THE PHYSICAL PHENOMENA RESPONSIBLE FOR EXCESS NOISE IN SHORT-CHANNEL MOS DEVICES

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Abstract – **The physical phenomena responsible for the excess noise in short- channel MOS devices are explained based on the non-equilibrium noise theory. Comparing the MOS excess noise with the well known excess noise in a mesoscopic conductor, it is suggested that the physical origins of both are the same. Using this theory, it is proposed that the noise sources used in the Impedance Field Method (*IFM*) should contain not only the usual thermal noise component, but also a partially suppressed shot noise term which accounts for the limited number of inelastic scattering events in the channel. The theoretical predictions of a simplified model based on this theory are presented and compared with the measurement results. It is shown both theoretically and experimentally that the non-equilibrium noise component is smaller when larger gate to source voltage is applied. The accurate calculation of the suppression factor, which is in general a function of device terminal voltages, remains a challenge.**

I. INTRODUCTION

Understanding noise in submicron MOS devices is an important unsolved problem in the area of mixed-signal modeling. With recent demonstrations of analog and RF CMOS design [1][2], more and more effort is now being devoted to solving this problem. Experimental observations (*e.g.* [3] and [4]) have shown that in short channel devices the actual drain current noise of the device is much higher than the one predicted by the long channel model. Different approaches have been tried for explaining and modeling this excess noise. Although some of these methods can predict some excess noise, they frequently fail to predict the drain current noise with reasonable accuracy. Calculation of the correlation factor between gate current noise and drain current noise (fig. 1) is even more difficult to perform. This factor plays a key role in noise figure prediction of CMOS LNA topologies [1].

Most of the existing methods erroneously assume the equilibrium noise formulation to be valid under non-equilibrium conditions. In fact, the equilibrium Johnson-Nyquist noise formulation is never proved to be valid when the device is not in thermal equilibrium. The mathematical formulations of thermal noise using Browning Particle Model [5] and Lossless Transmission Line [6] are not generally applicable to non-equilibrium conditions. Although, the noise associated with a macroscopic conductor is experimentally seen to be the same under equilibrium and non-equilibrium conditions, this might not be the case for small dimension devices.

Short channel MOS devices are not in fact the only devices showing non-equilibrium excess noise. In a mesoscopic conductor, with only one scatterer in its channel, it is shown, both theoretically [7] and experimentally [8], that the non-equilibrium noise is different from the equilibrium one.

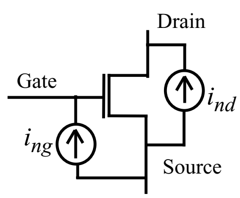

Fig. 1. Equivalent noise sources in MOS devices.

In this paper we try to make a connection between the non-equilibrium noise in mesoscopic conductor and the excess noise in short channel MOS devices. We illustrate that in the light of non-equilibrium noise theory, the modeling of excess noise in short channel MOS devices can be improved.

We will provide a brief survey on existing theories for noise in MOS devices in section II. Section III is devoted to non-equilibrium noise theory. Some theoretical predictions and experimental results will be provided in section IV to verify the validity of the proposed method.

II. EXISTING THEORIES

A. Long-channel formulation of MOS noise

The classical equation governing drain current noise power spectral density of long channel MOSFET's (fig. 1) can be written as

$$\overline{i_{nd}^2} = \gamma 4kTg_{do}\Delta f \qquad (1)$$

where T is the electron temperature, g_{do} is the channel conductance with zero drain-to-source voltage and γ is a constant which is equal to 2/3 for long-channel devices working in saturation region. The gate noise component, i_{ng}^2 can also be calculated using this simple model and it is shown that the correlation between i_{ng} and i_{nd} is $0.395j$ [9].

These results are achievable using Impedance Field Method (*IFM*) in which the channel is divided into small slices as shown in fig. 2 and an equilibrium thermal noise source is associated with each slice [10]. The power spectral density of each of these equilibrium noise sources is [11]:

$$\overline{i_n^2} = 4q^2 nD_n\frac{\Delta y\Delta z}{\Delta x}\Delta f \qquad (2)$$

where q is the electron charge, n is the carrier density and D_n is the "real part of the noise diffusion coefficient" which can be approximated by the "spreading diffusion coefficient" in most cases [12]. The contribution of each noise source to the output current can be obtained by defining a dimensionless field impedance which is basically the ratio of the generated output current to the noise current source located between x and $x+\Delta x$ [10][12].

