1/f Noise Modeling at Low Temperature with the EKV3 Compact Model

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Outline

- **Introduction**
- **CMOS process, characterization & specific effects at low temperature (LT)**
- **Low frequency (LF) noise measurements at room & low temperature and physical models**
- **Compact modeling of LF noise with EKV3**
- **Conclusion**

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Introduction: aim of this work

- **Design of hybrid CMOS read-out circuits for night vision with high performance (cooled) IR imagers**
- **CMOS circuits also cooled at LT (77 - 200 K)**
- **Modeling difficulties: low temperature & analog circuits (weak/moderate inversion)**
- **IC design with 0.8, 0.5 and 0.35 µm CMOS and circuit simulation with the EKV2.6 charge based compact model**
- **More and more transistors in the pixel, need for more and more advanced CMOS processes**
- **0.18 µm process: new effects, e.g. INWE (STI), DITS (pockets)**
- **WCM 2008 (Boston): EKV3 is an accurate compact model for LT analog circuits design**
- **This work: test of the EKV3 LF noise model for analog transistors**

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CMOS process & characterization

Process

- Commercial process, optimized for room temperature
- 0.18 µm - 1.8 V (Tox=3.3 nm) & 0.35 µm - 3.3 V (6.5 nm)
- Different transistors: standard (STD), low Vth (LVT), zero Vth (ZVT)

DC characterization

- 1st step before LF noise measurements ⇨ std. and specific effects
- Id, Gm, Gmb, Gds ⇨ thermal noise
- Temperature range: 77 K - 300 K

LF noise measurements

- Transistors biased in saturation: Vds=VDD as in analog circuits
- L=Lmin - 20 µm
- W=Wmin - 20 µm
- $1/f^{\gamma}$ noise with $\gamma = 1.0 \pm 0.1$

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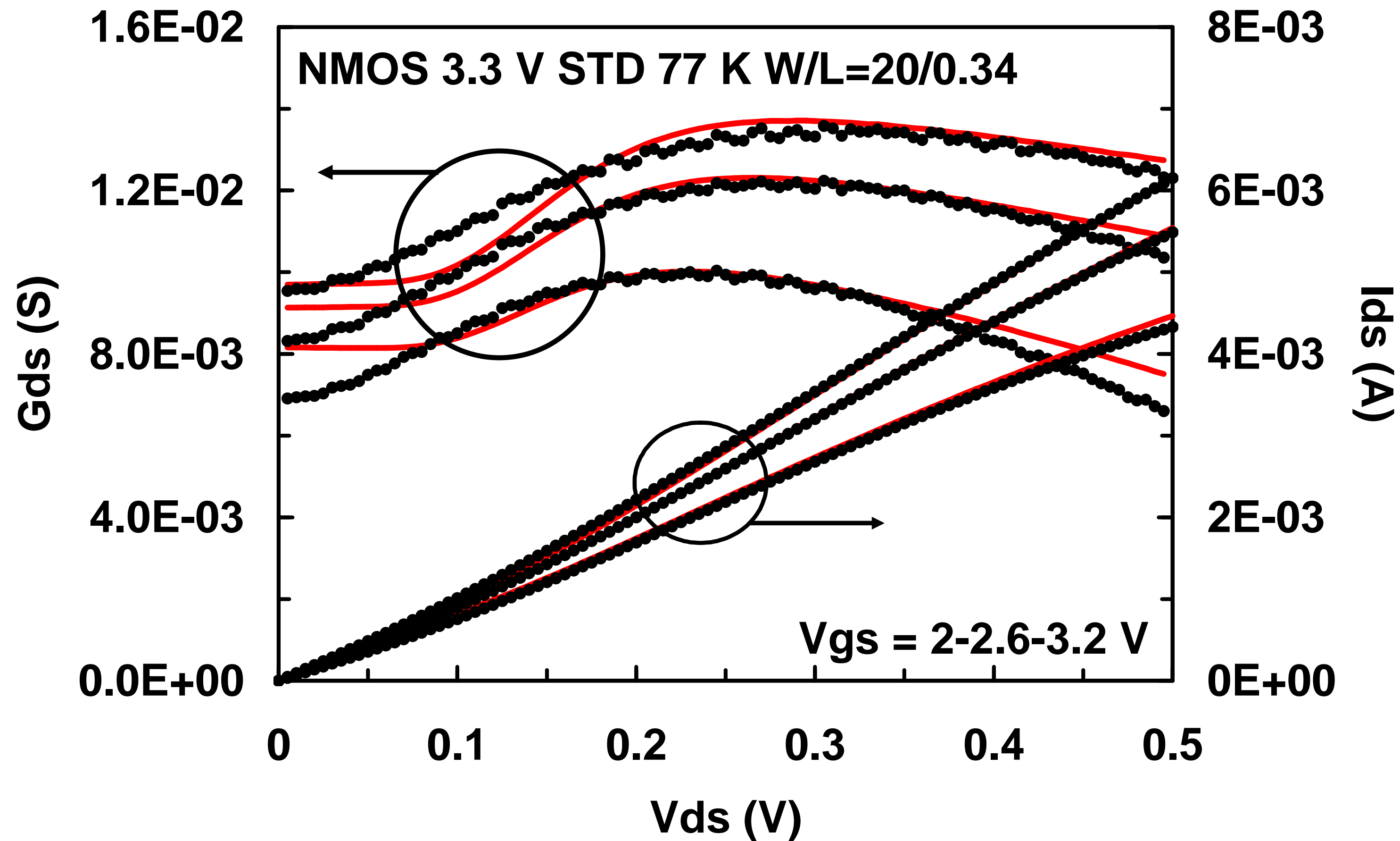
Specific effects at LT: 1st example

