NOISE ANALYSIS

Due to continuous improvement in the characteristics of MOS transistors, CMOS became a viable RF technology for wireless systems. With ever decreasing channel length of MOSFET, the issue of noise becomes more pronounced at RF. It affects overall sensitivity characteristics, dynamic range and signal-to-noise ratio of a system. Excess noise in short-channel MOSFETs hampers the use of CMOS technology for RF applications. Both passive and active components in a circuit will generate various types of noise. Hence it is always recommended to estimate noise effects prior to design of RF IC. This chapter provides modelling and analysis of the noise behavior of OGMOSFETs.

Noise is an unwanted perturbation to a wanted signal. The importance of analyzing the prediction of noise characteristics is essential for its application at RF. For example, while selecting the transistor for circuits such as LNA, measured noise parameters provided by the foundry are used. However it is not possible to provide measured noise parameters for all different geometry and biasing conditions. When measured, noise data is not available for some geometry and biasing conditions, the noise performance of such circuit is unknown. In such a scenario a model is developed to understand the noise behavior of MOSFET. To understand the noise behavior, number of noise models are developed[54,55]. To estimate optical effect on noise of optically gated MOSFET, a charge based noise model is presented. In the present work an attempt is made to investigate the optical effect on noise behavior of MOSFET.

The device characteristics are theoretically examined and analyzed. The simulation results are tested and tuned with MATLAB.

0.1 Sources of Noise

To understand noise behavior, a single MOSFET can be considered as a small circuit with different resistive, capacitive, and active components. Different noise sources in the MOSFET are as follows[57],

1. the noise at the drain with a power spectral density (PSD) \( S_{id} \),
2. the induced gate noise with a power spectral density (PSD) \( S_{ig} \),
3. the channel thermal noise \( S_{nch} = 4K T G_{nch} \),
4. the flicker noise \( S_{flicker} = g_m^2 \frac{K}{C_{ox}} W_{eff} L_{eff} \),
5. the terminal resistances thermal noise \( S_{vnr} = 4K T R_g \), \( S_{inrs} = 4K T / R_s \) and \( S_{inrd} = 4K T / R_d \),
6. the substrate resistances thermal noise \( S_{inrsb} = 4K T / R_{db}, S_{inrsb} = 4K T / R_{db}, \) and \( S_{inrdsb} = 4K T / R_{dsb} \).

‘R’ indicates different resistances in MOSFET, ‘S’ indicates PSD of respective noise.

In principle, flicker noise is a low-frequency noise and it mainly affects the low frequency performance of the device, so it can be ignored at very high frequency. However, the contribution of flicker noise should be considered in designing some radio frequency (RF) circuits such as mixers, oscillators, or frequency dividers that up-convert the low-frequency noise to higher frequency and deteriorate the phase noise or the signal-to-noise ratio. Channel resistance and all terminal resistances contribute to thermal noise at high frequency (HF), but typically channel resistance dominates in the contribution of the thermal noise from the resistances in the device. Induced
gate noise is generated by the capacitive coupling of local noise sources within the channel to the gate, and usually it plays a more important role as the operation frequency goes much higher than the frequency at which channel thermal noise dominates.

0.2 Channel Thermal Noise

Shot noise and thermal noise are essentially two different names for the same physical phenomenon called diffusion noise. Thermal noise assumes that the system is in thermal equilibrium, which only applies strictly if no bias is applied to the device. When there is bias, the carrier collisions produce noise called either diffusion noise or velocity-fluctuation noise. Since behavior of these kinds of noise agrees well with Johnsons thermal noise model, they are often called thermal noise.

Although all the noise sources contribute to the total noise at HF, the dominant contribution still comes from the channel thermal noise having a PSD given by,

\[ S_{\text{ind}} = 4KTG_{\text{ch}} \]

where \( G_{\text{ch}} \) is the channel thermal noise conductance, and \( \gamma \) is a bias-dependent factor, which is proportional to \( \alpha_{\text{sat}}(\text{long}) = g_mR_{\text{Nin}} \) for long channel. From Kleins noise model for short channel[56],

\[ \alpha_{\text{sat}} = \alpha_{\text{sat}}(\text{long}) \cdot \left(1 + \frac{1}{G_{\text{Nf}}} \right) \]

where \( \tau_r \) is a relaxation time (of the order of 1 ps) used as a fitting parameter[52]

![Figure 1: Simplified Small-Signal Schematic for Noise Calculation.](image)

Simplified small signal schematic of MOSFET for noise is as shown in Figure 5.1. V1 and V2 indicate gate and drain voltage respectively.

