Modeling Shielding Effectiveness Measurements for Nano-scale Samples

Szilvia Nagy[1] and András Fehér[2]

***Abstract* – If thin metallic layers grown on compound semiconductor substrates are heat treated Ohmic contacts can be formed. In case of the layers being thin enough, fractal-like topology of the metallic clusters can occur instead of continuous layers. This fractal behavior can be seen in many other cases for various material systems. The layers arising are mostly analyzed by a kind of scanning microscopy or other 2D and 3D image generating methods. Mechanic and electronic properties, like the conductivity, can be determined, too.**

In the present work a sample holder for measuring another electromagnetic property, namely the shielding effectiveness is being studied. The shielding effectiveness of these structures carry information about the quality of the Ohmic contact built during the growth process. Furthermore, the connection of the topology and the shielding properties of various material systems can be mapped. The equipment for determining the shielding effectiveness or the reflectivity of such small scale, thin, planar samples is modeled by finite element method.

According to the model, the *S* matrix elements of the developed sample holder depends only slightly on the shape and the position of the specimen under test.

***Keywords* – Shielding effectiveness, EMC, compound semiconductor**

I. INTRODUCTION

Ohmic contact can be generated on compound semiconductor substrates by growing thin metallic layers upon the surface and heat treating the system. The Ohmic contacts occur depending on the composition of the materials and the growing and thermal treating circumstances. If the layers of are thin enough, the metal can form clusters with fractal-like topology [1,2,3], instead of continuous layers. Fullerene layers molecular beam epitaxially grown on vanadium selenide substrate form a system of islands consisting of more plateaus with different fractal dimensions and inner structure [4]. Measuring shielding effectiveness of these materials with nano-scale patterns on their surface can provide a lot of information about the layers without actually measuring them on scanning electron or atomic force microscopes.

For measuring shielding effectiveness or permittivity more methods are available. Standard IEEE-STD-299 requires a shielded enclosure with a hole in one of the side walls and a really large sample, thus its prescriptions can not be fulfilled with compound semiconductor slices. Within the other possibilities, like partially filling a microwave line with the sample, or touching a specially designed head to the bulk specimen, we have chosen the only method, which can be adapted for a usually 300 micron thick, planparallel, but otherwise irregularly shaped, rigid and fragile slice of compound semiconductor sample. The sample holder of this method is a coaxial aerial, cut in two halves perpendicular to its axis, similar to the device in the former standard [5]. The variation of this sample holder appears in many fields of electromagnetic compatibility literature, from metal coated fibers [6,7], polymers [8] to nanomaterials [9, 10]. In the later applications, only one of the coaxial aerial halves is used, the other part is substituted by a prefect metallic reflector, which can easily be gilt, and gives a possibility to heat the sample.

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II. SAMPLE HOLDER DESIGN

The sample holders are designed so, that they would match the standard N-type connectors of the network analyzer. The planned measuring setup is according to standard [5], except for the frequency range, which is in our case 100 MHz to 10 GHz. Probably, later wider frequency range could be also studied.

The sample holder is an enlarged coaxial aerial separated in two halves, and the material under test is held between these parts as it is shown in the upper part of Fig. 1. The lower part of Fig. 1 illustrates the method with only one coaxial lin part and a reflector [10].

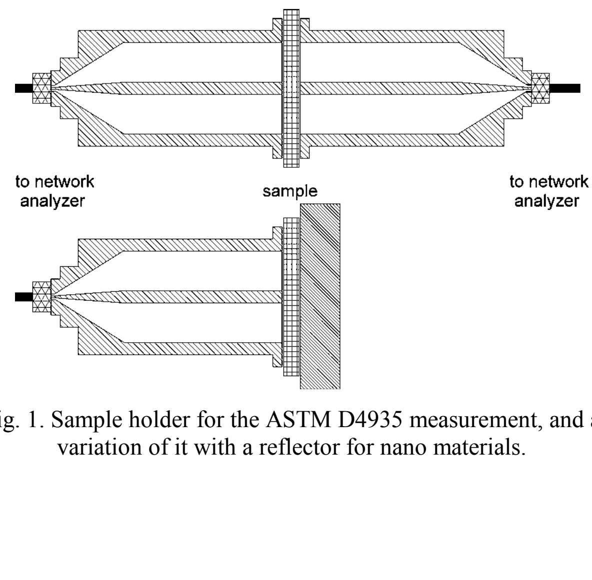

Fig. 1. Sample holder for the ASTM D4935 measurement, and a variation of it with a reflector for nano materials.

