Physical Origin of the Excess Thermal Noise in Short Channel MOSFETs

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***Abstract*—The physical origin of the excess thermal noise in short channel MOSFETs is explained based on numerical noise simulation. The impedance field representation and extraction method demonstrate that the drain current noise is dominated by source side contributions. Analysis identifies local ac channel resistance variations as the primary controlling factor. The nonlocal nature of velocity results in a smaller derivative of the velocity with respect to the field which in turn causes a higher local ac resistance near the source junction.**

***Index Terms*—Hydrodynamics, MOSFETs, semiconductor device modeling, semiconductor device noise, simulation.**

I. INTRODUCTION

WHILE the drain thermal noise of long channel MOSFETs agrees with the van der Ziel model [1], considerably larger noise has been observed in MOSFETs with channel lengths below 1.7 μm [2]–[5]. Recent compact modeling approaches have explained this phenomenon using local *voltage* noise sources [4]–[7]. However, the use of local voltage noise sources in device modeling suffers from the spatial correlation of the noise sources [8], [9]. This results in a dominant noise contribution near the drain junction, which is more significant when the hot carrier effects are included [5]–[7]. By contrast, quasi-2-D numerical simulation results for HEMT devices have suggested that the drain noise of the FET is not in fact dominated by the drain-side but rather by the source-side contributions [10]. Recent numerical noise simulation results have qualitatively demonstrated the observed excess thermal noise in 0.25 μm MOSFETs based on the hydrodynamic (HD) formulation [11]. However, the physical mechanism responsible for such excess noise has not been identified. This paper investigates the physical origin of the excess noise by comparing the differences between local and nonlocal carrier transport models in noise simulation.

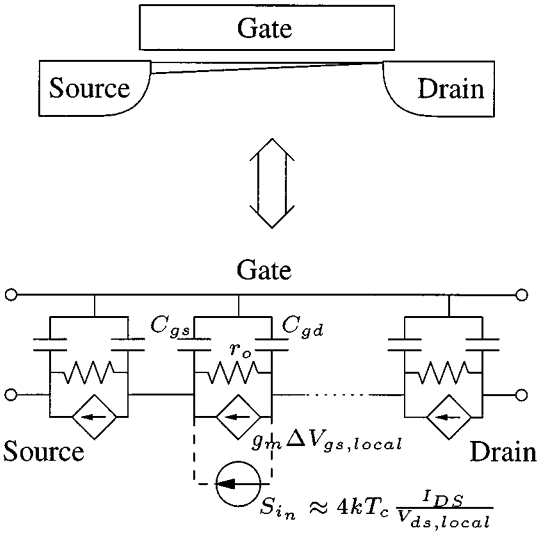

Fig. 1. Small-signal equivalent representation of the MOSFET used in noise simulation.

II. NOISE SIMULATION

Noise power and correlation spectra of the drain and gate currents have been obtained using noise simulation that combines a one-dimensional active transmission line model with two-dimensional (2-D) device simulation. As shown in Fig. 1, each segment in the MOSFET uses a localized small-signal equivalent circuit, as is commonly used in SPICE. The local small-signal parameters are extracted using two-dimensional dc device simulation with MEDICI [12]; ac behavior is modeled using local perturbations of static quantities acquired from three adjacent bias conditions [13], [14].

In the framework of the *impedance field* representation [13]–[15], device noise at electrodes is determined by two independent factors: local fluctuations and their propagation to terminal electrodes. To avoid the spatial correlation, local fluctuations are modeled by *current* noise sources (S_{i_n}) that bridge each lumped segment as illustrated in Fig. 1. Then propagation to the drain electrode using the impedance field (ΔA_d) gives a current noise power at the drain electrode of

$$S_{i_d} = |\Delta A_d|^2 \, S_{i_n}. \tag{1}$$

The total noise power is acquired by summing (1) over all segments of the device.

Manuscript received October 3, 2000. This project was initiated by DARPA under Contract Army-DABT63-94-C-0055 and then supported by Texas Instruments through customized research under SRC Contract 99-NJ-695. The review of this letter was arranged by Editor K. De Meyer.

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Publisher Item Identifier S 0741-3106(01)01374-X.

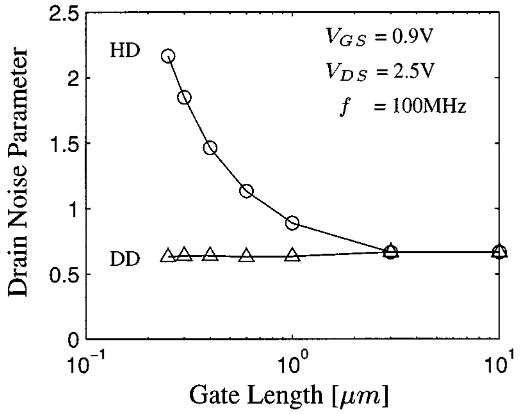

Fig. 2. Gate length dependence of drain noise parameter (γ [no unit]) comparing HD and DD model results.

