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CARRIER FLUCTUATION NOISE IN A MOSFET CHANNEL DUE TO TRAPS IN THE OXIDE†

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Abstract—If for a section Δx of a MOSFET channel δN_t is the fluctuation in the number of trapped carriers and δN the corresponding fluctuation in the number of carriers in the channel, then $S_{\delta N}(f) = S_{\delta N_t}(f)(\delta N/\delta N_t)^2$. We have here evaluated $-\delta N/\delta N_t$ from first principles and compared the results with those obtained by other investigators. It turns out that $-\delta N/\delta N_t$ is unity for very strong inversion and that it decreases to an extremely small value at very weak inversion.

It is usually assumed that flicker noise in MOSFETs is caused by fluctuations in the number of free carriers in the conducting channel[1–5]. These fluctuations, in turn, are due to the interaction between free carriers and oxide traps via surface states[2–5].

We investigate here conventional MOS structures. Fu and Sah[6] have investigated an epitaxial n-channel MOSFET, to which our study does not apply. Our results therefore affect in no way the results of Fu and Sah's paper.

If for a section Δx of a MOSFET channel δN_t is the fluctuation in the number of trapped electrons, and δN is the corresponding fluctuation of the number of electrons in the channel, then

$$S_{\delta N}(f) = S_{\delta N_t}(f)(\delta N/\delta N_t)^2. \tag{1}$$

It is the aim of this note to evaluate $-\delta N/\delta N_t$ exactly and to show that this expression reaches unity for strong inversion and is much less than unity for weak inversion. The derivation goes in two steps.

(a) *Relation between the change in the flat band voltage* V_{FB} *and charge fluctuation in the channel*

Consider an n-channel MOSFET, then under the gradual channel approximation, we have

$$V_G - V_{FB} = \frac{-q \cdot Q_s(y)}{C_0} + \phi_s(y) - \phi_B. \tag{2}$$

Then for a small change in V_{FB} for constant V_G, we have

$$\Delta\phi_s(y) = \frac{-\Delta V_{FB}}{1 - \dfrac{q}{C_0}\cdot\dfrac{\partial Q_s(y)}{\partial\phi_s(y)}} \tag{3}$$

Now,

$$q\Delta Q_{\text{inv}}(y) = q\cdot\frac{\partial Q_{\text{inv}}(y)}{\partial\phi_s(y)}\cdot\Delta\phi_s(y). \tag{4}$$

Then, from (4) we have,

$$q\cdot\Delta Q_{\text{inv}}(y) = \frac{-q\cdot\dfrac{\partial Q_{\text{inv}}(y)}{\partial\phi_s(y)}}{1 - \dfrac{q}{C_0}\cdot\dfrac{\partial Q_s(y)}{\partial\phi_s(y)}}\cdot\Delta V_{FB}. \tag{5}$$

We have used here the following notation: V_{FB} = Voltage to be applied to the gate in order to make the bands flat. $Q_s(y)$ = Total charge induced (no./area) in the silicon structure at a distance "y" from the source towards the drain. It is a negative quantity in our case. $Q_{\text{inv}}(y)$ = Inversion layer charge (no./area) at a distance "y" from the source towards the drain. It is a negative quantity for our case. ϕ_B = Bulk semiconductor potential (positive for n-type semi-conductor). $\phi_s(y)$ = Potential of the semiconductor surface at a distance "y" from the source towards the drain. ϵ_{ox} = Relative dielectric constant of oxide. ϵ_s = Relative dielectric constant of semiconductor.

(b) *Relation between change in* V_{FB} *and the trapped charge carriers*

In order to derive this relation we compare the situation to a capacitor whose lateral dimensions are large compared to the separation between the plates. This corresponds to the oxide capacitance C_0 per unit area. Now, by definition, V_{FB} is the voltage required at the gate to make the bands flat. Hence, the effect of an added carrier to the traps is taken account of fully if we determine the change in V_{FB} due to its presence because once the bands are flat the situation before and after the trapping is the same as far as the semiconductor side of the MOS structure is concerned.

Let a charge ΔQ be trapped at a distance x_0 from the top plate. Then if the plate separation $x_0 \ll$ the plate dimensions it does not matter whether ΔQ is a point charge or it is spread over a plane at a distance x parallel to the plates of the capacitor. In this way we can make use of Gauss's law to determine the potential difference between the plates. Without the trapped charge, let for a voltage V_0, the charge on each plate be Q_0. Then $Q_0 = C_0 V_0$. With the trapped charge, in order to have the same charge Q_0 on the lower plate, we have to have a charge $(Q_0 - \Delta Q_0)$ on the upper plate. Hence,

$$\frac{Q_0 - \Delta Q_0}{\epsilon_0\cdot\epsilon_{ox}}\cdot x + \frac{(Q_0 - \Delta Q_0 + \Delta Q_0)(x_0 - x)}{\epsilon_0\cdot\epsilon_{ox}} = V'$$

