Low-Frequency Noise in SiGeC-Based pMOSFETs

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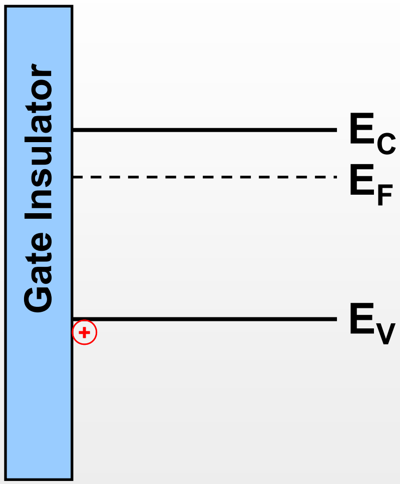
Outline

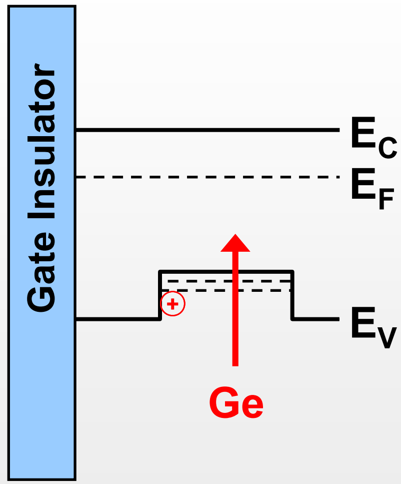
- **Performance of SiGeC MOSFETs**
  - Comparison Si : SiGe : SiGeC
- **Experimental results**
  - DC and LFN experiments
  - Trends, variations, modeling
- **Discussion on LFN behavior**
  - Noise scaling
  - ΔN model, trap density
- **Conclusions**

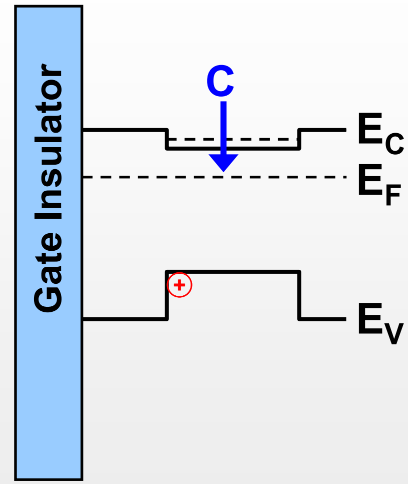
Comparison Si : SiGe : SiGeC

	Si	SiGe	SiGeC
• Mobility	$\mu_n/3$	$\sim\mu_n$	$\sim\mu_{SiGe}$
• Strain	No	High	Relaxed

