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A de-embedding technique for metallic nanowires in microwave characterization

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ABSTRACT

The application of metallic nanowires as transmission lines at microwave frequencies has attracted interest of the nanoelectronics community in recent years. The size reduction of wires down to nano-scale inevitably introduces more challenges not only in the fabrication but in the characterization techniques. The aim of this work is to build a reliable framework to characterize a single metallic nanowire in the millimeter wave range by means of a tailored-designed coplanar waveguide platform. We conduct a comprehensive analysis on the characteristic impedances and the propagation constants of nano-scale aluminum metallic wires in relation to the change of line dimension as a function of frequency from 1 to 100 GHz. A method to subtract the effect of pads and contact impedance from the measurement based on an equivalent circuit model and a cascade-based de-embedding theory is employed. We propose a quasi-TEM equivalent circuit model in the analysis to predict the measured frequency-dependent transmission line parameters. A comparison between simulated and measured result will be presented.
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1. Introduction

One way to achieve extremely high density circuit is to use nano-size interconnects. Nanowires (NWs) are considered as essential components to build future nanoelectronic devices in the millimeter wave range [1–3]. Over the past few years, research groups have focused on investigating the potential of carbon nanotubes (CNTs) for RF applications and thanks to their excellent electrical properties, CNTs are promising candidates to serve as next generation interconnects [4]. The pioneering work of Burke has revealed their interesting characteristics at high frequencies [5,6]. However, the production of CNTs with well-controlled geometries and properties remains a challenge. Only very recently has this idea been extended to semiconducting and metallic NWs [7,8]. As they are compatible with the CMOS processes, they can be fabricated into desired geometries or arrays, thereby improving the impedance matching to realize a nanowire-based device [9].

To date, the electrical properties of metallic NWs at high frequencies are not well understood. The current approach for studying a single NW is to measure the two-port scattering parameters (*S*-parameters) of a Ground-Signal-Ground (GSG) test structure with a NW bridging the signal path [3,7]. Then, the transmission line characteristics of the NW are estimated from the *S*-parameters. The major challenge lies in extracting broadband intrinsic RF response of the wire from measurement. The issues include very small signal level and presence of pad parasitics [10]. Thus, a reliable characterization framework needs to be established.

We have previously reported the characterization up to 65 GHz on a single aluminum (Al) NW with a linewidth and thickness of 100 nm [11]. A coplanar waveguide (CPW) structure was designed and fabricated as a vehicle to test NWs. This paper follows up on previous work and extends the measured frequency range up to 100 GHz. Al wires with different geometries are tested allowing us to accurately determine the properties of the lines as dimension changes. We have applied a method to systematically extract the frequency response of these miniaturized transmission lines, minimizing the pad parasitics and correcting the contact impedance. Using the measured data, the transmission line parameters per unit length can be calculated. Furthermore, we propose a quasi-TEM based model to validate the de-embedding technique and to approximate the line characteristics using equivalent circuit elements throughout the experimental frequency range. Finally, the measured and simulated results are compared and discussed.

2. Fabrication and measurement

2.1. Fabrication

The test device includes an individual Al metal line embedded in between a CPW structure (the two ground planes and RF pads) as shown in Fig. 1. Four dimensions of the line are chosen. Table 1 summarizes the geometric parameters of the Devices-Under-Test (DUT).

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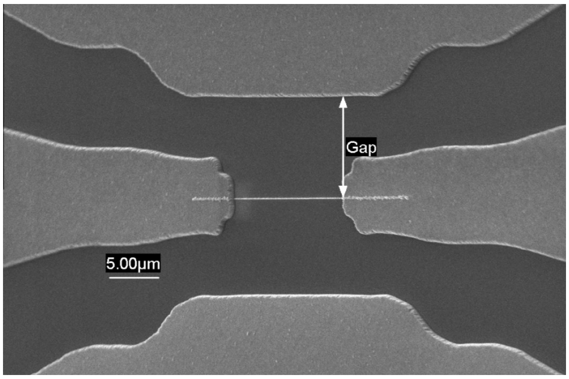

Fig. 1. SEM image of a nano-size Al wire embedded in a CPW structure.

Table 1
Geometric parameters of the lines in CPW configuration.

Sample No.	Linewidth (µm)	Thickness (nm)	Gap (µm)
1	1	50	9.5
2	0.5	100	9.75
3	0.1	100	9.95
4	8	500	6

The substrate is a standard silicon wafer (resistivity: 5–10 Ω cm) with a 500 nm thick SiO_2 layer on the front and back side. The Al wires for sample Nos. 1–3 are fabricated by electron beam lithography (EBL) and lift-off method. First, line features are patterned in JBX-6300FS Electron Beam Lithography System with PMMA 950 K 4% (0.3 µm thick) as resist. Next, an Al layer is deposited by evaporation with a deposition rate of 0.1 nm/s. After a subsequent lift-off process in acetone, Al lines can be obtained. The wires for sample No. 4 are fabricated in a single step together with CPW structures.