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or

$$V' = V_0 \frac{-\Delta Q_0}{C_0} \cdot \frac{x}{x_0} \quad \text{or} \quad \Delta V = \frac{-\Delta Q_0}{C_0} \cdot \frac{x}{x_0}.$$

Hence,

$$\Delta V_{FB} = \frac{-\Delta Q}{C_0} \cdot \frac{x}{x_0}. \tag{6}$$

(c) *Calculation of* $-\delta N/\delta N_t$

We have from (5)

$$q \cdot \Delta Q_{\text{inv}}(y) = \frac{\frac{q}{C_0} \cdot \frac{\partial Q_{\text{inv}}(y)}{\partial \phi_s(y)} \cdot \frac{\Delta Q}{A} \cdot \frac{x}{x_0}}{1 - \frac{q}{C_0} \cdot \frac{\partial Q_s(y)}{\partial \phi_s(y)}}$$

Now let the electron concentration in the oxide traps in number/cm^3 be $n_{TO}(x)$ and let there be a fluctuation $\Delta n_{TO}(x)$ in it at a distance "x" from the gate metal. Then, the corresponding charge fluctuation is $\Delta Q = q(\Delta n_{TO}(x)\Delta x \cdot \Delta A)$ where $\Delta x \cdot \Delta A$ is a small volume element about the point "x" where the density fluctuation occurred. If the fluctuation $\Delta n_{TO}(x)$ is uniform over the whole area of the plate then the contribution due to each ΔA adds up and ΔA is replaced by A and then

$$q \cdot \Delta Q_{\text{inv}}(y) = \frac{\frac{q}{C_0} \frac{\partial Q_{\text{inv}}(y)}{\partial \phi_s(y)}}{1 - \cdot \frac{q}{C_0} \cdot \frac{\partial Q_s(y)}{\partial \phi_s(y)}} \cdot \frac{x}{x_0} \cdot q[\Delta n_{TO}(x) \cdot \Delta x]. \tag{7}$$

Hence, the ratio: Fluctuation in free electron density in channel over the fluctuation in trap occupancy causing electron fluctuation

$$\frac{\delta N}{\delta N_t} = \frac{q \cdot \Delta Q_{\text{inv}}}{q \cdot \Delta n_{TO}(y) \cdot \Delta x} = -\frac{\frac{q}{C_0} \frac{\partial Q_{\text{inv}}(y)}{\partial \phi_s(y)}}{\frac{q}{C_0} \frac{\partial Q_s(y)}{\partial \phi_s(y)} - 1} \cdot \frac{x}{x_0} \simeq -R \frac{x}{x_0} \tag{8}$$

Putting $\phi_B = (kT/q)U_B$ and $\phi_s(y) = (kT/q)U_s(y)$ we have

$$R = \frac{\frac{\partial Q_{\text{inv}}(y)}{\partial U_s(y)}}{\frac{\partial Q_s(y)}{\partial U_s(y)} - \frac{C_0 kT}{q^2}}. \tag{8a}$$

From Kingston and Neustadter[7]

$$Q_s(y) = -2 \cdot n_i \cdot L_D \sqrt{(2)} \times \sqrt{[(U_B - U_S)\,\text{Sinh}\,(U_B) + \text{Cosh}\,(U_s(y)) - \text{Cosh}\,(U_B)]}$$

Therefore

$$\frac{\partial Q_s(y)}{\partial \phi_s(y)} = \frac{-\sqrt{(2)}n_i L_D\,[\text{Sinh}\,(U_s(y)) - \text{Sinh}\,(U_B)]}{\sqrt{[(U_B - U_s(y))\,\text{Sinh}\,(U_B) + \text{Cosh}\,(U_s(y)) - \text{Cosh}\,(U_B)]}} \tag{9}$$

Also, we have

$$\delta Q_{\text{inv}}(y) = \frac{-n_i L_D}{\sqrt{(2)}} \int_{U_s(y)}^{U_B} \times \frac{[e^{U(x)} - e^{U_B}](-dU(x))}{\sqrt{[U_B - U_s(x))\,\text{Sinh}\,U_B + \text{Cosh}\,U_s(x) - \text{Cosh}\,U_B]}}$$

$$\frac{d\delta Q_{\text{inv}}(y)}{dU_s(y)} = \frac{-n_i L_D[e^{U_s(y)} - e^{U_B}]}{\sqrt{(2)} \cdot \sqrt{[(U_B - U_s(y))\,\text{Sinh}\,(U_B) + \text{Cosh}\,U_s(y) - \text{Cosh}\,(U_B)]}} \tag{9a}$$

where

$$\delta Q_{\text{inv}}(y) = Q_{\text{inv}}(y)|_{U_s = U_s} - Q_{\text{inv}}(y)|_{U_s = U_B}$$

therefore,

$$\frac{\partial Q_{\text{inv}}(y)}{U_s(y)} = \frac{\partial \delta Q_{\text{inv}}(y)}{\partial U_s(y)}$$

