Circuit Modeling of High-Frequency Electrical Conduction in Carbon Nanofibers

Francisco R. Madriz, John R. Jameson, Shoba Krishnan, Xuhui Sun, and Cary Y. Yang, *Fellow, IEEE*

***Abstract*—We show that the simplest possible circuit model of high-frequency electrical conduction in carbon nanofibers from 0.1 to 50 GHz is a frequency-independent resistor in parallel with a frequency-independent capacitor. The resistance is experimentally determined and represents the total dc resistance of the nanofiber and its contacts with the electrodes. The capacitance is obtained as a free parameter and has not been previously observed. The experimental method utilizes a ground–signal–ground test structure whose two-port scattering parameters (S-parameters) can be described to within ±0.5 dB and ±2° using a simple lumped-element circuit model. The nanostructure is placed in the signal path of the test structure, and its equivalent circuit is deduced by determining what additional elements must be added to the test structure circuit model to reproduce the resulting changes in the S-parameters. This methodology is applicable to nanowires and nanotubes.**

***Index Terms*—Carbon nanofiber, circuit model, electrical transport, ground–signal–ground (GSG), high frequency, nanostructures, scattering parameters (S-parameters).**

I. INTRODUCTION

ELECTRICAL conduction at high frequency in nanoscale systems such as nanotubes and nanowires is of great interest to the nanoelectronics community due to their potential applications in high-speed devices and circuits. One approach to studying high-frequency conduction is to measure the two-port scattering parameters (S-parameters) of a ground–signal–ground (GSG) test structure in which the nanoscale system forms part of the signal path. This approach has been used, for example, to study single-wall carbon nanotubes [1], multiwall carbon nanotubes [2]–[4], and bundles of carbon nanotubes [5]. The primary difficulty with this approach is that the measured S-parameters represent the electrical response not just of the nanostructure itself but also of the entire test structure. Thus, a procedure is required to separate the contribution of the nanoscale system from that of the test structure.

One common technique for achieving this separation is numerical de-embedding [6], which has been used, for example, to study conduction in carbon nanotubes at high frequency [1]–[5]. An alternate technique is to build a circuit model that accurately describes the S-parameters of the test structure in the absence of the nanoscale system (i.e., the "open" structure) and then deduce what new elements must be added to the circuit model to describe the S-parameters obtained *after* the nanostructure has been placed in the signal path. These additional circuit elements characterize electrical conduction in the nanostructure itself.

These two approaches, de-embedding and circuit modeling, aim to provide the same information about the nanostructure under test. However, circuit modeling has an advantage in that it also yields an in-depth physical understanding of the test structure. This understanding is very useful, as the design of the GSG test structure is of critical importance in obtaining highly accurate measurements. In particular, because transmission through individual nanoscale systems (e.g., a single carbon nanotube) can be rather small, it is important to minimize the loss and transmission due to the test structure itself. It is also preferable for the open test structure to exhibit S-parameters that have the simplest possible dependence on frequency so that small changes in the S-parameters can be more easily discerned when the nanostructure is added to the signal path.

Recently [7], we have reported a GSG open test structure that exhibits lower transmission than those previously reported [2]–[5] and has S-parameters whose frequency dependence is quite simple. It was shown that the S-parameters of the test structure can be described to within ±0.5 dB and ±2° from 0.1 to 50 GHz using an RC circuit consisting of two frequency-dependent capacitors, two frequency-dependent resistors, and one frequency-independent resistor [7]. Experimental procedures were provided for measuring all of the circuit elements, leaving no free parameters in the model [7].

In this paper, we utilize this test structure to study high-frequency electrical conduction in carbon nanofibers, which are of potential interest as an interconnect material for next-generation integrated circuit technology [8]. The same circuit modeling approach is taken as before [7]. First, the S-parameters of the open test structure are measured, and a circuit model is constructed. Then, the nanofiber is added to the signal path and the S-parameters are re-measured. Finally, the resulting changes in the S-parameters are used to deduce a circuit model describing the nanofiber itself.

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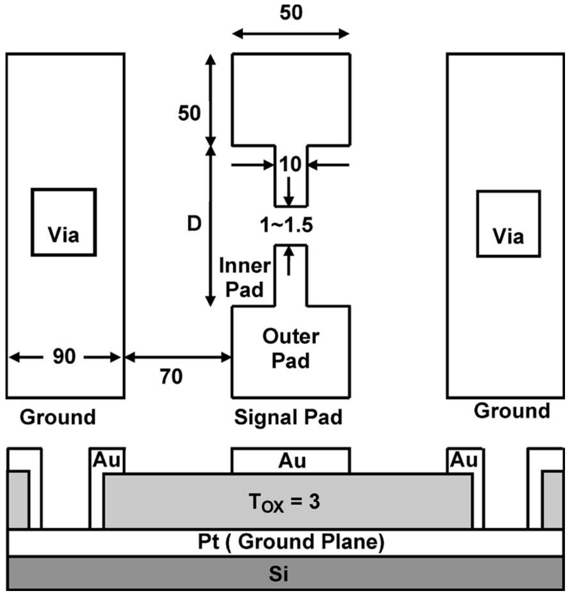

Fig. 1. Layout of the GSG test structure. Dimensions are in micrometers, and the drawing is not to scale.

