CORRELATION BETWEEN MOST 1/f NOISE AND CCD TRANSFER INEFFICIENCY

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Abstract—The 1/f noise in MOS transistors has been investigated and is shown to correlate with charge transfer inefficiency experiments on surface-channel CCDs. Both independent phenomena can be quantitatively explained by the same interface state model. The oxide trap density turns out to vary by more than a factor 10. The 1/f noise is compared with McWhorter's number fluctuation model and with the mobility fluctuation model. The oxide trap density is calculated from the charge transfer inefficiency in surface CCDs. Both the quantitative agreement between oxide trap density and 1/f noise and the observed dependence of 1/f noise on gate voltage here give strong arguments in favour of the McWhorter model. The investigated MOS transistors fall into a category that cannot be explained by the present mobility fluctuation model.

1. INTRODUCTION

A generally accepted theory for the 1/f noise in MOS transistors is still lacking. However, there are several models in circulation. One of these ascribes the 1/f noise in the conductance to carrier density fluctuations $\Delta N$. These fluctuations are caused by tunnelling of free-charge carriers into oxide traps close to the Si–SiO$_2$ interface[1]. This McWhorter model has many supporters. Arguments in favour of the McWhorter model are the observed proportionality between interface trap density and 1/f noise[2–6]. Another model considers the 1/f noise as a bulk effect caused by mobility fluctuations due to lattice scattering[7]. There is a category of low-noise MOSTs the noise of which cannot be explained by mobility fluctuations[8].

This controversy of $\Delta N$ versus $\Delta \mu$ in MOSTs still exists because[8,9], on the one hand, under certain bias conditions, noisy devices usually agree with both models, and on the other the proportionality between interface state densities (ranging from $10^{10}$ to $10^{13}$ cm$^{-2}$ eV$^{-1}$) and 1/f noise for 11 different MOSTs was not observed. In the non-ohmic region of MOSTs the 1/f noise in the conduction is always a mixture of $\Delta \mu$ and $\Delta N$. If mobility fluctuations are taken to be the noise source, then the number fluctuation contribution is due to fluctuation of the effective gate voltage induced by mobility fluctuations[10]. Believing in an oxide-trap model, the mobility fluctuation contribution can be included as stemming from $\Delta N$-induced gate-voltage fluctuations which modulate the mobility[11] by means of a mobility reduction factor. In order to avoid this ambiguity, our noise results were mainly obtained in the ohmic region of the MOST characteristics.

Independent noise sources $\Delta N$ and $\Delta \mu$ have been assumed by Katto et al.[12] and by Mikoshiba[13], and a unification of the $\Delta N$ and the $\Delta \mu$ model could account for all Mikoshiba's data[13]. Recently, it has been shown[14] that charge trapping according to the McWhorter model accounts for the small-signal charge transfer inefficiency (SCTI) in CCDs. The oxide trap density may be found from SCTI measurements[14], and this quantity, more than the interface state density, plays a natural part in the $\Delta N$ model. Correspondingly, the comparison of the SCTI experiments in CCDs and the 1/f noise in on-chip MOSTs makes it possible to investigate the $\Delta N$ model quantitatively.

In this paper the emphasis lies on the MOST 1/f noise. New experimental results on 1/f noise in $n$-channel MOSTs are presented. In the range of effective gate voltages between 0.1 V and 5 V 1/f noise has been measured. The results will be compared with existing $\Delta N$ and $\Delta \mu$ models.

2. 1/f NOISE MODELS

Let us consider the two possibilities $\delta \mu$ or $\delta N$ for explaining the fluctuations in the conductivity:

$$\delta \sigma = q \mu \delta n,$$

$$\delta \sigma = q n \delta \mu.$$  

The assumption of mobility fluctuations was introduced by Hooge[15]. He suggested that the spectral density of the relative mobility fluctuation of a free-charge carrier is given by

