High Frequency Noise in Manufacturable Carbon Nanotube Transistors

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Abstract -- **HF noise parameters were measured and modeled for the first time for wafer-scale manufacturable CNTFETs. These first multi-tube multi-finger CNTFETs exhibit still relatively high values for the minimum noise figure (NF_{min} = 3.5 dB at 1 GHz). Based on detailed compact modeling, the origin of this noise can be explained by the existence of the parasitic network and metallic tubes.**

Keywords-component: Carbon Nanotube, CNTFET, Noise parameters.

I. INTRODUCTION

Carbon nanotube field-effect transistors (CNTFETs) feature quasi-ballistic transport at fairly large (relaxed device size) tube lengths L_{CNT} up to 1μm and are therefore very promising devices for high-frequency (HF) low-noise applications. Due to low scattering the carrier velocity in CNTs can reach very high values. In conjunction with a very good gate control (thin high-κ dielectric) high transconductances and very low intrinsic capacitances are possible. Hence, short channel CNTFETs are expected to reach THz operating frequencies [1][2]. According to theory, CNTFETs have the potential for high linearity [3] and limited noise. Such features are beneficial for both broadband power and low-noise front-end applications.

While single-tube CNTFETs may be promising devices for digital applications, their intentional placement on a chip and wafer-scale fabrication is still far from meeting any practical requirements. However, multi-tube multi-finger CNTFETs, which are needed to deliver sufficient output power for practical HF applications, have been demonstrated to be operating up to several GHz [4][5]. Most recently, a wafer-scale manufacturable 10 GHz CNTFET process technology was reported in [6][7], and the first amplifier with such a technology was demonstrated in [8]. High-frequency (HF) noise investigations are therefore becoming of high interest for practical applications.

For existing fabricated CNTFETs the main obstacle for carrier flow in a semiconducting tube is the Schottky-barrier at the source. Once the carriers have tunneled through this barrier, they experience only a few phonon scattering events. Thus thermal noise is negligible compared to the shot noise across the Schottky barrier. Shot noise suppression [9] due to Pauli exclusion principle and Coulomb interaction is only expected for short channel CNTFETs at very low temperatures. At very high injection, electron-electron interaction may be present in a short channel device and can create an additional source of current fluctuations.

So far, noise investigations of CNTs mostly have been addressed the low-frequency noise (LFN) behavior in single-tube CNTFETs [10][11][12][13]. It has been shown that the current along the tube surface can easily be disturbed by trapping and de-trapping of carriers. Thus, LFN is relative high compared to conventional technologies but can be scaled down with the number of tubes in parallel.

HF noise parameter measurements in single-tube CNTFETs [14][15] are of little practical importance due to the very low current range (about 20-30 μA maximum) of a single-tube CNTFET. The resulting high input and output impedance complicates the measurements with common instrumentation based on a 50 Ω reference impedance. Presently fabricated CNTFETs for HF analog applications use thousands of tubes in parallel and, thus, feature practically useful impedance levels. To our knowledge, for comparable transistor structures the noise parameters and figures of merit (FoMs) that are relevant for circuit design purposes have not been considered yet. In this work we report, to our best knowledge, on the first experimental investigation of HF noise parameters in n-type long-channel CNTFETs.

II. DUT, EXPERIMENTAL AND NOISE MODEL

The investigated structures consist of a multifinger layout with a fixed gate length L_g = 0.35 μm, a gate width *of* W_g = 40 μm and 20 gate fingers, total W_g = 800 μm. The total source-drain spacing (channel length) is 800 nm. The devices were fabricated with the process technology described in [6][7]. On-wafer DC and AC (frequency range 0.1-10.5 GHz) standard characteristics were measured with PNA 8361C. The low impact of self-heating was verified by pulsed $I_d(V_{ds})$ measurements with different pulse widths (300 ns to 1 ms). Noise parameters (in source-load matching conditions) were measured in the 1-8 GHz frequency range with a Maury Microwave tuner system. The pad de-embedded peak transit frequencies were around f_T = 9 GHz at V_{ds}=1.9 V. The deembedding of pad parasitics was performed using a 2-step ("open", short" dummies) method, while for the noise parameters the correlation matrix technique was employed. The schematic view and layout are given in Fig.1. Investigated CNTs had thousands of tubes in parallel (here only 6 tubes in the Fig.1,a).