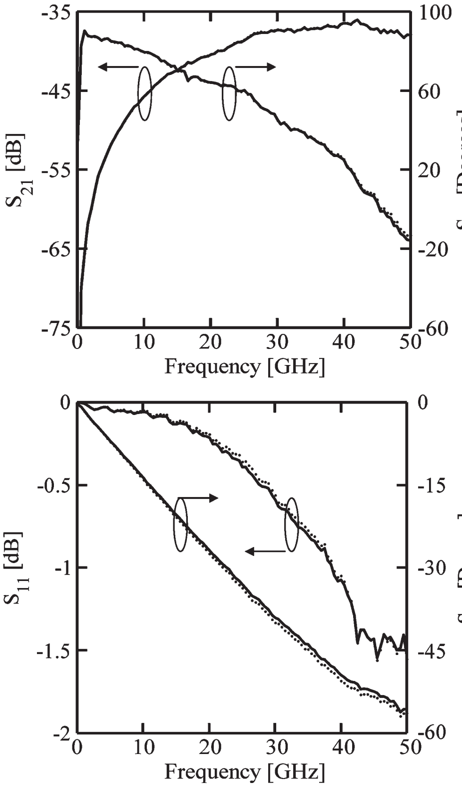

Fig. 2. Comparison of the (solid line) experimental and (dotted line) calculated S-parameters of the open test structure.

II. High-Frequency Conduction in Carbon Nanofibers

A. S-Parameters of the Open Test Structure

A vector network analyzer was used to measure the S-parameters of the open test structure, which is shown in Fig. 1. To minimize the noise at high frequency, a flat power calibration was performed across the entire frequency range of the instrument (0.1–50 GHz). Then, a line, reflect1, reflect2, and match (LRRM) calibration method was employed [9]. At frequencies above 40 GHz, the LRRM method offers higher accuracy and repeatability than other calibration methods. As shown in Fig. 2, the S-parameters of the open test structure exhibit simple frequency dependence with no abrupt changes in the slope.

B. Circuit Model of the Open Test Structure

The circuit model [7] of the open test structure is shown in Fig. 3. R_T is the contact resistance between the GSG probe tip and the signal pad, C_{PG} is the capacitance between the signal pad and the ground, R_{PG} represents conduction between the signal pad and the ground, as well as any other loss mechanisms in the SiO_2 layer, C_{PP} is the capacitance between the signal pads and the GSG probe tips, and R_{PP} represents conduction and losses between the signal pads. Other effects, such as the inductance of the signal pads, have been made negligibly small by the design of the test structure [7] and/or are accounted for implicitly when the values of the circuit elements are measured experimentally.

The values of the circuit elements in the model were measured using the procedures described previously [7]. The resulting circuit model yields S-parameters that are in excellent agreement with the measured S-parameters, as shown in Fig. 2. The small fluctuations in the S-parameters at high frequency are likely the result of multiple interactions between the test structure and the surrounding environment (e.g., probe station, cables, etc.). These fluctuations were reproducible, did not drift with time, and could not be removed by averaging over many measurements.

C. S-Parameters of Carbon Nanofibers

Having obtained an accurate circuit model of the open structure, we now place a nanofiber between the two signal pads and re-measure the S-parameters. The nanofibers used for this study ranged from 5 to 10 μm in length and from 70 to 200 nm in diameter. They were suspended in isopropyl alcohol, subjected to ultrasound for dispersion, and then dropped onto a wafer containing arrays of open test structures. In total, ten open structures were found to have a single nanofiber spanning the 1.5- to 2-μm gap between their signal pads. A scanning electron microscope (SEM) image of a typical example is shown in Fig. 4.