⇨ **Freeze-out in LDD zones + ioniz. by lateral field**



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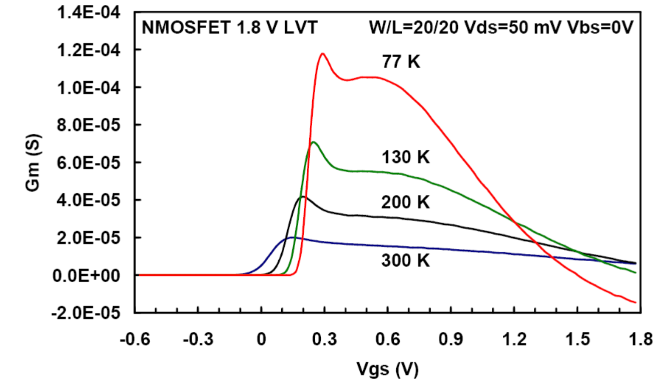
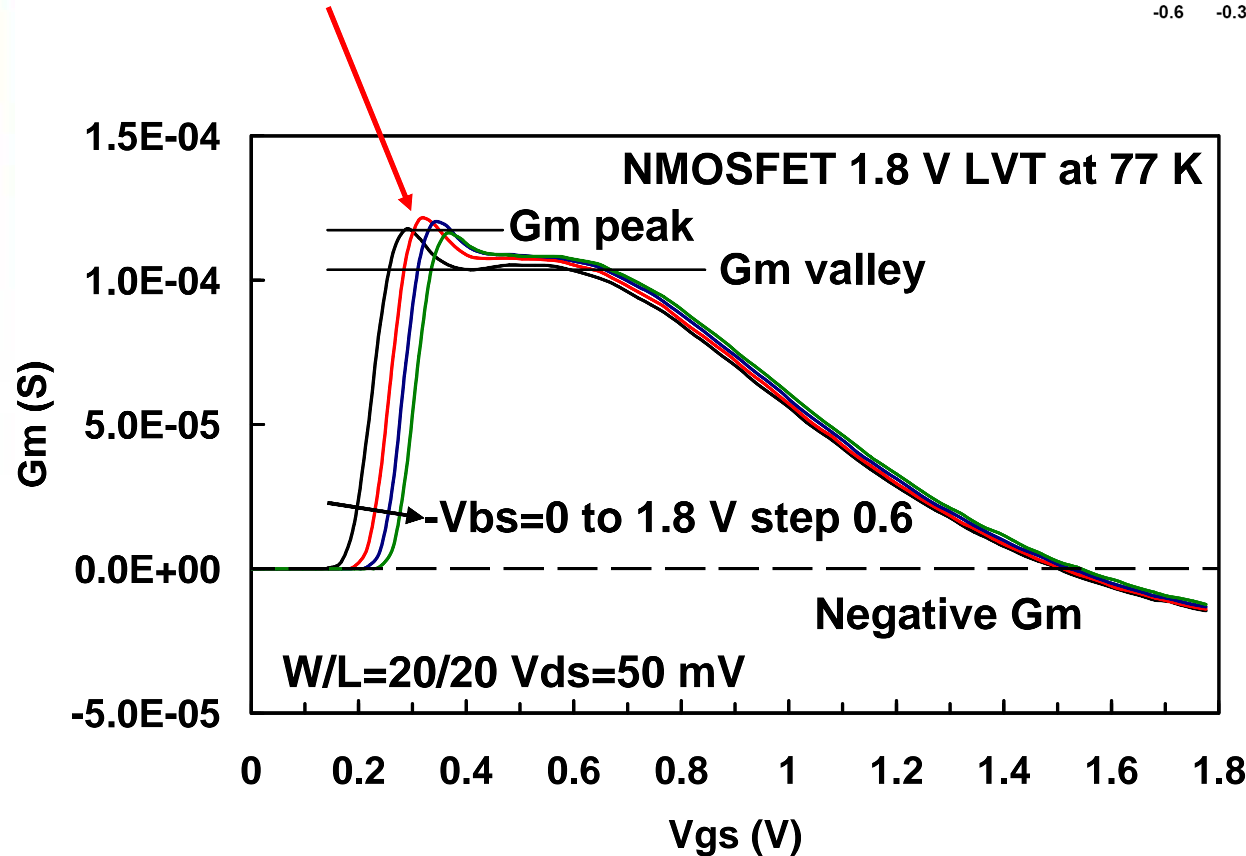
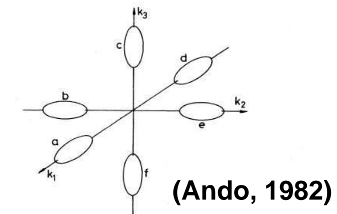
Specific effects at LT: 2nd example