For the sample holder given in the upper subplot of Fig. 1 one side of the coaxial transmission line is driven by a network analyzer while the transmitted signal is measured on the other side. The size of the equipment, according to ASTM D4935, is 5.24” for the outermost diameter, the inner diameter of the outer cylinder is 3”, while the diameter of the inner conductor copper rod is 1.3”. Of course, these parameters can be scaled, in [2] a 133 mm flange diameter specimen holder with the coaxial aerial diameters 76 mm:33 mm, and a smaller, 14 mm:6 mm coaxial line was tested with 33 mm and 44 mm flanges. The size of the sample holders for nano materials was significantly smaller. Our specimen holder is filled with Teflon, thus the scaling is a little bit different (according to

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln \frac{b}{a} \tag{1}$$

with a and b being the inner and outer radii of the coaxial line, which were in our case 1.5 mm and 5 mm.

According to the standard [5], in order to have the same capacitive coupling between the two halves of the device with or without sample, a reference should be prepared having the same material properties as the sample, but covering only the conductive surfaces of the sample holder surface. The shape of the reference and the sample according to the standard is given in Fig. 2.

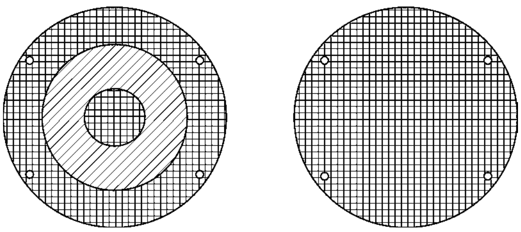

Fig. 2. Geometry of the reference and the sample according to [5].

In case of the reference, the dark circle and ring in Fig. 2 is made of the same material as the sample. The reference as well as the sample can be deposited on the surface of a dielectric disc, which is symbolized by the lightly covered area between the parts of the reference. Both objects should be measured at the same frequencies, and the shielding effectiveness *SE* is the ratio of the received reference and the load power,

$$SE = 10 \log \frac{P_{\text{ref}}}{P_{\text{sample}}}. \tag{2}$$

The thickness of the studied material must be much less than the free wavelength of the electromagnetic wave propagating in the coaxial transmission line in TEM mode.

With a network analyzer or a simple directional decoupler the reflected signal can also be measured. Using both the transmitted and the reflected signals, the *S* matrix parameters S_{21} and S_{11} can be measured. [11]

The sample holder operates correctly up to the frequency, where besides the TEM mode, higher order modes appear [5], i.e., until

$$f_c = \frac{1}{\pi\varepsilon} \frac{2c}{a+b} \tag{3}$$

with c being the speed of the light. For the above described sample holder this cut-off frequency is a little less than 10 GHz.

Studying Fig. 2, one can clearly say, that it is almost impossible to prepare reference and sample from GaAs or other compound semiconductor of such shape, and it is rather hard to mask the reference during the growth and thermal treatment processes, according to the figure, and still providing the same material properties as those of the sample.

The results theoretically calculated [3] and measured according to standard ASTM D4935 are usually in sufficient correlation. This gave the idea, that instead of the reference, which can not be prepared for compound semiconductor substrates with thin metallic layers with nano-scale topology, we can model the results and measure only the sample and the empty substrate.

