Noise Modeling at Quantum Level for Multi-Stack Gate Dielectric MOSFETs.

Zeynep Çelik-Butler

Industrial Liaisons: Ajit Shanware, Luigi Colombo, Keith Green, TI; Hsing-Huang Tseng, SEMATECH, Ania Zlotnicka, Freescale

Students:

Bigang Min, Siva Prasad Devireddy, Tanvir Morshed, Shahriar Rahman

University of Texas at Arlington

P. O. BOX 19072

Arlington, TX 76019

Outline

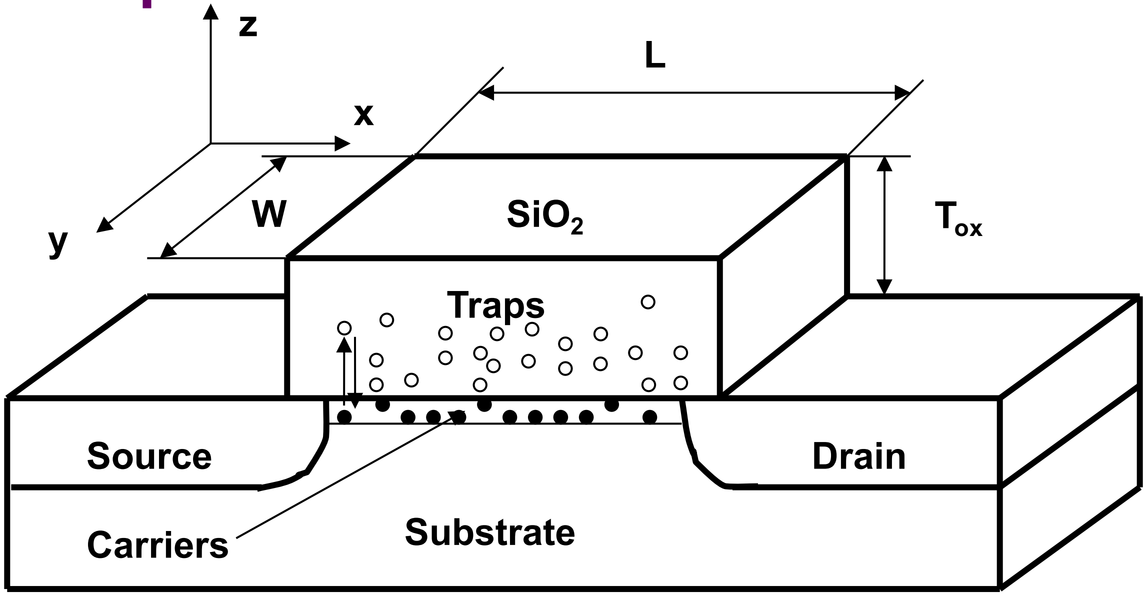
- Noise Modeling
  - Unified Flicker Noise Model
  - Multi-Stack Unified Noise Model (MSUN)
- Experimental Verification
  - Metal-Gated HfO_2/SiO_2 NMOSFETs – different interfacial layer processing
  - Poly-Gated HfSiON/SiON NMOSFETs – variable interfacial layer thickness
- Conclusions and Future Work

Unified Flicker Noise Model*

- Based on correlated number and mobility fluctuations theory.
- Equi-energy tunneling process.
- Traps in the gate dielectric trap/de-trap channel carriers
- Trapping/de-trapping phenomenon causes fluctuations in the carrier number.
- Fluctuations in carrier mobility due to remote Coulomb scattering from trapped charge.
- Uniform distribution of traps in the gate dielectric with respect to distance and energy level.

*K. K. Hung, P. K. Ko, C. Hu, Y. C. Cheng, "A unified model for the flicker noise in metal-oxide-semiconductor field-effect transistors," *IEEE Trans. Electron Devices*, vol. 37, pp.654-665, 1990.

Physical Mechanism for Noise



K. K. Hung, P. K. Ko, C. Hu, Y. C. Cheng, “A unified model for the flicker noise in metal-oxide-semiconductor field-effect transistors,” *IEEE Trans. Electron Devices*, vol. 37, pp.654-665, 1990.

Channel carriers tunnel back and forth from the traps in the gate oxide causing fluctuations in the number of carriers. By virtue of Coulomb scattering from oxide trapped charges there are fluctuations in carrier mobility that cause additional noise in correlation with the carrier number fluctuations.