B. Hot electron effects and velocity saturation

When the excess noise was reported in 1986 [3][4] with γ as high as 7.9 (12 times larger than its long-channel value of 2/3), the first approach towards its explanation was hot electron effects. These studies generally use elevated electron temperature in the classic thermal noise formulation, eq. (1) [13]. Although this approach predicts some excess noise in short channel devices, it cannot predict noise parameters with reasonable accuracy and does not provide enough understanding about noise behavior in short-channel devices. Also this approach suggests that the phenomenon responsible for excess noise is associated with the drain end of the channel where hot electron effects are maximum. This, in fact, does not agree with the quasi-2-D numerical simulation results for HEMT devices where the source end of the channel is shown to be responsible for most of the excess noise [14].

Velocity saturation has also been introduced to be responsible for the excess noise. Using velocity saturation formulation, γ as high as 3.5 has been achieved and compared with some measurement results [15]. In [15], it is claimed that the devices reported in [3] have been operating in avalanche region resulting to an unusually high γ of 7.9.

In another investigation the velocity fluctuation of carriers associated with small number of scattering events is proposed as responsible for excess noise [16]. It is said that having only "some of the carriers" moving ballisticly but others experiencing scattering inside the channel, results in velocity fluctuation and excess noise in short channel devices. Although the physical argument given in [16] is completely different from the one we present in this paper, the end result is somehow related. In both cases, having limited but finite number of scattering (inelastic scattering events in our argument) is introduced as the origin of excess noise.

C. Multi-Dimensional simulation and Impedance Field Method (IMF) with various transport models

One way to explain the excess noise in short channel devices is to make detailed multidimensional simulations. These simulations are extremely lengthy and are not suitable for model extraction especially because they fail to provide insight. Nevertheless, these simulations have shown excess noise for MOS devices and predicted that the noise is associated with the source end of the channel [15]. To the best of the authors' knowledge, all of these simulations use the equilibrium model for noise (eq. (2)) which can be the main reason of their failure in accurate noise prediction. Multidimensional simulation can be done using various orders of transport model. Drift-diffusion transport model, however, has been reported to fail in predicting excess noise even in 3-D simulations [17]. This implies that higher order transport models like the hydrodynamic model are necessary.

One alternative approach is to use the well-known one-dimensional *IFM* with device parameters extracted from 2D simulations. To this end, the device can be segmented along the channel and the *IFM* can be employed to calculate the output noise (fig. 2). The power spectral density of the noise sources in this case is still given by (2) but physical values of n and D_n are obtained from detailed 2-D simulations. This, in fact, has been done and the results of such an analysis using hydrodynamic and drift-diffusion transport models are compared in [12]. It is shown that the hydrodynamic transport model gives much better results compared to the drift-diffusion transport model implying that the key issue in modeling noise in submicron devices is a thorough understating of the transport mechanism and not 3D effects.

The results presented in [12] show that, although the method is quite good in predicting the noise performance in high values of V_{gs} it fails for small values of V_{gs} where fewer scattering events are expected. As we will see in the following section this supports the need for a non-equilibrium noise model to enhance simulation accuracy. Also it is worth mentioning here that the existence of a shot noise component in drain current noise has been proposed for modeling purposes [18]. To the best of the authors' knowledge the existence of a shot noise component has never been associated with the limited number of inelastic scattering events in the channel. In the next section we will physically justify the existence of the shot noise component in the drain current noise based on the non-equilibrium noise theory.

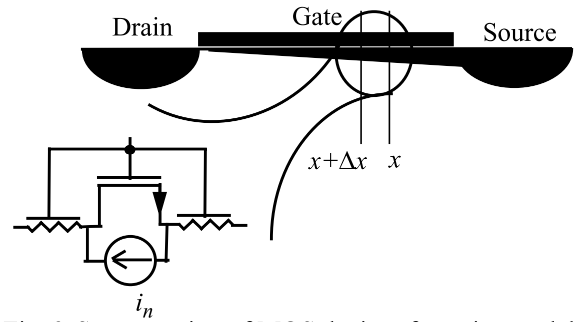

Fig. 2. Segmentation of MOS devices for noise modeling

III. NON-EQUILIBRIUM NOISE THEORY APPLIED TO MOS DEVICE

A. Noise in mesoscopic conductors

Consider a mesoscopic conductor with J non-interfering transverse modes, each of them having a constant scattering coefficient T_j. If all scattering events are assumed to be elastic, the power spectral density of the non-equilibrium noise of this mesoscopic conductor is [7]:

$$S_I = 4kTG_Q\sum_{j=1}^{J}T_j + 2eI_{tot}\left(1-\sum_{j=1}^{J}T_j\right) \quad (3)$$

Where k is Boltzmann's constant, T is the absolute temperature, G_Q is the intrinsic conductance of each transverse mode in the absence of any scatterer ($2e^2/h$), T_j is the elastic scattering coefficient associated with the jth mode, e is the electron charge, h is the Planck's constant and I_{tot} is the total current passing through the conductor. The above equation is valid under condition $eV>>kT$ where V is the voltage applied across the conductor. Also note that the validity of this equation is not dependent upon separation of the transverse modes as far as they can be considered independent.

