Impact of process variability and noise on the radiofrequency performance of carbon nanotube field-effect transistors

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Abstract

Carbon nanotube field-effect transistors (CNFET) are one possible candidate to substitute silicon-based integrated circuit (IC) technology, as the performance increase of conventional transistors witnessed during the last decades will arrive at its ultimate limits in the near future. Intense research on carbon nanotube (CNT) technology has been performed not only regarding digital circuitry such as logic or memory, but also radiofrequency (RF) devices for analog applications. The potential for high intrinsic device speed [1] and demonstration of CNFETs with a cut-off frequency f_T as high as 80 GHz [2] have underlined the status of CNT-based devices as a candidate for future RF circuitry. However, in the existing literature there is still missing a global view of the CNFETs' RF performance to accurately estimate the future impact of this novel technology. There is a need for not restraining this analysis to f_T or intrinsic gain g_{int} limits [3], but also include other effects crucial for the success of this promising technology, such as the impact of realistic manufacturing process variability and particularly noise on a whole set of important RF figures of merit (FoM). In this work we present models capturing noise and variability effects and determine their impact on the FoMs f_T, g_{int}, maximum oscillation frequency f_{max}, threshold voltage V_{th} variability, and minimum noise figure NF_{min}.

The simulations performed within the scope of this work are done based on a CNFET compact model developed at Stanford University [4-6]. We have extended it by including a variability model (Fig. 1), considering realistic tube diameter statistical variation due to growth process imperfections (obtained by data reported in literature [7]). The model includes as well the probability of having metal tubes in the transistor channel. Furthermore, we investigate on the impact of imperfect metal tube removal processes, which only incompletely remove performance-degrading metal tubes of the CNFET channel and partially remove semiconducting ones. In addition, we have developed a CNFET noise model, including thermal, shot and flicker noise as well as an estimation of channel-induced gate noise.

For a given device geometry (32 nm gate length, 2 µm gate width, a channel made of an array of 100 CNTs with 20 nm inter-tube spacing, 3 nm high-κ gate dielectric) the model predicts excellent peak f_T and f_{max} values of 645 GHz and 2.17 THz, respectively, determined for an optimum biasing current I_{fTmax} of 7.8 µA per tube (Fig. 3). However, Monte-Carlo simulations show that these values as well as the devices' V_{th} exhibit significant variation due to CNT diameter variability. Such dispersion decreases when the number of tubes per device increases (Figs. 3 and 4). The impact of metallic tubes on the dynamic performance is limited (Fig. 6), but an efficient removal process has to be applied to not only obtain device speed, but also device gain (Fig. 5). Noise analyses have revealed the severe impact of flicker noise on the RF performance of CNFETs. However, if optimum noise matching is used, NF_{min} at 50 GHz is as low as 1.03 dB (Fig. 7). This value may yet be slightly degraded by metal tubes in the device channel (Fig. 8). Comparing our obtained results with the demands on Si-based devices as stated by the International Technology Roadmap for Semiconductors [8] lets us conclude that in terms of speed CNFETs are able to outperform conventional silicon devices of the year 2015. However, due to today's manufacturing processes' shortcomings CNFETs are still in a disadvantage regarding their V_{th} matching and high flicker noise level.

References

[1] J. Guo *et al.*, IEEE Trans. Nanotechnol., **4** (2005) 715-721.
[2] L. Nougaret *et al.*, Appl. Phys. Lett., **94** (2009) 243505 - 243505-3.
[3] S.O. Koswatta *et al.*, IEEE Trans. Microw. Theory Tech., **59** (2011) 2739-2750.
[4] J. Deng and H.S.-P. Wong, IEEE Trans. Electron Devices, **54** (2007) 2377-2385.
[5] J. Deng and H.S.-P. Wong, IEEE Trans. Electron Devices, **54** (2007) 3186-3194.
[6] J. Deng and H.S.-P. Wong, IEEE Trans. Electron Devices, **54** (2007) 3195-3205.
[7] S. Salamat *et al.*, IEEE Trans. Nanotechnol., **10** (2011) 439-444.
[8] ITRS 2011 Edition, avail. online, http://www.itrs.net/Links/2011ITRS/Home2011.htm