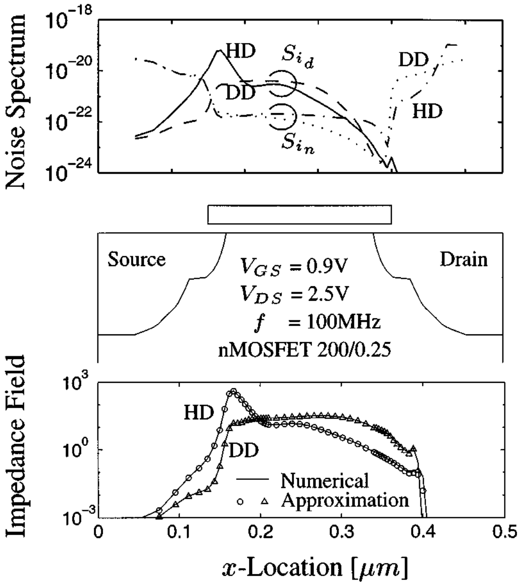

Fig. 3. Comparing the HD model with the DD model along the channel for noise spectral density distribution of the local noise source (S_{i_n} [A^2/Hzμm]) and its actual contribution to the drain noise (S_{i_d} [A^2/Hzμm]); and the impedance field ($|\Delta A_d|^2$ [no unit]).

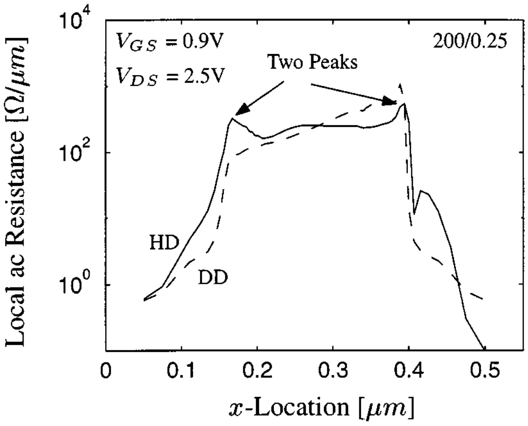

Fig. 4. Local ac resistance distribution, comparing the HD model (solid line) with the DD model (dashed line).

III. RESULTS AND DISCUSSIONS

Excess noise is defined as deviation from the van der Ziel model [1]:

$$S_{i_d} = 4kT\gamma g_{d0} \tag{2}$$

where g_{d0} is the drain output conductance under zero drain bias and γ is a noise factor. As contrasted in Fig. 2, for decreasing channel length, the *nonlocal* HD formulation shows gradual deviation from the long channel value of γ (2/3 in the saturation region) whereas the purely *local* drift-diffusion (DD) model remains constant. The spectral density distribution of S_{i_d} in Fig. 3 shows clearly that the excess noise in the HD results originates due to a peak at the metallurgical source junction. Since the two models yield almost the same values of S_{i_n} in that location in Fig. 3, recalling (1) implies that the impedance field (ΔA_d) differentiates the effects between the two models on noise simulation. The impedance fields, shown in the bottom of Fig. 3, reveal significant differences between the HD and DD models across the entire device channel. The impedance field is numerically calculated based on network analysis principles, but it can be conceptualized by cascading three sub-MOSFETs: $M_S(0,\, x)$, $M_C(x,\, x + \Delta x)$, and $M_D(x + \Delta x,\, L)$, resulting in the following simplified approximation (symbols in Fig. 3):

$$\Delta A_d \approx \frac{r_{o_C} g_{m_D}}{1 + r_{o_S} g_{m_D}} \approx r_{o_C} g_{m_D}. \tag{3}$$

The parameterization in (3) suggests that the local ac resistance (r_{o_C}) is primarily responsible for the source side peak of the impedance field; additionally, the impact of r_{o_C} is amplified by g_{m_D} as the device length becomes smaller. Fig. 4 shows that the HD results exhibit two peaks in the ac resistance distribution, localized at the metallurgical junctions. For any segment of the semiconductor, higher ac resistance directly represents a smaller derivative of the velocity with respect to field ($\partial v/\partial \mathcal{E}$) because

$$R_{\text{ac}} = -\frac{\partial \mathcal{E}}{qn\partial v}\,\frac{l}{A}. \tag{4}$$

Unfortunately, the direct measure of the term is difficult since the electric field change near the source junction is extremely small and varies two dimensionally with drain bias. In terms of physical effects, the DD model assumes that carrier velocity is directly determined by the electric field. In reality, velocity depends physically on the carrier energy whose changes are not spatially synchronous with changes of the electric field because of the *nonlocal* nature of carrier transport. This phenomenon is primarily reflected in higher order transport models [16] such as the HD formulation and easily observed near the drain junction where the spatial variation of the electric field is sufficiently abrupt. By contrast, the electric field variation near the source junction is quite small; the HD model gives almost the same value of velocity as can be extracted based on the classical $v-\mathcal{E}$ relationship. However, the nonlocal effect produces spatial latency in response to the electric field change, and effectively makes velocity less sensitive to the field at the source-end compared to that predicted using the DD model. Hence, the HD model exhibits a smaller derivative of the velocity with respect to the field, which subsequently causes a higher local ac resistance and larger impedance field.

IV. CONCLUSIONS

This work analyzes excess thermal noise in short channel MOSFETs, using a hybrid numerical noise simulation method. Drain current noise is dominated by the source-side contributions. Moreover, the excess noise is caused not by the local noise source but by the effects of the impedance field. While both the DD and HD models show almost the same values of velocity due to small electric field at the source, the nonlocal transport behavior causes a small derivative of velocity with respect to the electric field. The resulting higher local ac resistance near the source junction increases the impedance field and is directly reflected in excess noise and strong gate length dependence. This phenomenon can not be accounted for using the conventional DD model because of the local nature in the $v - \mathcal{E}$ relationship. Thus, higher order transport models, such as the HD formulation, are essential in considering noise simulations for scaled MOSFET devices.

ACKNOWLEDGMENT

The authors would like to thank Prof. M. Lundstrom of Purdue University for helpful discussions concerning transport models, and Texas Instruments for mentoring and promoting this project.

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