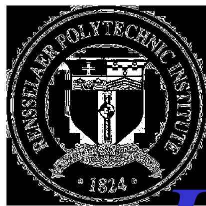

Low Frequency Noise in GaN-Based HFETs, MOSHFETs, MESFETs and MOSFETs

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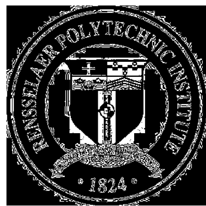


Talk outline

Introduction

Low frequency noise in GaN

Low Frequency Noise in GaN HFETs, MOSHFETs

Generation-recombination and 1/f noise

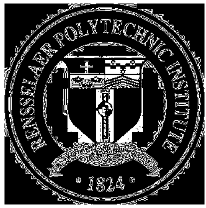
Noise from the channel, surface or contacts

The role of the gate leakage current

Low Frequency Noise in GaN *MESFETs and MOSFETs*

Role of contacts

Possible origin of noise?



Introduction: Noise Mechanisms

S_I (A^2/Hz)

1/f noise

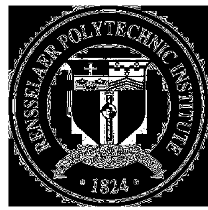
generation-recombination noise

Nyquist noise
$S_I = 4kT/R$

Shot noise
$S_I = 2eI$

10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}

10^{-1} 10^{1} 10^{3} 10^{5}



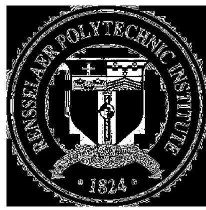
What is the reason to study the low frequency noise in semiconductors and semiconductor devices?

The higher is the working frequency, the more important is the level of the low-frequency noise.

Low frequency noise poses a lower limit of signal level in the broad-band circuits.

A possible control parameter for steps in technological cycle of the semiconductor device production.

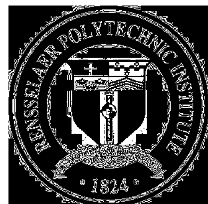
Reliability predictor.



More reasons

Low frequency noise is a very sensitive tool to study contact phenomena, surface properties, defect migration, volume and surface degradation processes, stability and reliability of the devices.

Studies of the generation-recombination noise might allow us to identify local defects with low concentrations and high capture cross sections.



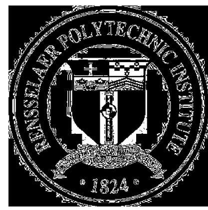
Low frequency Noise in GaN and GaN-based devices

generation-recombination +1/f noise

$$\alpha = \frac{S_I}{I^2} fN$$

First publications - α=1 - 10^{-2}

Recent results α= 10^{-5} - 10^{-3}



References (G-R noise)

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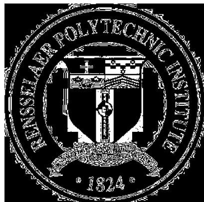


Noise spectra

Sp1, Sp2, Sp3 - sapphire substate

Sc1- SiC substrate

S_i/I^2, dB/Hz

-60
-70
-80
-90
-100
-110
-120
-130
-140
-150

10^0 10^1 10^2 10^3 10^4 10^5

Frequency f, Hz

Sp3

Sp2

1/f

Sp1

SC1

Hooge Parameter α

10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

GaN HFET
on Sapphire [8-9]

GaN[7]

GaAs[1-2]

Si [1-2]

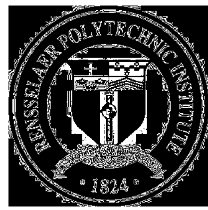
SiC [3-4]

GaAs
HEMTs [5]

GaN
HFET
on SiC [9]

GaN
MOS-HFET [10]

Si
NMOS [6]