After deposition, the nanofibers were "annealed" by passing a constant current between the signal pads for 60 s. The dc resistance between the two signal pads was then measured. This resistance R_{dc} includes the probe contact resistance R_T, the resistance of both signal pads, a contribution R_F from the "bulk" of the nanofiber, and, presumably, also a contribution R_C from each of the nanofiber/pad contacts, all in series. The resistance of the inner and outer pads is ignored since it does not affect S_{21} and S_{11}. R_T was found to be about 2 Ω [7], with small probe-to-contact variability. The only influence R_T has is on the magnitude and the phase of the reflection parameter S_{11}, which, in turn, does not depend on the behavior of the

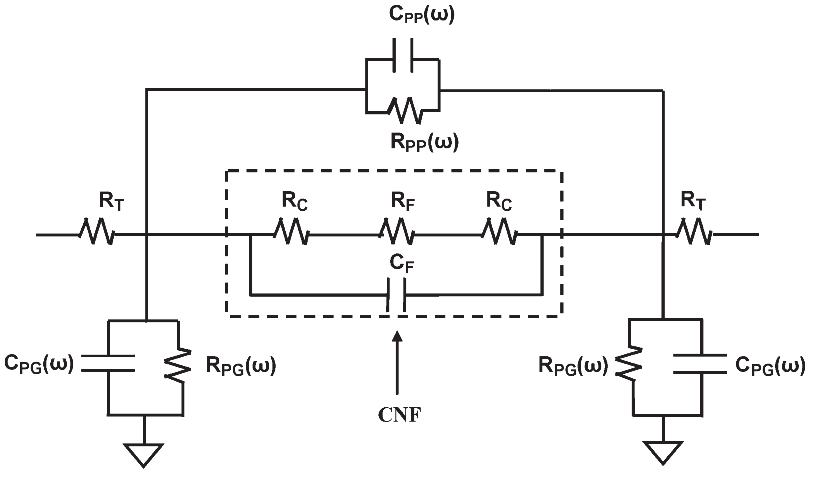

Fig. 3. Circuit models of the open test structure and the carbon nanofiber. The elements inside the dotted line represent the carbon nanofiber.

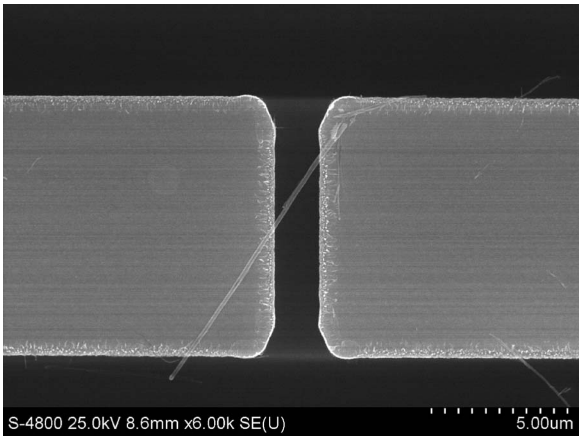

Fig. 4. SEM image of a carbon nanofiber in contact with the Au signal pads of the open test structure in Fig. 1.

nanostructure. Thus, for our analysis of CNF characteristics, we can assume $R_{\rm dc} \approx R_F + 2R_C$.

Figs. 5 and 6 show the S-parameters measured after the nanofiber in Fig. 4 was annealed. The frequency dependence of S_{21} shown in Fig. 5 differs from that of the open structure (Fig. 2), indicating that the CNF is contributing to the transmission between the signal pads. In contrast, S_{11} (Figs. 2 and 6) has not changed significantly. This is consistent with the previous observation [7] that S_{11} is determined almost exclusively by the contact resistance R_T between the probe tip and the signal pad, which is not altered by the nanofiber.

D. Circuit Model of Carbon Nanofibers

Finally, we ask what additional elements must be added to the circuit model of the open structure in order for the model to reproduce the changes in the S-parameters observed after the nanofiber was added to the signal path. As noted above, for dc currents, the signal path behaved as a resistance $R_F + 2R_C$. A reasonable starting point for a circuit model of the nanofiber is, therefore, to treat it simply as a resistor. As shown in Fig. 5, such a model does indeed yield a reasonable agreement with the experimental S-parameters. However, the difference between the model and the experiment is not as small as it was for the open structure (see Fig. 2), indicating that a refinement of the model might be possible.

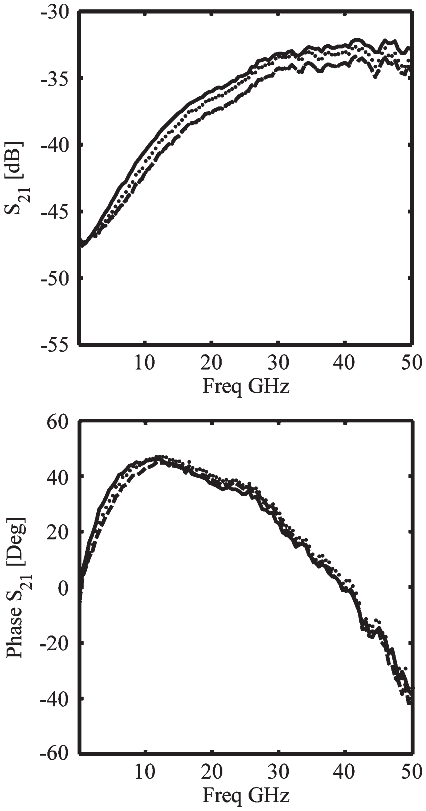

Fig. 5. S_{21} (transmission) of the test structure with the nanofiber shown in Fig. 4. (Solid line) Measured result. (Dotted line) From the model (see Fig. 3) with $R_{\rm dc} = 22$ kΩ (measured) and $C_F = 0.15$ fF. (Dashed line) From the model with $R_{\rm dc} = 22$ kΩ and $C_F = 0$ fF.