0.3 HF Noise Parameters

The noise at HF is characterized by three parameters:

1. the minimum noise factor \( NF_{\text{min}} \) or minimum noise figure given by, \( NF_{\text{min}} = 10 \cdot \log(F_{\text{min}}) \)
2. the input referred noise resistance, $R_v$

3. the optimum source admittance, $Y_{opt} = G_{opt} + jB_{opt}$

-for which the minimum noise figure is obtained [31]. These noise parameters can be calculated analytically as,

$$R_v = \frac{\alpha_{sat}}{g_m} D_c$$  \hspace{1cm} (4)

$$G_i = \frac{\alpha_{sat}}{g_m} (\omega C_{gs})^2 \phi$$  \hspace{1cm} (5)

$$G_c = \omega^2 R_g C_{gs} \frac{\alpha_{sat}}{g_m}$$  \hspace{1cm} (6)

$$B_c = \omega C_{gs} \frac{X}{D_c}$$  \hspace{1cm} (7)

$$D_c = 1 + \alpha_g + \alpha_{sub}$$  \hspace{1cm} (8)

Some of the model parameters are described as below,
Input referred gate resistance noise,

$$S_{vRg} = g_m R_g$$  \hspace{1cm} (9)

Input referred channel noise,

$$\alpha_{sat} = g_m R_{Nin}$$  \hspace{1cm} (10)

Output referred substrate resistance noise,

$$S_{isb} = g_m b^2 R_{sub}$$  \hspace{1cm} (11)

Output referred channel noise,

$$\nu_{ch} = g_m^2 R_{Nin}$$  \hspace{1cm} (12)

Note that parameters $R_v, G_i, G_c, B_c$ are frequency and optical flux density dependent parameters.

Where, $\alpha_g$ is the ratio of the noise PSD of the gate resistance to the input referred channel noise and $\alpha_{sub}$ is the ratio of the output referred substrate resistance to the output referred channel noise and are given by,

$$\alpha_g = \frac{g_m R_g}{g_m R_{Nin}}$$  \hspace{1cm} (13)

$$\alpha_{sub} = \frac{g_m b^2 R_{sub}}{\alpha_{sat} g_m}$$  \hspace{1cm} (14)

For short-channel devices biased in strong inversion and in saturation, the lateral electrical field could become larger than the critical field $E_c$, resulting in the carrier velocity to saturate close to the drain and eventually even all along the channel. Since the carrier velocity is limited, an additional charge builds up in the saturation region close to the drain resulting in additional thermal noise and, therefore, an increase of the noise excess factor $\alpha_{sat}$ as compared to the long-channel value.

Parameters $\phi$ and $\chi$ account for the induced gate noise and its correlation to the drain noise

$$\phi = 1 + \alpha_{sub} + \frac{\beta_{sat}}{\alpha_{sat}} + 2C_g \sqrt{\frac{\beta_{sat}}{\alpha_{sat}}}$$  \hspace{1cm} (15)

$$X = 1 + \alpha_{sub} + C_g \sqrt{\frac{\beta_{sat}}{\alpha_{sat}}}$$  \hspace{1cm} (16)
The optimum source admittance is calculated as,

\[ Y_{\text{opt}} = G_{\text{opt}} + jB_{\text{opt}} \]  \hspace{1cm} (17)

\[ G_{\text{opt}} = \sqrt{\frac{G_i}{R_v} - B_c^2} \] \hspace{1cm} (18)

\[ B_{\text{opt}} = -B_c \] \hspace{1cm} (19)

\[ NF_{\text{min}} = 10. \log(F_{\text{min}}) \] \hspace{1cm} (20)

\[ F_{\text{min}} = 1 + R_v(G_{\text{op}} + G_c) \] \hspace{1cm} (21)

Equation 5.21 describes the Minimum noise figure, \( F_{\text{min}} \).

### 0.4 Two Port Structure

Figure 5.3 shows the two port structure of OGMOSFET with and without noise sources.

![Noisy and Noiseless Two Port Network](image)

Parameters related to the noisy two port equivalent circuit as shown in figure 5.3 are PSD of input noise voltage source \( S_{\nu R_g} \) and PSD of input noise current source \( S_{\nu i} \). It is expressed as,

\[ S_{\nu R_g} = 4KTR_\nu \] \hspace{1cm} (22)

\[ S_{\nu i} = 4KTG_i \] \hspace{1cm} (23)

Correlation admittance responsible for correlation between \( i_n \) and \( \nu_n \) is given as,

\[ Y_c = G_c + B_c \] \hspace{1cm} (24)

Correlation factor \( c_c \) between \( i_n \) and \( \nu_n \) is defined as,

\[ C_c = Y_c \sqrt{R_v/G_i} \] \hspace{1cm} (25)

Figure 5.4 shows equivalent circuit of figure 5.3 which is a high frequency noise model of OGMOSFET. \( S_{\nu g} \) is the PSD of gate induced noise.
0.5 Result and Discussion

Numerical computation and simulation of noise is carried out for OGMOSFET to understand its noise behavior under illumination. Simulation is carried out for optical power of 0.25mW at 300\(^0\)K. The polysilicon gate is assumed to be transparent to light and passes almost 90\% of light through it. Due to absorption of light, carrier concentration beneath the gate region increases, which affects noise parameters of the device. To simulate the device model, gate resistance is taken as 4\(\Omega\) and substrate resistance is of 1m\(\Omega\).