Hooge Parameter References

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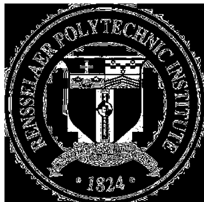
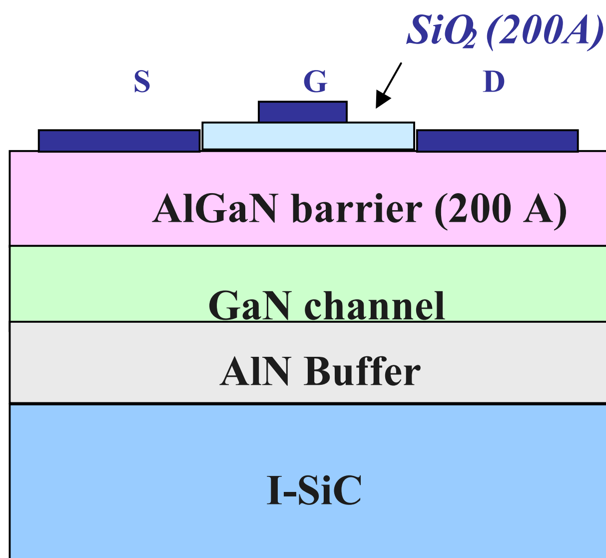
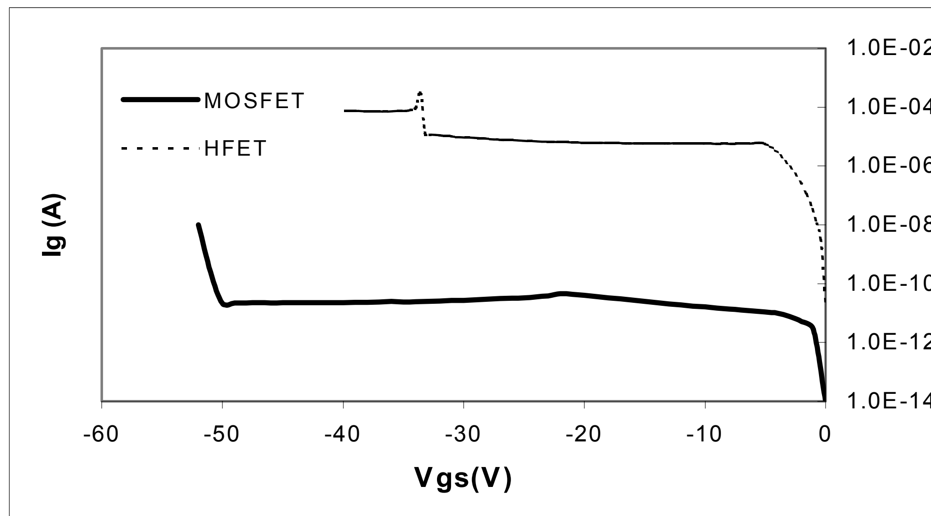


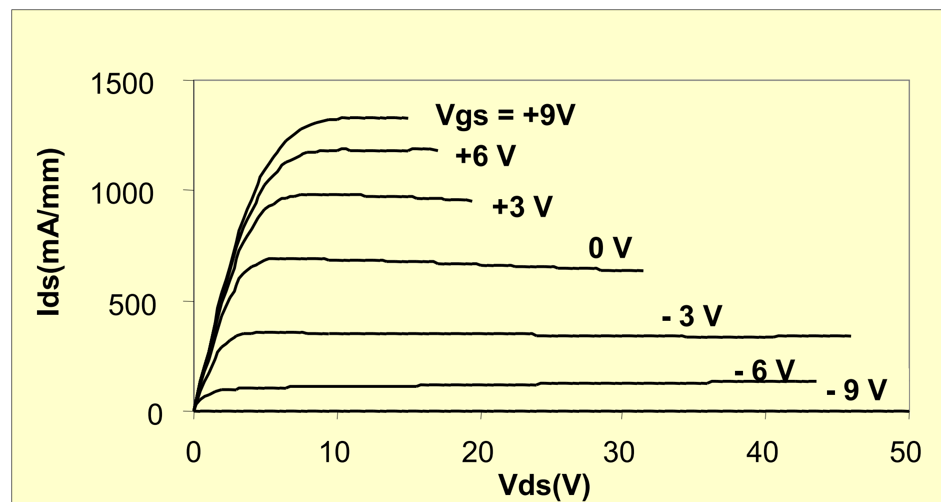
SiO_2/AlGaN/GaN Devices (MOS-HFET)