$$\frac{S_\mu}{\mu^2} = \frac{\alpha}{f}.$$
Conductance $G$ is proportional to $N_{tr} = \Sigma \mu_i$ with $\mu$ the average mobility over $N$ carriers and $\mu_i$ the mobility of each carrier. When each carrier contributes to the conductance and to the noise independently of the others, one finds $\langle \Delta G^2 \rangle \propto N \langle \Delta \mu_i^2 \rangle$ and

$$
\frac{S_{\nu}}{G^2} = \frac{\alpha}{Nf'},
$$

which holds for homogeneous samples with $N$ free carriers[15]. The parameter $\alpha$ was believed to be a constant of $2 \times 10^{-2}$ for metals and semiconductors. Later it was found that the parameter $\alpha$ decreases systematically when the mobility is reduced by scattering mechanisms other than lattice scattering[16]. From experimentally obtained results on Ge, GaAs, Si, and Bi it was concluded that impurity surface and optical phonon scattering reduce $\mu$, in comparison with the value $\mu_i$ which is the mobility associated with lattice scattering only. Thereby the $\alpha$ value is reduced as follows[16,17]:

$$
\alpha = (\mu/\mu_i)^2 \alpha_1,
$$

with $\alpha_1$ the noise parameter when only lattice scattering is present.

Even $\alpha_1$ does not seem to be constant. Recent investigations on silicon-implanted layers have shown that the noise parameter $\alpha_1$ can be of the order of $10^{-6}$ for well-annealed samples and of the order of $10^{-4}$ in poorly annealed samples[18].

In 1939 Surdin[9] explained the 1/f noise in terms of number fluctuations $\Delta N$ by considering a superposition of generation–recombination spectra with the appropriate distribution in time constants $\tau$. Consider an $n$-type semiconductor with $N$ free charge carriers and a number of fully ionized donors $N_i$. The traps $N_t$ are occupied by a number of $n_i$ electrons. Charge neutralises $N + n_i = N_i$, hence $\Delta N = -\Delta N_t$. When $N \ll N_i$, the number of states in the conduction band and $N \gg n_i$, the generation–recombination noise for this two-level system becomes

$$
S_N(\nu) = \Delta N^2 \left(1 + \frac{2\pi\nu}{\nu_0}\right).
$$

Under the above conditions we have $\Delta N^2 = N_i^2$ for $N_t > n_i$, $\nu^2 = \nu_0 D_t N_i/n_i$ with $s$ the capture cross-section of the oxide trap, $\nu_0$ terminal velocity of the charge carrier, and $D_t$ the trap density equal to $N_i/\Omega$ with $\Omega$ the sample volume[19–22]. Depending on whether the traps are situated through the volume of the sample or localized at the surface, the generation–recombination noise is a volume or a surface effect.

Taking a number of traps with the normalized distribution function in $\tau$ between $\tau_i$ and $\tau_i$,

$$
g(\tau) = \frac{1}{\tau \ln \tau_i/\tau_i},
$$

Surdin[9] was first to calculate a 1/f spectrum in the range of $1/2\pi\tau_i < \nu < 1/2\pi\tau_i$ for independent trapping processes:

$$
S_N(\nu) = \int_{\tau_i}^{\tau_i} g(\tau) \Delta N^2 4\pi \frac{1 + (2\pi\nu/\tau_i)^2}{1 + (2\pi\nu/\tau_i)^2} d\tau = \frac{\Delta N^2}{\tau_i} \ln (\tau_i/\tau_i) \nu. \quad (8)
$$

$\Delta N^2$ is the variance in $N$ due to all the trapping processes together. Outside the 1/f region there is a white and 1/f' branch that hardly contribute to the total integral from $\nu = 0$ to $\nu = \infty$ if $\tau_i \gg \tau_i$.

