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RF Noise Characteristics of SOI MOSFET's

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1. Introduction

Low noise figure (*NF*) is one of the important requirements in the receiver chain of the wireless RF front-end for the transistors operating in the 1 to 3 GHz range [1]. The potential of sub-1dB *NF* in BulkMOS was demonstrated in [2, 3]. The experimental *NF* of Silicon-On-Insulator (SOI) MOSFET's has been presented in [4] and [5]. However, correlations with the bias conditions and transistor parameters have not been reported.

In this work, the noise characteristics in RF operation of floating body SOI MOSFET's are presented and modeled. Shot noise due to impact ionization is identified as the *NF* limiting mechanism for SOI devices.

2. RF Noise Mechanisms and Model.

The small signal MOSFET equivalent circuit with its associated noise sources is shown in Fig.1. At RF frequencies much lower than the transistor f_T cutoff frequency, (f_T/f)>10, the induced gate noise $\overline{i_{gn}^2}$ can be neglected [3]. Conventionally, the MOSFET noise is modeled considering, (1) gate resistance noise $\overline{v_{Rg}^2}$, (2) MOS channel thermal noise $\overline{i_{Dth}^2}$, and (3) substrate resistance thermal noise $\overline{v_{Rsub}^2}$. In this work, we newly formulate the noise sources by including (4) the shot noise associated with the drain impact ionization current I_i: $\overline{i_{ii}^2} = 2qI_i\Delta f$. This term is important in floating body SOI MOSFET's, where the impact ionization manifests as the well-known "kink" effect. As a function of the MOS channel current I_{ch}, impact ionization coefficient *M*, and parasitic bipolar current gain β,

$$I_i = (M-1)/[1-\beta(M-1)]\cdot I_{ch}, \qquad (1)$$

with *M* a function of the drain voltage V_d, and the ionization length λ_i: $(M-1) = (A_i/B_i)(V_d - V_{dsat})\exp(-B_i\lambda_i/(V_d - V_{dsat}))$

The total drain noise power spectral density can be expressed as

$$S_{id} = \left(\overline{i_{Dth}^2}/\Delta f\right) + \left(\overline{i_{ii}^2}/\Delta f\right) \cong 4kT_L\gamma g_{do} + 2qI_i \qquad (2)$$

where γ is the noise coefficient and g_{do} is the drain conductance at zero drain bias [3].

The minimum noise figure *NFmin* was calculated using the described analytical model and the circuit in Fig.1.

3. Comparison with Experimental Devices

NMOS transistors of three technologies were evaluated: as summarized in Table I. Details are given in [6]. SIMOX wafers with p-type substrate resistivity of 10Ωcm and ~10^3Ωcm were evaluated. The same transistor gate-multifinger layout (Lf=5um, Nf=60) was used in the three technologies. Noise figure was measured on-wafer and the effect of the Pads was de-embedded.

A. Effect of Substrate. The substrate resistance R_{bb} thermal noise couples to the channel through the back gate transconductance g_{mb}. The *NF*-vs-substrate resistivity has a bell-shaped characteristic as described in Fig.2. Measured and calculated *NF*'s are shown in Fig.2 for the SOI and Bulk 0.25um transistors. *NFmin* as low as 0.4dB was measured for the 0.25um SOI devices. Compared with Bulk, SOI benefits from a smaller g_{mb} than Bulk and reduced *NF* on high-ρ substrate.

B. Impact Ionization and Floating Body Effects. Fig.3 shows the measured (symbols) and model calculated (lines) *NFmin* as a function of drain voltage for Bulk and SOI devices. Clear from these results is the rapid increase of *NF* as V_d increases for the SOI transistors. This phenomenon is related to the impact ionization shot noise, which is enhanced by the floating body and parasitic bipolar effects, as indicated by (1). This point is further illustrated in Fig.4, where the correlation between the "kink" in *Vth*-vs-V_d and the rise in *NF*-vs-V_d in Fig.3 can be appreciated. The drain on-set voltage for the "kink" in *Vth* is $V_{dk} \cong B_i\cdot\lambda_i/3$ [7] and depends on the ionization characteristic length $\lambda_i \sim \sqrt{Tox\cdot Tsi}$. *NFmin* is approximately flat for the BulkSi device, due to the lower impact ionization and the low body resistance that inhibits the parasitic bipolar action.

The effect of λ_i on the SOI *NFmin* is shown in Fig.5. As the model and Fig.5 suggest, relaxing the drain electric field, e.g. by LDD engineering, would result in a wider operating range. It is worth noting that λ reduces with technology scaling bringing a tradeoff in transistor design for RF applications.

4. Conclusions.

The noise at RF in SOI MOSFET's was analyzed and modeled. The Noise Figure behavior of floating body SOI MOSFET's is explained by the shot noise associated with impact ionization. The model successfully explains the experimental *NF* data and indicates the tradeoff in SOI devices limiting the supply voltage. Moreover, the analytical model indicates the contribution of each noise mechanism and gives useful guidelines for device optimization, and the optimum bias condition.