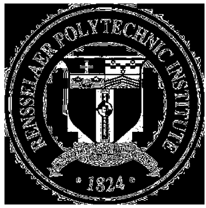




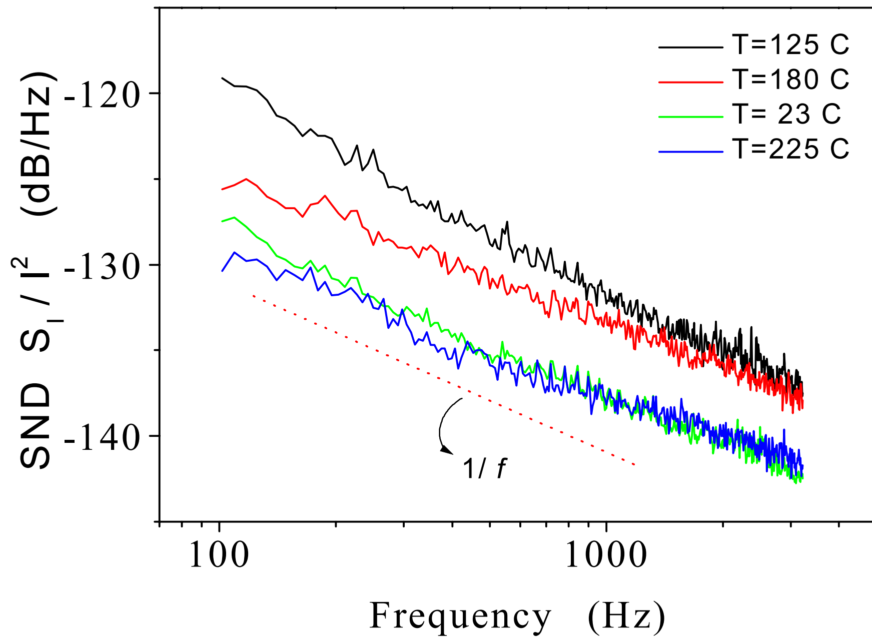
Low Gate leakage

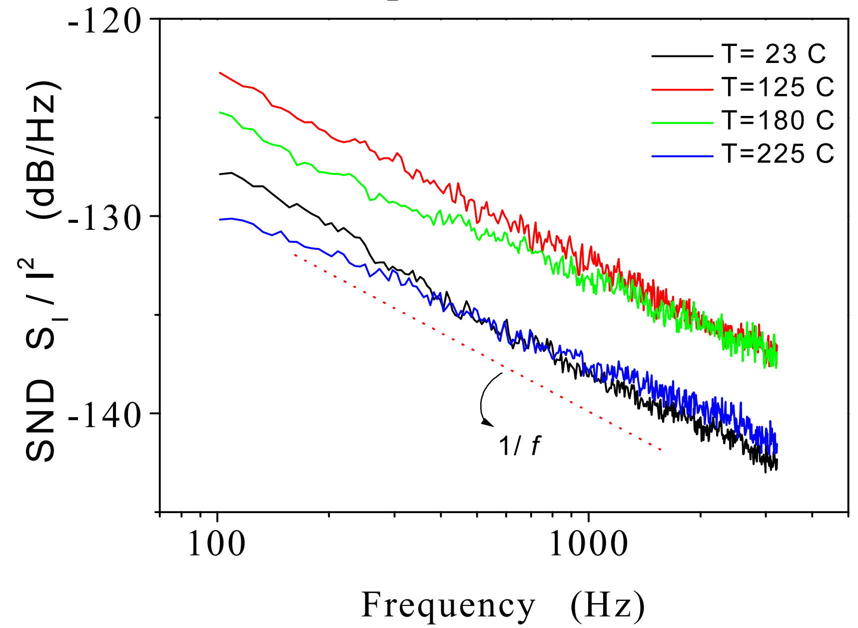
Higher Channel current

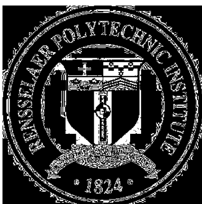




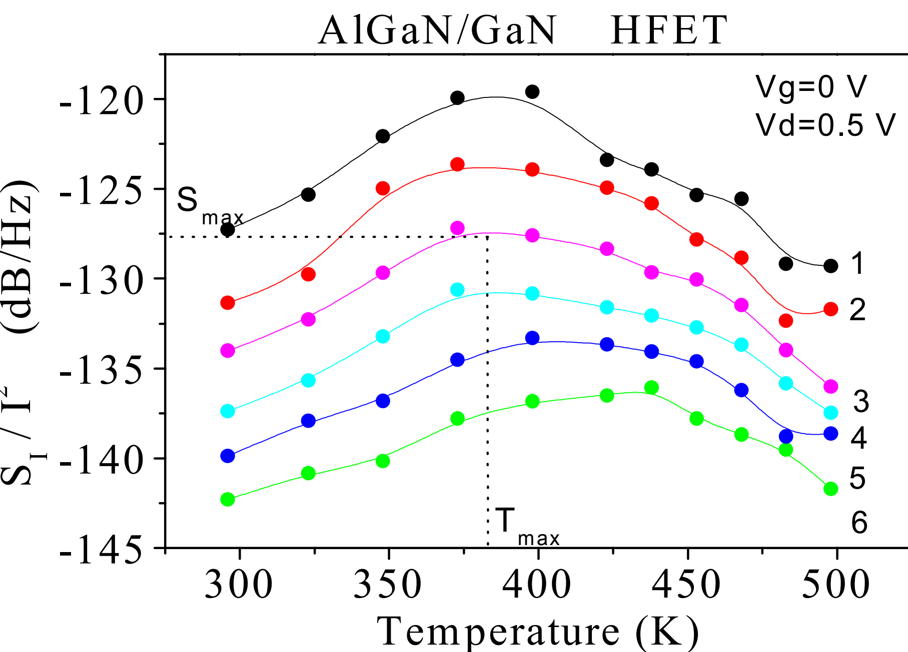
Noise spectra (1/f)