III. SIMULATIONS

For simulation we have used the RF toolbox of the finite element program package COMSOL Multiphysics. Although the sample holder was almost cylindrical, because of the rectangular flanges, no symmetry of the device could be used. However, because of the almost cylindrical samples, i.e., the slices of a grown GaAs crystal, the model contained cylindrical sample. This sample was shifted and cut for studying the effects of various sized samples with various geometry. The applied frequency domain was 100 MHz to 10 GHz, the geometries can be identified from the resulting plots.

First, the sample holder without sample and with air filling was tested, and after verifying, that the results agree with the theory, we have placed a cylindrical sample coaxially with the specimen holder in between the flanges. The flanges are designed to be large enough, so that the field at its edges should be negligible. The resulting electric and magnetic field is summarized in Fig. 3.

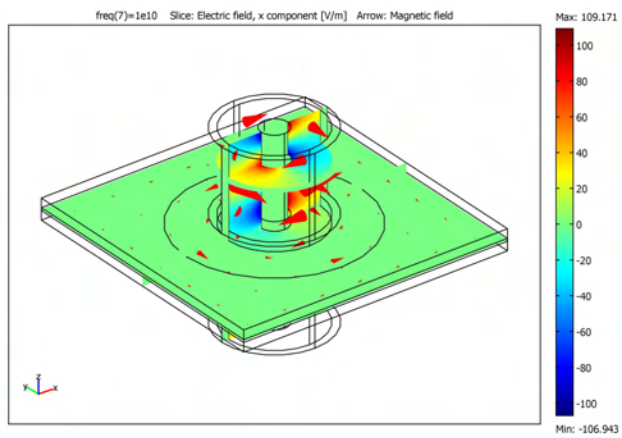

Fig. 3. Electric and magnetic field plotted in color slices and arrows for the centrally placed sample. The inner conductor is of diameter 3 mm, the outermost conductor’s diameter is 10 mm.

The slightly disturbed TEM mode of a coaxial line is recognizable. Clearly, the electromagnetic field concentrates at the centre of the sample. Similar results arose in all of the studied frequencies, the energy density between the flanges was very small. This result suggests, that the shape of the sample is indifferent as long as it covers the high energy density central region of the sample holder. To test this suggestion, we have modified the sample, by shifting it 3 mm off the center, and by cutting a slice of it, and filling with air at the outer cylinder of the sample holder. The two resulting electromagnetic field plots are given in Fig. 4.

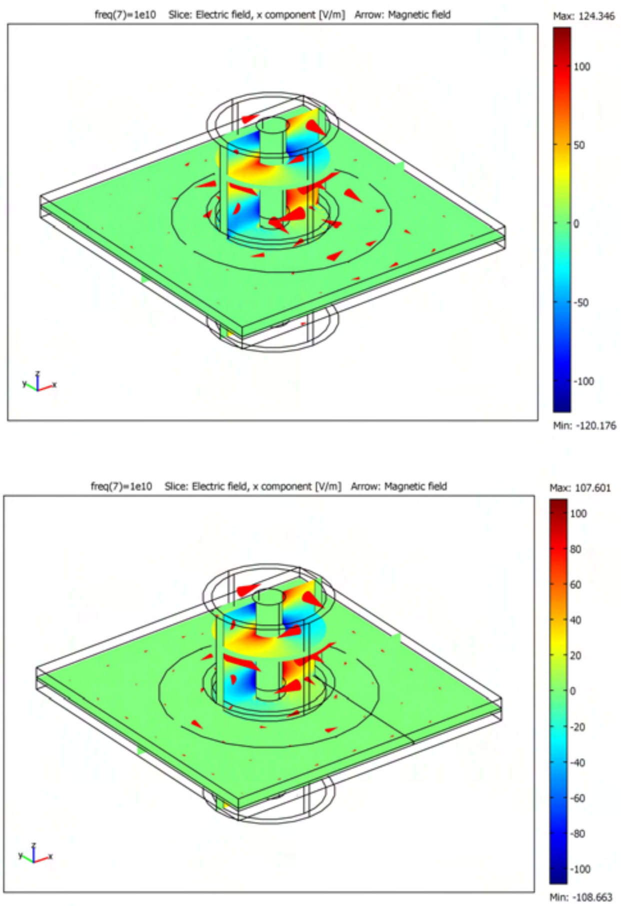

Fig. 4. Electric and magnetic field plotted in color slices and arrows for the off-centered placed and sliced samples, respectively.