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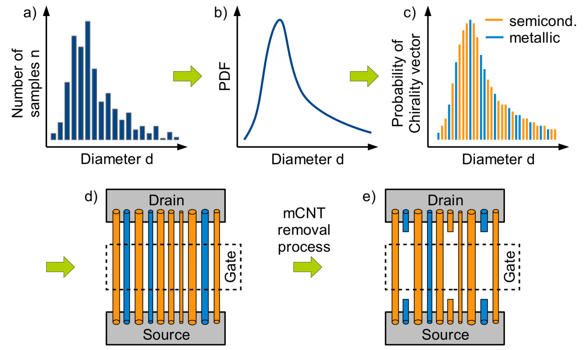
Figures



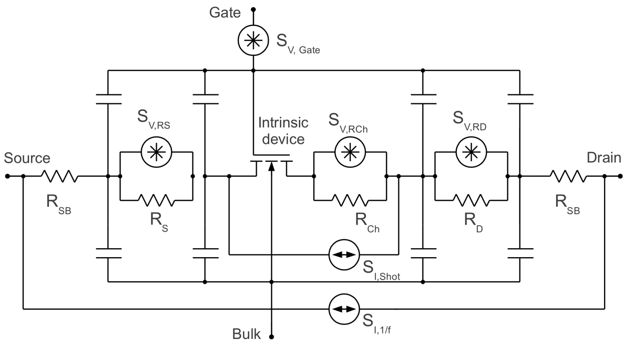
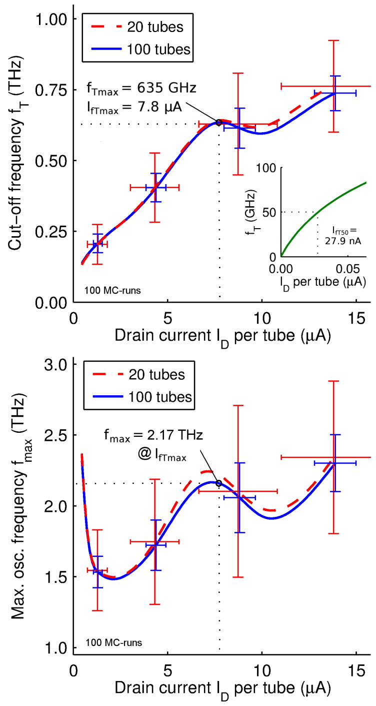
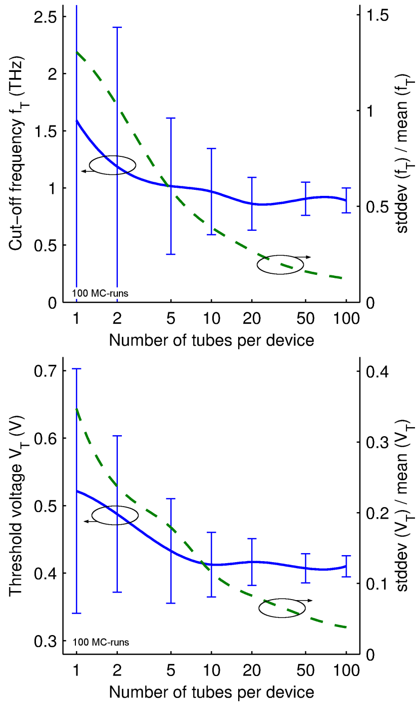


Fig. 1: Variability model for CNFETs: a) Statistical diameter distribution based on measured arrays of CNTs. b) Probability density function approximating the real diameter distribution. c) Probability of chirality vectors representing certain tube diameters and either mCNTs or sCNTs. d) CNFET with multi-tube channel, considering process variability. e) CNFET after imperfect mCNT-removal process.