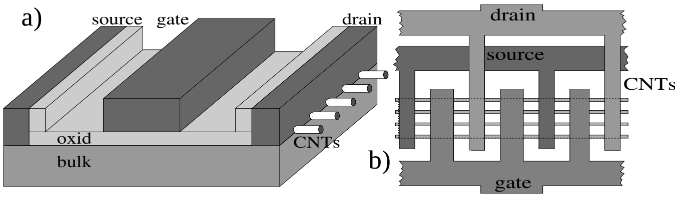

Fig. 1. Schematic view (a) and layout (b) of multi-tube CNT-FET.

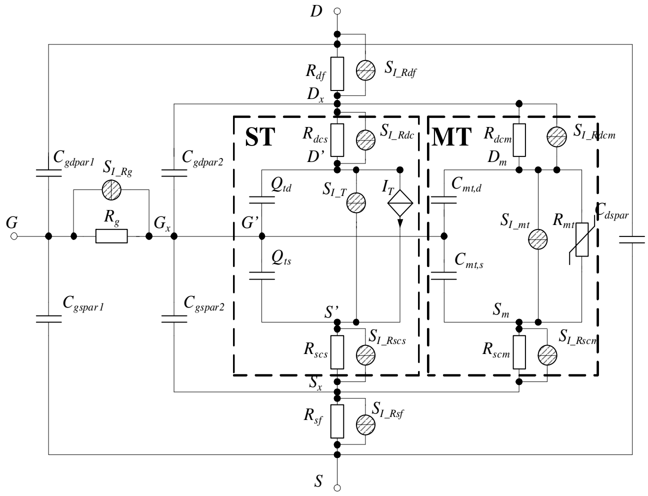

Fig. 2. Compact noise model equivalent circuit of multi-tube CNTFET. ST is the semiconducting tube model, MT corresponds to the metallic tube model.

A new semi-empirical compact model (CM) [6] was used for DC, HF and noise parameter analysis. In Fig.2 C_{gdpar1}, C_{gspar1}, C_{dspar} are the parasitic feed-line capacitances (Fig.1, b); C_{gdpar2}, C_{gspar2} are the parasitic finger-capacitances (Fig.1, a); Q_{td}, Q_{ts} are the quantum semiconducting tube charges; $I_T(V_{gs},V_{ds})$ is drain current source modeling the semiconducting tubes (STs); $I_{mt}(V_{ds})$ is nonlinear current modeling of the metallic tubes (MTs); $C_{mt,s}$ and $C_{mt,d}$ are bias independent capacitances of the MTs, R_{mt} models the nonlinear equivalent resistance of the MTs; R_{dcs}, R_{scs}, R_{dcm}, R_{scm} are the source and drain contact resistances of the STs and MTs; resistances; R_g, R_{sf}, R_{df} are gate, source and drain finger resistances. The noise model consists of two shot noise sources, related to STs and MTs (S_{I_T}, S_{I_mt}) and the thermal noise sources of resistive circuit elements.

III. RESULTS AND DISCUSSION

The transfer characteristics of the investigated CNTFET in Fig.3 exhibit two current components, one related to STs and the other related to MTs. The latter causes the visible V_{ds} dependent offset. Since the CM describes the transfer and output characteristics $I_d(V_{gs}, V_{ds})$ fairly well (cf. Fig.3 and Fig.4), it was used to subtract the influence of the MTs from the measured total drain current. The resulting I_d characteristics exhibit typical FET behavior. The MT to ST ratio can be estimated from the I_d currents of single-tube transistors (single tube CNTFET characteristics are not shown) to that of de-embedded multi-tube FETs, resulting in a factor of 1.5. The existence of MTs impacts not only the DC characteristics but also the HF response. Despite the MTs the multi-tube CNTFET exhibits high transconductance, reaching a peak value g_m = 100 mS/µm at V_{gs} = -1.5 V (Fig.5).