Peak in Gm on lightly doped NMOSFET (< 8 10^{16} cm^{-3})

⇨ Sub-bands quantization effect (Cryogenics, 2009)







(Ando, 1982)

FIG. 5. Schematic constant-energy surfaces for the conduction band of silicon, showing six conduction-band valleys in the ⟨100⟩ direction of momentum space. The band minima, corresponding to the centers of the ellipsoids, are 85% of the way to the Brillouin-zone boundaries. The long axis of an ellipsoid corresponds to the longitudinal effective mass of electrons in silicon, $m_l = 0.916m_0$, while the short axes correspond to the transverse effective mass, $m_t = 0.190m_0$.

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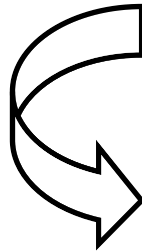
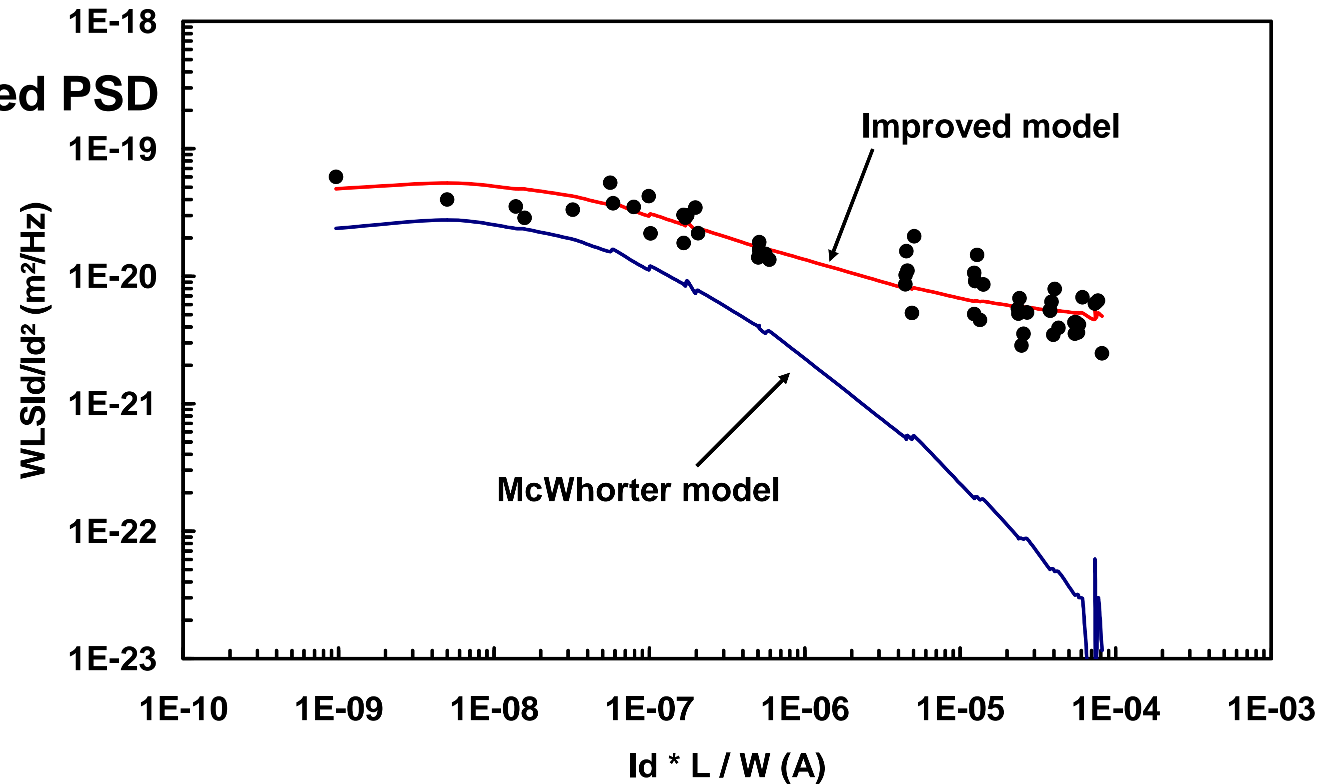
1/f noise measurements at room temperature