• Gap Tuning



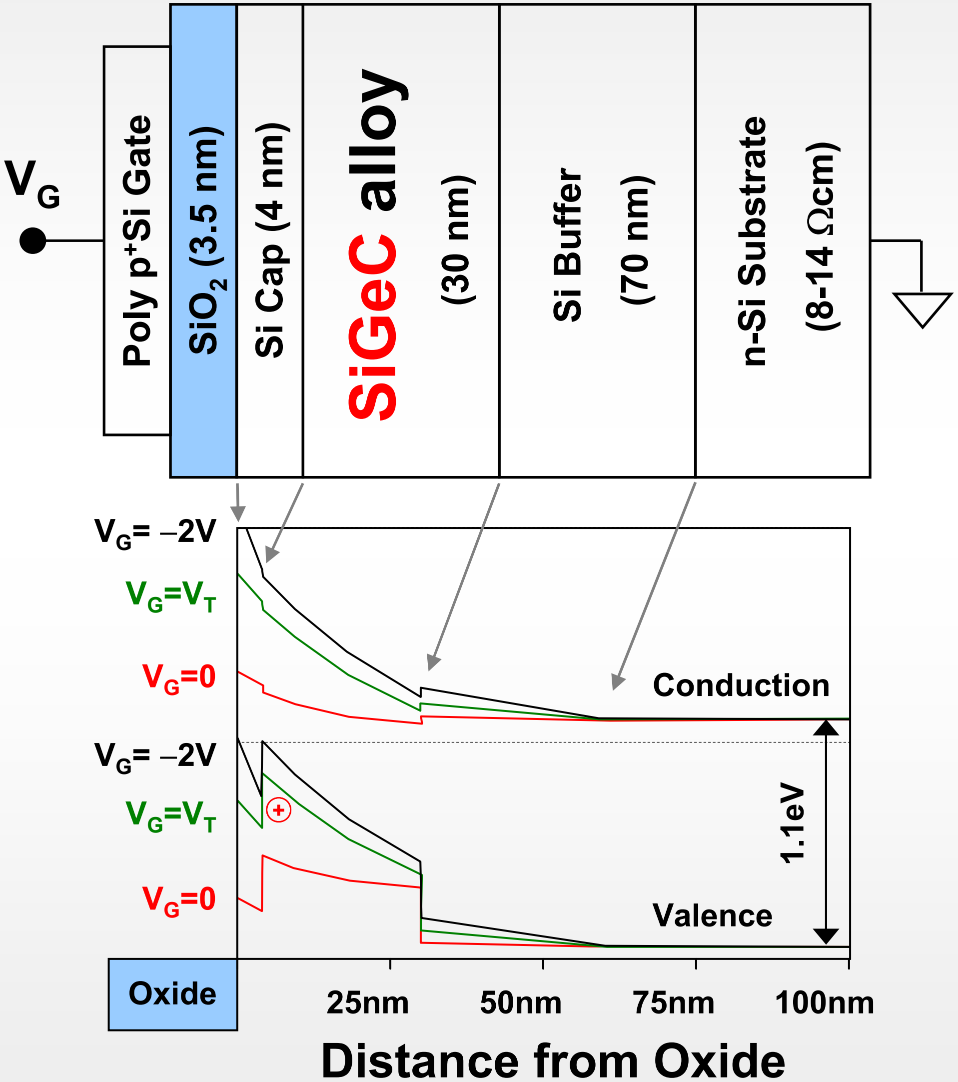




Low-Freq. Noise in pMOSFETs

	Si	SiGe	SiGeC
• ΔN	?	$S_{I_D} = S_{V_G}\, g_m^2$ G. Ghibaudo, *et al*, SSE, **46**, 393 (2002) Y.-J. Song, *et al*, TED, **50**(4). 1152 (2003) A. Lambert, *et al*, TED, **46**(7), 1484 (1999)	?
• $\Delta\mu$	Yes	Sometimes S. Okhonin, et al, TED, **46**(7), 1514 (1999) N. Lukyanchikova, *et al*, EDMO, 181 (2001) G. Ghibaudo, *et al*, SSE, **46**, 393 (2002)	?
• $S_{I_D} \propto {}^{1}/_{Area}$	Yes	Yes A. Lambert, *et al*, TED, **46**(7), 1484 (1999)	?

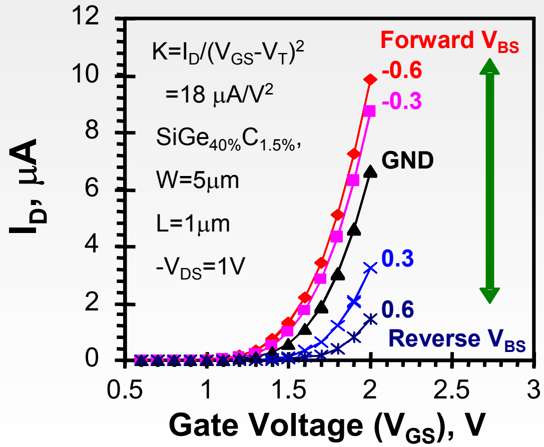
SiGeC pMOSFET Samples

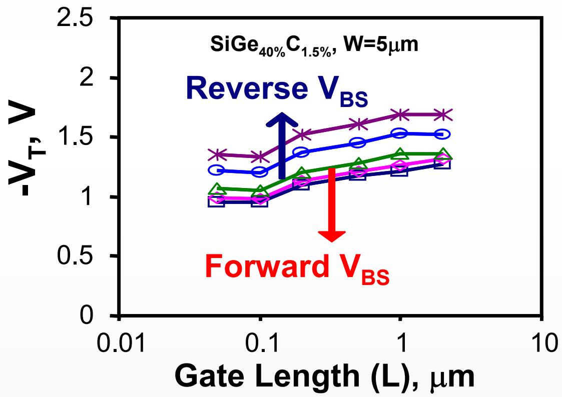


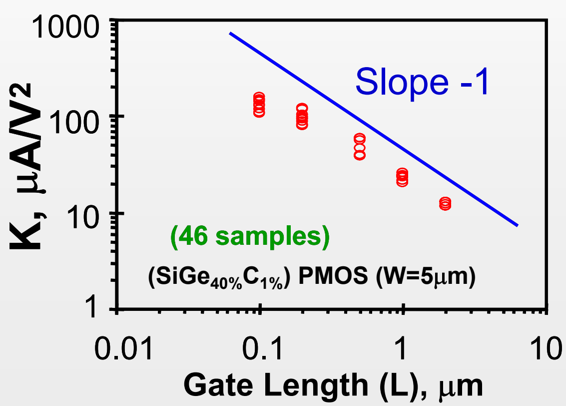
- **Alloy**
  - $SiGe_{40\%}C_{1.5\%}$
  - $SiGe_{40\%}C_{1\%}$
  - $SiGe_{40\%}C_{0.5\%}$
  - $SiGe_{40\%}$
  - Si
- **Channel Sizes**
  - Width (W)= 5 μm
  - Length (L)=0.1-2μm
- **Number of Samples**
  - DC: more than 200
  - LFN: more than 20
- **Data Files ~ 3000**