Differences of the electromagnetic field are visible not only in the outer regions of the flanges, but in the coaxial line, too.

The matrix elements S_{11} and S_{21} for all the samples were calculated for the 100 MHz to 10 GHz region of frequency, and plotted in Fig. 5. The results of the various samples are not distinguishable on this scale, except at 10 GHz, which is out of the operating domain of the sample holder.

In order to study the differences of the S matrix elements of the modified samples from those of the original one are given in Fig. 6. It can be seen, that for lower frequencies the shifting of the samples cause less error, than the irregular, not cylindrical shape of it, while at higher frequencies, especially around the cut-off frequency, it results in resonances. The irregular shape of the sample seem to shift the S matrix elements with a slightly larger value, but it is not affected by reaching the cut-off frequency. Since the values of S_{21} are larger at the lower frequency domain and smaller at high frequencies, its relative error is less for the cylinder slice than for the shifted cylinder. Opposite statement holds for S_{11}.

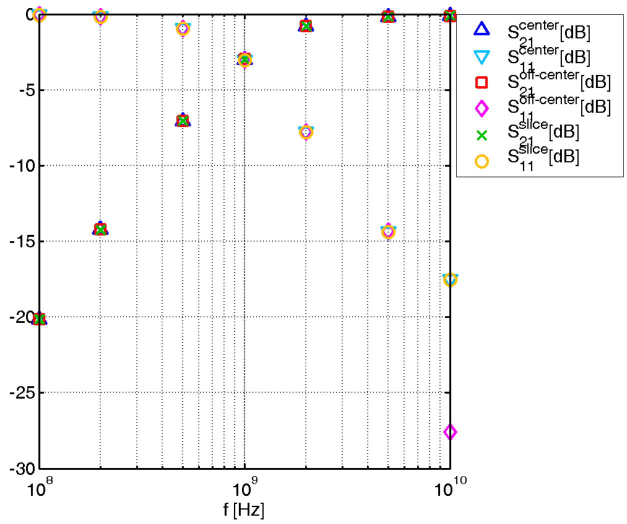

Fig. 5. S matrix elements for the, centered, off-centered placed and sliced samples, respectively.

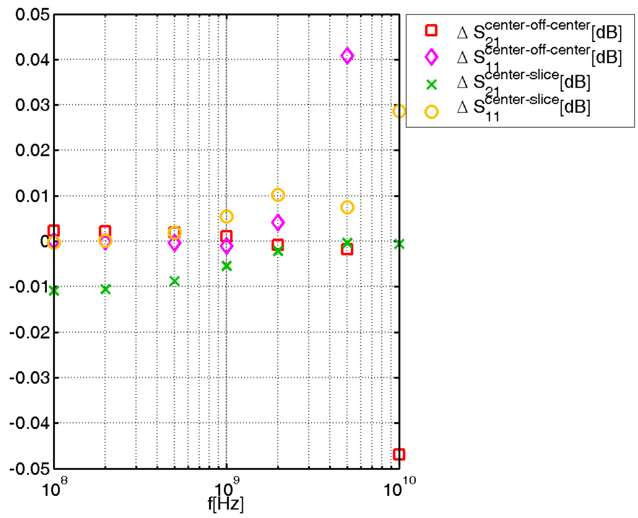

Fig. 6. Differences of the S matrix elements from the original, centered, cylindrical sample for the off-centered placed and sliced samples, respectively.

IV. Conclusion

A coaxial line based sample holder for thin, small, rigid, irregularly shaped planar samples is studied both by numerical simulations and by measurements. The numerical study showed, that due to the large flanges of the specimen holder the non central regions of the sample affect only slightly the main results, which was also proven by network analyzer measurements previously. Comparing numerical and measured data can result in shielding effectiveness and dielectric constant determination methods without reference sample.

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