In 1955 McWhorter[1] gave a physical interpretation of the distribution function $g(\tau)$ in eqn (7). He assumed a homogeneous distribution of traps in the oxide on top of the semiconductor surface and the probability of penetration into the oxide layer to be governed by a tunnelling process. Correspondingly, the probability of penetration is proportional to $\exp(-x/x_0)$ and $\tau(x)$ becomes

$$
\tau(x) = \tau_0 e^{-x/x_0},
$$

where $x_0$ is a characteristic decay length of the wave function and is of the order of 1 Å. The normalized $\tau$-distribution function for traps distributed uniformly between the Si–SiO$_2$ interface and a distance $x_2$ from that interface becomes

$$
\tau(x) = 0 \quad \text{for} \quad x > x_2.
$$

In general, $x_2 = 30 \, \text{Å}$ is chosen for the 1/f noise, which leads to $x_2/x_0 = 30$. Then $\ln(\tau_i/\tau_i) = 30$ results in a range of $\tau$ values over 13 decades. When the oxide trap density $D_0$ [cm$^{-3}$ eV$^{-1}$] is only a weak function of the energy around the Fermi level, we find

$$
\Delta N^2 = x_0 D_0 kT \Omega
$$

with $\Omega$ the Si–SiO$_2$ interface area of the channel. The energy $kT$ must be expressed in eV units. The relative noise in the resistance is equal to that in the conductance

$$
S_R/G^2 = S_N/N^2 = x_0 D_0 kT \Omega/x_2 N^2 f. \quad (11)
$$

From inspection of this expression and eqn (4), it follows that in the $\Delta N$ model, $\alpha$ is equal to

$$
\alpha = x_0^2 D_0 kT \Omega/x_2 N.
$$

For an inversion layer at room temperature, with a gate oxide capacitance per unit area of $3.4 \times 10^{-8}$ F/cm$^2$ and an effective gate voltage of 1 V, for $x_0 D_0 = 10^{10}$ cm$^{-2}$ eV$^{-1}$ and $x_0/x_2 = 1/30$, $\alpha$ be-
comes $4 \times 10^{-5}$, which is a value often observed in high-quality bulk silicon. This means that only considering the $a$ value is not enough to discriminate between the $\Delta N$ and the $\Delta \mu$ model. To decide between the two models, it is important to determine whether $a$ is proportional to $1/N$ ($\Delta N$ model) or independent of $N$ ($\Delta \mu$ model). The $\Delta \mu$ model based on Hooge’s empirical relation results in a relative noise inversely proportional to $N$ which indicates a bulk effect. The $\Delta N$ model based on McWhorter’s oxide-trap model results in a $1/N'$ proportionality by considering the $1/f$ noise as a surface effect. In Surdin’s $\Delta N$ model the $1/f$ noise was still considered to be a bulk effect because the traps were not located at the surface but in the bulk. The bulk–surface controversy as originating from $1/f$ noise is seen from eqns (4) and (12) or eqn (5) and (13).

### 3. NOISE RELATIONS FOR MOSTs

Let us assume an $n$-channel MOST; length and width are denoted by $l$ and $W$. The free-electron concentration being a function of the distance $y$ from the source, is given by $n(y)$. The mobility is assumed to be the same in the whole channel. The current in the channel is then

$$I = Wq \left( \mu n(y) E(y) + D \frac{dn(y)}{dy} \right).$$  

(14)

The diffusion term can be neglected in uniform channels when the effective gate voltage $V_G^* = V_G - V_T$ satisfies the condition

$$V_G^* > \frac{kT}{q} \left[ \frac{(y/l)(1-v)}{1 - 2(y/l)(v - v^2/2)} \right],$$  

(15)

where $v = V/V_G^*$, the ratio of the drain-source voltage to the effective gate voltage. At room temperature the diffusion term is negligible, in the ohmic region ($v \rightarrow 0$) for $V_G^* > 25$ mV. In the saturation region the diffusion term increases at the drain side of the channel ($y = l$). Ignoring the diffusion term, the Nyquist noise and the $1/f$ noise in the current are found to be

$$S_I(f) = \frac{4kT}{R_0} \left( 1 - v + v^2/3 \right) + \frac{a_0 qIV}{f^2} + \frac{a qV}{f^2}.$$  

(16)

The first term in (16) represents the thermal noise in the current[21], the second represents the $1/f$ noise[10]. Following the $\Delta N$ interpretation, $a$ in (16) must simply be replaced by the expression of (13). If the $\Delta \mu$ interpretation is followed, $a$ can be replaced by $(\mu/\mu_0) a_0$, given by eqn (5). In a more elaborated model for $\Delta \mu$ fluctuations[10], the inversion layer was considered to be three dimensional. The decrease in mobility and $a$ with increasing $V_G^*$ was mainly attributed to an increasing surface scattering with increasing $V_G^*$. For $V_G^*$, at which the mobility reduction becomes significant, $a$ in (16) can be replaced by $a_1 V_G^*/\rho_{EFF}$ as given in [7] and [10]. In Ref. [23] the mobility reduction and the reduction in $a$ was considered as a pure hot-electron effect leading to similar results as the three-dimensional treatment.

