



HAL
open science

Improved physics-based analysis to discriminate the flicker noise origin at very low temperature and drain voltage polarization

B Cretu, D. Boudier, E. Simoen, A. Veloso, N. Collaert, C. Claeys

► **To cite this version:**

B Cretu, D. Boudier, E. Simoen, A. Veloso, N. Collaert, et al.. Improved physics-based analysis to discriminate the flicker noise origin at very low temperature and drain voltage polarization. Solid-State Electronics, 2020, pp.107771. 10.1016/j.sse.2020.107771 . hal-02475438

HAL Id: hal-02475438

<https://hal.science/hal-02475438>

Submitted on 22 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Improved physics-based analysis to discriminate the flicker noise origin at very low temperature and drain voltage polarization

B. Cretu^{1,*}, D. Boudier¹, E. Simoen^{2,3}, A. Veloso², N. Collaert² and C. Claeys⁴

¹Normandie Univ, ENSICAEN, UNICAEN, CNRS, GREYC, 14000 Caen, France

²Imec Kapeldreef 75 B-3001 Leuven, Belgium

³Solid-State Physics Department, Ghent University, 9000 Gent, Belgium

⁴E.E. Dept. KU Leuven, Kasteelpark Arenberg 10, B-3001 Leuven, Belgium

*corresponding author: bogdan.cretu@ensicaen.fr

Abstract—Low frequency noise study is performed at deep cryogenic temperature of 10 K in p-channel gate-all-around (GAA) nanowire (NW) FETs. As expected, the carrier number fluctuations mechanism explains the flicker noise origin for conventional fixed applied drain bias.

At very low applied drain biases step-like effects impact the drain current transfer characteristics. Noise measurements performed at a fixed very low drain voltage as a function of the applied gate bias show that the gate voltage flicker noise behavior follows a $|I_{DS}|^{3/2}/g_m^2$ law. It was already proved that this dependency may be modeled considering classical transport theory, in the framework of the mobility fluctuations mechanism from Coulomb scattering interactions.

The noise measurements performed at fixed gate voltage as a function of the applied drain bias show that the gate voltage $1/f$ noise levels present a deviation from the $|I_{DS}|^{3/2}/g_m^2$ law. In order to explain this behavior, an improved model is proposed mainly considering some additional hypotheses: the inversion charge dependency on the applied drain bias and the fact that the impact of the drift component of the drain current may be neglected when measurements are made at low fixed gate voltage biases for very low applied drain voltages.

The results show that for the lower drain biases considered in this work, the flicker noise behavior may be explained using physical-based models derived from classical transport considerations for cryogenic temperatures by the mobility fluctuations mechanism originating from Coulomb scattering interactions. This may be surprising, and suggests that even if step-like effects impact the DC measurements, there is a polarization interval in which they do not impact the $1/f$ noise.

Index Terms—GAA NW FETs, low frequency noise, flicker noise, cryogenic temperature, mobility fluctuations, carrier number fluctuations

I. INTRODUCTION

The interest in very low temperature operation of CMOS devices and circuits is well known [1,2]. Additionally,

growing interest to use nanometric technologies to design and implement quantum computing control systems together with the qubits are evoked recently [3,4]. It is important to have a thorough insight in the carrier transport and in particular in the low frequency noise at these deep cryogenic temperatures.

An analytical expression for the drain current $1/f$ noise power spectral density S_{id} in strong inversion, taking into account the mobility fluctuations mechanism is reported in [5]. As this expression needs to estimate additional parameters in particular the threshold voltage (V_{th}) and the low-field mobility attenuation factor (θ_{it}), it works only from moderate to strong inversion operation. However, this expression cannot be used when step-like effects are present in the drain current transfer characteristic because the parameter estimation cannot be performed properly, in particular for V_{th} and θ_{it} . Concerning carrier number fluctuations, it is specified that the flat-band voltage noise fluctuations (S_{vfb}) are assumed to be constant with bias and so the general expression [6] should be still valid at very low temperature operation.

An original approach concerning the mobility fluctuations ($\delta\mu$) model and carrier number with correlated mobility fluctuations model ($\delta n + \delta\mu$) valid at very low temperature operation was proposed in [7]. It takes into account the mobility law that governs the carrier transport for temperatures lower than 40 K in classical transport considerations, i.e., the Coulomb scattering at low vertical fields and surface roughness at high vertical fields [8, 9]. However, this model is valid only in moderate inversion operation.

A more detailed analysis was made in [10] and the methodology presented in [7] is extended from weak to moderate inversion. Additional to the mobility law considered, assuming as usual that the inversion charge from weak to moderate inversion presents an exponential dependency with the applied drain bias, the expressions for the $\delta\mu$ and $\delta n + \delta\mu$ models developed from weak to moderate inversion operation are reminded in Table 1 (from Table 3 of [10]):

Table 1Summary of $\delta\mu$ and $\delta n + \delta\mu$ models as a function of I_{DS} and g_m

	weak to moderate inversion
$\delta n + \delta\mu$	$S_{v_{gs}} = S_{v_{rb}} \left[1 + c4_dn \left(\frac{I_D^{3/2}}{g_m} \right)^2 \right]$ (1)
$\delta\mu$	$S_{v_{gs}} = \frac{c6_d\mu}{f} \frac{I_{DS}^{3/2}}{g_m^2}$ (2)

where the $c4_dn$ and $c6_d\mu$ are constant coefficients defined in [10].