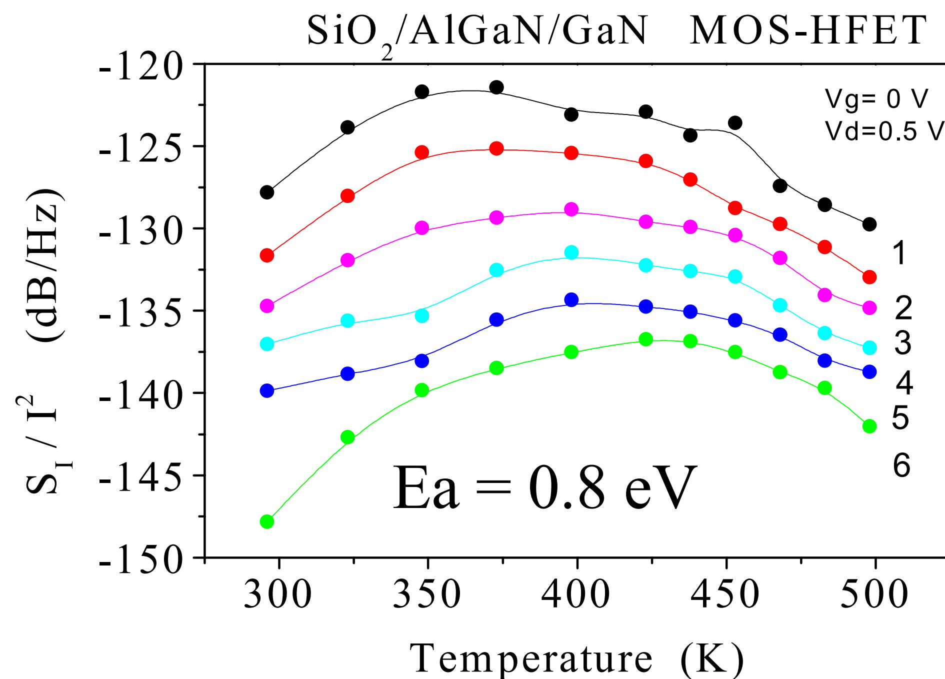






Temperature dependencies noise density for AlGaN/GaN HFETs and MOS-HFETs

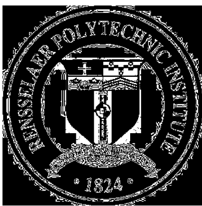




Frequency *f* (Hz): 1 - 110, 2 - 200, 3 - 400, 4 - 800, 5 - 1600, 6 - 3200 Hz.

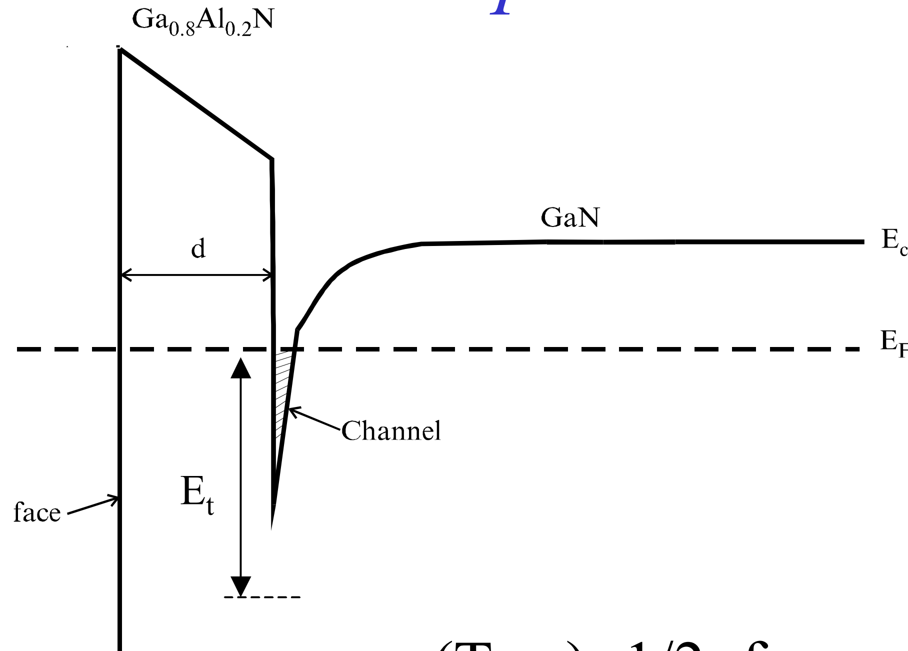
☛Such *S(T)* dependencies are typical for the noise from local levels

$\tau(T_{max})=1/2\pi f$ Same activation energies!



What is the origin of the GR noise?

G-R process in the channel???



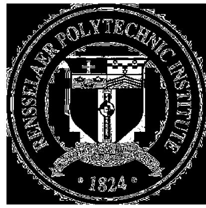
$$\frac{S_I}{I^2} = \frac{4N_{ts}}{L_0 W n_s^2} \frac{\tau F(1-F)}{1+(\omega\tau)^2}$$

N_{ts} :the trap sheet concentration,
L_0 channel length
W : channel width
n_s is the electron sheet concentration,
$\omega = 2\pi f$ is the circular frequency,
$\tau = \tau_c F$ is the time constant associated with return to equilibrium of the occupation of the level,
F : Fermi - Dirac occupancy function,
τ_c :the capture time constant

$$\tau(T_{max}) = 1/2\pi f$$

$$\tau = \tau_c$$

$$\tau_c = \frac{1}{\sigma n_s v_F}$$



What is the origin of the noise?

$$\sigma \cong \frac{1}{\tau n_s v_F}$$

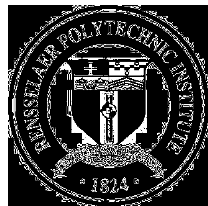
No! Not channel!