At saturation ($v = 1$) the noise becomes

$$S_I(f) = \frac{4kT}{R_0} \left( 1 - v + v^2/3 \right) \frac{a qIV}{f^2} + \frac{a qV}{f^2}.$$  

(17)

The saturation current is given by

$$I_s = \mu CV_G^2/2l^2,$$

where $C$ is the gate oxide capacitance and $N = CV_G^2/\rho$ is the total number of free carriers in the channel at $v \rightarrow 0$. At saturation, the total number of free-charge carriers is two-thirds of the value at $v \rightarrow 0$ and the relative current noise $S_{I_s}/I_s^2$ is twice the value at $v \rightarrow 0$[10].

The voltage noise $S_V$ between source and drain under constant current is given by $S_V = r$, with $r$ the dynamic resistance at the operation point; $r$ is given by $R_{n}/(1 - v)$ and $S_V$ becomes

$$S_V = 4kTR_0 \left( \frac{1 - v + v^2/3}{1 - v/2} \right)^2 + \frac{aqIVR_0^2}{f^2(1 - v)^2}.$$  

(18)

From the experimentally observed frequency $f_c$, at which the $1/f$ noise and thermal noise contributions are equal we calculate $a$ values as a function of bias conditions for $v < 0.1$:

$$\alpha = \frac{4kTf_c}{\mu kv^2}.$$  

(19)

The equivalent input noise voltage $S_{V_{eq}}$ of a MOST is found by $S_{V_{eq}} = V_{eq}/g_m$, with $g_m$ the transconductance. This results in the following expression:

$$S_{V_{eq}}(f) = 4kTR_0 \left( 1 - v + v^2/3 \right)^2 + \frac{aqIV}{fC}.$$  

(20)

At saturation and $a$ independent of $V_G^*$, $S_{V_{eq}}(f)$ is of the form $A_1/V_G^* + BV_G^*$. From the point of view of signal-to-noise ratios $S_{V_{eq}}$ is the significant quantity. The gate voltage at which the thermal and $1/f$ noise contributions are equal for a frequency $f_c$ at saturation is given by

$$V_G^* = \left( \frac{4kTf_c^2}{\rho q} \right)^{1/2}.$$  

(21)

When $V/V_G^* \geq 1$, $v = 1$ in eqns (15), (16), (18), and (20).
4. CALCULATED DEPENDENCE OF THE NOISE PARAMETER \( \alpha \) ON \( V_G^* \)

For the \( \Delta N \) model \( \alpha \) is inversely proportional to \( V_G^* \) as can be seen from (13):

\[
\alpha = \frac{x_2 D_0 k T \theta}{x_2 C_{ox} V_G^*}, \tag{22}
\]

where \( C_{ox} \) is the gate oxide capacitance per unit area and \( k T \) is expressed in electron volts. \( \alpha \) vs \( V_G^* \) is presented in Fig. 1 for a MOST at 300 K with \( x_2/x_0 = 30, \ x_0 D_0 = 10^{10} \text{ cm}^{-2} \text{ eV}^{-1} \) and an oxide capacitance per unit area of \( 3.4 \times 10^{-8} \text{ F cm}^{-2} \) (SiO\(_2\) thickness of 1000 \( \text{ Å} \)). The curve indicated by \( \Delta N \) represents eqn (22), with the above-mentioned values for the parameters. At low \( V_G^* \), \( \Delta N^2 \) in (6), (8), and (11) must be replaced by \( N \) because the number of trapped electrons around the Fermi level becomes larger than the number of free electrons in the inversion layer. Under this condition \( \alpha \) levels off at lower \( V_G^* \). In the \( \Delta \mu \) model \( \alpha \) is independent of \( V_G^* \) if the mobility does not change with increasing \( V_G^* \). Owing to scattering mechanisms other than lattice scattering [16, 17], \( \alpha \) is given by (5). Mobility reduction at increasing \( V_G^* \) is due to increasing surface scattering and hot-electron effects. At low drain–source voltage the mobility in our samples is well described by