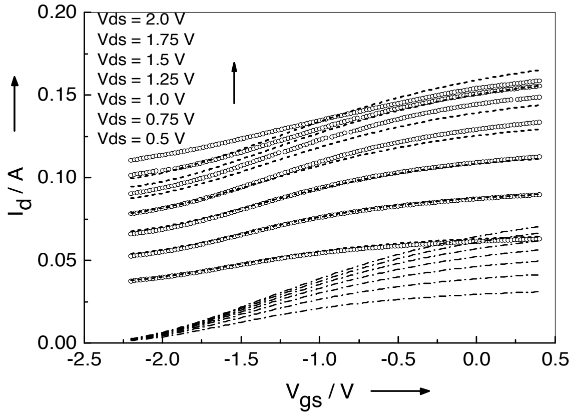

Fig. 3. CNTFET I_d vers. V_{gs} at different V_{ds}. Symbols are measured data, dashed lines is CM and dash-dotted lines correspond to the case without metallic tubes (MT).

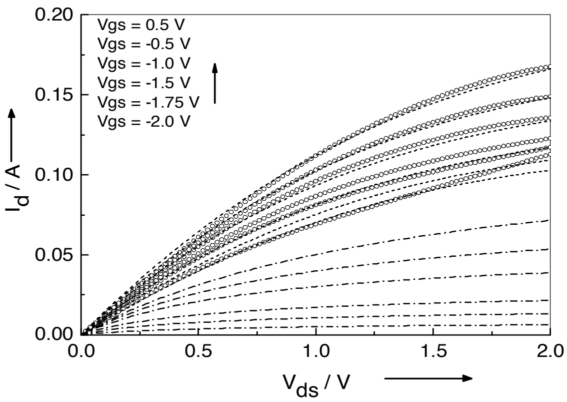

Fig. 4. CNTFET I_d versus V_{ds} at different V_{gs}. The same notation as in Fig.3 holds.

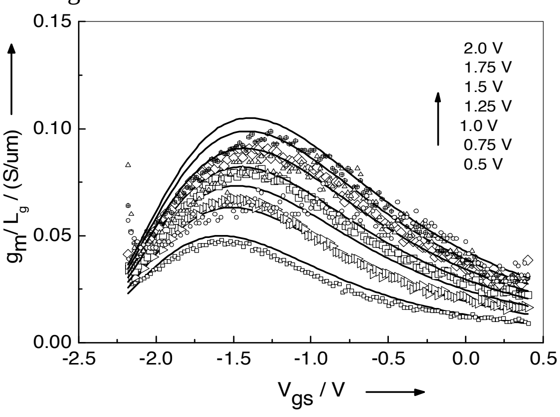

Fig. 5. Measured and simulated transconductance.

Since HF noise parameters are very sensitive to the HF transistor parameters, the impact of parasitic network (PN) and MTs on the HF response of multi-tube CNTFETs is further analyzed below. The current gain cut-off frequency (f_T) was extracted from measured s-parameters of CNTFETs in a “hot” state. The CM yields good agreement of f_T for multi-tube CNTFETs including MTs and PN (cf. Fig.6, [6][7]). The peak value of the complete CNTFET (incl. STs and MTs) increases to more than 100 GHz if the impact of the PN is removed. Transistor can not operate without the access network (metallic fingers, see Fig.1, b) and this evaluation shows the potential for layout optimization. The capacitances (C_{gspar1}, C_{gdpar1}, C_{dspar}) of the access network were measured and modeled. The capacitances of the MTs: $C_{mt,s}$ and $C_{mt,d}$ were also evaluated from a CNTFET structure, containing only MTs and showing the same range of I_d (V_{gs}) at high negative V_{gs}. The $C_{mt,s}$ and $C_{mt,d}$ were found in the ranges of 35 fF. This means that impact of MTs on f_T and f_{max} is not very high (f_T and f_{max} without MT network increases only by a few GHz, not shown in the Fig.6 and Fig.7).