The effective conductance of each transverse mode in the presence of the scatterer will be G_QT_j. Assuming there is no interaction among scatterers or among transverse modes, the total conductance of the conductor is the sum of the conductances associated with each transverse mode. Consequently, the first term in (3) is simply the equilibrium noise power spectral density. The second term, called the non-equilibrium noise, is a sub shot noise power spectral density due to the elastic scatterer. Note that in the absence of scattering events (T_j's =1) the shot noise term vanishes and the noise power spectral density is simply the Johnson-Nyquist thermal noise.

In the presence of scattering events, however, we always

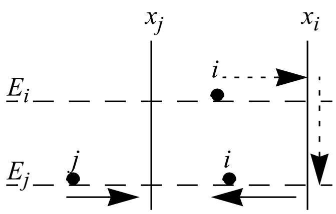

Fig. 3. Non-independence of scattering events in a macroscopic conductor.

have a non-equilibrium noise term proportional to current. This noise is experimentally observed as well [8]. Considering the fact that in a macroscopic conductor we always have scattering events, the question would now be: "why is that this term is never seen in a macroscopic conductor?" The answer to this question is given in the next subsection.

B. Noise in macroscopic conductors

The absence of the non-equilibrium noise component in macroscopic conductors is explained using the Pauli exclusion principle and the presence of numerous inelastic scattering events in a macroscopic conductor. Suppose an electron i with energy E_i (Fig. 3.) undergoes an inelastic scattering event at x_i on its way from reservoir 1 (*i.e.* source) to reservoir 2 (*i.e.* drain). The inelastic scattering causes a change of energy for i which moves it to another energy level E_j and (using an oversimplified 1-D model) changes its motion back towards reservoir 1. In a macroscopic conductor, however, there is a high probability that another electron, j, with energy E_j is also moving from reservoir 1 to reservoir 2. If i and j meet each other at x_j, where there is a scatterer for E_j, the Pauli exclusion principle says that since two electrons cannot stay in identical states, after the scattering there would be one electron moving towards reservoir 1 and one electron towards reservoir 2. This result would be independent of the scattering behaviors of the scatterer located at x_j. This, in fact, says that given that a nonelastic scattering event has happened at x_i the scatterer located at x_j would not have any effect on electron transport. The end result is that the independency of scattering events no longer holds. In other words, there is a correlation between noise components caused by different scattering sites and they would not simply add up any more.

A detailed analytical simulation shows that this process results in suppression of the non equilibrium noise term in (3)[19]. This simulation reveals that for a beam splitter with T_1=0.5 and no inelastic scattering at eV=1000kT the non-equilibrium noise term in (3) is more than 100 times greater than the equilibrium noise component. Inducing 20 scattering events in the channel will reduce this ratio to 7 which is still quite significant. In the limit of numerous inelastic scattering the shot noise component will be totally suppressed and the Johnson-Nyquist equilibrium noise will be recovered.

C. Noise in short channel MOS devices with limited number of inelastic scattering events

The number of inelastic scattering events in the channel region of a MOS device can be estimated by comparing the mean free path of electron in silicon with the channel length. Mobility, effective mass and mean-free-path in a semiconductor are related through the following equation:

$$\mu = \frac{e \times l_m}{m \times V_{th}} \quad (4)$$

where e is the electron charge, l_m is the mean-free-path, m is the electron mass inside the semiconductor, V_{th} is the thermal velocity and μ is the mobility.

In silicon the reported value of mobility in the bulk is 1360cm^2/V-sec, thermal velocity is around 10^{5}m/sec and the electron's effective mass is 1.1m_o where m_o is the free electron mass. Using these values the mean free path will be around 85nm. Considering the fact that surface scattering is dominant inside the channel the expected mean-free-path for the electrons in the channel is expected to be somewhat shorter than this. The channel length for which excess noise was reported for the first time is 0.7μm [3]. This means that the number of inelastic scattering events is believed to be on the order of 10. As explained in the previous subsection, with so few inelastic scattering events the non-equilibrium noise component will not be negligible. Consequently the formulation of MOS noise needs to be revisited. This theory also predicts that for higher gate to source voltages smaller excess noise is expected because more scattering events will occur due to surface scattering inside the channel. This is consistent with experimental results [3].

If we include the non-equilibrium noise component in each of the noise sources used in the impedance field method, the final drain current noise will have a term of the same kind. This is because the drain current noise is a linear function of the local noise sources in *IFM*. Namely, for more practical analysis (3) can be rewritten as:

$$S_I = S_I^{Equ} + N(V_{gs}, V_{ds}) \times 2eI_{tot} \quad (5)$$

where S_I^{Equ} is the equilibrium noise term and N is a coefficient characterizing the behavior of the scattering mechanisms and in general will be a function of biasing condition.