\[
\mu = \frac{\mu_0}{1 + \theta V_G^*}, \tag{23}
\]

where \( \theta \) is the mobility reduction factor, and \( \mu_0 \) the effective mobility at low \( V \) and \( V_G^* \) far below the mobility reduction regime. In Fig. 1, \( \alpha \) vs \( V_G^* \) in the \( \Delta \mu \) model is presented for \( \theta = 0 \) (V\(^{-1}\)) , \( \mu_0/\mu_1 = \frac{1}{2} \) and \( \alpha_1 = 10^{-3} \) (curve 2). Taking into account the thickness of the inversion layer, the concentration and mobility profile, as well as the decrease in the inversion-layer thickness with increasing \( V_G^* \), \( \alpha \) vs \( V_G^* \) was predicted for an experimentally observed \( \mu_1 \) and \( \theta \) [7]. The results are presented by curve 3 for \( \theta = 1/20 \) V\(^{-1}\), \( \mu_0/\mu_1 = \frac{1}{4} \) and \( \alpha_1 = 10^{-3} \). From the surface scattering model it was found that the effective mobility was of the form \( \mu = \mu_1/(1 + v/t) \), where \( v \) is a characteristic length, related to the mean free path of electrons, the oxide charge and the diffuse scattering at the interface [7].

The total inversion-layer thickness in this model is \( 4t \), with \( t \) the average distance of the carriers from the interface, being of the order of 100 A [7, 8]. From the model [7, 8] \( \alpha \) is calculated as \( v/t = (\mu_1/\mu_0 - 1) + \mu_1 \theta V_G^*/\mu_0 \), and \( \alpha \) is given in terms of \( v/t \) as

\[
\alpha = \frac{1 + v/t}{(1+v/2t)(1+v/3t)(1+v/4t)} \alpha_1. \tag{24}
\]

Only for \( \mu < 0.1 \mu_1, \alpha \propto \mu^2 \alpha V_G^* \). \( \Delta N \) model [23] taking into account hot-electron effects as the only source of mobility reduction results in \( \alpha = \alpha_1(1 + \theta V_G^*) \). The result is presented by curve 4 in Fig. 1. From Fig. 1 we see that \( \Delta \mu \) models result in an almost constant \( \alpha \) value for \( \theta \leq 1/20 \text{ V}^{-1} \), and \( 0.1 \text{ V} < V_G^* < 3 \text{ V} \), the \( \Delta N \) model resulting in \( \alpha \propto V_G^* \). 

5. EXPERIMENTAL RESULTS

The MOST and CCD were \( n \)-channel devices on \( \langle 100 \rangle \) Si with a substrate doping of \( N_s = 8 \times 10^{14} \text{ cm}^{-3} \). The gate oxide thickness was 1000 A, and polysilicon gates were used. Parameters concerning the geometry of the CCD are tabulated in Ref. [14]. The channel length of the MOSTs was 10 \( \mu \text{m} \) and the width 100 \( \mu \text{m} \).