Fabrication details: G. Kar, *et al*, Semiconductor Science and Technology, **17**, 938 (2002)

DC Experiments

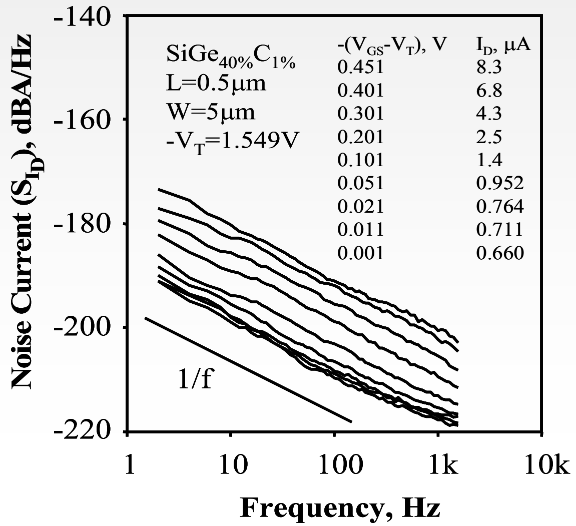


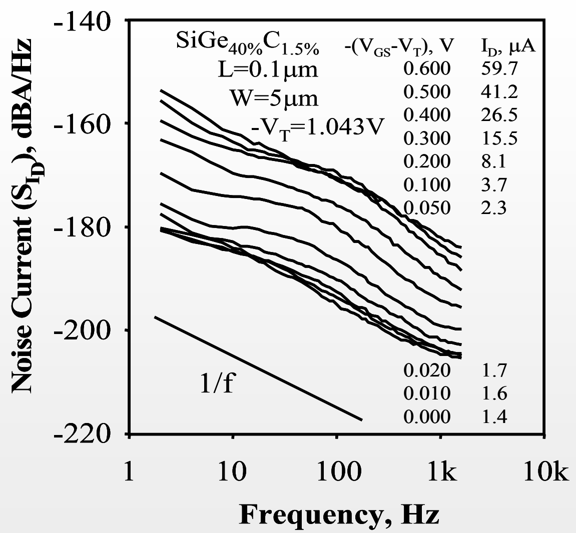




- **Wafer Mapping**
  - Leakages
  - Proper I-V
- **Transfer I-V Curves**
  - $V_{GS}= |V_T-0.3V|$ … -2V
  - $V_{DS}=$ -1V … -50mV
  - $V_{BS}=$ -0.6 … +0.6V
- **DC Modeling**
  - Strong to Weak Inversion
  - Parameter Extraction
- **Statistics**
  - $V_T(V_{BS})$, g_m(bias)
  - $K=I_D/|V_{GS}-V_T|^2$

1/f and Lorentzian LF Noise

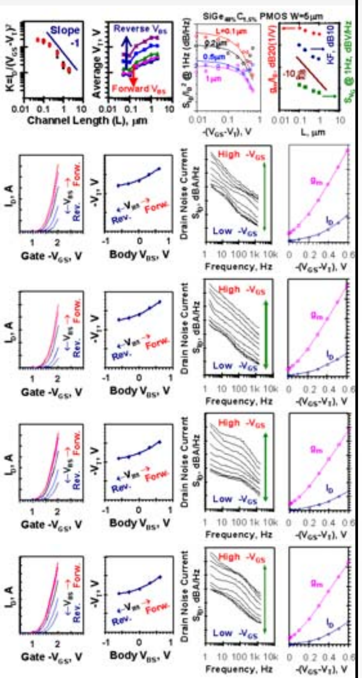




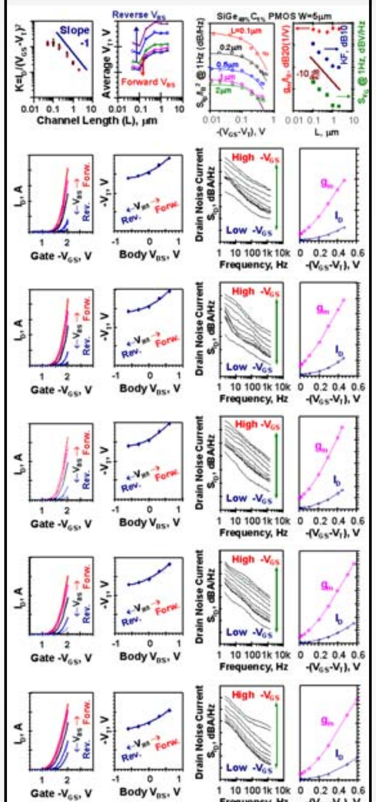
- **Biasing**
  - V_{GS}= $|V_T$-0.1V$|$ … -2V
  - V_{DS}= -1V … -50mV
  - V_{BS}= -0.6 … +0.6V
- **S_{I_D} Spectra (about 800)**
  - 2Hz – 1.6kHz
  - S_{I_D}/I_D^2, S_{I_D}/g_m^2
- **Corresponding DC**
  - V_{GS}, V_{GS}-V_T
  - I_D
  - g_m