Fig. 2: Noise model for CNFETs, including thermal channel noise due to acoustic, phonon and elastic scattering ($S_{V,RCh}$), thermal noise in the tube end regions ($S_{V,RS}$, $S_{V,RD}$), shot noise due to the ballistic character of the device ($S_{I,Shot}$), channel-induced gate noise ($S_{V,Gate}$) as well as flicker noise ($S_{I,1/f}$).





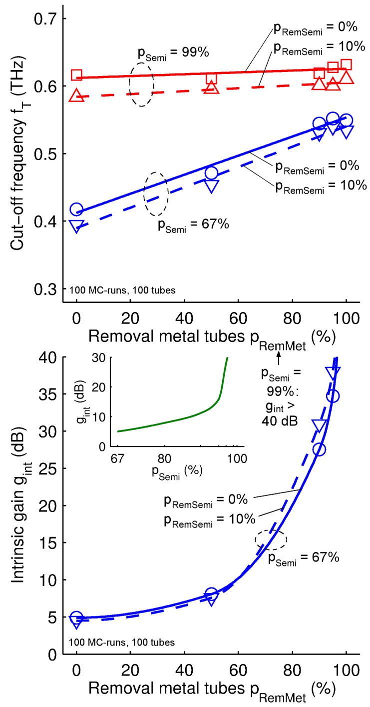
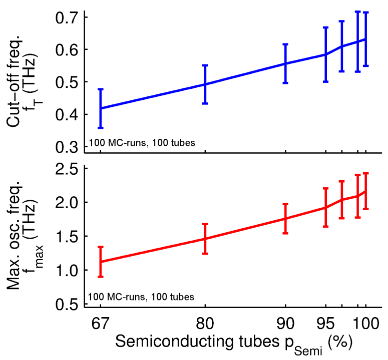
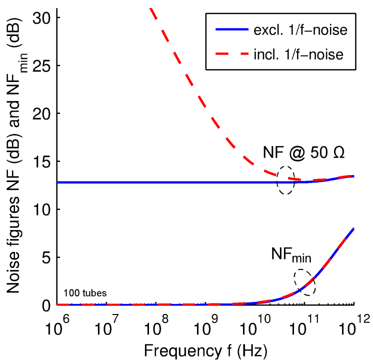


Fig. 3: Cut-off frequency and max. oscillation frequency vs. drain current. The optimum bias current for peak f_T is indicated. Error bars show standard deviation due to CNT variability.

Fig. 4: Cut-off frequency and threshold voltage variation vs. number of tubes in the channel. Error bars indicate the standard deviation due to CNT diameter variability.

Fig. 5: Cut-off frequency and intrinsic gain vs. efficiency of metal tube removal (p_{RemMet}). Tube growth quality (p_{Semi}) and the unwanted removal of sCNTs ($p_{RemSemi}$) are considered.





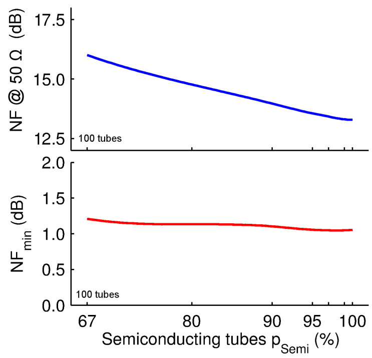


Fig. 6: Cut-off frequency and maximum oscillation frequency vs. probability of growth of semiconducting tubes. Error bars indicate the standard deviation.

Fig. 7: Noise figure at 50 Ω source impedance and minimum noise figure as a function of frequency. The impact of flicker noise is shown.

Fig. 8: Noise figure at 50 Ω source impedance and minimum noise figure at 50 GHz vs. probability of growth of semiconducting tubes.