PMOSFET 3.3 V
295 K, f=1 Hz

- **Plateau in weak inversion: Hooge mobility fluctuation model not applicable**
- **McWhorter's carrier number model applicable, but has to be improved in strong inversion**

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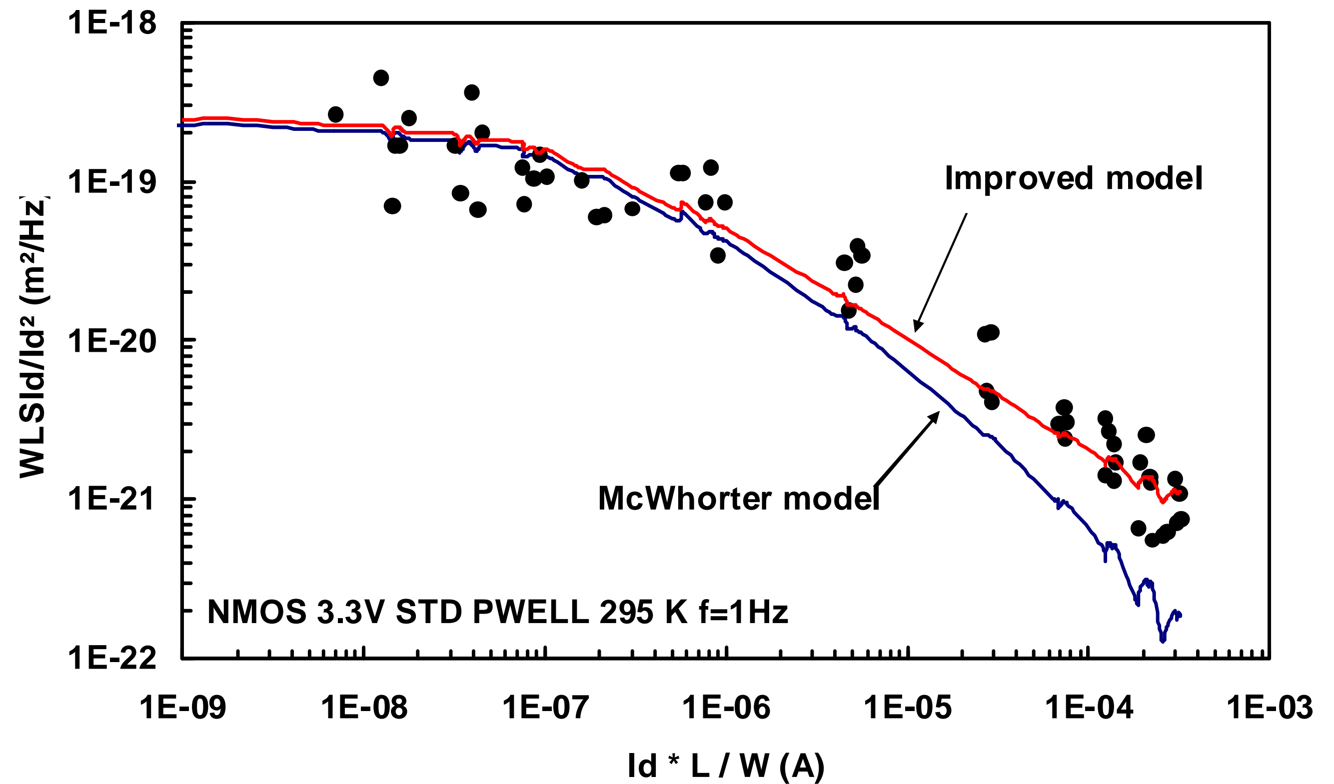
1/f noise measurements at room temperature