Extensive DC and LFN Data

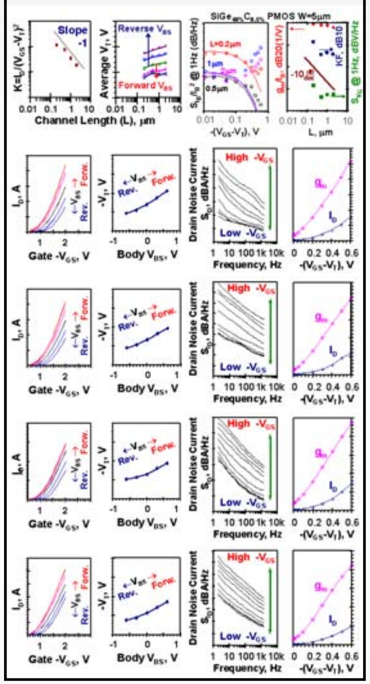
$SiGe_{40\%}C_{1.5\%}$



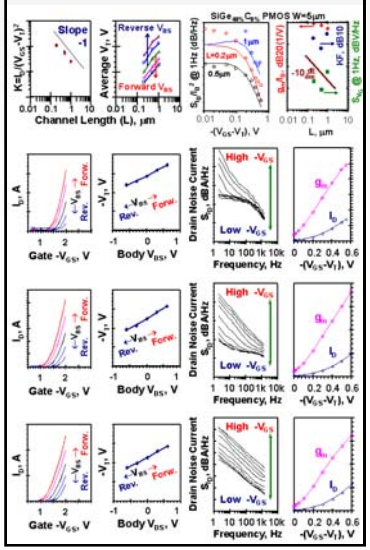
$SiGe_{40\%}C_{1\%}$



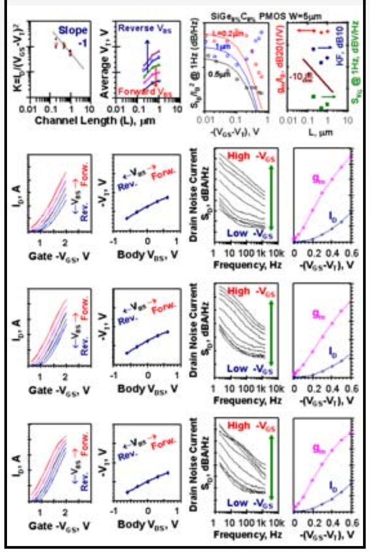
$SiGe_{40\%}C_{0.5\%}$



$SiGe_{40\%}C_{0\%}$



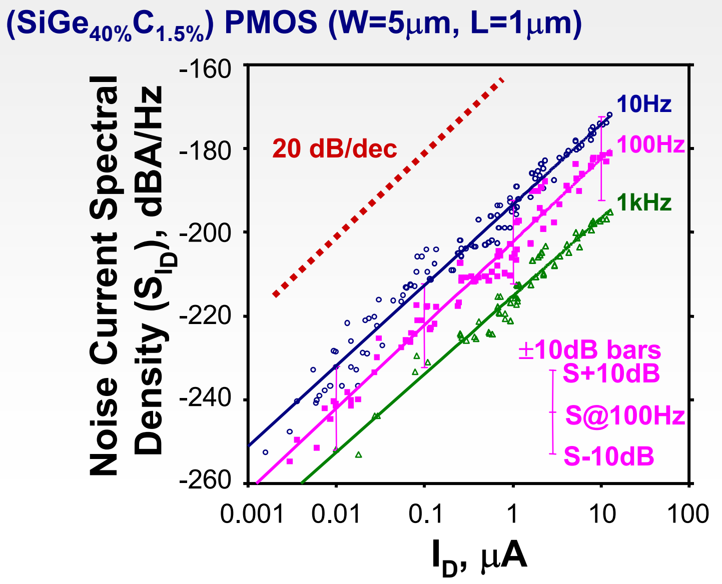
$SiGe_{0\%}C_{0\%}$

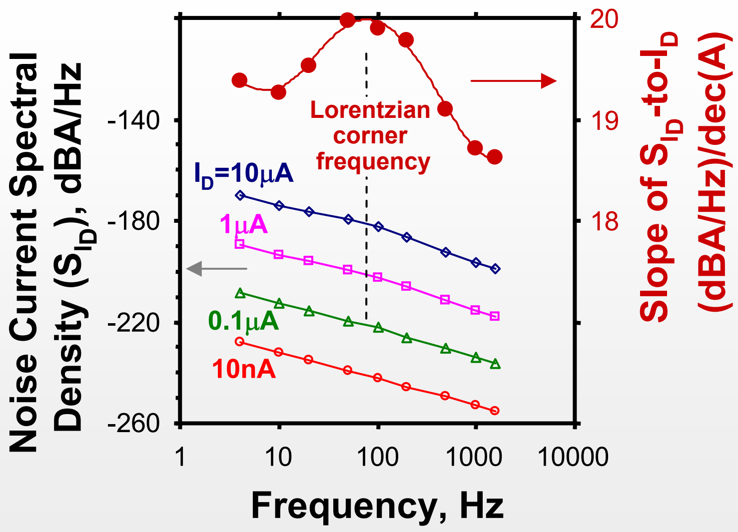