Unified Flicker Noise Model Expressions

$$\tau = \tau_0 \exp(\gamma z)$$

$$\gamma = \frac{4\pi}{h}\sqrt{2m^*\Phi}$$

$$S_{I_d} = \frac{kTI_d^2}{\gamma fWL}\left(\frac{1}{N} \pm \alpha_{sc}\mu_{eff}\right)^2 N_t$$

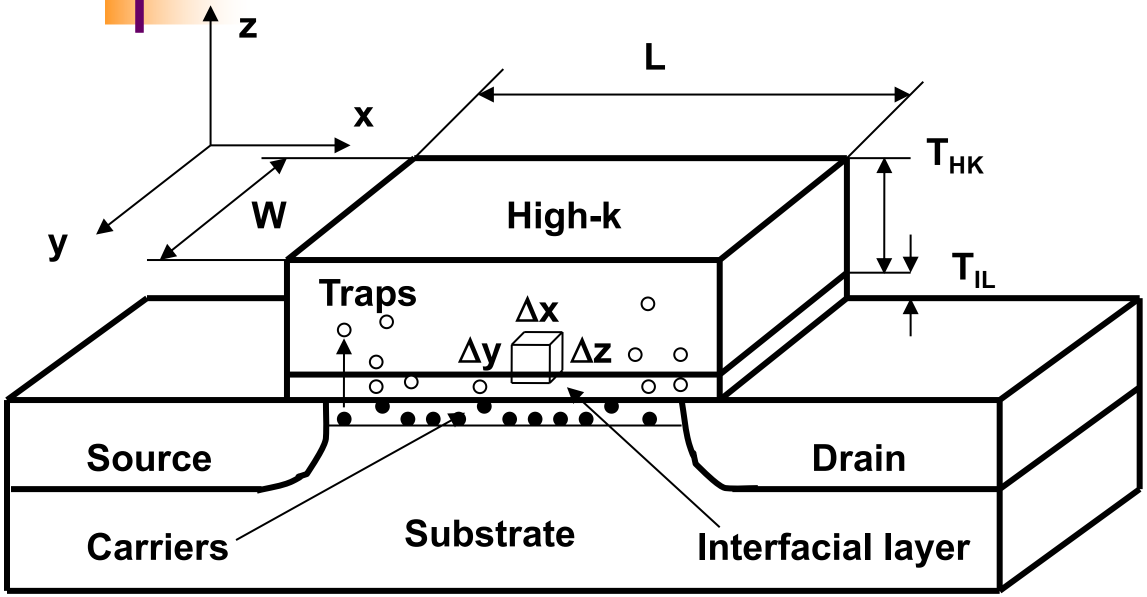
K. K. Hung, P. K. Ko, C. Hu, and Y. C. Cheng
IEEE Trans. Electron Devices, vol. 37, pp.654-665,1990

BSIM Low Frequency Noise Model

$$S_{Id} = \frac{kTq^2 I_d \mu_{eff}}{\gamma C_{ox} f^{EF} L_{eff}^2}\left[NOIA \log\left(\frac{N_0 + N^*}{N_L + N^*}\right) + NOIB\left(N_0 - N_L\right) + \frac{NOIC}{2}\left(N_0^2 - N_L^2\right)\right]$$

$$+ \frac{kTI_d^2 \Delta L_{clm}}{\gamma W f^{EF} L_{eff}^2}\left[\frac{NOIA + NOIB.N_L + NOIC.N_L^2}{\left(N_L + N^*\right)^2}\right]$$

High-k Gate Stack Scenario



Channel carriers tunnel into the traps in high-k and interfacial layer causing fluctuations in carrier number and mobility in a correlated way.

The uniform dielectric trap density assumption does not hold.

The different trap profiles and various physical properties of high-k/interfacial layer materials like physical thicknesses, barrier heights etc. affect the 1/f noise.