NMOSFET 3.3 V
295 K, f=1 Hz

⇨ **Same improved model applies for NMOSFET**

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The improved McWhorter's LF noise model

1 - Standard McWhorter carrier number fluctuations

$$SI_d = [1 + \alpha \mu C_{ox} \frac{I_d}{G_m}]^2 G_m^2 S_{Vfb}(f)$$

units: A²/Hz

2 - Correlated mobility fluctuations at high current

$$S_{Vfb}(f) = \frac{kT q^2 \lambda N_t(E_F)}{WL C_{ox}^2} \frac{1}{f^\gamma}$$

units: V²/Hz

S_{Vfb}: flat-band voltage fluctuations

N_t: oxide trap volume density per unit energy at E_F (eV^{-1} cm^{-3})

λ: tunnel attenuation distance (0.1 nm)

α: Coulomb scattering coefficient (Vs/C) ~ 10^4 for electrons, 10^5 for holes at RT

For 3.3 V STD p-MOSFETs: α=3x10^5 @ 295 K

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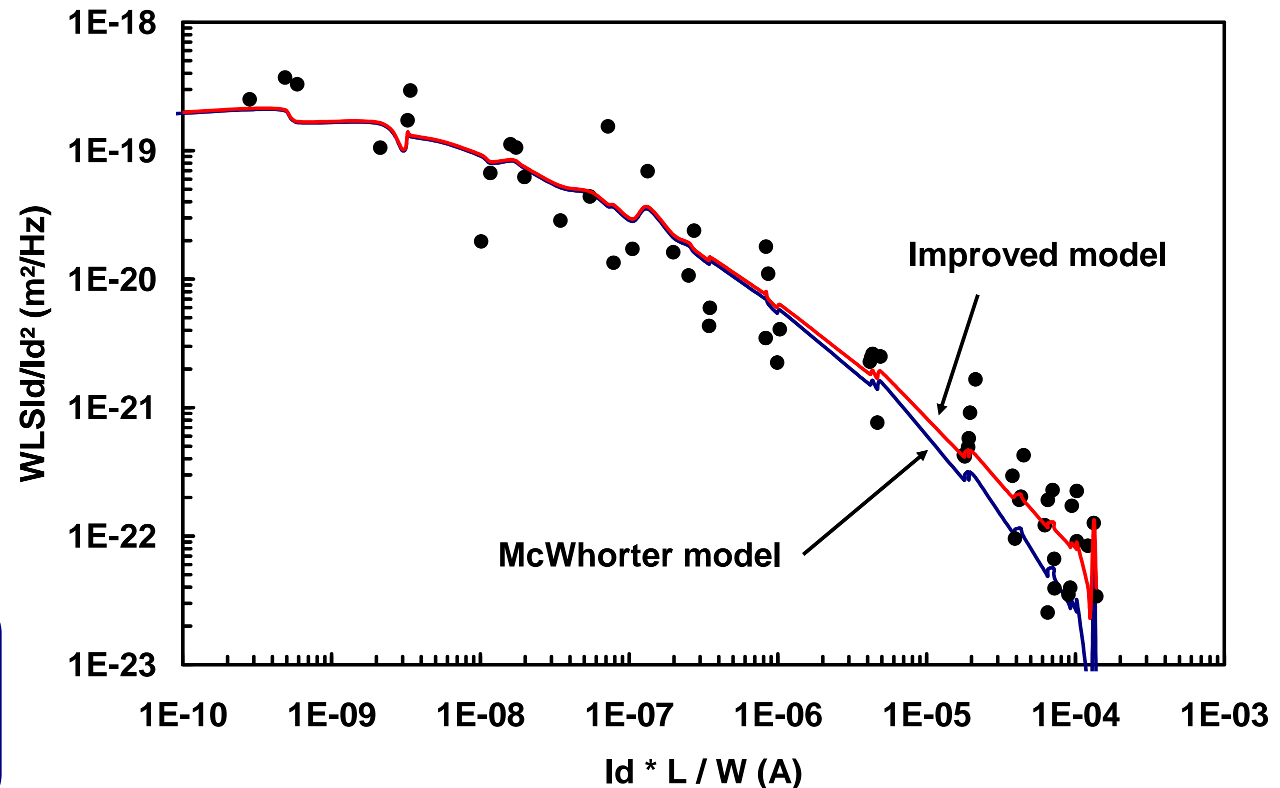
Noise measurements at 77 K



