Stability Analysis for Carbon Nanotube based Field Effect Transistors

Saeede Afsharmehr, Mehrnoosh Zeinalkhani, Mohammadali Ghorbani, and Alireza Heidari

Abstract—We present Nyquist stability criterion for small-signal equivalent circuit model of carbon nanotube field effect transistors (CNTFETs). To the best of our knowledge, this is the first instance that such analysis has been done for CNTFETs so far. In this analysis, the dependence of the degree of relative stability in CNTFETs on the length and diameter of channel tube is acquired. It is shown that increasing both the tube length and diameter causes higher stability.

Index Terms—Carbon nanotube field effect transistor (CNTFET), Nyquist Stability.

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1 INTRODUCTION

High mobility, low-defect structure, direct band gaps, symmetric bands, and intrinsic-nanometer scale of carbon nanotubes (CNTs) has led to an intense research effort into the viability of utilizing CNT field-effect transistors (CNTFETs) as a promising replacement for, or complement to traditional silicon MOSFETs [1], [2]. Semiconducting CNTs have been instead used to demonstrate field-effect transistors (FETs) having quasi-1-D channels [2]. The CNTFET can be characterized by: the highest carrier mobility at room temperature of any known material, nearly two orders of magnitude better than existing semiconductor technology, highly scalable, low-power, and low leakage current relatively to the applied voltages and low inverse subthreshold slope. With ultra-long (~ 1μm) mean free path (MFP) for elastic scattering, a ballistic or near-ballistic transport in the channel can be obtained with an intrinsic carbon nanotube (CNT) under low voltage bias leading to higher transconductance compared to any other materials. Due to near ballistic transport and the high band-structure-limited velocity in CNTs, CNTFETs also promise good potential for radio-frequency (RF) applications. The quasi-1-D structure provides better electrostatic control over the channel region than 3-D devices (bulk CMOS) and 2-D device (fully depleted SOI) structures [3], [4], [5], [6]. A circuit-compatible SPICE model for single-wall nanotube FET (SWNT-FET) is used to model ac characteristics and gain Transfer Function of the SWNT-FET. This Transfer Function achieved from SWNT-FET configured as a common-source amplifier.[5] Briefly it is a physics-based model that also includes device nonidealitics such as the quantum confinement effect in the circumferential and the channel length directions, the capacitance and resistance of the doped source/drain SWNT region, as well as the possible SB resistance of source/drain contact[5].

A planar gate structure which is closer to the reality than the coaxial gate structure is used in the modeling. A complete compact circuit model is illustrated in Fig. 2 where CGB is the coupling capacitance between gate and substrate that is derived as $C_{GB}=C_{BG}=L_g C_{sub} C_{ox}/(C_{tot}+C_{Qs}+C_{Qd})$. The substrate-to-gate capacitance C_{sub} can be calculated with the simple equation $C_{sub}=2\pi k_2 \varepsilon_0/\ln(2H_{sub}/d)$. The parameters H_{sub} and k_2 represent the bulk dielectric material thickness and dielectric constants respectively. C_{ox}, the capacitance between the gate and channel, and $C_{tot}=C_{ox}+C_{sub}+C_c$, C_c is the capacitance between the channel and external drain [4]. C_{xy}/C_{yx} is the transcapacitance pairs. LMS is the magnetic inductance which is three orders smaller than L_{KS}, the quantum inductance of CNT [7].The kinetic inductance is estimated as $L_{KS}=hl/4q^2 v_F$, where v_F is the carrier velocity [6]. In this figure R_S and R_D represent series resistance due to scattering. C_{gs}/C_{sg} includes the geometrical capacitance (CES Electrostatic capacitance) in series with the quantum capacitance;the quantum capacitance is multiplied by four because of the band structure degeneracy. Therefore:

$$\frac{1}{C_{gs}} \approx \frac{1}{C_{ES}} + \frac{1}{C_Q} \tag{1}$$

$$C_{ES} = \frac{2\pi\varepsilon}{\cosh^{-1}(2h/d)} \approx \frac{2\pi\varepsilon}{\ln(h/d)} \tag{2}$$

where h and d denote CNT's height and diameter, respectively [9]. $C_{sb}=C_{sg}(C_{sub}/C_{ox})$ and $C_{db}=C_{dg}(C_{sub}/C_{ox})$. The R_{ds} of CNTFETs is generally expressed as $R_{ds}=R_{SB}+(h/4e^2)(l/\lambda)$ where R_{SB} is the contact resistance, l is channel length and λ is the electron mean free path [10], [11], [12].