Theoretical details of the calculation of N remains a challenge. as a zeroth other approximation, however, N can be assumed to be independent of V_{ds}. In this case, the numerical value of N can be calculated using a measurement of noise for a specific value of V_{gs} and V_{ds} and its value can be used to calculate the noise power spectral density for the same value of V_{gs} and different values of V_{ds}. Some of the theoretical predictions achieved using this approximation along with experimental results will be provided in the next section.

IV. EXPERIMENTAL VS. THEORETICAL RESULTS

Here we make use of some of the early results [3][4] published concerning excess noise (Table I). Here, γ_{ne} is a non-equilibrium noise factor defined by:

$$S_I = \gamma_{ne} 4KTg_{do} \quad (6)$$

and the normalized N, N_n, is defined by:

$$N_n = \frac{2eN}{4KT} \quad (7)$$

where we have assumed a constant electron temperature which might not be an accurate assumption when V_{ds} is changing. Using (5), (6), and (7) the equations governing N_n and γ_{ne2} will be:

$$N_n = \left(\frac{\gamma_{ne1} - \gamma_{eq}}{I_1}\right) \times g_{do} \quad (8)$$

Table I: Experimental vs. theoretical results for noise in short channel MOS devices. We have assumed that electron temperature is independent of I_d, which might not be an accurate assumption.

V_{gs} (V)	g_{do} (mS)	V_{ds1} (V)	I_{d1} (mA)	γ_{ne1}	Normalized N N_n(V^{-1})	V_{ds2} (V)	I_{d2} (mA)	Predicted γ_{ne2}	Measured γ_{ne2}	Comments
0.97	34.2	1	9.5	2.24	5.66	3	14	2.98	2.87	L=0.75µm [4]
1	2.4	1	0.6	2.92	9.01	4	1.2	5.17	7.93	L=0.7µm [3]
2	5.6	1	3	2.22	2.90	4	3.7	2.58	4.78	L=0.7µm [3]
3	8	3	6.6	2.96	2.77	4	6.9	3.06	3.31	L=0.7µm [3]
4	10.4	3	9.6	2.38	1.85	4	9.9	2.43	2.68	L=0.7µm [3]
5	11.2	4	13	2.55	1.62	5	13.2	2.57	3.42	L=0.7µm [3]

$$\gamma_{ne2} = \gamma_{eq} + \frac{N_n}{g_{do}} \times I_2 \quad (9)$$

where γ_{eq}=2/3 is the equilibrium noise factor. Using these equation the values of N_n and γ_{ne2} are calculated using the values given in [3] and [4]. The predicted value of γ_{ne2} is then compared to its measured reported values. The final results can be seen in Table I.

A remarkable result is that for a specific device, N_n drops as V_{gs} is increased. This is expected by our current theory. As we increase V_{gs} more scattering events are expected due to surface scattering mechanism. This causes more suppression of the non-equilibrium noise component and consequently smaller N_n.

Although the method is quite successful in predicting the result given in [4], the prediction of results given in [3] is not that satisfactory. Three reasons might be responsible for this inaccuracy. First the assumption of constant electron temperature might not be valid when we change V_{ds}. Secondly, as suggested by [15], the devices in Abidi's work [3], are operating close to the avalanche region. This can cause extra noise because of the noisy avalanche process. Finally the initial assumption of independency of N from V_{ds}, is something that needs to be theoretically verified.

V. CONCLUSION

The physical phenomenon responsible for excess noise in short channel MOS devices is introduced as the non-equilibrium noise built in to all electrical elements. We explained that this inherent noise process is not seen in a usual macroscopic conductor due to the presence of numerous inelastic scattering events. In a short channel MOS device, however, the number of scattering events inside the channel is on the order of 10 for each electron. We presented an analytical simulation results showing that even with 20 scattering events per electron the non-equilibrium noise component can be quite significant. Consequently, Johnson-Nyquist noise formula will not be valid for a short channel MOS and the existing theories need to be revisited.

The theoretical calculation of non-equilibrium noise component requires thorough understanding of all scattering processes inside the channel. Nevertheless, using some simplifying assumptions the accuracy of the theory is verified based on some published data. Under the assumption of independency of non-equilibrium noise coefficient from the drain voltage, we presented some theoretical results and compared them with published data. We specifically verified that the decrease of non-equilibrium noise for larger gate voltages predicted by his theory is experimentally observed. The detailed theoretical calculation of the non-equilibrium noise coefficient and its dependency to biasing conditions remains an open area for research.

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