Multi-Stack Unified Noise Model (MSUN)

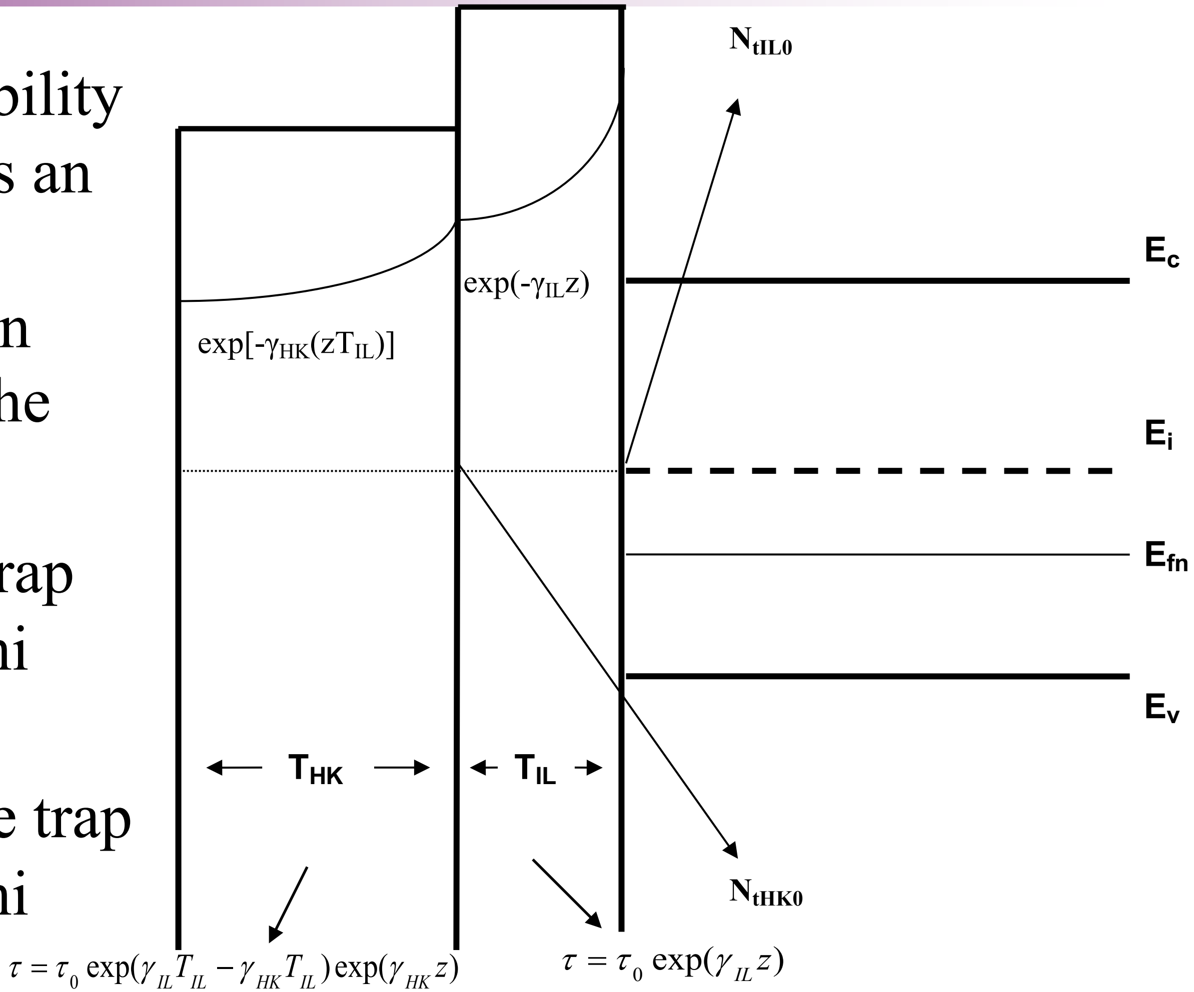
- Based on correlated number and mobility fluctuations theory
- Equi-energy tunneling process
- Traps in the gate dielectric layers trap/de-trap channel carriers
- Trapping/de-trapping phenomenon causes fluctuations in the carrier number
- Fluctuations in carrier mobility due to remote Coulomb scattering from trapped charge
- Scalable with regards to the high-k/interfacial layer physical thicknesses
- Takes different dielectric material properties into account
- Considers non-uniform distribution of traps in the high-k/interfacial layer with respect to distance and energy level