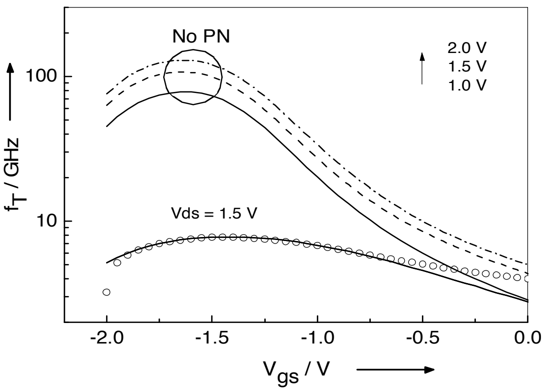

Fig. 6. Measured (symbols) and simulated (solid line) f_T vs. V_{gs} at V_{ds}=1.5 V. Simulated f_T (V_{gs}) for CNT without PN.

A more relevant FoM for power applications is the maximum oscillation frequency f_{max}, which includes parasitic resistances. Its value increases to about 100 GHz after removing the impact of the PN (cf. Fig.7).

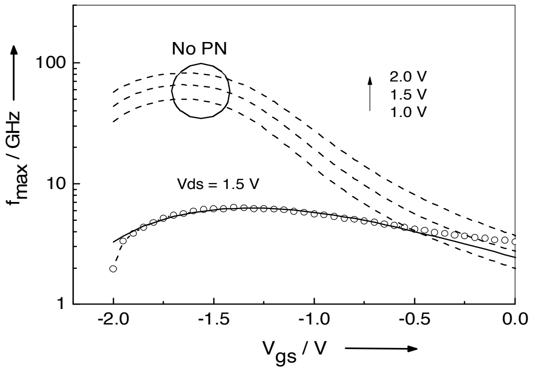

Fig. 7. Measured (symbols) and simulated f_{max} vers. V_{gs} at V_{ds}=1.5 V. Simulated (dashed) f_{max} (V_{gs}) for CNT without MT.

Measured and simulated HF noise parameters are given in Fig.8 and Fig.9. A comparatively high minimum noise figure (NF_{min}) is observed, which is not very bias dependent. Measured noise resistance is around R_n = 300 Ω (not shown in this paper) indicating strong sensitivity of NF to source mismatch. Therefore in a 50 Ω (mismatched) environment NF_{min} = 3.5 dB (@1 GHz) increases to more than double (NF = 8 dB). R_n exhibits a slight drop with frequency, due to the capacitive surrounding network. Note that towards low RF frequencies (f < 2 GHz) R_n increases with frequency decrease. This can be explained by the impact of gate noise, related to leakage current, which is not covered by this version of CM. For larger gate area devices I_b was around 200 pA. Therefore gate noise is more expressed in a CNTFET with a larger gate area. Due to this at f < 2 GHz measured NF_{min} is slightly higher, compared to the simulated value (Fig.8). Since the CM (Fig.2) with its defined noise sources describes NF_{min} fairly well we have performed simulations without MTs and PN, Fig.8. The MTs have only a slight impact on NF_{min} (Fig.8, dashed line). Note that the noise of the MTs itself is negligible. However, the MTs increase the noise via their parasitic capacitances and the related transistor transfer function degradation. In contrast impact has PN to NF_{min} is noticeable (dashed-dotted line in Fig.8). Therefore optimization in terms of PN is desired for a low noise and high speed applications.