Numerical data available through www.**RDIE.ca**

Marinov, *et al*, www.RDIE.ca, **1**(1), 1 (2004)

Trend of Noise Results





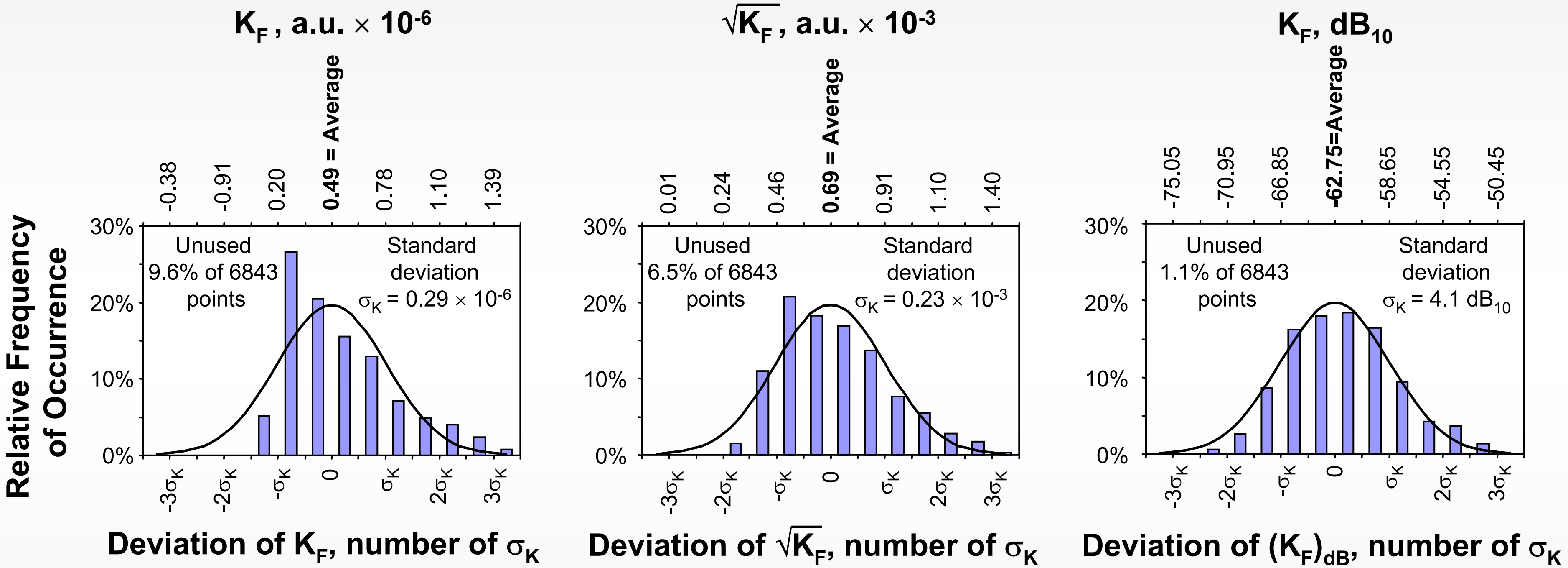
Despite variations

- $S_{I_D} \propto I_D^2$
- S_{I_D} spectra ~ 1/f

$$(S_{I_D})_{avg} = (K_F)_{avg} \frac{I_D^2}{f}$$

Distribution - $K_F = S_{I_D} \times f / I_D^2$

($SiGe_{40\%}C_{1.5\%}$) PMOS (W=5µm, L=1µm)