Typical Band Diagram for High-k Stack

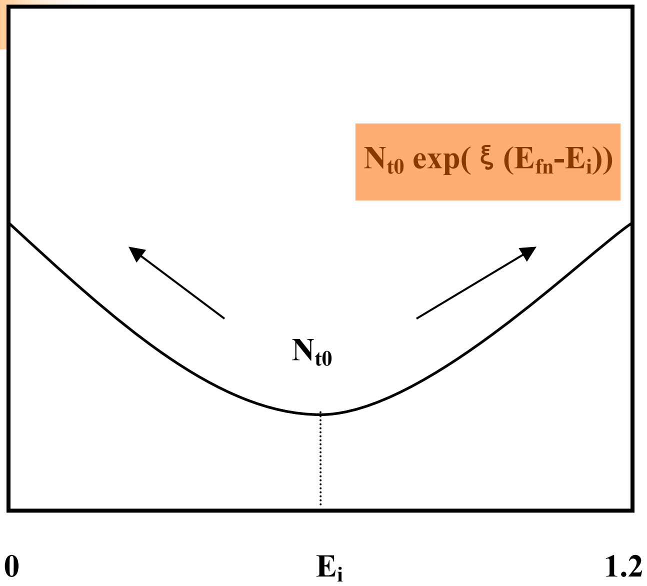
Carrier tunneling probability into the gate dielectric is an exponentially decaying function with attenuation rates corresponding to the dielectric material.

N_{tIL0} – IL/Si interface trap density at intrinsic Fermi level

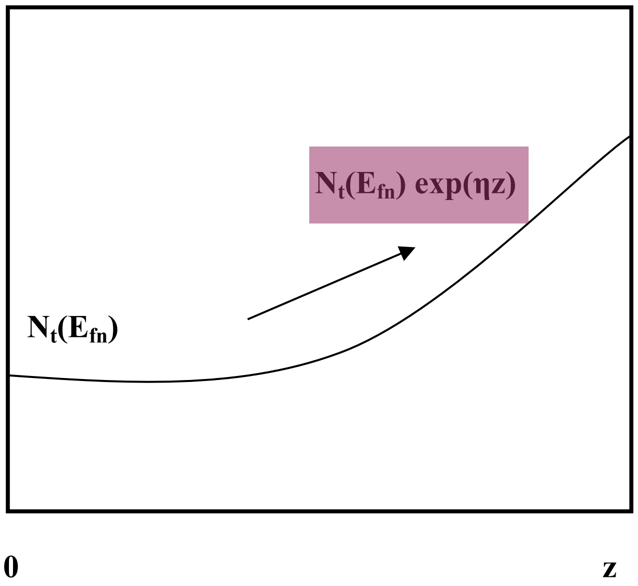
N_{tHK0} – HK/IL interface trap density at intrinsic Fermi level



Trap Density Profile in SiO_2



N_{t0} exp(ξ(E_{fn}-E_i))
=N_t(E_{fn})



N_{t0} is the trap density at the Si/SiO_2 interface and intrinsic Fermi level. Trap density increases exponentially towards the band edges at a rate defined by parameter ξ.

N_t(E_{fn}) is the trap density at the Si/SiO_2 interface and quasi-Fermi level. Trap density increases exponentially into the gate dielectric.

