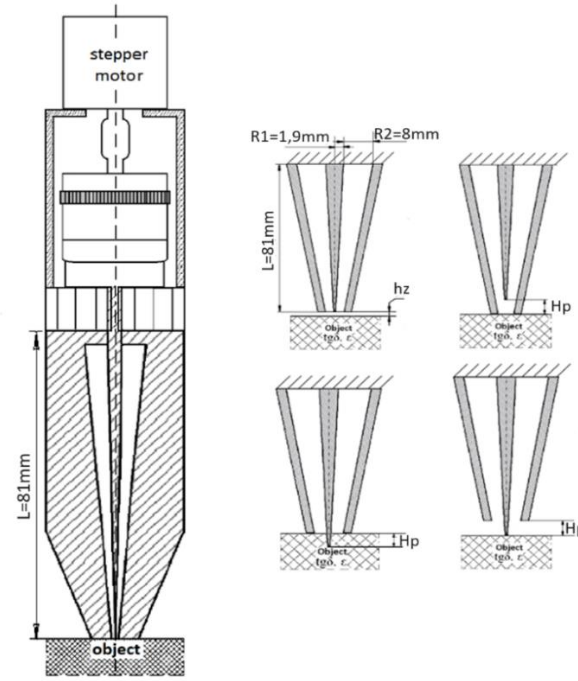

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Fig. 8 – Schematic representation of a RMT with a movable tip (a) and main operating modes of the probe (b)

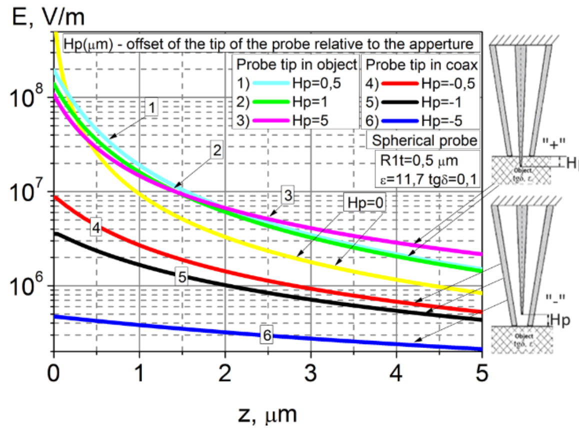

Fig. 9 – Field distribution along the depth of a tunable RP for different positions of the tip relative to the aperture

The probe in question can also be used in the diagnostics of nano-objects. However, to increase the sensitivity of the RMT, if necessary, moving the tip into the inside of the object will not work for obvious reasons. A suitable option may be to extend the tip of the central core of the coax beyond the aperture so that the tip is in contact with the object or with a small gap, as shown in Fig. 8 [14]. This is also one of the possible operating modes of the sensor in question. Quantitative results of studying nanostructured porous silicon are presented in Fig. 10. However, it is necessary to take into account in this case the significantly increased radiation losses in the radial line at the tip-sample distance.

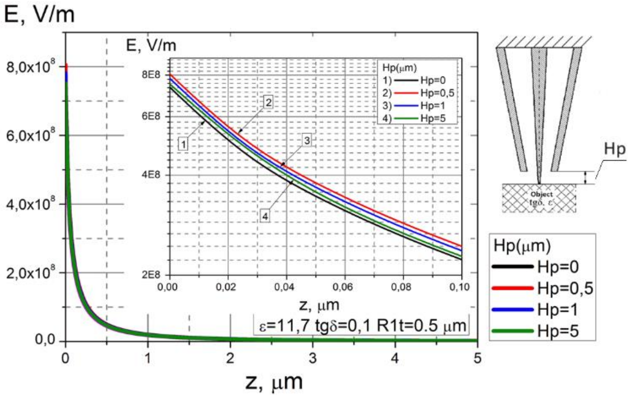

Fig. 10 – Field distribution along the depth of a tunable RP when the probe tip extends to the surface of the object

As can be seen from the results presented in the figure, it is not possible to achieve a significant increase in sensitivity in this way. Upon closer examination of the inset to Fig. 10, one can notice that the degree of protrusion of the tip still affects the magnitude of the field strength within the limits of its evanescence. However, this is not enough to consider this option of increasing the sensitivity of the sensor for studying this kind of objects appropriate. Apparently, radiation losses with such a design change, combined with the rather small dimensions of the probe, greatly distort the picture.

CONCLUSION

As a result of numerical studies of the field distribution in the aperture part of coaxial resonator probes, the following provisions were established:

As the radius of the probe tip increases, a slight violation of the field evanescence is observed. This is expressed primarily by the fact that the steepness of the decline in field strength with depth becomes smoother, and the form of the dependence itself smoothly passes from exponential to quasilinear.

The tip-sample distance not only significantly reduces the field energy in the object under study, but also the locality. In addition, the presence of a distance between the tip of the probe and the object introduces a systematic error in the diagnostic results.

The use of a coaxial resonator with a biased central conductor as a sensitivity control tool is more preferable than the tip-object distance when using a classic quarter-wave RMT.

When the tip extends from the probe aperture directly into the inside of the object to a significant depth (Hp>10*R1t), the radiation losses become so high that the sensor begins to radiate and goes into monopole antenna mode.

When studying nanoobjects using the extension of a submicron-sized tip from the probe aperture, a significant increase in field strength does not occur. This is presumably due to significantly increased losses due to radiation into the radial line at the gap between the resonator and the object in such a system.

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Електродинамічні властивості резонаторних зондів для локальної НВЧ діагностики наноелектронних об'єктів

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У роботі основну увагу приділено деталізації розподілу ближнього еванесцентного поля залежно від геометрії апертурно-утворюючої області, електрофізичних властивостей об'єктів, що досліджуються, та оцінки прийомів сканування властивостей об'єктів по глибині. Наведено результати дослідження електродинамічних властивостей резонаторних зондів з коаксіальною апертурою, розроблених для локальної НВЧ діагностики різних об'єктів. Зокрема, аналізується вплив розміру та форми вістря, відстані вістря-зразок на розподіл поля класичного чвертьхвильового вимірювального резонаторного перетворювача. Наводяться кількісні залежності, що всебічно характеризують систему зонд-об'єкт по локальності та чутливості. Обговорюються різні варіанти зміни геометрії апертурного вузла зондів для оптимізації характеристик перетворення НВЧ сенсорів. Наводяться результати дослідження розподілу поля зонда з чутливістю, що перебудовується, за рахунок зміни положення кінця вістря щодо площини апертури. Встановлено залежність розподілу поля від усунення вістря у такому зонді. Досліджено різні варіації режимів роботи зонда з чутливістю, що перебудовується: занурення вістря в апертуру зонда, висування вістря усередину об'єкта, висування вістря зонда з апертури до поверхні об'єкта.

Ключові слова: Резонаторні зонди, Чвертьхвильовий резонатор, Розподіл поля на відстані вістря-зразок, Нанооб'єкти, Електродинамічні властивості, Метод скінченних елементів, Локальна мікрохвильова діагностика, Регульована чутливість, Ближне поле, Екванесцентне електромагнітне поле.