Averaging of Noise Power S·f/I²

fails

Averaging of Noise Current i·√f/I

fails

Log-Normal Noise Log(S·f/I²)

applies

Log-Normal LFN Model

- **Exponential-Logarithmic form for noise equation**
  - **Exponential**

$$S_{I_D}(f,\text{bias}) = \frac{(K_F)_{avg} \cdot I_D^2(\text{bias})}{f} 10^{\pm t \cdot \sigma_{dB}/10dB} = \frac{(K_F)_{avg} \cdot I_D^2(\text{bias})}{f} \exp(\pm t \cdot \sigma_{Np}); \sigma_{Np} \approx 0.23\sigma_{dB}$$

  - **Logarithmic**

$$S_{I_D}(f,\text{bias})\big|_{dB} = (K_{F,dB})_{avg} + 20dB \cdot \log_{10}(I_D) - 10dB \cdot \log_{10}(f) \pm t \cdot \sigma_{dB}$$

- **Noise averaging**

$$(K_{F,dB})_{avg} = \frac{10dB}{N} \sum_{j=1}^{N} \log_{10}\left(\frac{S_{I_D}}{I_D^2} f\right)_j$$

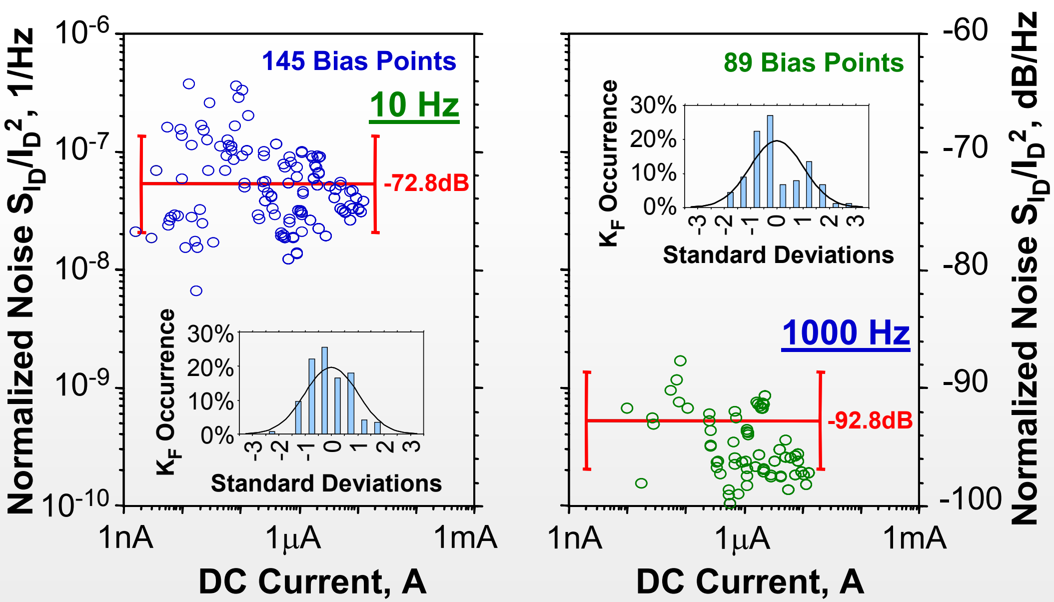
  - **Geometric (arithmetic in dB)**

$$\sigma_{dB} = \sqrt{\frac{1}{N-1} \sum_{j=1}^{N} \left[10dB \cdot \log_{10}\left(\frac{S_{I_D}}{I_D^2} f\right)_j - (K_{F,dB})_{avg} \right]^2}$$

- **Model parameters**
  - **Average Noise: $K_F = 10^{(K_{F,dB})/10dB}$**
  - **Log-Normal deviation: σ_{dB}**
  - **t=(1,...,3) for confidence probability (60%,...,99%)**