On the other hand, the Nyquist diagram that is a complex plane of coordinates with a real (horizontal) axis and an imaginary (vertical) axis can be a powerful tool for investigating the system relative stability [8], [13], [14], [15]. Point (-1,0), in this complex plane, is the critical point for stability. When inside the diagram, for the system to be more stable, the point must move toward outside the diagram, as

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- *Saeede Afsharmehr, Institute for Advanced Studies, Tehran 14456-63543, Iran.*
- *Mehrnoosh Zeinalkhani, Institute for Advanced Studies, Tehran 14456-63543, Iran.*
- *Mohammadali Ghorbani, Institute for Advanced Studies, Tehran 14456-63543, Iran.*
- *Alireza Heidari, Institute for Advanced Studies, Tehran 14456-63543, Iran, E-mail: Prof.Alireza.Heidari@InstituteforAdvancedStudies.us*

its parameters are varied. Otherwise, the farther the point moves from the diagram, the more stable is the system. In this letter, using the Nyquist diagram as a criterion, we examine the relative stability of a SWNT-FET common source configuration that is shown in Fig. 2.

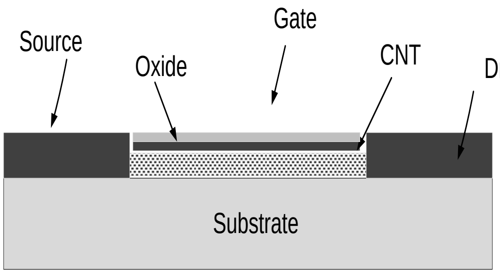

Fig. 1. The 2D cross-sectional layout of fabricated SWNT-FET.

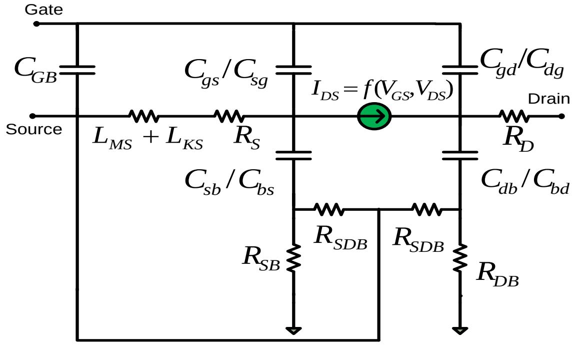

Fig. 2. Small-signal SWNT-FET device model. $C_{xy}=\partial Q_x/\partial V_y$. C_{gs}/C_{sg}, C_{gd}/C_{dg}, C_{sb}/C_{bs}, and C_{db}/C_{bd} are transcapacitance pairs.

2 RELATIVE STABILITY

In the configuration shown in Fig. 2, an SWNT-FET of channel length (l) and carbon nanotube (CNT) diameter (d) that is represented by a coupling capacitance (C_{GB}) , magnetic inductance (L_{MS}) and kinetic inductance (L_{KS}) , transcapacitance pairs (C_{xy}/C_{yx}), source/drain resistance (R_S/R_D), (R_{SB}/R_{DB}), and (R_{SDB}) (all in per length units). Using these elements, the input-output transfer function becomes

$$H(s)=V_o(s)/V_i(s)=\sum_{i=0}^{4} a_i s^i / b_i s^i \qquad (3)$$

where $s = j\omega$ is the complex frequency and coefficients a_i and b_i are given in the appendix.

By varying the nanotube dimensions (18 ≤ l ≤100 nm and 1 ≤ d ≤ 5 nm) and generating various Nyquist diagrams, we have studied the effect of SWNT-CNTs geometry on the relative stability of the configuration shown in Fig. 2. In this analysis, we have assumed that R_S = R_D =3 kΩ, λ=700 nm and h=140 nm.

Fig. 3 shows the Nyquist diagram for the configuration of Fig. 2, for nanotube of l =50 nm and d =1, 3, and 5 nm. As can be seen in Fig. 3, the critical point (-1,0) is located inside the diagram for all three given diameter. However, as d increases, the critical point (-1,0) moves toward outside. Fig. 4 shows similar Nyquist diagram for CNTFET with d = 5 nm and l =18, 50, and 100 nm. Fig. 4 also shows that the critical point (-1,0) also moves toward outside. In other hand, this means, as d or L_{CH} increases, that the relative stability of the CNTFET increases. In fact as d increases C_{ES}, C_{sb}, C_{db}, and C_{GB} increase. Due to an increase in C_{ES}, C_{gs}, C_{gd} increases. As l increases, L_k, LM, R_{SDB}, and R_{SB} increases. Note that, while C_{ES}, C_{GB}, C_{gs}, C_{gd}, R_{SDB}, and R_{SB} are the dominant parameters in determining the switching delay, the effects of variations in LK and LM on the switching delay are negligible. Hence, as increase in either of C_{GB}, C_{gs}, C_{gd}, R_{SDB}, and R_{SB} gives rise to the CNTFET switching delay. As the switching delay increases, the step response of the CNTFET tends to damp more rapidly, and the system becomes more stable.

