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Contact resistance extraction methods for short- and long-channel carbon nanotube field-effect transistors

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ABSTRACT

Three different methods for the extraction of the contact resistance based on both the well-known transfer length method (TLM) and two variants of the Y-function method have been applied to simulation and experimental data of short- and long-channel CNTFETs. While for TLM special CNT test structures are mandatory, standard electrical device characteristics are sufficient for the Y-function methods. The methods have been applied to CNTFETs with low and high channel resistance. It turned out that the standard Y-function method fails to deliver the correct contact resistance in case of a relatively high channel resistance compared to the contact resistances. A physics-based validation is also given for the application of these methods based on applying traditional Si MOSFET theory to quasi-ballistic CNTFETs.

1. Introduction

Carbon nanotube field-effect transistors (CNTFETs) have the potential to become relevant for RF electronics due to the outstanding electrical characteristics of the carbon nanotubes (CNTs) used as a channel. Fabricated CNTFETs have already achieved an intrinsic transit frequency of 80 GHz and extrinsic transit and maximum oscillation frequencies of around 10 GHz as well as a maximum available power gain of 10 dB at 2 GHz [1,2].

Among the extraordinary electrical characteristics, such as low scattering rate and high current-carrying capability, the intrinsic linearity [3–6] is expected to be beneficial for future high-frequency applications such as CNTFET amplifiers, mixers and switches once the technology related issues are solved [2]. A full review of the state-of-the-art of CNTFET technology for RF applications can be found in [2].

One of the key effects that limits the performance of CNTFETs, and thus its RF linearity, is the resistance associated with the interconnection between the CNT and the metal contacts, which is commonly labeled as the contact resistance.

Extracting the values for this contact resistance from experimental data is of interest to various research disciplines: from a technological point of view this value represents a quantification of the contact quality while from a modeling point of view this resistance can be associated with the series resistance in the equivalent circuit of a CNTFET compact model. In addition, the extracted value can also be used for verifying sophisticated contact models based on, e.g., atomistic simulations.

In the literature, different methods for extracting the contact resistance of CNTFETs are discussed. Interestingly, the extracted values can differ by orders of magnitude. Therefore, in this paper the reliability of three often found methods is analyzed and compared based on simulation and experimental data.

This paper is organized as follows. Section 2 introduces a definition of the contact resistance and explains its physical origin. Section 3 describes the methodologies applied to extract the value associated to the contact resistance. The methods have been applied to synthetic data from a compact model and numerical device simulations as well as to measurements of single- and multi-tube CNTFETs. The corresponding results are discussed in Section 4.

2. The contact resistance in CNTFETs

The total resistance R_{tot} of a CNTFET measurable at the terminals can be seen as the sum of the resistance R_{ch} of the channel and the contact resistances $R_{CS/D}$ associated with the source and drain contacts, i.e., $R_{tot} = R_{ch} + R_{CS} + R_{CD}$. The separation of the total resistance into channel and contact resistance is not unique. Especially in the case of Schottky-barrier transistors the impact of the Schottky barrier on the $I-V$ characteristics can be lumped either

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into the channel or into a bias dependent contact resistance depending on the motivation for doing the extraction. In this work, the contributions of the source and drain contacts are lumped into a total contact resistance $R_C = R_{CS} + R_{CD}$ which includes the impact of the Schottky barriers unless specified otherwise.

The channel resistance R_{ch} depends on the number of scattering events in the channel. The shorter the channel, the smaller is the number of scattering events, and, thus, the smaller is the contribution of R_{ch} to R_{tot}. For very short channels and ohmic contacts, R_{tot} approaches its ballistic limit corresponding to the value of the quantum resistance R_q of about 6.5 kΩ per subband. Experimentally, defects can affect considerably the channel resistance even when the channel length is short. The devices considered here are working in the quasi-ballistic and in the diffusive regimes. For the latter, a quantifiable contribution of R_{ch} to R_{tot} is thus expected.

As shown in Fig. 1, in general, two main material interfaces contribute to the contact resistance in CNTFETs: the first material interface is in between the metal and the nanotube portion under the metal (coated CNT region) while the second material interface is in between the coated and uncoated nanotube portion.

The first interface can be influenced by several parameters such as contact geometry, contact length [7], the material used for the fabrication [8], and any interfacial layer that may be present between the metal and the nanotube. At the second interface, a change of the electronic structure of the metal-coated tube portion due to the interaction with the metal induces a potential step (barrier) [9–11]. An important contribution to the height of the potential step is the Schottky barrier height ϕ_{SB} which is defined as the difference between the Fermi level and the value of conduction band of the CNT at the interface between the metal coated and uncoated tube portion.

3. Contact resistance extraction methods

Three different extraction methodologies are used in this work: the transfer length method (TLM) [12] widely known in the MOSFET and bipolar transistor community and two methods based on the Y-function [13] developed for Si MOSFETs using simple analytical MOSFET equations. The Y-function has been used recently to extract the contact resistance of CNTFETs in [14,15].