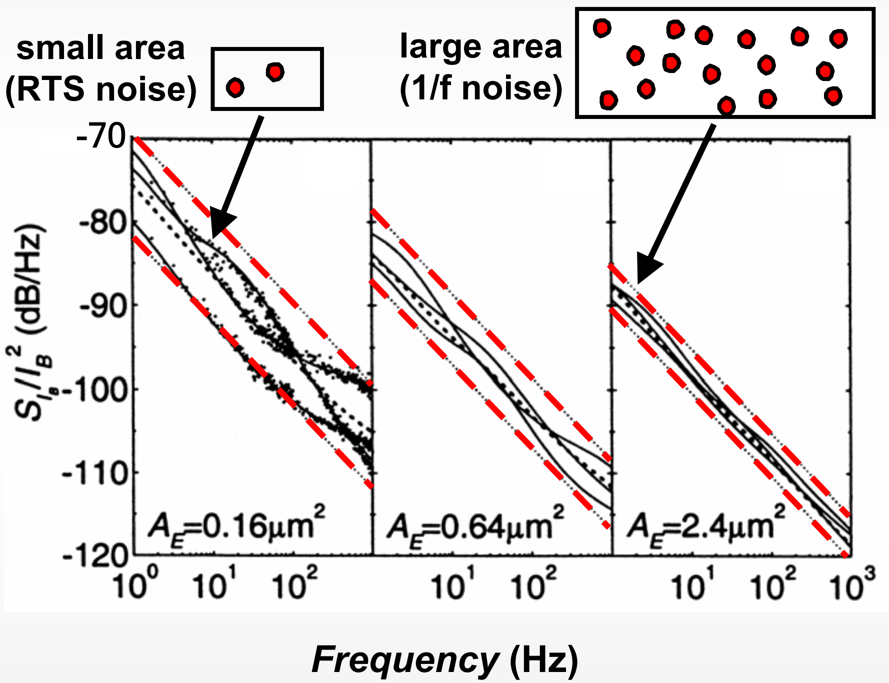
Population Requirements

- N>250 for K_F and σ_K evaluation
  - Frequency points ≥ 30
  - Bias points ≥ 8
- N>2000 for inspection of distribution
  - Frequency points ≥ 50
  - Bias points ≥ 60
- Small Population:



Similarity to PE-BJT

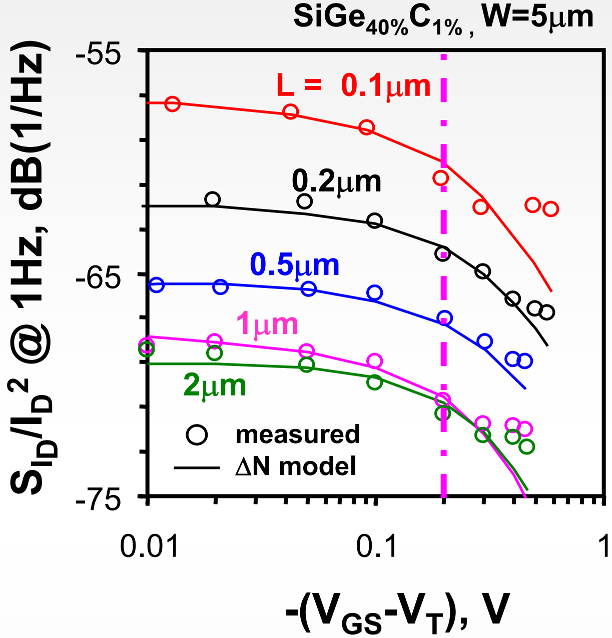
M. Sanden, *et al*, TED, **49**(3), 514 (2002)

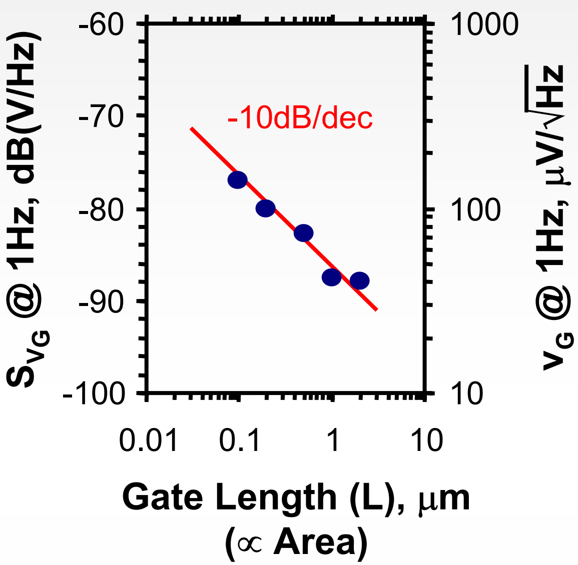


- $S_{I,avg} \propto 1/f$
- $S_{I,avg} \propto I_{DC}^2$
- $S_{I,avg} \propto 1/\text{Area}$
- $S_{I,dev} \propto 10^{(t\times\sigma_{dB}/10dB)}$

ΔN noise?