References

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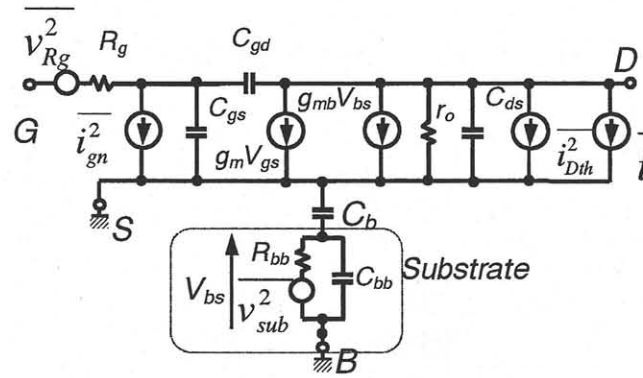

Fig.1: Small-signal equivalent circuit and noise sources of the MOS transistor.

Table I: Device Parameters

	SOI-1	SOI-2	Bulk
Gate Length. L	0.25um	0.35um	0.25um
Tox	4.5nm	7nm	4.5nm
Top Si Thickness	5nm	5nm	----
BOX Thickness	100nm	100nm	----
Bipolar Gain, β	2	2.7	0
Impact Ionization, Bi	8×10^5 V/cm		
Ionization length, λi	35nm	65nm	70nm
"Kink" on-set voltage, Vdk	1V	1.3V	----
Noise Coefficient, γ	1.1	1	1.4
Substrate Resistance, R_{bb}	$3\times10^5\Omega$	$3\times10^2\Omega$	100Ω

$$Si_{sub} \cong \omega^2 C_g^2 \left(\frac{g_{mb}}{g_m}\right)^2 \frac{R_{bb}}{1+\omega^2 C_b^2 R_{bb}^2}$$

$$R_{bb} \propto \rho$$

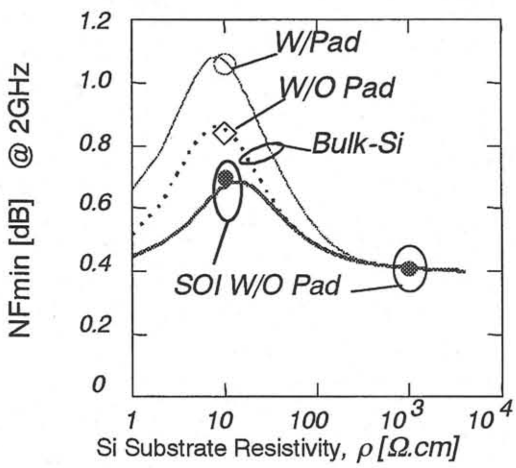

Fig.2: At the top of the figure, the equivalent input referred substrate noise power spectral density is shown. The figure shows measured (marks) and simulated *NF*-vs-substrate resistivity for 0.25um Bulk and SOI NMOSFET's.

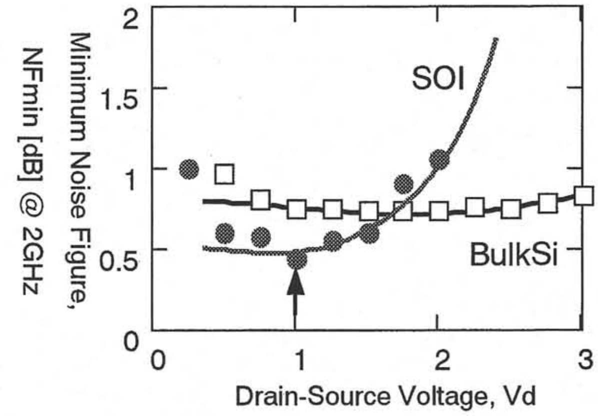

Fig.3: Measured (marks) and model calculated (lines) minimum noise figure *NFmin* of a) 0.25um SOI on high-ρ substrate, and b) 0.25um BulkSi NMOSFET's.

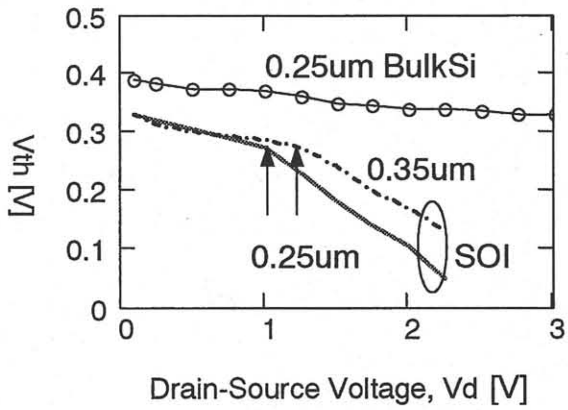

Fig.4: Measured threshold voltage *Vth* for the devices in Fig.2. A correlation between the "kink" in the floating body SOI devices, and the rise in *NFmin* for *Vd>Vdk* is observed. Arrows indicate the "kink" on-set voltage *Vdk*.

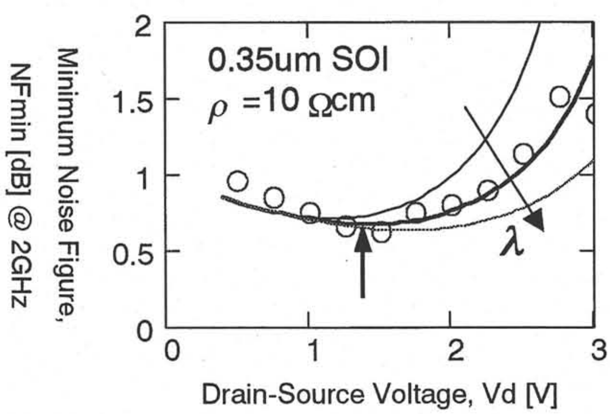

Fig.5: Effect of the impact ionization characteristic length λ on the noise figure of floating body SOI MOSFET.