Absorption of optical power of incident radiations cause generation of excess carriers beneath SiO\(_2\)/Si interface. There is fluctuation in carrier density caused by emission and capture of carrier traps. Generation and recombination noise is generated as a result of this fluctuation and which is negligible.

PSD of channel thermal noise and channel thermal noise conductance is calculated with equation 5.1 and 5.2 and is tabulated in the following table,

<table>
<thead>
<tr>
<th>Noise calculated with eqn.5.1,5.2</th>
<th>Dark</th>
<th>Illumination</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSD of Channel Thermal Noise</td>
<td>0.0017</td>
<td>0.0102</td>
</tr>
<tr>
<td>Channel Thermal Noise Conductance</td>
<td>0.016</td>
<td>0.098</td>
</tr>
</tbody>
</table>

Different parameters used for analytical modelling of noise in equations 5.8, 5.15 and 5.16 are observed under dark and illumination condition. Table 5.2 shows that each parameter value decreases under illumination.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\varphi)</th>
<th>X</th>
<th>DC</th>
<th>(\Omega)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dark</td>
<td>1.523</td>
<td>1.074</td>
<td>1.217</td>
<td>0.071</td>
</tr>
<tr>
<td>illuminated</td>
<td>1.252</td>
<td>0.939</td>
<td>1.063</td>
<td>0.027</td>
</tr>
</tbody>
</table>
It is seen in chapter 2 that transconductance of OGMOSFET increases under illumination. Equation 5.4 shows that an increase in transconductance decreases the noise resistance. Figure 5.5 shows reduction in noise resistance under illumination. From table 5.2, it is seen that all parameters decrease considerably under illumination, which compensates the increase in transconductance of equation 5.5 and 5.6 thereby decreasing noise correlation factor Gc and noise current factor Gi as shown in figure 5.6 and 5.8. Figure 5.7 is the phase of correlation admittance. Noises calculated with equation (5.9)-(5.12) are summarized in table 5.3 under dark and illumination condition.

Table 3: Input Output Noises under Dark and Illumination condition.

<table>
<thead>
<tr>
<th>Noise</th>
<th>Dark</th>
<th>Illuminated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input referred gate resistance noise</td>
<td>0.039</td>
<td>0.120</td>
</tr>
<tr>
<td>Input referred channel noise</td>
<td>17.49</td>
<td>11.28</td>
</tr>
<tr>
<td>Output referred channel noise</td>
<td>0.016</td>
<td>0.098</td>
</tr>
<tr>
<td>Output referred substrate resistance</td>
<td>0.0031</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

Figure 4: Noise Resistance Vs Normalized Frequency.
Magnitude and phase of optimum source admittance decreases under illumination due to decrease in noise resistance and noise current factor. Figures 5.9-5.11 illustrate reduction in optimum source admittance. Magnitude of $Y_{op}$, noise correlation factor and noise resistance causes considerable reduction in noise figure of OGMOSFET which is figure of merit to calculate noise.
Figure 8: Noise Parameter Gop Vs Normalized Frequency.

Figure 9: Noise Parameter Bop Vs Normalized Frequency.

Figure 10: Optimum Source Admittance Vs Frequency.

It is shown by figure 5.12.

PSD of input noise voltage current source, computed from equation 5.22 and 5.23 is shown with figure 5.13 and 5.14. It increases under illumination. Optical effect on correlation admittance
and correlation factor is as shown in figure 5.15 and 5.16. It shows improvement as that of dark condition.
0.6 Conclusion

All noise parameters $N_{F_{\text{min}}}, G_{\text{opt}}, B_{\text{opt}}$ and $R_e$ and $G_i, G_c, B_c$ under optical illumination are calculated for the optical flux density in $1 \times 10^{15} \text{ wb/m}^2$. Under dark condition the optical flux density is assumed to be zero. Under dark condition results are in good agreement with [52]. The noise model of MOSFET under illumination is studied and the effect of illumination on noise parameters is estimated. It is possible to control noise parameters by controlling the intensity and frequency of incident radiation. Consequently the device can be used as LNA and optical detection at HF.

Optical effects on noise parameters of MOSFET are observed. Results shows decrease in magnitude of noise parameters of MOSFET. Decrease in noise resistance by 12.35Ω causes reduction in thermal noise. The noise figure of the device reduces by 0.7dB. It seen that optical effect on noise of the MOSFET can be estimated.