- For $f = 400$ Hz ($\tau = 1/2\pi f = 8 \times 10^{-4}$ s^{-1}), and for
- $n_s = 1.2\times10^{13}$ cm^{-2},

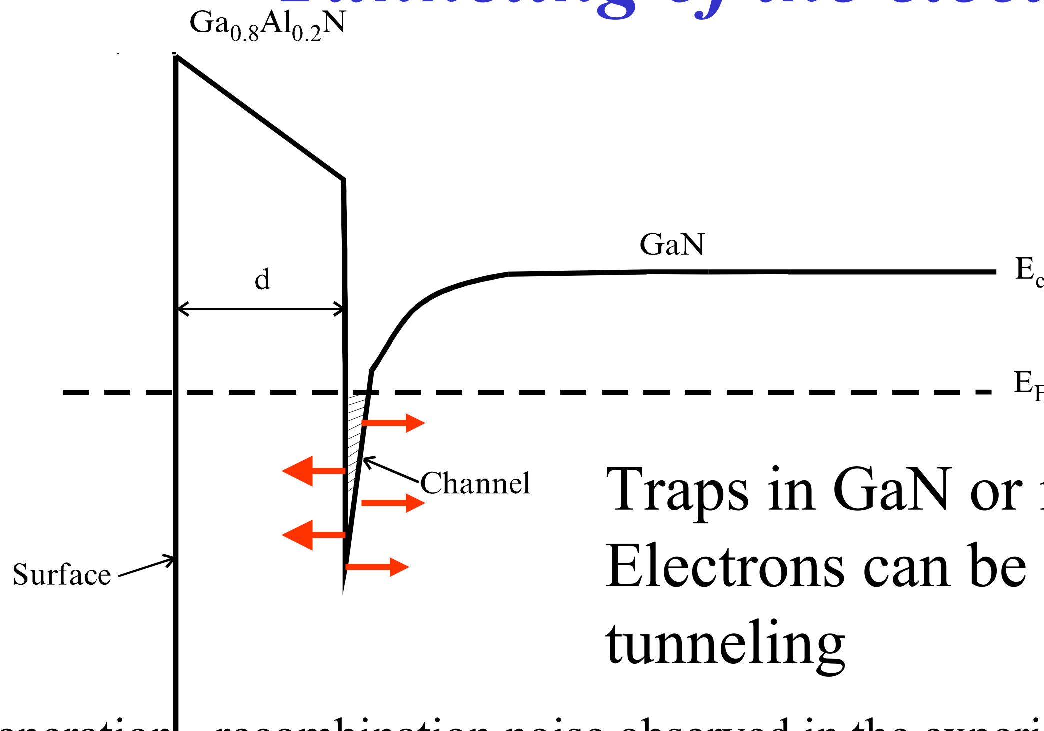
- $\sigma \approx 3\times10^{-18}$ cm ($T = T_{max} \approx 380$ K)

- This value of the capture cross section is *too small to be realistic*.

For degenerate 2D gas the source of low frequency generation-recombination noise, with any activation energy, cannot be located directly in the 2D channel.



What is the origin of the G-R noise? Tunneling of the electrons?

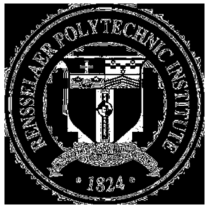


No!!

Traps in GaN or in AlGaN. Electrons can be captured via tunneling

The generation - recombination noise observed in the experiments cannot also be explained by the tunneling of electrons from the 2D gas to GaN or AlGaN, because these processes do not require an activation energy

Two choices to distinguish – AlGaN or GaN buffer – we tell you later



Back to 1/f: Drain voltage dependencies

1×10^{-13}
f=200 Hz
1×10^{-14}
V_d
1×10^{-15}
V_d^2
1×10^{-16}
1×10^{-17}
Vg= -2V
1×10^{-18}

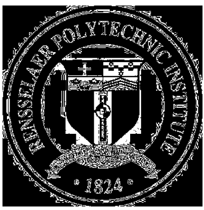
0.1
1

Drain voltage V_d, V

S_{Id}, A^2/Hz

10^{-2}
10^{-3}

Drain current I_d, A

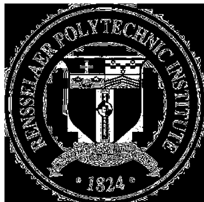


Where does 1/f noise come from?

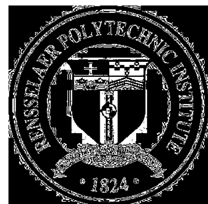
$$\frac{S_{RCh}}{R_{Ch}^2} \sim 1/N \sim R_{ch}$$

$$\frac{S_{Id}}{I_d^2} = \left(\frac{S_{Rs}}{R_s^2} \frac{R_s^2}{(R_s + R_{ch})^2} \right) + \left(\frac{S_{RCh}}{R_{Ch}^2} \frac{R_{Ch}^2}{(R_s + R_{ch})^2} \right)$$