PMOSFET 3.3 V
77 K, f=1 Hz

- **Improved McWhorter's model still applicable at low temperature**
- **Lower α Coulomb scattering coefficient (5×10^3 @ 77 K)**
- **Same result for NMOSFET, but different α coefficient**

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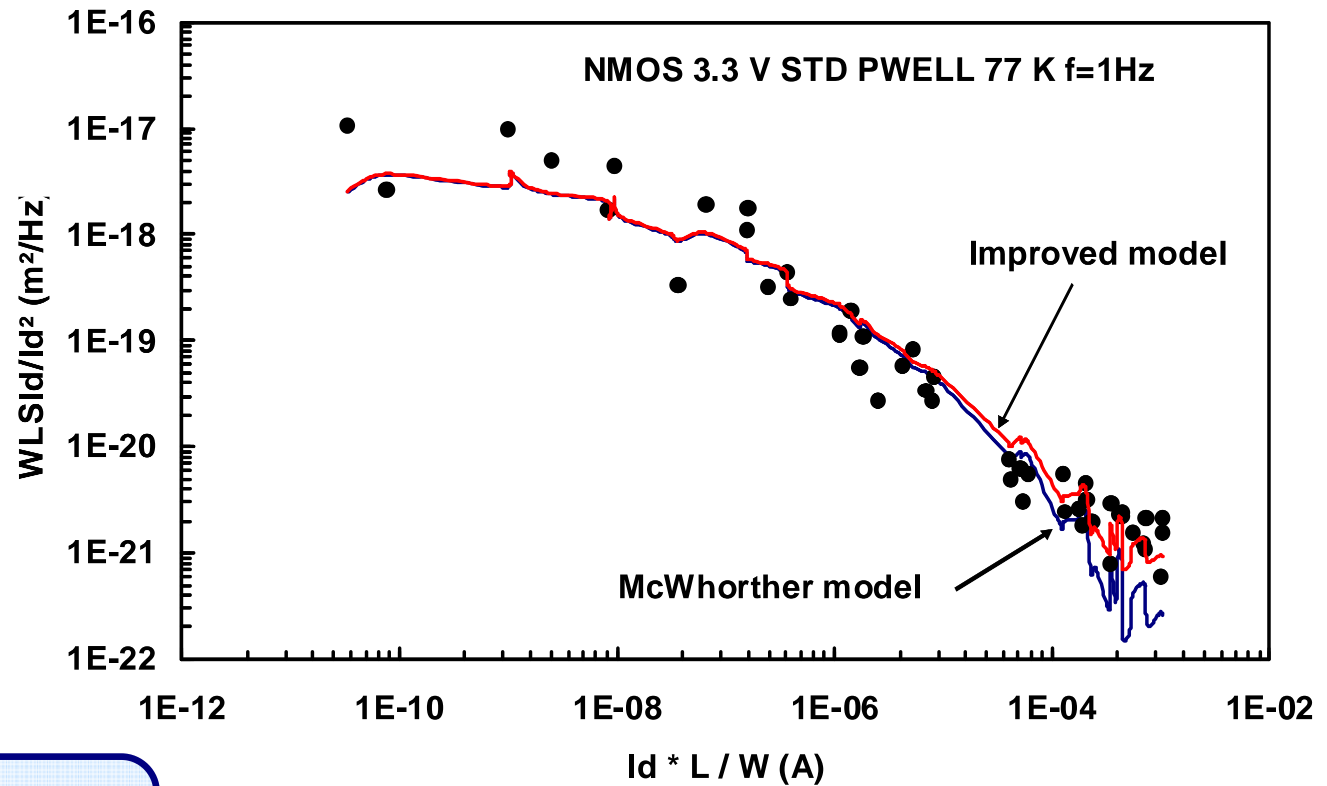
Noise measurements at 77 K



NMOSFET 3.3 V
77 K, f=1 Hz

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LF noise modeling in EKV2.6 and EKV3

EKV2.6

$$S_{Id} = \frac{KF\, G_m^2}{C_{ox} W_{eff} L_{eff} f^{AF}}$$

EKV3

$$S_{Id} = \frac{KF\, G_m^{EF}}{C_{ox} W_{eff} L_{eff} f^{AF}}$$

Three parameters: KF, AF, EF ≠ 2

Simple but efficient model ?