In this work, the $1/f$ noise behavior for p-channel GAA NW FETs is investigated at 10 K operation. To avoid misunderstanding, as p-channel devices are studied in this work, for all further equations, all applied voltages and current are presented in absolute value.

The presence of step-like effects is evidenced in the drain current and transconductance behavior with the applied gate voltage at fixed very low drain bias.

The methodology to extract the $1/f$ and Lorentzian noise parameters, developed in [11], is further described through a noise spectrum example. The evolution of the $1/f$ noise versus the applied gate voltage follows the $|I_{DS}|^{3/2}/g_m^2$ as in [10] (see (2) reminded here), suggesting that the mobility fluctuation mechanism dominates the $1/f$ noise. Moreover, this indicates that the $\delta\mu$ model proposed in [10] explains $1/f$ noise evolution with the applied gate voltage for both n- and p-type GAA NW FET channels, even if the devices are biased in operation conditions for which step-like behavior occurs in the transfer characteristics.

However, when the measurements are made as a function of the applied drain voltage at fixed low gate bias, the developed model in [10] cannot conveniently explain the $1/f$ noise magnitude behavior. This trend was already observed for n-type channel in [10].

Improved analysis is made and a novel model is constructed. The additional hypotheses compared to those considered in [10] are: the inversion charge dependency on the applied drain bias is taken into account using as usual a trapezoidal approximation; the impact of the drift component of the drain current may be neglected when measurements are made at fixed $|V_{GS}|$ if $|V_{DS}|$ is very low and $|V_{DS}| \ll |V_{GS}|$.

Finally, without any other assumptions on the origin of the step-like effect on the drain current, the proposed model explains the flicker noise behavior at very low applied drain voltages in the framework of mobility fluctuations. This surprising result suggests that the $1/f$ noise mechanism is different from the one responsible for the step-like behavior.

II. RESULTS AND DISCUSSION

Low frequency noise (LFN) measurements were performed at wafer-level on p-channel GAA NW FETs fabricated at imec on 300 mm wafers. The process description may be found in [12]. Details on the measurement set-up are given in [13]. The LFN study was focused at very low temperature

(i.e., 10 K) for a fixed gate length of 60 nm.

A. DC measurements, step-like transport evidence

From Fig. 1, it may be observed that the drain current normalized by the applied drain bias does not superpose for lower $|V_{DS}|$ values and presents step-like effects. The effect is more clearly represented in Fig. 2, showing the transconductance for two different drain biases. Using the method presented in [11], the conditions to observe quantum transport are fulfilled, i.e., a ΔE higher than the energy induced by the drain voltage ($q|V_{DS}|$) and higher than the thermal energy (about 862 μeV at 10 K). Indeed, from the minima of the oscillations in the transconductance behavior, the subband energy spacing ΔE between the successive energy subbands may be estimated [14-16]; it is found that the estimated ΔE is between 0.9 - 2 meV.

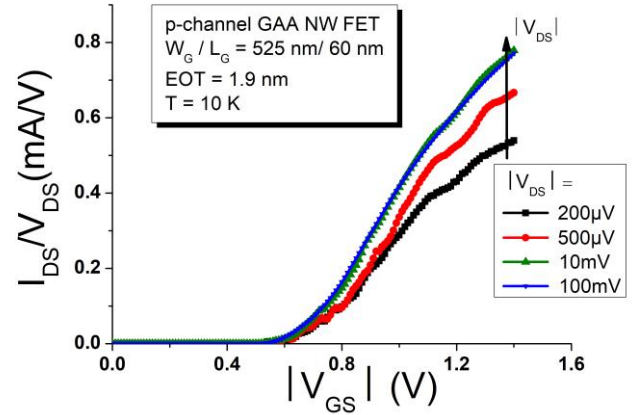


Fig. 1 Drain current normalized by the applied drain bias characteristic as a function of the applied gate voltage for different drain biases.

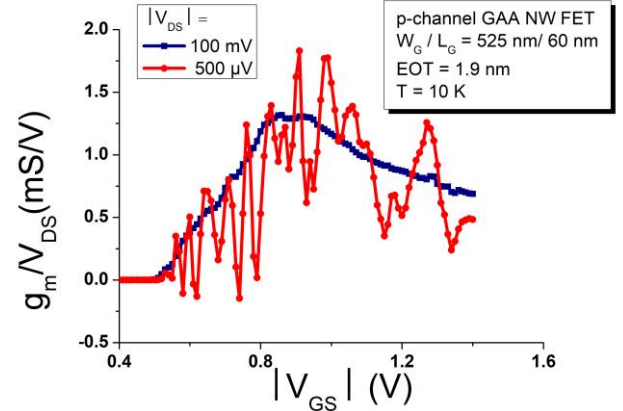


Fig. 2 Normalized transconductance as a function of the applied gate voltage from two different drain biases, i.e., $|V_{DS}| = 100$ mV and $500 \mu V$.

B. Low frequency noise measurements

Typical drain current noise power spectrum is shown in Fig. 3. In order to estimate the low frequency noise parameters, the same methodology presented in as in [7,10,11,13,15,16] is applied, assuming that the white noise, flicker noise and generation-recombination noise are non-correlated noise

sources. The LF noise is given by the general expression [13]:

$$S_{v_g}(f) = \frac{S_{id}}{g_m^2} = W_n + \frac{K_f}{f^\gamma} + \sum_{i=0}^N \frac{A_i}{1 + \left(\frac{f}{f_{oi}}\right)^2} \quad (3)$$

where S_{vg} is the input-referred voltage noise, W_n is related to the white noise level, K_f/f^γ gives the flicker noise with a frequency exponent γ , and the last term of the equation presents a sum of Lorentzian components, with A_i the plateau value and f_{oi} the characteristic frequency.