The bias charge in CCD was varied over a range corresponding from \( 10^{10} \) to \( 5 \times 10^{11} \text{ cm}^{-2} \) \( (V_G^* \leq 2.4 \text{ V}) \), and a small modulation of less than \( 5 \times 10^9 \text{ cm}^{-2} \) was used to determine the small-signal charge transfer inefficiency (SCTI). Using the McWhorter model, excellent agreement between theory and SCTI experiments was obtained [14]. From the experimentally observed SCTI value \( x_{0Q} \text{ cm}^{-2} \text{ eV}^{-1} \) was calculated. The result for sample A was \( 1.6 \times 10^9 \text{ cm}^{-2} \text{ eV}^{-1} \), for B \( 4.8 \times 10^{10} \text{ cm}^{-2} \text{ eV}^{-1} \), and for C \( 2.2 \times 10^{10} \text{ cm}^{-2} \text{ eV}^{-1} \). By changing the bias charge for \( 0.05 \text{ V} < V_G^* < 2.4 \text{ V} \) no appreciable change in \( x_{0Q} \) was observed. This uniform oxide trap density was observed in the energy range of 0.3 eV to 0.2 eV below the bottom of the conduction band. In the same range of gate voltages the 1/f noise in the MOSTs has been measured in order to compare the results with the noise predicted by the models.

![Fig. 1. The calculated 1/f noise parameter \( \alpha \) vs the effective gate voltage \( V_G^* \). Curve 1: Number fluctuations, using eqn (22) with \( x_2/x_0 = 30, \ x_0 D_0 = 10^{10} \text{ cm}^{-2} \text{ eV}^{-1} \), \( C_{ox} = 3.4 \times 10^{-8} \text{ F cm}^{-2} \), and \( T = 300 \text{ K} \). Curve 2: Mobility fluctuations with \( \theta = 0 \) (V\(^{-1}\)) , \( \mu_0/\mu_1 = \frac{1}{2} \) and \( \alpha_1 = 10^{-3} \). Curve 3: \( \Delta \mu \) based on increasing surface scattering with \( V_G^* \). Equations (23) and (24) are used. Curve 4: \( \Delta \mu \) based on hot-electron effects from Ref. [23]. Curves 3 and 4 have been constructed for \( \theta = 1/20 \text{ V}^{-1} \), \( \mu_0/\mu_1 = \frac{1}{4} \).

\[
\text{Only for } \mu < 0.1 \mu_1, \frac{\alpha}{\mu^2} \propto V_G^* ^2.
\]
From earlier interpretations of $1/f$ noise in MOSTs in terms of the $\Delta \mu$ model it is known that there is a category of MOSTs that cannot be interpreted in this way[8]. Whether or not a given MOST belongs to this category can be seen from the conductance, $G$, as a function of the gate voltage $V_G^*$, observed at 77 K and 300 K. When $G$ vs $V_G^*$ at 77 K shows a maximum or a mobility degradation factor $\theta_\gamma$, larger than the value at room temperature, $\theta_{300}$, then a low-noise device can be expected with an $\alpha$ value that depends on $V_G^*$ as predicted by the $\Delta N$ model.

Figure 2 represents the observed $G$ vs $V_G^*$ at 300 K and 77 K. At 77 K a weak maximum is seen at $V_G^* = 20$ V which indicates a MOST of a category the noise of which can be interpreted in terms of the $\Delta N$ model[8]. The results of MOST B is presented in Fig. 2. In Fig. 3 the $R$ vs $1/V_G^*$ plot at the two temperatures shows how $\mu_0$ and $\theta$ can be obtained from the experimental results. From the $R$ vs $1/V_G^*$ plot $\mu_0$ is calculated as

$$\mu_0 = \frac{\frac{d}{dR} \frac{1}{W_{COX}}}{d(V_G^*)}.$$  \hspace{1cm} (25)

$\theta$ is given by

$$\theta = R_0 \frac{\frac{d}{dR} \frac{1}{V_G^*}}{dR},$$  \hspace{1cm} (26)

where $R_0$ is the extrapolated $R$ value in the $R$ vs $1/V_G^*$ plot for $V_G^* \to \infty$. The results presented in Fig. 3 are from MOST A. In the voltage range applied eqn (23) well describes the mobility degradation. The $\theta_\gamma$/$\theta_{300} > 1$ again indicates a $\Delta N$ noise MOST. The observed $\mu_0$, $\theta$, and $x_0D_0$ values for the MOSTs are presented in Table 1.

Figure 4 represents the spectral noise density in the source-drain voltage as a function of frequency. A constant drain source current was used and the MOSTs were biased in the ohmic region ($V = V_G^*$, $V$ $\to$ 0). No generation recombination noise was observed.