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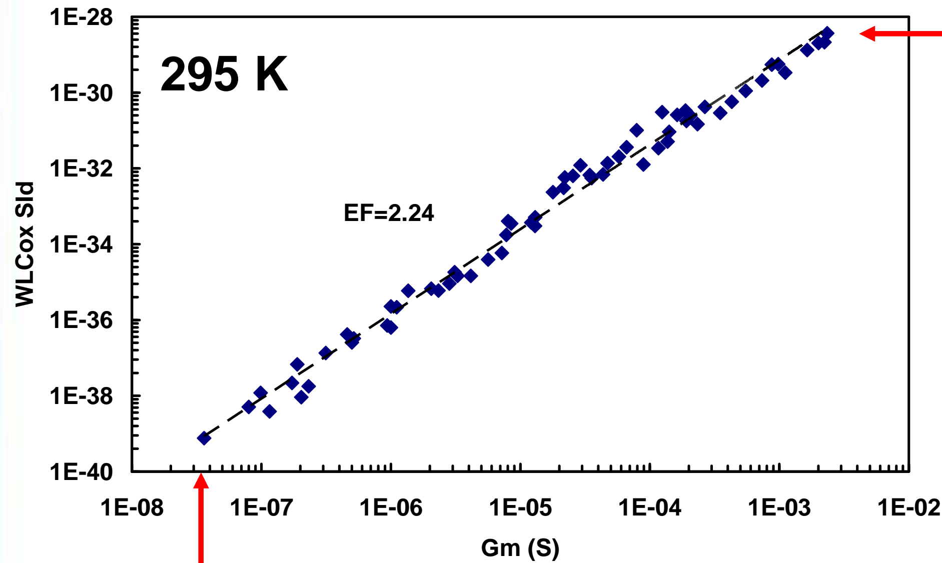
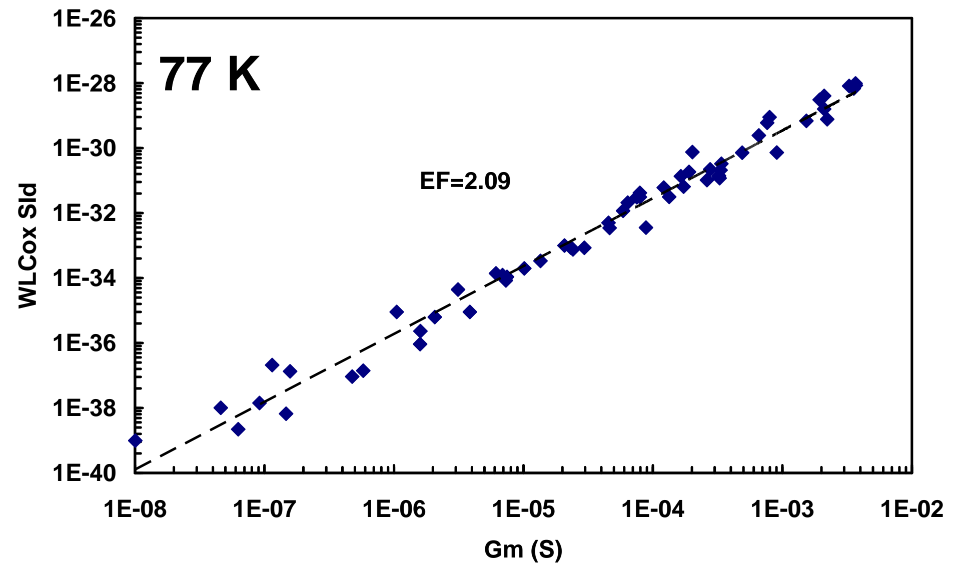
Experimental results: NMOSFET