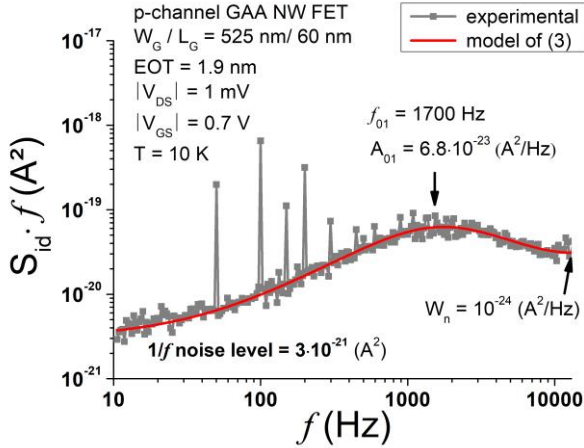


Fig. 3 Typical application of noise parameters estimation.

The estimated $1/f$ noise levels were made using the methodology detailed in [11]: the flicker noise level may be estimated considering the mean values of the $S_{v_g}(f) \cdot f$ at different frequencies f for which the white noise contribution may be neglected and $ff_{01} \ll 1$. If these conditions are fulfilled, the relative error of the K_f level estimation is less than about 15% considering frequencies lower than $f \leq 258$ Hz. Of course, if $ff_{01} \ll 1$ is no longer true, the method loses accuracy and the relative error increases. The measurement error is less than 10%. This strategy was used to estimate all the $1/f$ noise levels of the studied noise spectra.

Table 2

Estimation of K_f using a first order approximation of equation (1) (e.g.

$$S_{v_g}(f) \cdot f \approx K_f + A_1 \cdot f \quad (\text{i.e. (3) of [11]})$$

	$f(\text{Hz})$	$S_{v_g}(f) \cdot f$ (V ²)	$K_f(10^{-21} \text{V}^2)$	
1	12	$3.8 \cdot 10^{-21}$	2.9 (2&1)	2.93 (3&1)
2	20	$4.4 \cdot 10^{-21}$	3 (3&2)	3.02 (4&2)
3	30	$5.1 \cdot 10^{-21}$	3.1 (4&3)	3.14 (5&3)
4	80	$8.8 \cdot 10^{-21}$	3.4 (5&4)	3.4 (6&4)
5	258	$20.2 \cdot 10^{-21}$	3.6 (6&5)	4.3 (7&5)
6	410	$29.8 \cdot 10^{-21}$	6.08 (7&6)	
7	595	$40.5 \cdot 10^{-21}$		

In Fig. 4 the drain current behavior in the time domain representation corresponding to the noise power spectral

density represented in Fig. 3 is plotted. The observed RTS events seem to be randomly distributed and no clear correlation may be made with the Lorentzian contribution observed from the frequency domain representation. This suggests that the Lorentzian contribution observed in Fig. 3 is not related to an RTS event, but to a general generation – recombination mechanism.

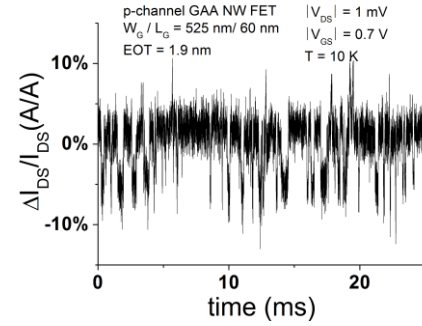


Fig. 4 Drain current versus time for $|V_{DS}| = 1$ mV and $|V_{GS}| = 0.7$ V. RTS switching may be observed but no clear correlation with the Lorentzian observed from the noise frequency domain representation can be made.

1) $1/f$ noise behavior versus $|V_{GS}|$ for a conventional applied drain bias ($|V_{DS}| = 50$ mV)

The estimated input referred gate voltage $1/f$ noise levels (K_{f_vg}) for a conventional applied drain voltage of $|V_{DS}| = 50$ mV are plotted in Fig. 5. One can note that K_{f_Vgs} is almost constant; suggesting that the carrier number fluctuations due to carrier trapping in the oxide layer prevails on the $1/f$ noise at this applied $|V_{DS}|$. This assumption is confirmed by the good agreement between the normalized drain current $1/f$ noise (K_{f_Sids}) and the $(g_m/I_{DS})^2$ ratio [6]. The flat-band noise S_{vfb} is estimated at about $0.9 \cdot 10^{-9} \text{V}^2/\text{Hz}$.

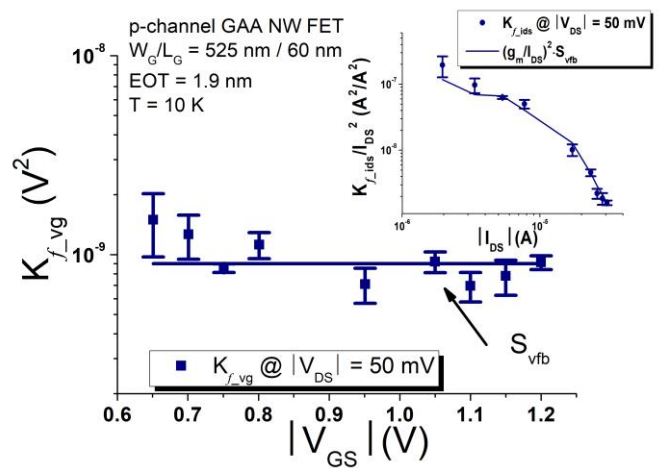


Fig. 5 Input referred $1/f$ noise levels as a function of the applied gate voltage at fixed $|V_{DS}|$ of -50 mV and at 10 K operation. In inset: normalized drain current noise versus the drain current.