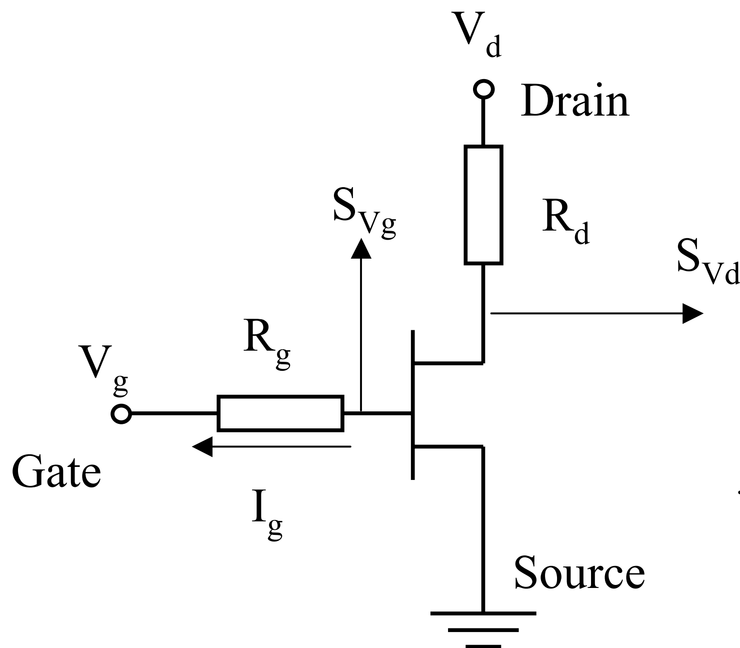
$R_{Ch} \nearrow \quad \frac{S_{Id}}{I_d^2} \searrow$



Location of the noise sources



Contribution of gate current fluctuations to output noise



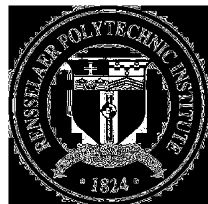
$$\frac{S_{Id}}{I_d^2} = \frac{S_{Ig}}{I_d^2}$$

additive contribution

$$\frac{S_{Id}}{I_d^2} = \frac{S_{Ig}}{I_d^2} \frac{r^2}{4} g^2$$

S_{ig} amplified by the transistor

S_{Vg} is spectral noise density of gate voltage fluctuations,
g is external transconductance in the linear region,
$r = V_d/I_d$ *is* the output resistance



Gate current fluctuations and output noise

experiment

Transistor 1 (Low leakage)

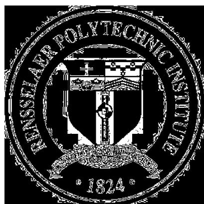
Transistor 2 (High leakage)

S_{Id}/I_d^2, dB/Hz

Drain Current I_d, A

calculated from measured S_{Ig}

Measurements of the correlation between gate and drain current fluctuations confirmed these results



Relative spectral noise density of drain current fluctuations at constant drain voltage

$$\alpha = \frac{S_{Id}}{I_d^2} Nf$$

S_{Id}/I_d^2, dB/Hz

-80
-90
-100
-110
-120
-130
-140

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}

Drain current I_d, A

HFETs (4H-SiC)

MOS-HFETs (4H-SiC)

HFET (6H-SiC, $\alpha=10^{-4}$)

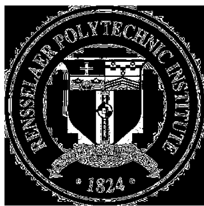
$V_g=0$

$\alpha=10^{-3}$

$V_g=0$

$V_d=0.5$ V

f=200Hz



GaN MESFETs and MOSFETs

- Heterostructure Growth : low pressure MOCVD
- SiO_2 deposition for MOSFETs: 7 nm by PECVD
- Ohmic Contacts : Ti/Al/Ti/Au (100 Å /300 Å /200 Å /1000 Å)
- Helium ion implantation was used to isolate devices
- Source-drain spacing L_{sd} = 5 µm
- Gate length, L = 2 µm,
- Gate width, W = (150 -250) µm.