Figure 5 represents the normalized noise $fS_{V}^* / V^2$ as a function of the gate voltage and $R$ vs $V_G^*$. The main feature of these experimental results is the proportionality $fS_{V}^* / V^2 \propto V_G^*^{-2}$; furthermore, we found the following trend: the lower the $x_0D_0$, the lower the relative noise. Both trends are in agreement with the McWhorter model presented by eqn (12) or eqns (13) and (18). From SCTI measurements $x_0D_0$ is observed in the range of $3x_0$ to $6x_0$ from the SiO$_2$ interface[14]. The value $x_0D_0$ is found to be constant in the applied range of $V_G^*$.

For all MOSTs holds $R \propto 1/V_G^*$ for 0.1 V $< V_G^* < 1$ V, which indicates a negligible mobility reduction. The MOSTs B and C almost coincide in the $R$ vs $V_G^*$ plot of Fig. 5. This is due to the small difference in $\mu_0$ as can be seen from Table 1.

Figure 6 represents $\alpha$ vs $V_G^*$. The values were obtained from experimental results with the help of
The $x_0D_o$ values were obtained from SCTI measurements\cite{14}. The observed proportionality $\alpha \propto V_{tT}^{-1}$ cannot be explained by the refinements of the $\Delta \mu$ model of Fig. 1, curves 3 and 4. The observed mobility reduction factors at room temperature for all MOSTs are about $1/20$ V$^{-1}$ as can be seen from Table 1. The experimentally found $\alpha$ values agree well with the $\Delta N$ model predictions given by (13). The leveling off in the $\alpha$ vs $V_{tT}'$ plot for MOST C occurs at $N/WI = 2.1 \times 10^{10}$ cm$^{-2}$. That concentration is a factor 40 larger than the effective trap density $x_0D_o kT$. For even smaller values of $V_{tT}'$ eqn (11) for $\Delta N$ does not hold.

The details of the model describing the hot-electron effect on mobility and 1/f noise are irrelevant for the parameter $\gamma = f(S_v/V^2) R^2 V_{tT}'^3$ as was demonstrated in Ref. [23]. Therefore $\gamma$ was calculated from the experimentally observed spectra. The results are to be seen in Fig. 7. In the $\Delta \mu$ model $\gamma$ must be independent of $V_{tT}'$. The experimental results indicate that the $\Delta \mu$ model, even with the details of the hot-electron effect, cannot explain the results.

Figure 8 represents the equivalent input noise as a function of the experimentally found oxide trap density $x_0D_o$. The dotted line represents the predicted noise following (20) and (22) for the $\Delta N$ model with $v \rightarrow 0$. The dots have been obtained at a fixed $V_{tT}' = 1$ V. There is a quantitative agreement between the $\Delta N$ model and the experimental results.

Considering only 1/f noise we find from eqns (20) and (22) or (13) the following expression for the equivalent input noise voltage:

$$S_{v_{eq}} = \frac{q^2 kT x_0D_o(1 - v/2)}{C_{ox} (x_2/x_0) Wl f}.$$  \hspace{1cm} (27)

The correspondence between the expression for $fS_v$ used in this work, eqn (27), and the equivalent input noise derived by Van der Ziel\cite{11} is seen from the following. Van der Ziel showed that at $v \rightarrow 0$

$$S_{v_{eq}} = q^2 N_{ox}/C_{ox} Wl f.$$  \hspace{1cm} (28)

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**Table 1**

<table>
<thead>
<tr>
<th>MOST</th>
<th>$\mu_0$ (cm$^2$/Vs)</th>
<th>$\theta$ (V$^{-1}$)</th>
<th>$x_0D_o$ (cm$^{-2}$ eV$^{-1}$)</th>
<th>$\alpha$ at $V_{tT}' = 1$ V</th>
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<tbody>
<tr>
<td>A</td>
<td>950</td>
<td>0.054</td>
<td>1.6 x 10$^9$</td>
<td>1.8 x 10$^6$</td>
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<tr>
<td>R</td>
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<td>0.06</td>
<td>4.8 x 10$^9$</td>
<td>1.5 x 10$^5$</td>
</tr>
<tr>
<td>C</td>
<td>720</td>
<td>0.043</td>
<td>2.2 x 10$^{10}$</td>
<td>4.2 x 10$^5$</td>
</tr>
</tbody>
</table>