Since the impedance of a two-terminal device generally contains both real and imaginary parts, representing resistive and reactive components, respectively, as viewed from the terminals, it is reasonable to explore whether the agreement with the experiment can be improved by adding an imaginary term to the impedance of the nanofiber model. This approach is supported by a recently reported RLC circuit model for a carbon nanotube [3], which yields an impedance with a negative

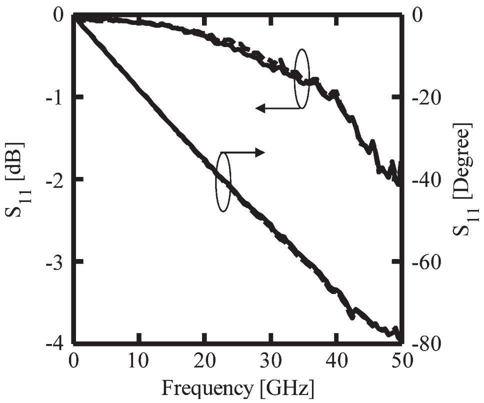

Fig. 6. S_{11} (reflection) of the test structure with the nanofiber shown in Fig. 4. (Solid line) Measured result. (Dotted line) From the model (see Fig. 3) with $R_{\mathrm{dc}} = 22$ kΩ (measured) and $C_F = 0.15$ fF. (Dashed line) From the model with $R_{\mathrm{dc}} = 22$ kΩ and $C_F = 0$ fF. The dashed and dotted lines are on top of each other as expected, making it difficult to distinguish between them.

TABLE I
SUMMARY OF THE MEASURED AND EXTRACTED CHARACTERISTICS OF CNF DEVICES

Device	Diameter (nm)	Length (μm)	R_{dc} (kΩ)	C_F (fF)
1	71	2.2	49	0.1
2	72.3	1.9	38	0.05
3	100	1	15.5	0.25
4	100	2	17.5	0.12
5	147	3	16	0.15
6	150	1.3	15.5	0.08
7	155	1.37	23.5	0.15
8	160	1.32	22	0.15
9	175	5	54	0.25
10	200	2.1	15	0.7

reactive component assuming a negligible inductive effect. Neglecting inductive contribution is reasonable in our case, as the dimensions of the measured nanofibers are sufficiently large. Thus, we place a capacitor C_F in parallel with the resistance $R_F + 2R_C$. In this simple RC circuit model, the resistance $R_{\mathrm{dc}} = R_F + 2R_C$ is still the measured value for the combined CNF and contact resistance. Capacitance C_F, on the other hand, is treated as a free parameter, but it is the only fitting parameter in the entire circuit model. As seen in Fig. 5, the disagreement between the experiment and the circuit model is largely eliminated by the choice $C_F = 0.15$ fF.

Table I summarizes the values of R_{dc} and C_F obtained for all nanofibers tested. No clear dependence of C_F on the diameter or length of the nanofiber is evident, as one would expect, as it simply represents the reactive part of the total impedance of the entire nanostructure [3]. Plausible sources for its existence might be the capacitance at the nanofiber/pad contacts and/or polarization of the nanofiber in its axial direction. The proper physical interpretation of the capacitance is complicated by the fact that a capacitor in parallel with a resistor is simply a Thévenin equivalent circuit for a complex system, albeit a useful one. Any circuit model yielding the same impedance would produce equally good agreement with the experiment. Nevertheless, in the case of 1-D nanostructures such as CNF, nanotubes, and nanowires, the interpretation of the physical origin based on circuit modeling is limited to considerations of transports across contacts and within the nanostructure itself. Thus, the RLC circuit model proposed in [3] and its simplified RC equivalent used here are excellent starting points for understanding the electrical behaviors of 1-D nanostructures at high frequencies.

III. CONCLUSION

Based on extensive measurements and circuit modeling, high-frequency electrical conduction in carbon nanofibers can be described by a frequency-independent capacitance in parallel with a frequency-independent resistance. The resistance is experimentally determined and represents the total dc resistance of the nanofiber and its contacts with the electrodes. The capacitance C_F is obtained as a free parameter and has not been previously observed. This methodology is applicable to nanowires and nanotubes. Future studies include examining the physical origin of C_F and the improvement of the electrode contacts as described in [10].

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