2) $1/f$ noise behavior versus $|V_{GS}|$ at fixed low drain bias ($|V_{DS}| = 500 \mu\text{V}$)

The K_{f_vg} as a function of the applied gate voltage for a fixed applied $|V_{DS}|$ of $500 \mu\text{V}$ is represented in Fig. 6.

Using the model of (1) for carrier number correlated to mobility fluctuations ($\delta n + \delta \mu$) the K_{f_vg} behavior cannot be explained. However, for sufficiently high $|V_{GS}|$ (higher than about 0.8 V) the K_{f_vg} present little variations, which may suggest that the carrier number fluctuations may explain the $1/f$ level behavior. The estimated S_{vfb} is about $15 \cdot 10^{-9} \text{ V}^2/\text{Hz}$, in contradiction with the value estimated from measurements executed at a $|V_{DS}|$ of 50 mV .

However, for all applied $|V_{GS}|$, the experimental noise behavior is fully explained using the $\delta \mu$ model of (2). This result suggest that Coulomb scattering fluctuations dominate the flicker noise and explain the $1/f$ noise levels evolution with the applied gate voltage at very low applied drain bias, as in the case of n-type channel [10].

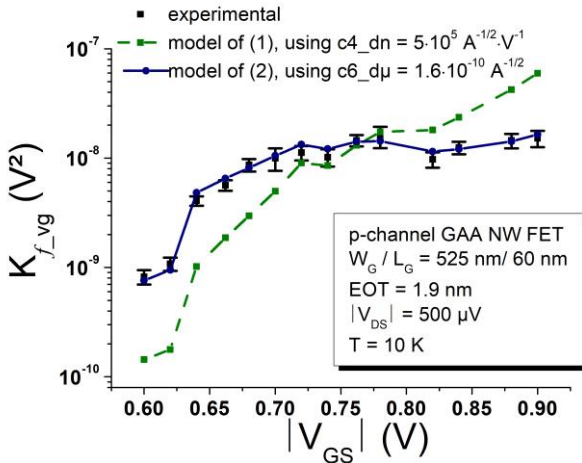


Fig. 6. Input referred $1/f$ noise levels as a function of the applied $|V_{GS}|$ at a fixed $|V_{DS}|$ of $500 \mu\text{V}$ and at 10 K operation. Good agreement between experimental data and the $\delta \mu$ model of (2) may be observed.

3) $1/f$ noise behavior versus $|V_{DS}|$ at a fixed gate bias ($|V_{GS}| = 0.7 \text{ V}$)

The estimated flicker noise levels as a function of the applied drain voltage at a fixed $|V_{GS}|$ of 0.7 V are plotted in Fig. 7.

The behavior of the K_{f_vg} level shows initially a slight increase with the increase of $|V_{DS}|$, followed by a quick decrease of about one decade with the further increase of the applied $|V_{DS}|$ in the range of about $3 \text{ mV} - 30 \text{ mV}$. For $|V_{DS}|$ higher than about $30 - 40 \text{ mV}$ up to 100 mV , the K_{f_vg} levels present a very slight increase.

From Fig. 7 it is obvious that the $\delta n + \delta \mu$ model of (1) is in disagreement with the experimental data. Assuming the carrier number fluctuations mechanism leads to consider a flat-band noise independent on the applied drain voltage at fixed $|V_{GS}|$. This implies that the behavior of the $1/f$ noise levels versus $|V_{DS}|$ presented in Fig. 7 cannot be explained in the

framework of the carrier number or mobility fluctuations correlated to number fluctuations mechanisms for all applied $|V_{DS}|$ range. However, for $|V_{DS}|$ higher than about 30 mV , a very slight increase of the K_{f_vg} levels around values of $1.8 - 2.6 \cdot 10^{-9} \text{ V}^2/\text{Hz}$ can be observed. These values are in the same range with the S_{vfb} obtained from measurements as a function of $|V_{GS}|$ at fixed $|V_{DS}|$ of 50 mV . This suggests that when measurements are made as a function of $|V_{DS}|$, for sufficiently high $|V_{DS}|$, (i.e. $>$ about $30 - 40 \text{ mV}$) the carrier number fluctuations can explain the $1/f$ noise.

The $\delta \mu$ model of equation (2) leads to a decrease of the $1/f$ noise with the increase of $|V_{DS}|$, but it cannot conveniently explain the $1/f$ noise behavior.

In order to explain the flicker noise evolution with the applied drain voltage for $|V_{DS}|$ lower than about $30 - 40 \text{ mV}$, a novel physical-based model is constructed in the next section.