Substituting in (8a) we get

$$R = \frac{e^{U_s(y)} - e^{U_B}}{2[\text{Sinh}\,(U_s(y)] - \text{Sinh}\,(U_B)) + 2C_0 \sqrt{\left(\frac{T}{n_i q \epsilon_0 \epsilon_s}\right)} \sqrt{[(U_B - U_s(y))\,\text{Sinh}\,U_B + \text{Cosh}\,U_s(y) - \text{Cosh}\,U_B]}} \tag{8b}$$

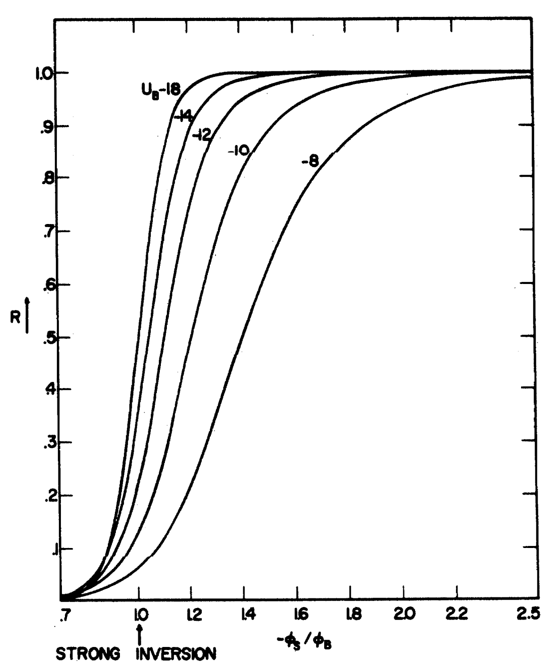

Fig. 1. $R = -\delta N/\delta N_t$ versus the normalized surface potential U_s/U_B with U_B as a parameter, for a p-type substrate.

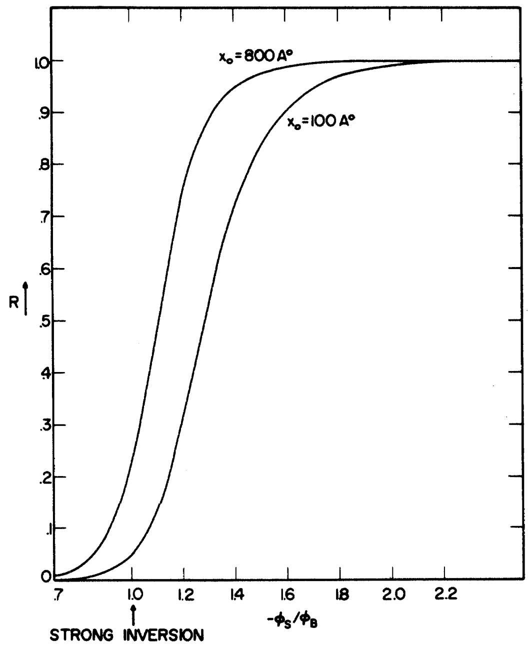

Fig. 2. R versus the normalized surface potential U_s/U_B at $U_B = -18$, with the oxide thickness x_0 as a parameter for a p-type substrate.

We now bear in mind that only traps very close to the interface are effective in producing 1/f noise at measurable frequencies so that $x/x_0 \simeq 1$ or $\delta N/\delta N_t \simeq -R$.

The results are shown in Figs. 1 and 2 for a p-type substrate. It is seen that for $U_s(y) \rightarrow U_B$ we have $R \rightarrow \delta$ for typically $\delta = 10^{-10}$. Also for $U_S - U_B < |U_B|$ we have $R \rightarrow 1$. The plot of R for intermediate values of $U_s(y)$ are plotted in Fig. 1 for different values of U_B.

It is observed that R rises from near zero (typically 10^{-10}) to unity for a MOSFET as we vary the surface potential by changing the gate bias of the MOSFET. It is also seen that for given inversion states characterized by the ratio $(-U_s(y)/U_B) > \cdot 9$ R is lower for smaller $|U_B|$ (lower doping, see Fig. 1).

Further, for a given inversion state, R decreases as the gate oxide thickness is decreased. The net effect of a lower x_0 is therefore to shift the R as shown in Fig. 2.

We have hereby extended the theory of flicker noise in MOSFETs due to traps in the oxide. The results of most investigators[2, 4, 5] are correct at *very* strong inversion only, since they take $\delta N/\delta N_t = -1$.

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