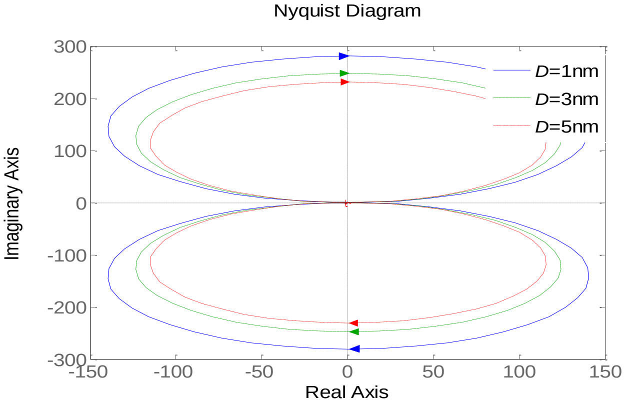

Fig. 3. The Nyquist diagrams for SWCNTFETs configuration of Fig. 2 for l=50 nm and 1≤ d ≤5 nm.

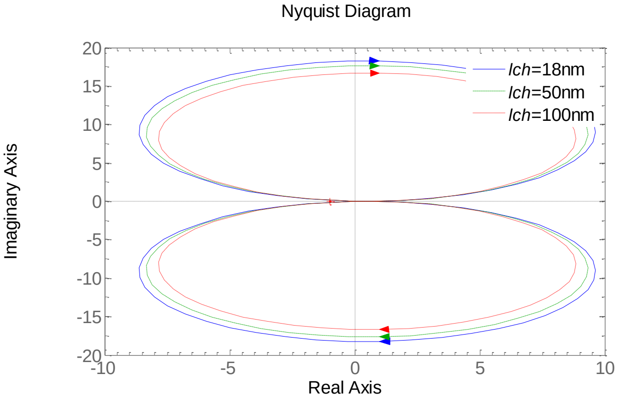

Fig. 4 The Nyquist diagrams for SWCNTFETs configuration of Fig. 2 for d=1 nm and 18≤ l ≤100 nm.

3 CONCLUSION

Using small signal model with Nyquist stability diagrams, the relative stability for CNTFET has been studied. We have shown that with increasing either the diameter or length of channel of the CNTFET, the relative stability increases, and hence, the system becomes more stable. This is because an increase in either parameter gives rise to switching delay and, hence, its step response tends to damp faster, and as a result, the system become more stable.

APPENDIX

Coefficients a_i and b_i in (3) are as follows:

$$a_0 = R_D g_m C_{gs}[X_1 X_2 + X_3]$$

$$a_1 = R_D[(g_m C_{gs}(R_{SDB}(C_{db}X_2 - X_4X_1) + C_{sb})$$
$$+ C_{gs}C_{gd}((1+\frac{R_{SDB}}{R_{DB}})(X_2 + X_3) - C_{gs}C_{GB}X_3)]$$

$$a_2 = R_D[C_{gs}C_{gd}(R_{SDB}(X_2C_{db} - X_4X_1) + C_{sb})$$
$$- g_m C_{gs}R_{SDB}(C_{db}X_4 - R_{SDB}C_{GB}C_{sb}X_1) + C_{GB}C_{sb}C_{gs}$$
$$- C_{sb}C_{db}(C_{GB} + C_{gs} + C_{gd})]$$

$$a_3 = -R_D[C_{gs}C_{gd}R_{SDB}(C_{db}X_4$$
$$- R_{SDB}C_{GB}C_{sb}X_1) + g_m C_{gs}R^2{}_{SDB}C_{db}C_{GB}C_{sb})$$

$$a_4 = -R_D C_{gs}C_{gd}R^2_{SDB}C_{GB}C_{sb}C_{db}$$

$$b_0 = C_{gs}R_{SDB}X_2X_1 + C_{gs}X_3$$

$$b_1 = C_{gs}R_{SDB}[C_{db}X_2 - X_1X_4)] + C_{gs}C_{sb}$$
$$+ R_D C_{gs}(C_{gd} + C_{db})((R_{SDB}X_2X_1) + X_3)$$

$$b_2 = -C_{gs}R_{SDB}(C_{db}X_4 - R_{SDB}C_{GB}C_{sb}X_1) + R_D C_{gs}(C_{gd} + C_{db})$$
$$(R_{SDB}(C_{db}X_2 - X_1X_4) + C_{sb}) - C^2_{db}R_{SDB}C_{gs}R_D X_2$$
$$+ C_{sb}R_D C_{db}(C_{gd} + C_{db})$$

$$b_3 = -C_{gs}R^2_{SDB}C_{GB}C_{sb}C_{db} - R_D R_{SDB}C_{gs}(C_{gd} + C_{db})$$
$$(C_{db}X_4 - R_{SDB}C_{GB}C_{sb}X_1) + C^2_{db}R_{SDB}R_D C_{gs}X_4$$

$$b_4 = C_{GB}C_{gs}C_{gd}C_{sb}C_{db}R^2_{SDB}R_D$$

$$X_1 = \frac{1}{R_{SDB}} + \frac{1}{R_{DB}}, X_2 = \frac{1}{R_{SDB}} + \frac{2}{R_{SB}}$$
$$X_3 = \frac{1}{R_{SDB}} + \frac{1}{R_{SB}}$$
$$X_4 = C_{GB} + 2C_{sb} + \frac{R_{SDB}C_{GB}}{R_{SB}} + \frac{C_{GB}C_{sb}}{C_{gs}}$$

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