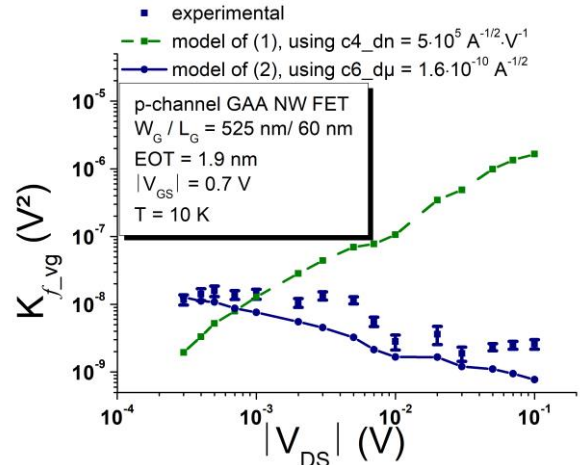


Fig. 7. Input referred $1/f$ noise levels as a function of the applied $|V_{DS}|$ bias at a fixed $|V_{GS}|$ of 0.7 V and at 10 K operation. To construct models of (1) and (2), the same noise parameters as obtained from measurements as a function of the applied gate voltage at fixed $|V_{DS}|$ of $500 \mu\text{V}$ were used. The model of (1) is definitively not in agreement with the data; the model of (2) even if it seems to reproduce the same tendencies cannot conveniently explain the flicker noise behavior.

III. THEORETICAL APPROACH

A. Inversion charge

In a general manner, because the barrier of the electrons seen at the drain is $|V_{DS}|$ larger than the barrier at the source, one can write [17]:

$$n(L) = n(0) \exp\left(\frac{-q|V_{DS}|}{k_B T}\right) \quad (4)$$

where $n(L)$ and $n(0)$ represent the charge density close to the drain, and close to the source, respectively. k_B is the Boltzmann constant, T is the temperature and q is the

elementary charge.

Considering as usual a trapezoidal approximation (as for (1.3.23) of [18]), one can write:

$$Q_i = \frac{qN_s}{WL} = \frac{n(0) + n(L)}{2} = \frac{n(0)}{2} \left[1 + \exp\left(\frac{-q|V_{DS}|}{k_B T}\right) \right] \quad (5)$$

where Q_i is the inversion charge density at arbitrary $|V_{GS}|$ and N_s is the total free carrier number.

B. Total free carrier number

Considering a source referenced model, the drain current for a transistor with effective channel gate width W and length L may be written as (e.g. (4.3.5) of [18]):

$$|I_{DS}| = \frac{W}{L} \frac{k_B T}{q} \mu_{eff} [n(0) - n(L)] + \mu_{eff} W |Q_i| \frac{\partial \Psi_s}{\partial x} \quad (6)$$

where μ_{eff} is the effective mobility, ψ_s is the surface potential and x represent the position in the channel measured from the source end. The first term of (6) represents the diffusion component of the drain current, while the second term the drift one, respectively.

It may be assumed that when measurements are made at a fixed applied gate voltage and for very low applied $|V_{DS}|$, respecting also that $|V_{DS}| \ll |V_{GS}|$ the drift component may be neglected (i.e. $\partial \Psi_s / \partial x \approx 0$).

Considering this hypothesis, (6) becomes:

$$|I_{DS}| = \frac{W}{L} \frac{k_B T}{q} \mu_{eff} [n(0) - n(L)] \quad (7)$$

For temperatures lower than 40 K the effective mobility μ_{eff} may be expressed by [8, 9]:

$$\mu_{eff} = \frac{2\mu_m}{\frac{Q_i}{Q_m} + \frac{Q_m}{Q_i}} \quad (8)$$

where μ_m is the maximum of the effective mobility and Q_m is the corresponding inversion charge density. This expression represents a simplified description of the scattering law including Coulomb and surface roughness scattering processes [9].

It can be easily demonstrated that in weak to moderate inversion when the approximation $Q_i < Q_m$ may be considered, the effective mobility will read:

$$\mu_{eff} = 2\mu_m \frac{Q_i}{Q_m} \quad (9)$$

Assuming (6) and (9), the drain current expressed in (7) can be derived as:

$$|I_{DS}| = \frac{W}{L} \frac{k_B T}{q} \frac{2\mu_m}{Q_m} Q_i n(0) \left[1 - \exp\left(\frac{-q|V_{DS}|}{k_B T}\right) \right] \quad (10)$$

Finally from (10) and (5) one obtains:

$$|I_{DS}| = \frac{W}{L} \frac{k_B T}{q} \frac{\mu_m}{Q_m} q^2 \frac{N(0)^2}{(WL)^2} \left[1 - \exp\left(\frac{-2q|V_{DS}|}{k_B T}\right) \right] \quad (11)$$

where $N(0)$ represent the number of free carriers at the source.

From (11) and (5) one can obtain the expression for the total free carrier number:

$$N_s = \frac{WL}{2q} \sqrt{\frac{\frac{LQ_m}{W\mu_m} \frac{q}{k_B T}}{\left[1 - \exp\left(\frac{-2q|V_{DS}|}{k_B T}\right) \right]}} \left[1 + \exp\left(\frac{-q|V_{DS}|}{k_B T}\right) \right] \sqrt{|I_{DS}|} \quad (12)$$

C. 1/f noise improved equations

Considering only the inversion charge correction, the carrier mobility fluctuations mechanism ($\delta\mu$) [19] reads using (5) in (2):

$$S_{v_{gs}} = \frac{c6-d\mu}{f} \frac{I_{DS}^{3/2}}{g_m^2} \frac{2}{\left[1 + \exp\left(\frac{-q|V_{DS}|}{k_B T}\right) \right]} \quad (13)$$