L_{ds}

W

L

SiO_2

Sapphire

L_{ds}

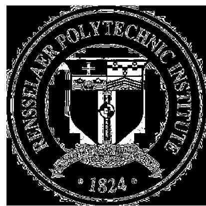
W

L

GaN, $N_d \approx 10^{18}$ cm^{-3},
~60nm

undoped GaN, ~2µm

Sapphire



MESFET current voltage characteristics

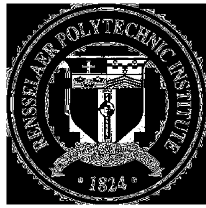
R_C, < 0.5 Ω mm,

$\mu_n \approx$ 100 cm²/Vs

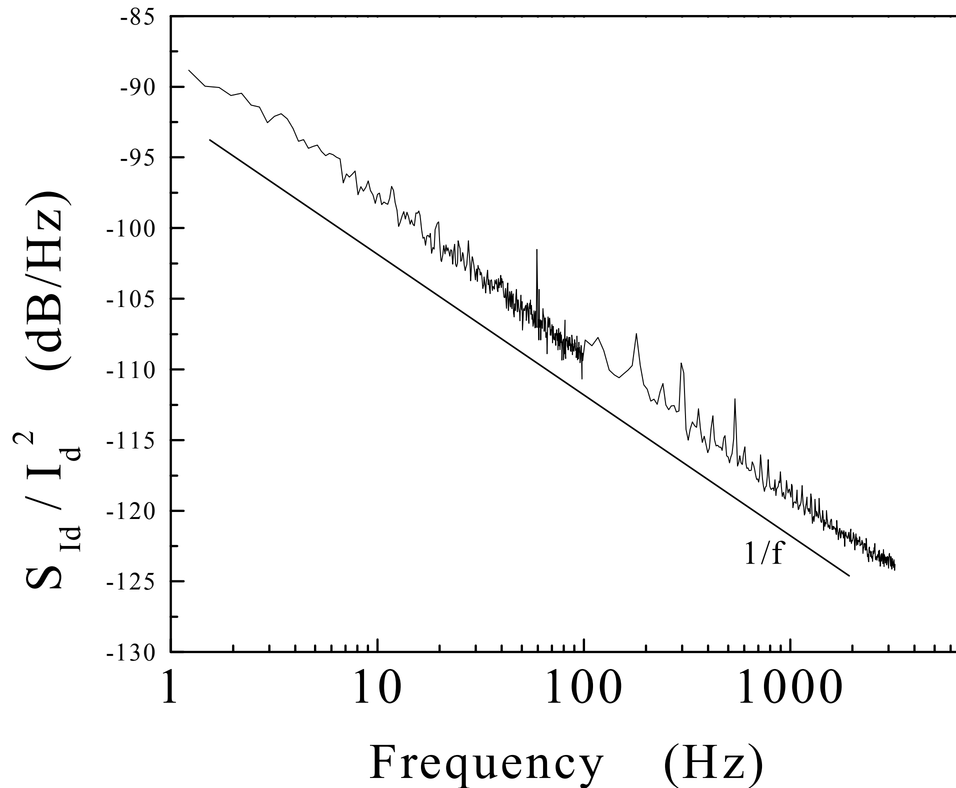
$V_{th} \approx$ 5.5 V

Notice extremely Low Leakage

The maximum drain current $I_d \approx$ 300 mA/mm The maximum transconductance $g \approx$ 70 mS/mm.

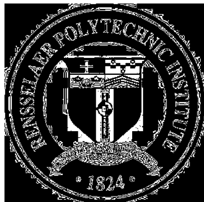


Noise spectra



The noise spectra S_{Id}/I_d^2 have the form of $1/f^{\gamma}$ noise with γ close to unity (γ = 1.0-1.15) for both MESFETs and MOSFETs.

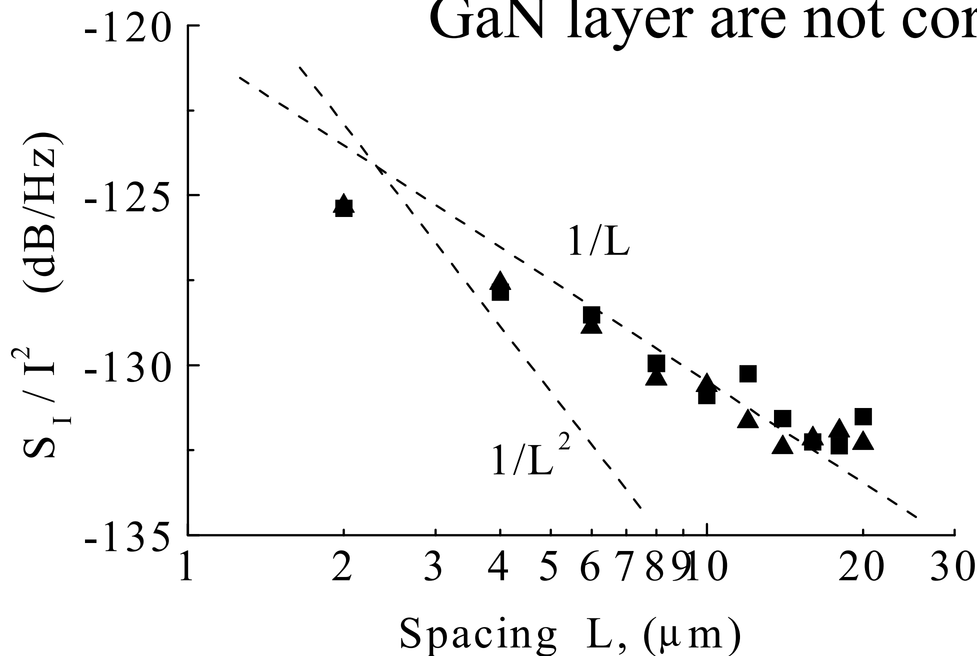
At low drain biases, V_d<1V, the spectral noise density of drain current fluctuations S_{Id} was proportional to the square of the drain voltage $S_{Id} \sim V_d^2$.