ΔN model for LFN





$$\frac{S_{I_D}}{I_D^2} = S_{V_G}\left(\frac{g_m}{I_D}\right)^2$$

$$g_m^2 = \left(g_{m,SiGeC} + g_{m,cap}\right)^2$$

$$S_{V_G} = S_{FB} \propto 1/\,Area$$

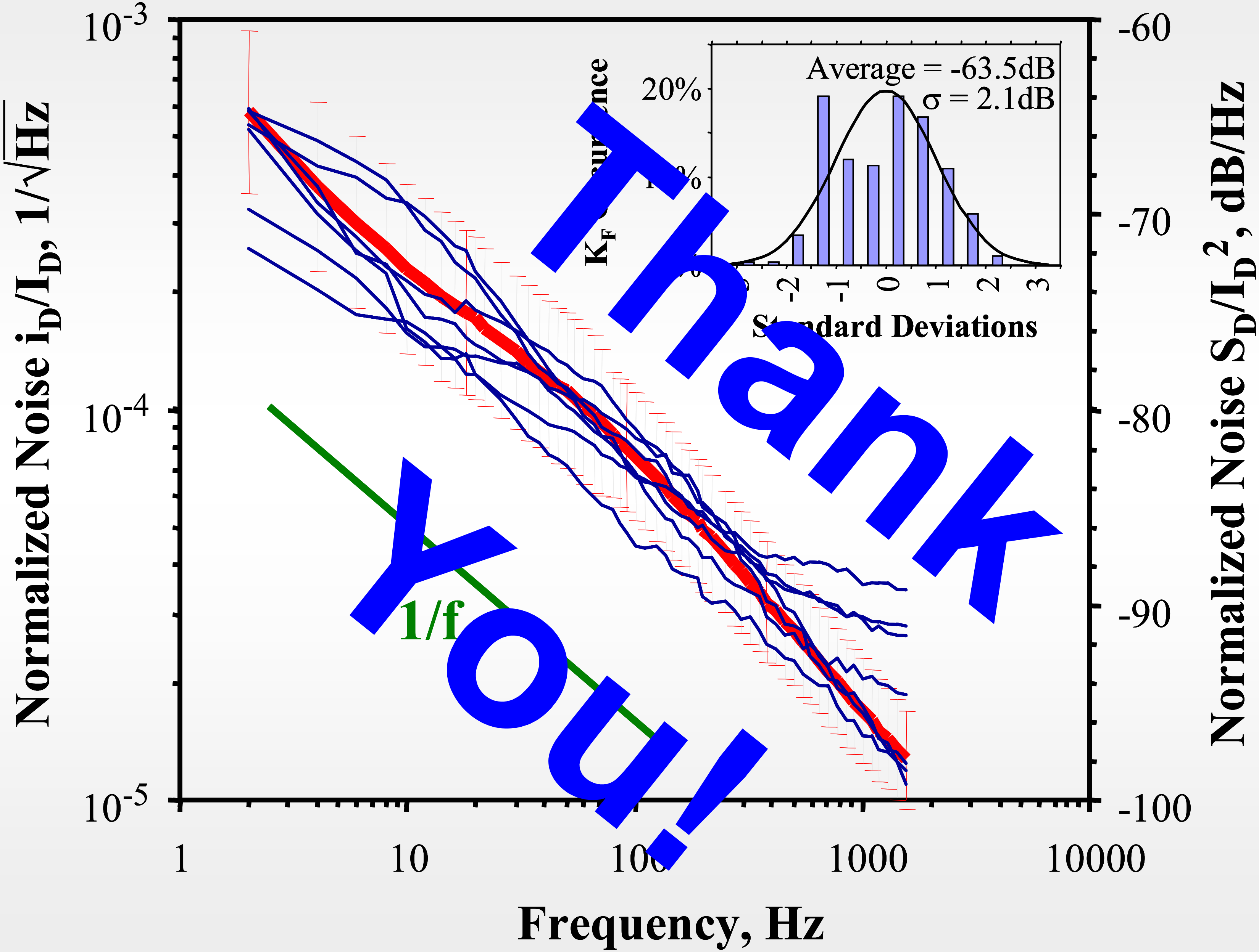
G. Ghibaudo, *et al*, SSE, **46**, 393 (2002)

Number fluctuation in all samples for

$|V_{GS}-V_T|<0.2V$

Conclusion

- **Experiments of SiGeC pMOSFETs**
  - Detailed LFN measurements
  - Necessary DC characterization
- **ΔN noise for $|V_{GS}-V_T|<0.2V$**
  - LFN can be referred to gate terminal
  - Trade-off between noise performance and GeC concentration
- **Noise scaling**
  - $(S_{I_D})_{avg} \propto I_D^2/(f\times Area)$
  - Log-normal distribution $\Rightarrow$ averaging and deviation in dB
- **Several factors contribute to LFN at increased gate biasing $|V_{GS}-V_T|>0.4V$**


Thank You!
Normalized Noise i_D/I_D, $1/\sqrt{Hz}$
Normalized Noise S_D/I_D^2, dB/Hz
Frequency, Hz
10^{-3}
10^{-4}
10^{-5}
1
10
100
1000
10000
-60
-70
-80
-90
-100
1/f
Average = -63.5dB
σ = 2.1dB
20%
K_F
-2 -1 0 1 2 3
Standard Deviations