The TLM requires the fabrication of a test structure with long CNTs [8], which allows the placement of various contacts on the tube with different spacings L_{ch} in between the contacts. The CNT should lie on a substrate with a global back gate to bias the device properly. The resistance R_{tot} between each pair of contacts is obtained from the $I-V$ measurements at these contacts. The contact resistance is extracted from the linear extrapolation of the $R_{tot}(L_{ch})$ plot towards $L_{ch} = 0$. However, the need for typically μm-long CNTs makes the fabrication of these test structures challenging in, e.g., purified solution based technologies.

The Y-function method is based on a combination of the current and transconductance equations in order to avoid the effects of the mobility reduction on the determination of device model parameters [13]. In general, the Y-function is defined as

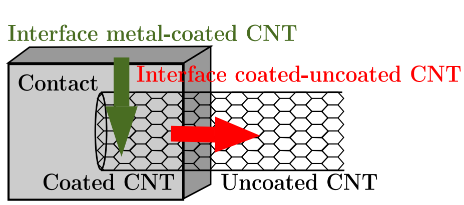

Fig. 1. Internal device interfaces involved in the CNTFETs contact resistance. (Only one contact is shown).

$$Y = \frac{I_D}{\sqrt{g_m}}, \tag{1}$$

where I_D is the drain current and g_m the transconductance, defined as the derivative of I_D with respect to the gate-source voltage, V_{GS} at constant drain-source voltage, V_{DS}.

The device is considered within the strong inversion regime of the linear region at low drain-source voltages. The underlying transport model describing the current flow through the internal transistor is given by

$$I_D = \beta \frac{(V_{GS,i} - V_{th} - V_{DS,i}/2)}{1 + \theta_0 (V_{GS,i} - V_{th})} V_{DS,i}, \tag{2}$$

where $\beta = \mu_0 C_G \big/ L_{ch}^2$ with the gate capacitance $C_G = C_{ox} W L_{ch}$; C_{ox} is the area specific gate oxide capacitance, W is the effective channel width, L_{ch} is the effective channel length, μ_0 is the low field carrier mobility, θ_0 is the mobility reduction coefficient which quantifies the degradation of the carrier mobility due to the applied vertical field [12], V_{th} is the threshold voltage, and $V_{GS,i}$ and $V_{DS,i}$ are the internal gate-to-source and internal drain-to-source terminal voltages, respectively. The internal voltages are given by $V_{GS,i} \approx V_{GS} - I_D R_C/2$ and $V_{DS,i} \approx V_{DS} - I_D R_C$. Assuming $R_C = R_{CS} + R_{CD}$ leads to

$$I_D \approx \beta \frac{(V_{GS} - V_{th} - V_{DS}/2)}{1 + \theta (V_{GS} - V_{th} - V_{DS}/2)} V_{DS}, \tag{3}$$

where the extrinsic mobility degradation coefficient θ, including the contribution from the contact resistance [12], is given by

$$\theta = \theta_0 + R_C \beta. \tag{4}$$

Note that in the denominator of Eq. (3) the voltage drop over the intrinsic transistor diminished by the mobility reduction coefficient $(\theta_0 V_{DS,i}/2)$ has been neglected.

The Y-function method applied in [14,15], labeled here YFM_1, assumes $V_{GS} - V_{th} \gg V_{DS}/2$ and a negligible mobility reduction coefficient $(\theta_0 = 0)$. Hence the drain current expression used in YFM_1 is given as

$$I_D \approx \beta \frac{(V_{GS} - V_{th})}{1 + R_C \beta (V_{GS} - V_{th})} V_{DS}, \tag{5}$$

with the parameters V_{th} and β obtained from the intercept and slope of a linear plot $Y(V_{GS})$ [14,15]. Replacing I_D in Eq. (1) by Eq. (5), the Y-function reduces to

$$Y = \sqrt{\beta V_{DS}} (V_{GS} - V_{th}). \tag{6}$$

Defining $R_{tot} = V_{DS}/I_D$, the contact resistance $R_{C,Y1}$ is obtained by

$$R_{C,Y1} = R_{tot} - R_{ch}, \tag{7}$$

where the channel resistance is approximated at small V_{DS} with

$$R_{ch} \approx \frac{1}{\beta (V_{GS} - V_{th})}. \tag{8}$$

YFM_1 yields a range of contact resistance values for $R_{C,Y1}$ according to the range of the applied gate bias voltages V_{GS}.

In [16] an improved method was developed for the extraction of the contact resistance in SOI-MOSFETs which considers the mobility reduction coefficient, θ_0, in Eq. (3) but still assumes $V_{GS} - V_{th} \gg V_{DS}/2$ in the denominator. In this work, however, the latter approximation is not considered in the calculations. Thus, Eq. (3) is used as the underlying transport model. The related extraction method is labeled here with YFM_2. Replacing I_D in Eq. (1) by Eq. (3), the Y-function reduces to

$$Y = \sqrt{\beta V_{DS}} \left(V_{GS} - V_{th} - \frac{V_{DS}}{2} \right). \tag{9}$$

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