strong inversion
Id ~ 1-10 mA

NMOSFET STD 3.3 V P-WELL
Tox=6.5 nm f=1 Hz

weak inversion
Id ~ 0.1-1 nA



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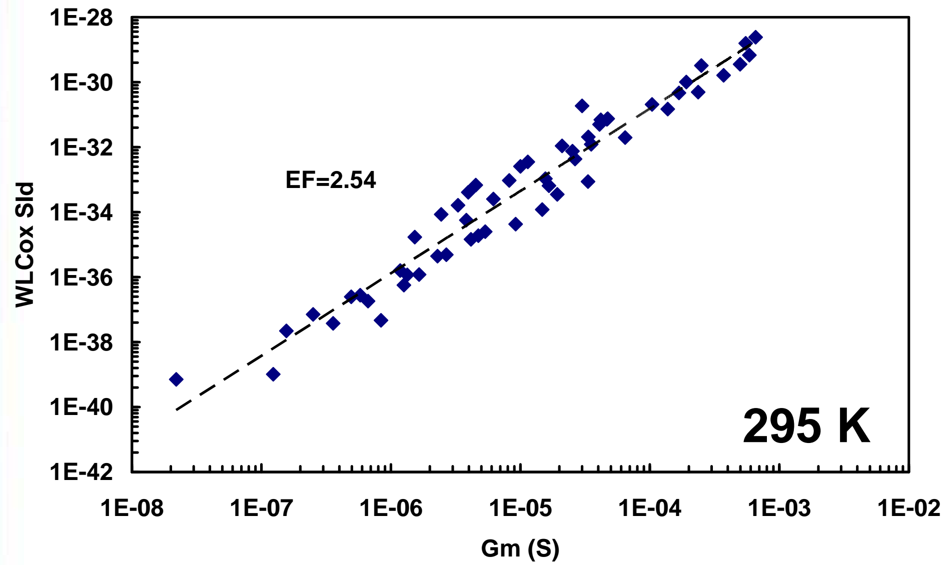
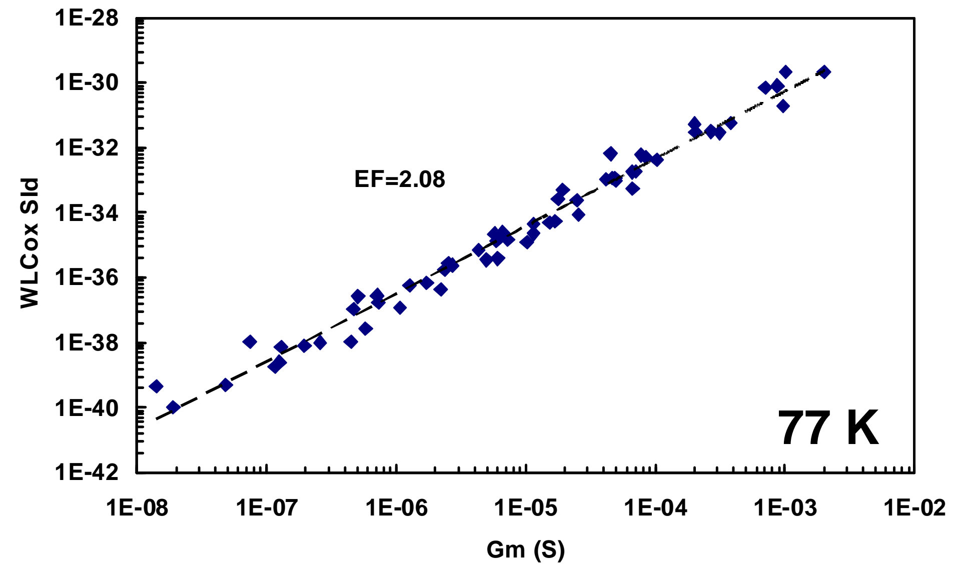
Experimental results: PMOSFET



PMOSFET STD 3.3 V N-WELL

Tox=6.5 nm f=1 Hz



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Conclusion

- **Presentation of some LFN measurements at low temperature in a 0.18 µm mixed-mode CMOS technology**
- **The improved McWhorter's model is applicable for NMOSFET and PMOSFET at RT and 77 K**
- **The Coulomb scattering coefficient is temperature dependent, it is lower at 77 K than at RT**
- **The LF noise model implemented in EKV3 allows precise modeling at RT and also at low temperature in a very wide range, from weak to strong inversion**
- **Measured EF parameter values are > 2 and are device- and technology-dependent**
- **Simple but efficient model for analog/digital IC design**

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