Considering (12), $\delta\mu$ fluctuations in the empirical law of Hooge [19] can be derived as:

$$\frac{S_{i_d}}{I_{DS}^2} = \frac{2\alpha_H q}{fWL\sqrt{|I_{DS}|}} \sqrt{\frac{W\mu_m}{LQ_m} \frac{k_B T}{q} \frac{1 - \exp\left(\frac{-qV_{DS}}{k_B T}\right)}{1 + \exp\left(\frac{-qV_{DS}}{k_B T}\right)}} \quad (14)$$

$$S_{v_{gs}} = \frac{S_{i_d}}{g_m^2} = \frac{const - \delta\mu}{f} \sqrt{\frac{1 - \exp\left(\frac{-qV_{DS}}{k_B T}\right)}{1 + \exp\left(\frac{-qV_{DS}}{k_B T}\right)}} \frac{|I_{DS}|^{3/2}}{g_m^2}$$

Using (5) and (9) the carrier number with correlated mobility fluctuations model ($\delta n + \delta\mu$) [5,6] can be expressed as:

$$S_{i_d} = g_m^2 S_{v_{gs}} \left[1 + \alpha_C C_{ox} \sqrt{\frac{L\mu_m}{WQ_m} \frac{q}{k_B T} \frac{1 + \exp\left(\frac{-q|V_{DS}|}{k_B T}\right)}{1 - \exp\left(\frac{-q|V_{DS}|}{k_B T}\right)}} \frac{|I_D|^{3/2}}{g_m} \right]^2 \quad (15)$$

Equations (14) and (15), combined with those expressed in Table 1 with respect of (5), will allow to have a complete equation based methodology in order to correctly identify the flicker noise origin at very low temperature from weak to moderate inversion, even in conditions in which the drift component of the drain current may be neglected, i.e. at very low applied drain voltages.

IV. DISCUSSION

The inversion charge given by (5) will not affect the interpretation of the experimental data if the measurements are made at fixed $|V_{DS}|$. The advantage of using (5) is that it permits to take into account the impact of the applied drain voltage when the measurements are made as a function of $|V_{DS}|$ at fixed applied $|V_{GS}|$.

Using (13) for measurements as a function of $|V_{GS}|$ will lead to a $c6_d\mu_corr$ given by :

$$c6_d\mu_corr = \frac{2 \cdot c6_d\mu}{1 + \exp\left(\frac{-q|V_{DS}|}{k_B T}\right)} \quad (16)$$

As $|V_{DS}|$ is fixed at 500 μV , a value of $c6_d\mu_corr$ of about $1.25 \cdot 10^{-10} \text{ A}^{-1/2}$ is obtained. The results by using this value in Eq. (11) for measurements as a function of $|V_{DS}|$ are plotted in Fig. 8. A reasonable agreement may be observed between the model and the data in 10-30 mV $|V_{DS}|$ range. However, the trend provided by the model using (13) for $|V_{DS}|$ lower than 10 mV does not agree well with the experimental data.

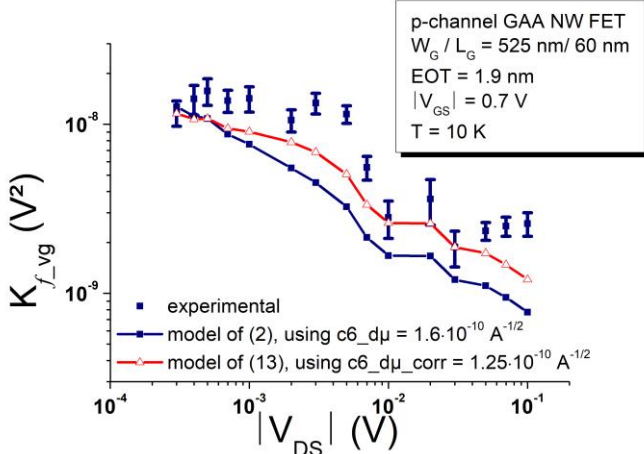


Fig. 8. Input referred $1/f$ noise levels as a function of the applied $|V_{DS}|$ bias at fixed $|V_{GS}|$ of 0.7 V and at 10 K operation.

A good agreement between the model of (14) and the data can be observed in Fig. 9 in particular for $|V_{DS}|$ lower than about 20 mV, namely in polarization conditions for which the hypotheses assumed in (14) apply. For much higher $|V_{DS}|$ the impact of the applied drain voltage on the surface potential may play a role. As the model of (13) which considers the drift component of the drain current is in agreement with data in the

10 -30 mV $|V_{DS}|$ range, all this suggests that the mobility fluctuations are responsible for the $1/f$ noise behavior for $|V_{DS}|$ lower than about 30 mV -40 mV.

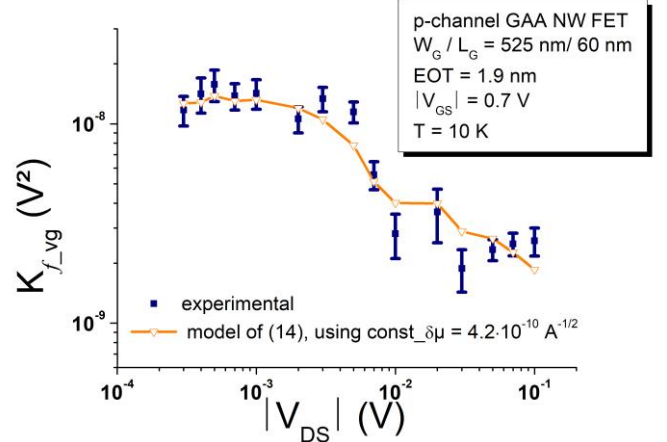


Fig. 9. Input referred $1/f$ noise levels as a function of the applied $|V_{DS}|$ bias at fixed $|V_{GS}|$ of 0.7 V and at 10 K operation. For $|V_{DS}|$ lower than about 10 mV, good agreement between experimental data and the $\delta\mu$ model of (12) may be observed.