To define the CPW structure, standard lithography is applied using AZ5412E as resist (1.3 µm thick), followed by evaporation of a 500 nm thick Al layer (deposition rate: 2 nm/s) and lift-off process. Notice that this layer is much thicker than that of sample Nos. 1–3. It is to avoid RF probes penetrating through the structure during the measurement. The size of the whole CPW structure depends on the length of the line (L). Five different lengths are chosen for evaluation (L = 17, 42, 92, 192 and 492 µm). A part of the signal pad with 100 µm in length is designed to be a tapered shape. The distance between the two ground planes is fixed at 20 µm. Fig. 2a shows a scanning electron microcopy (SEM) image of sample No. 3 connected to the pad. It is worthy to mention that the nanostructure obtained by this approach is polycrystalline and has a rough surface, as can be seen in Fig. 2b. The thru device for de-embedding is fabricated at the same time (Fig. 3).

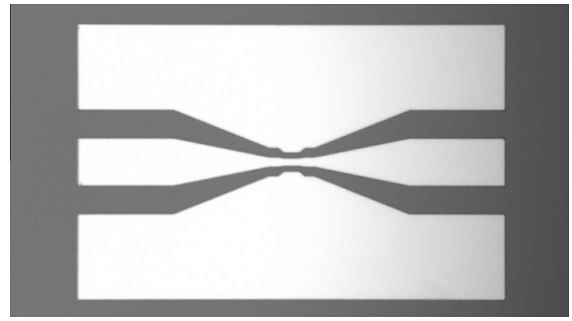

Fig. 3. Thru de-embedding test structure.

2.2. Measurement

The S-parameters of the CPW devices are measured using ANRITSU ME7808C Broadband Vector Network Analyzer (VNA) and a semi-automatic Cascade S300 station. The tests are conducted from 1 to 100 GHz using RF probes in GSG configuration with a pitch of 100 µm provided by Cascade Microtech, as shown in Fig. 4. The VNA is calibrated using the Cascade Impedance Standard Substrate (ISS, 104-783). The material of this substrate is alumina. We apply Load-Reflect-Reflect-Match (LRRM) calibration method using a commercially available software package WinCal from Cascade Microtech. LRRM has proven to offer the best accuracy and repeatability. It is also the least sensitive approach to probe to pad placement [12,13]. The reference plane is at the end of the probe tips. The calibration is verified on the thru standard within the general recommended limits of ±0.1 dB up to 100 GHz before testing. Each measurement is made with 201 data points using 128 averages in a 100 Hz IF bandwidth. The chuck is electrically connected to the ground probes.

3. Extraction of transmission line parameters

3.1. Pad parasitics subtraction

The "two-port de-embedding" method is applied in this study to remove the effect of the pads. It only requires a thru test structure [14]. This method belongs to a cascade-based technique. A thru test structure can be represented by two identical two-port networks in series, as shown in Fig. 5.

Their S-parameters can be derived from

$$S_{11p} = S_{22p} = \frac{S_{11t} + S_{22t}}{2 + S_{21t} + S_{12t}} \quad (1)$$

$$S_{12p} = S_{21p} = \sqrt{\frac{1}{2} \cdot (S_{12t} + S_{21t}) \cdot (1 - S_{11p^2})} \quad (2)$$

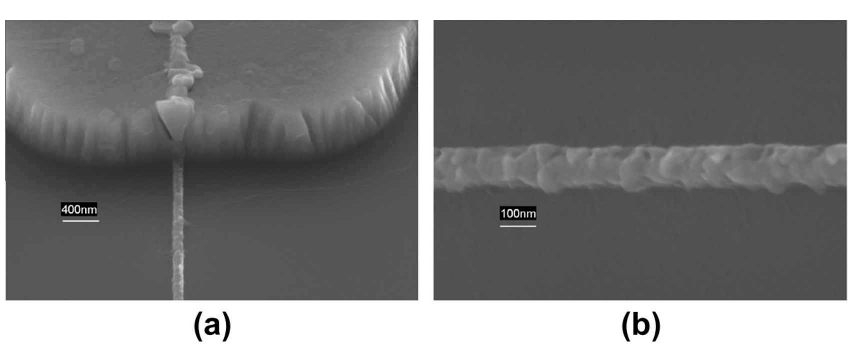

Fig. 2. SEM images of sample No. 3: (a) contact between the nano-size wire and the pad and (b) top view of the Al wire.

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