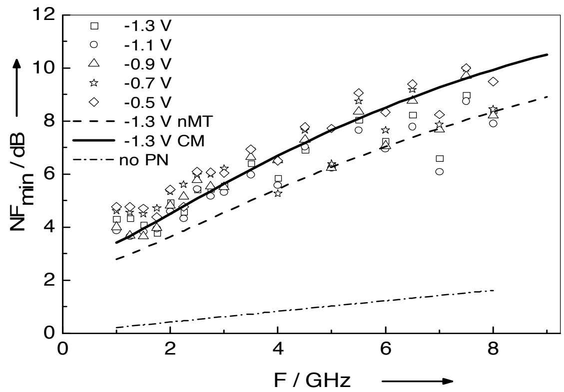

Fig. 8. Measured (symbols) and simulated NF_{min} at V_{ds}=1.5 V. Complete CNTFET (solid line), NF_{min} without MT elements (dashed line), NF_{min} without PN (dashed-dotted line).

NF_{min} was also measured for the device of W_g = 40 µm and 10 gate fingers, the total W_g = 400 µm. In this case similar results of NF_{min} were obtained: NF_{min} ranges between 3 and 8 dB at 1 - 8 GHz respectively.

The optimum reflection coefficient (S_{opt}) shows that multi-tube CNTFETs have a large parasitic capacitance network (Fig.9). De-embedded from PN Γ_{opt} has a tiny curve in the capacitance part of Smith chart (not shown here) which is also common for small area MOSFETs.

The results underline the importance of finding methods for reducing the PN in a wafer-scale process. Noise analysis show that the dominant noise mechanism in the complete transistor is the shot noise of the STs. The thermal noise of the resistive elements is of minor importance.

On one hand shot noise of ST is the most important noise source - on the other hand internal noise source has a low contribution and bias dependence of NF_{min} is quite weak due to influence of bias independent PN capacitances (Fig.8).

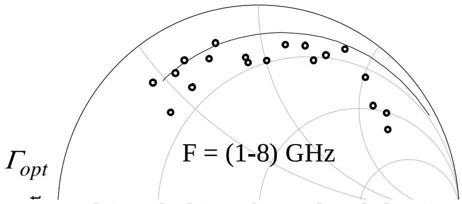

Fig. 9. Measured (symbols) and simulated (line) source reflection coefficient Γ_{opt} at V_{ds} = 1.5 V.

The S-D in the CNTFETs here was 800 nm. Such a length is too large for truly ballistic transport, especially at larger drain bias, where optical phonon scattering can occur. This contributes to the noise spectral density of the drain current fluctuation.

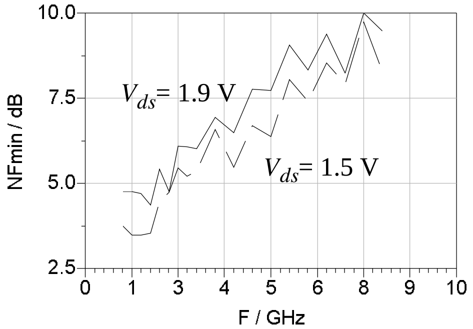

Fig. 10. Measured NF_{min} at V_{ds} = 1.5 V. and V_{ds} = 1.9 V, V_{gs} = -0.9 V.

Indeed, the trend of increasing NF_{min} with bias voltages in Fig.10 appears to confirm this assumption. The presence of hot electron effects was already reported in [6]. Nevertheless, this issue requires an additional investigation for multi-tube HF CNTFETs.

IV. CONCLUSIONS

HF noise parameters in manufacturable CNTFETs were measured and modeled (for the first time). CNTFETs with thousands of CNTs in parallel can be scaled to quite high drain currents (up to 150 mA). The peak value of the transit frequency f_T and maximum oscillation frequency f_{max} of such multi-tube CNTFETs can reach up to 10 GHz. Simulation based predictions show that after elimination of parasitic access network and metallic tubes f_T increases up to 100 GHz and f_{max} reaches 90 GHz. The HF minimum noise figure NF_{min} of multi-tube CNTFETs still exhibits relatively high values (3.5 dB at 1 GHz and 6 - 8 dB at 8 GHz). Such high values can be explained by the impact of the capacitive parasitics of the access network and partially by the metallic tubes although noise contribution of MTs themselves is negligible. Simulations applying the CM at eliminated PN show very low HF noise. Note that very similar NF_{min} values were obtained for other CNTFETs structures on the wafer with different S, D, G configuration and number of gates fingers in parallel.