Taking into account the results from noise measurements as a function of the applied gate voltage for $|V_{DS}| = 500 \mu\text{V}$, it may be suggested that the mobility fluctuations through the Coulomb scattering mechanism may explain the $1/f$ noise evolution at very low applied $|V_{DS}|$, while for $|V_{DS}|$ higher than about 30 - 40 mV the carrier number fluctuations will prevail.

In Fig. 10, it may be observed that the developed model explains also the behavior of $1/f$ noise levels as a function of the applied drain bias at fixed gate voltage for the n-type channel.

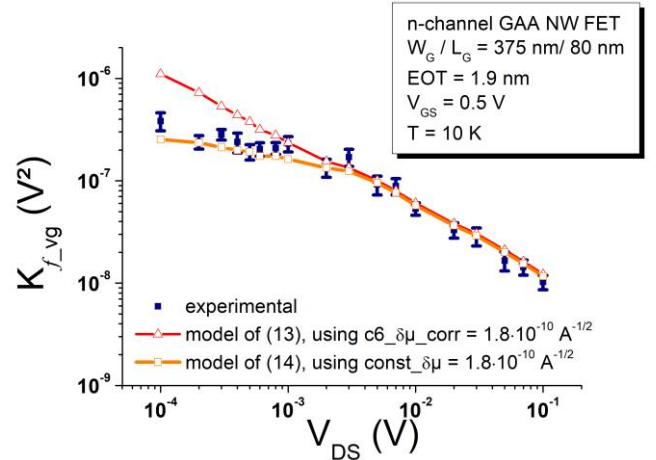


Fig. 10. Input referred $1/f$ noise levels as a function of the applied drain bias at fixed V_{GS} of 0.5 V and at 10 K operation for a n-channel device.

No additional mobility mechanism was considered in the mobility law for the constructed $1/f$ noise models of (14) and (15). The agreement between the developed model (i.e. (14)) and the results from n-type and p-type channel devices suggests that at this deep cryogenic temperature and in the low polarization range investigated the $1/f$ noise behavior could be

interpreted through mobility fluctuations using equations derived from classical carrier transport considerations.

The drain current and the transconductance oscillations behavior with the applied gate voltage at very low applied drain biases and temperature clearly present step-like effects (Figs. 1 and 2, as in [7, 10]). This presumes the impact of an additional mobility mechanism than considered in the low frequency noise models developed in [7,10] and here, e.g. inter/intra subband scattering mechanisms. However, to assume an additional mobility mechanism influencing the $1/f$ noise models is in disagreement with the results presented here and in [7, 10], because in this case the gate voltage flicker noise behavior will not follow a $|I_{DS}|^{3/2}/g_m^2$ law. This suggests that the responsible transport mechanism for $1/f$ noise and for the step-like current behavior observed may have different origins. Moreover, the RTS observed in Fig. 4 firstly suggests that the $1/f$ noise should be related to carrier trapping/detrapping. This hypothesis is contradicted by the experimental evolution of the flicker noise with a $|I_{DS}|^{3/2}/g_m^2$ law, which is related to the mobility fluctuation mechanism. This hypothesis may corroborate with results of [20]: the RTS noise may be generated by the atomic movement of a defect in SiO₂ giving rise to a change in the fixed charge position and could give mobility fluctuations without carrier trapping. A summation of such RTSs will also give rise to $1/f$ noise, not related to carrier number fluctuation but associated with a change in scattering (on a slow time scale by the atomic displacements) and, hence, with mobility fluctuations.

V. CONCLUSION

It was found that for conventional applied drain voltages (i.e. higher than about 30 – 40 mV) the carrier number fluctuations always explain the flicker noise behavior.

An original theoretical approach is constructed, leading to improved expressions which demonstrates that the experimental flicker noise behavior may be completely explained through the Coulomb scattering mechanism at very low drain biases, suggesting that in the investigated polarization interval, the $1/f$ noise mechanism may have a different origin than for the step-like behaviors observed in the drain current transfer characteristics.

The proposed model leads to a full diagnostic tool from weak to moderate inversion in order to discriminate the origin of the $1/f$ noise for temperatures lower than 40 K and at very low drain bias operation if no step-like effects occur.

ACKNOWLEDGMENT

This work was accomplished in the framework of a collaboration agreement between imec and GREYC. The devices have been processed in the frame of imec's Core Partner Program on Nanowire Logic Devices.

REFERENCES

[1] F. Balestra and G. Ghibaudo, "Device and circuit cryogenic operation for low temperature electronics," Kluwer Academic Publishers, 2001, pp. 3-35, DOI: 10.1007/978-1-4757-3318-1.

[2] E. Simoen, B. Dierickx, L. Warmerdam, J. Vermeiren, and C. Claeys, "Freeze-out effects on NMOS transistors characteristics at 4.2K," *IEEE Trans. Electron Dev.*, vol. ED-36, no. 6, pp. 1155-1161, Jun. 1989, DOI: 10.1109/16.24362.