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Fig. 4. The experimentally observed spectral noise density $S_v$ between drain and source versus frequency for MOST C with $V_{tT}' = 2.6$ V, channel resistance $R = 1.65$ k$\Omega$ for $I = O(0)$ and $I = 78.8$ mA (○). The intersection between the dotted lines representing the thermal and 1/f noise is indicated by $f_c$ at 1.5 kHz.

Fig. 5. The normalized 1/f noise $fS_v/V^2$ vs $V_{tT}'$ and $R$ vs $V_{tT}'$ for the MOSTs A, B, C. The experimental $R$ vs $V_{tT}'$ results are indicated by □, ▽ and ■ for MOSTs A, B, C respectively. The arrows point to the right-hand $R$ scale. Similarly, the $fS_v/V^2$ vs $V_{tT}'$ results are presented by ○, △, ●.
holds, with \( N'_{ss} \) expressed in \( \text{cm}^{-2} \). The ratio \( \eta \) between \( N'_{ss} \) and the surface state density \( N_{ss} \) [\( \text{cm}^{-2} \text{eV}^{-1} \)] was estimated to be \( 10^{-4} - 10^{-3} \text{eV} \) [11, 24]. Using the ratio to describe \( fV'_{eq} \) in eqn (28) in terms of \( N_{ss} \), and equating the expression with (27) leads to

\[ x_0D_0 = \left( \frac{x_2}{x_0} \right) \eta N_{ss}/kT. \]  

(29)

From our charge-pumping experiments \( N_{ss} \) was found to be \( 2 \times 10^{10} \text{eV}^{-1} \text{cm}^{-2} \) for MOST B. This leads to \( \eta = 2 \times 10^{-4} \text{eV} \) if \( x_2/x_0 = 30 \) is used. This \( \eta \) value is well within the expected range.

6. CONCLUSIONS

The experimentally observed proportionality \( fV'_{eq}/V^2 \propto V'_G^{*2} \) in the range \( \theta V'_G^{*} < 1 \) cannot be explained by the \( \Delta \mu \) model. The experimentally determined \( \alpha \propto V'_G^{*-1} \) indicates a \( \Delta N \) noise source, eqn (13), because in the applied range of \( V'_G^{*} \), \( x_0D_0 \) was observed to be constant.

In the \( \Delta \mu \) model with hot-electron effects \( \gamma = (fV_{eq}/V^2)R^3V'_G^{*3} \) is independent of \( V'_G^{*} \). The experimentally observed dependence \( \gamma \propto V'_G^{*-1} \) is in disagreement with the \( \Delta \mu \) model with hot-electron effect.

From the agreement between the oxide trap density \( x_0D_0 \) [\( \text{cm}^{-2} \text{eV}^{-1} \)] obtained from independent measurements of macroscopic parameters like the small-signal charge transfer inefficiency (SCTI) and the \( 1/f \) noise we have strong arguments for the physical significance of the McWhorter model.

All the results were obtained from a category of MOSTs showing either (i) a weak maximum in the \( G \) vs \( V'_G^{*} \) plot at 77 K or (ii) a mobility reduction at 77 K, \( \theta_{77} > \theta_{300} \), the mobility reduction at room temperature. In Ref. [8] these were the so-called category IIb MOSTs. It seems that for this category of MOSTs the bulk \( 1/f \) noise based on \( \Delta \mu \) is lower than the \( 1/f \) noise component stemming from \( \Delta N \).

It remains unsolved why \( \Delta N \) noise can be expected for MOSTs showing a weak maximum in \( G \) vs \( V'_G^{*} \) at 77 K or with \( \theta_{77} > \theta_{300} \).

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6. CONCLUSIONS

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REFERENCES