In summary, it can be stated that multi-tube CNTFETs with minimized parasitic network can yield relatively high f_T and f_{max} and low NF_{min}, making them good candidates for the high-speed low-noise applications.

ACKNOWLEDGEMENTS

RF Nano Corporation is acknowledged for providing wafers. US Air Force is acknowledged for financial support. The authors are in debted to Stefan Blawid and Anindya Mukherjee for valuable discussions.

REFERENCES

[1] J. Guo, S. Hasan, A. Javey, G. Bosman, and M. Lundstrom, IEEE Transaction on Nanotechnology, vol. 4, no. 6, pp. 715–721, Nov. 2005.

[2] M. Claus and M. Schröter, Proc. NSTI Workshop on Compact Modeling, volume 3, pages 566– 569, 2009.

[3] J. E. Baumgardner, A. A. Pesetski, J. M. Murduck, J. X. Przybysz, J. D. Adam, and H. Zhang, Applied Physics Letters, 91(5):052107, 2007.

[4] A. Le Louarn, F. Kapche, J.-M. Bethoux, H. Happy, et al., Appl. Phys. Lett., Vol. 90, pp. 233108, 2007.

[5] . Nougaret, H. Happy, G. Dambrine, V. Derycke, J. -P. Bourgo, A. A. Green, and M. C. Hersam, Appl. Phys. Lett., Vol. 94, pp. 243505, 2009.

[6] M. Schroter, S. Mothes, D. Wang, S. McKernan, N. Samarakone, M Bronikowski, Z. Yu, P. Kempf, Proc. Governm. Microcircuit Applic. & Critical Technol. Conf. (GomacTech), Orlando, FL, pp. -, March 2011 (accepted for publication).

[7] M. Schroter, P. Kolev, D. Wang, M. Eron, S. Lin, N. Samarakone, M. Bronikowski, Z. Yu, P. Sampat, P. Syams, S. McKernan, Proc. IMS-MTT, pp. -, 2011 (accepted for publication).

[8] M. Eron, S. Lin, D. Wang, M. Schroter and P. Kempf, "An L-band carbon nanotube transistor amplifier", Electron. Lett., Vol., pp. -, 2011 (accepted for publication).

[9] A. Betti, G. Fiori, G. Iannaccone, IEEE TED, Vol. 56, No. 9, pp. 2137-2143, 2009..

[10] Yu-M. Lin, J. Appenzeller, Z. Chen, P. Avouris, Physica E, 37, pp. 72-77, 2007.

[11] S. Reza, Q. T. Hyunh, G. Bosman, Journal of Applied Physics 100, 094318, pp. 1-5, 2006.

[12] G. Xu, F. S. Han, K. Ryu, A. Badmaev, B. Lei, Ch. Zhou, K. Wang, applied Physics Letters, 92, 223114, pp. 1-3, 2008.

[13] J. Appenzeller, Yu-M. Lin, J. Knoch, Zh. Chen, P. Avouris, IEEE Transactions on Nanotechnology, Vol. 6, No. 3,pp. 308-737, 2007.

[14] L. Roschier, P. Hakonen, K. Bladh, P. Delsing, K. W. Lehnert, L. Spietz, R. J. Schoelkopf, Journal of Applied Physics, Vol. 95, No. 3, pp. 1274-1286, 2004.

[15] F. Wu, T. Tsuneta, R. Tarkiainen, D. Gunnarsson, T. H. Wang, P. J. Hakonen, Phys. Rev. B, American Physical Society, 75, 125419, 2007.