[3] D. J. Reilly, "Engineering the quantum-classical interface of solid-state qubits," *npj Quantum Inf.*, vol. 1, Oct. 2015, Art. no. 15011

[4] E. Charbon, F. Sebastiano, A. Vladimirescu, H. Homulle, S. Visser, L. Song, and R. M. Incandela, "Cryo-CMOS for quantum computing," in 2016 IEEE International Electron Devices Meeting (IEDM), pp. 13.5.1–13.5.4, 2016, DOI: 10.1109/IEDM.2016.7838410.

[5] I.M. Hafez, G. Ghibaudo, and F. Balestra, "Flicker noise in MOS transistors operated at room and liquid helium temperatures," *Superlattices and Microstructures*, vol. 8, no. 1, pp. 101-104, 1990, DOI: 10.1016/0749-6036(90)90284-E

[6] G. Ghibaudo, O. Roux, Ch. Nguyen-Duc, F. Balestra, and J. Brini, "Improved analysis of low frequency noise in field-effect MOS transistors," *Phys. Stat. Sol. (a)*, vol. 124, no. 2, pp. 571-581, 1991, DOI: 10.1002/pssa.2211240225.

[7] B. Nafaa, B. Cretu, N. Ismail, O. Touayar, R. Carin, E. Simoen, and A. Veloso, "Low-frequency noise measurements at liquid helium temperature operation in ultra-thin buried oxide transistors – Physical interpretation of transport phenomena," *Solid-State Electron.*, vol. 150, pp. 1-7, 2018, DOI: 10.1016/j.sse.2018.08.010.

[8] G. Ghibaudo and F. Balestra, "Modelling of ohmic MOSFET operation at very low temperature," *Solid-State Electron.*, vol. 31, no. 1, pp. 105-108, 1988, DOI: 10.1016/0038-1101(88)90092-5.

[9] D. Jeon and D. Burk, "MOSFET electron inversion layer mobilities- A physically based semi-empirical model for a wide temperature range," *IEEE Trans. Electron Dev.*, vol. ED - 36, no. 2, pp. 1456-1463, 1989, DOI: 10.1109/16.30959.

[10] D. Boudier, B. Cretu, E. Simoen, A. Vesloso, and C. Claeys, "Discussion of the flicker noise origin at very low temperature and polarisation operation," 2019 International Conference on Noise and Fluctuations (ICNF'2019), pp. 45-48, 2019.

[11] D. Boudier, B. Cretu, G. Hellings, T. Schram, H. Mertens and D. Linten, "Low frequency noise analysis on Si/SiGe superlattice I/O n-channel FinFETs," accepted in *Solid-State Electron.*

[12] A. Veloso, M.J. Cho, E. Simoen, G. Hellings, P. Matagne, N. Colaert, and A. Thean, "Gate-all-around nanowire FETs vs. triple-gate FinFETs: on gate integrity and device characteristics," *ECS Trans.*, vol. 72 (2), pp. 85-95, 2016, DOI: 10.1149/07202.008Secst.

[13] D. Boudier, B. Cretu, E. Simoen, R. Carin, A. Veloso, N. Collaert, and A. Thean, "Low frequency noise assessment in n- and p-channel sub-10 nm triple-gate FinFETs: Part I: Theory and methodology," *Solid-State Electron.*, vol. 128, pp. 102-108, 2017, DOI: 10.1016/j.sse.2016.10.012.

[14] K. Morimoto, Y. Hirai, K. Yuki, and K. Morita, "Fabrication and transport properties of silicon quantum wire gate-all-around transistor," *Jpn. J. Appl. Phys.*, vol. 35, pp. 853-857, 1996, DOI: 10.1143/JJAP.35.853

[15] D. Boudier, B. Cretu, E. Simoen, A. Veloso, and N. Collaert, "Detailed characterisation of Si Gate-All-Around Nanowire MOSFETs at cryogenic temperatures," *Solid-State Electron.*, vol. 143, pp. 27-32, 2018, DOI: 10.1016/j.sse.2018.02.015.

[16] D. Boudier, B. Cretu, E. Simoen, A. Veloso, and N. Collaert, "Discussion on the $1/f$ noise behavior in Si gate-all-around nanowire MOSFETs at liquid helium temperatures," In *Proc. 2018 Joint International EUROSIOI Workshop and International Conference on Ultimate Integration on Silicon (EUROSIOI-ULIS)*, pp. 1-4, 2018, DOI: 10.1109/ULIS.2018.8354739.

[17] T. Grotjohn and B. Hoefflinger, "A parametric short-channel MOS transistor model for subthreshold and strong inversion current," *IEEE Trans. Electron Dev.*, vol. ED-31, no. 2, pp. 234-246, Feb. 1984, DOI: 10.1109/T-ED.1984.21507.

[18] Y. Tsididis, "Operation and modelling of the metal-oxide semiconductor transistor", Boston, MA : McGraw-Hill, 1998, ISBN: 0070655235

[19] F. Hooge, "1/f is no surface effect," *Phys. Lett. A*, vol. 29, no. 3, pp. 139-140, April 1969, DOI: 10.1016/0375-9601(69)90076-0.

[20] D.H. Cobden and M.J. Uren, "Random telegraph signals from liquid helium to room temperature", *Microelectronic Engineering*, vol. 22, no. 1-4, pp. 163-170, 1993, DOI: 10.1016/0167-9317(93)90150-4.