Contacts do not contribute much to noise

If contact noise and noise from GaN layer are not correlated:

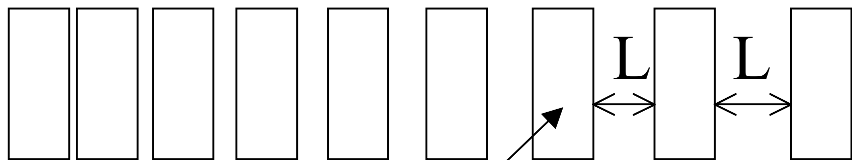
$$\frac{S_I}{I^2} = \frac{S_{Rc} + S_{GaN}}{R_{GaN}^2}$$



$$\frac{S_I}{I^2} = \frac{S_{GaN}}{R_{GaN}^2} \propto \frac{1}{L}$$ bulk or surface noise

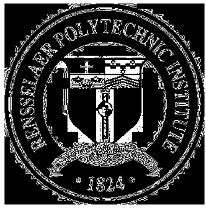
Relative spectral noise density S_I/I^2 versus distance L in TLM structure

$$\frac{S_I}{I^2} = \frac{S_{Rc}}{R_{GaN}^2} \propto \frac{1}{L^2}$$ contact noise



Ohmic contacts

$$\alpha = (2-3)\times 10^{-3}$$



1/f noise in MESFETs and MOSFETs

-80
-90
-100
-110
-120
-130

S_I / I^2 (dB/Hz)

bulk noise

SCR fluctuations

1'
1
2'
2

I_d^{-1}

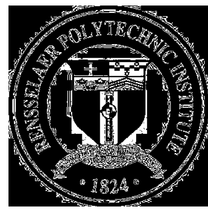
I^{-2}

contacts or surface

1×10^{-5} 1×10^{-4} 1×10^{-3} 1×10^{-2}

Drain Current I_d, A

Bulk noise ⟶ $\alpha = \frac{S_I}{I_d^2} \times N \times f$ $\alpha = (2-3)\times 10^{-3}$



1/f noise magnitude in bulk GaN

Hooge parameter	Carrier concentration, cm^{-3}	Mobility, cm^2/Vs	Ref.
$\alpha = 1\text{-}150$	10^{17} (p-GaN)	7-15	[1]
$\alpha = 3\text{-}5$	7×10^{17}(n-GaN)	60	[2-5]
$\alpha = 5\times 10^{-2}$	2×10^{17}(n-GaN)	790	[6]
$\alpha = (2\text{-}3)\times 10^{-3}$	10^{18} (n-GaN)	100	[7]

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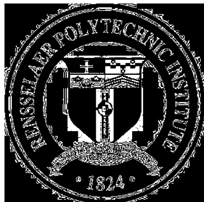


1/f noise as a result of fluctuations in density-of-state tail

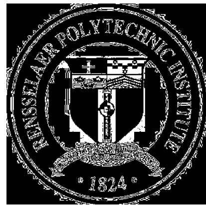
ε

0

ε_c

$\rho(\varepsilon)$

ε_F



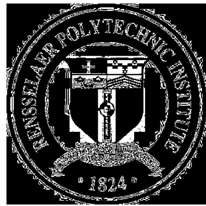
1/f noise model

$$\rho(\varepsilon) = \rho(0)\exp(\varepsilon/\varepsilon_0)$$

$$\tau(\varepsilon) = \tau(0)\exp(-\varepsilon/\varepsilon_1)$$

$$\tau(0) = \tau_0 F(0)$$

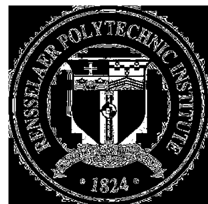
$$F = \frac{1}{1 + e^{-\frac{(\varepsilon_F - \varepsilon)}{kT}}}$$



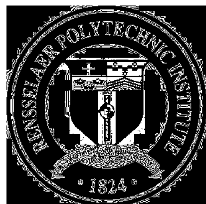
Non-degenerate limit (ε_f<<kT), low frequencies ($\omega\tau_0$<<1)

ν_1-ν_0<<1 $\nu_1=kT/\varepsilon_1$; $\nu_0=kT/\varepsilon_0$

$$\frac{S_n}{n_0^2}=\frac{\pi e^{\varepsilon_F/kT}N_0\varepsilon_1}{2Vn_0^2\omega\varepsilon_0}=\frac{\pi e^{\varepsilon_F/kT}\rho(0)\varepsilon_1}{2Vn_0^2\omega}$$



1/f noise as function of Fermi level position



Conclusions (for HFETs & MOSHFETs)

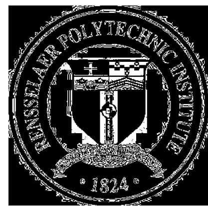
•Contacts do not contribute much to noise

• SiO_2 deposited on AlGaN in MOS-HFETs does not contribute much to noise

• GR noise with activation energy of $E_a \sim 0.8 - 1.0$ eV in both HFETs and MOS-HFETs.

•Trap responsible for G-R noise might be located in the AlGaN barrier layer

Gate current fluctuations might contribute to noise in high-leakage low-noise devices



Conclusions (for MESFETs and MOSFETs)

Noise properties of GaN MESFETs and MOSFETs are practically identical.

Only a weak contribution of generation-recombination noise at elevated temperatures.

Drain and source contacts do not contribute much to noise

The noise observed originates from GaN in the channel and in the source-gate and drain-gate lateral regions.

The Hooge parameter $\alpha = (2\text{-}3)\times 10^{-3}$. This value is of the same order of magnitude as in GaN/AlGaN HFETs and one order of magnitude less than for bulk n-type GaN ?