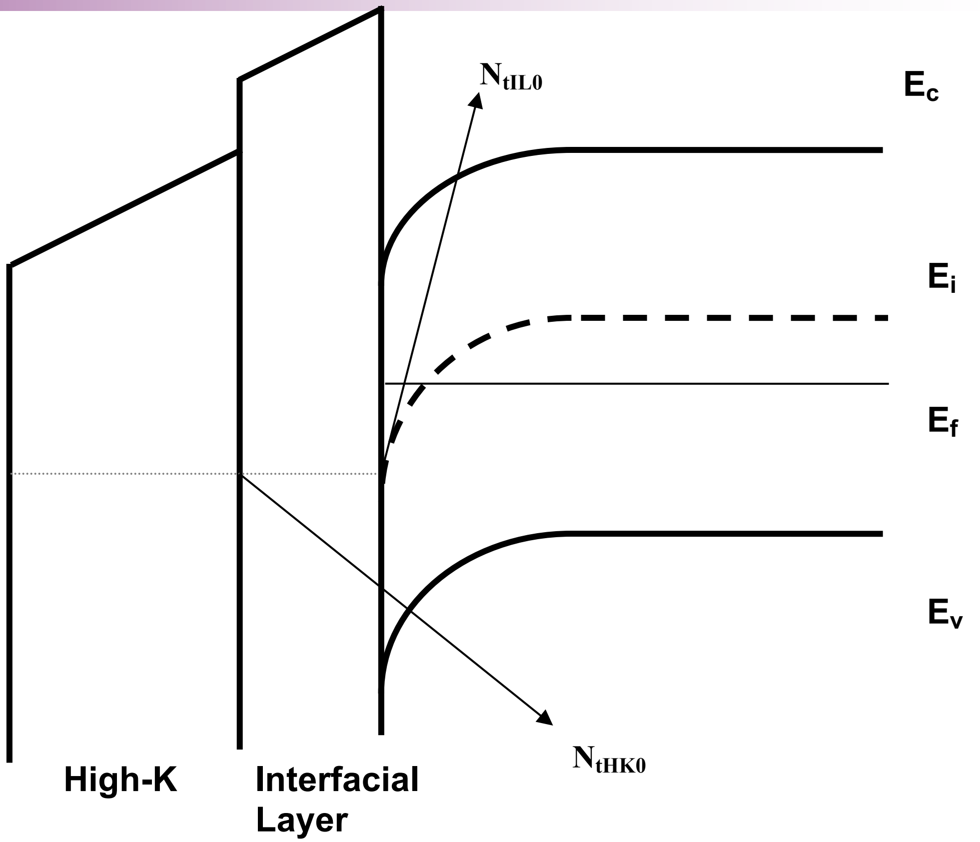
$$N_{tIL}(E_{fn},z) = N_{tIL0}\exp[\xi_{IL}(E_{fn}-E_i)+(q\lambda_{IL}V_{gIL}/T_{IL})z+\eta_{IL}z]$$

$$N_{tHK}(E_{fn},z) = N_{tHK0}\exp[\xi_{HK}(E_{fn}-E_i)+(q\lambda_{HK}V_{gHK}/T_{HK})z+\eta_{HK}z]$$

Z. Çelik-Butler, and T. Y. Hsiang, "Spectral dependence of 1/f$^\gamma$ noise on gate bias in n-MOSFETs," *Solid State Electron.*, vol. 30, pp. 419–423, 1987.

Modified Trap Profile by Energy Band Bending

The energy bands bend in both high-k and interfacial layers due to the applied gate voltage. Higher trap density towards the band edges means that the trap profile encountered by channel carriers at a particular location in the dielectric is altered due to band bending. This effect is reflected by the parameters λ_{IL} and λ_{HK}.



$$N_{tIL}(E_{fn},z) = N_{tIL0}\exp[\xi_{IL}(E_{fn}-E_i)+(q\lambda_{IL}V_{gIL}/T_{IL})z+\eta_{IL}z]$$

$$N_{tHK}(E_{fn},z) = N_{tHK0}\exp[\xi_{HK}(E_{fn}-E_i)+(q\lambda_{HK}V_{gHK}/T_{HK})z+\eta_{HK}z]$$

Z. Çelik-Butler, and T. Y. Hsiang, “Spectral dependence of $1/f^{\gamma}$ noise on gate bias in n-MOSFETs,” *Solid State Electron.*, vol. 30, pp. 419–423, 1987.

Trap Density in High-k Stack

Trap density for ($0<z<T_{IL}$)

$$N_{tIL}(E_{fn},z)=N_{tIL0}\exp[\xi_{IL}(E_{fn}-E_i)+(q\lambda_{IL}V_{gIL}/T_{IL})z+\eta_{IL}z]$$

$$\tau=\tau_0\exp(\gamma_{IL}z)$$

Trap density for ($T_{IL}<z<T_{HK}+T_{IL}$)

$$N_{tHK}(E_{fn},z)=N_{tHK0}\exp[\xi_{HK}(E_{fn}-E_i)+(q\lambda_{HK}V_{gHK}/T_{HK})z+\eta_{HK}z]$$

$$\tau=\tau_0\exp(\gamma_{IL}T_{IL}-\gamma_{HK}T_{IL})\exp(\gamma_{HK}z)$$

Total Noise

Power spectral density of the mean square fluctuations in the number of occupied traps for high-k/interfacial layer stack

$$S_{\Delta N_t}(x,f)=\int_{E_v}^{E_c}\int_{0}^{W}\int_{0}^{T_{IL}}4N_{tIL}(E,x,y,z)\Delta x f_t(1-f_t)\frac{\tau(E,x,y,z)}{1+\omega^2\tau^2(E,x,y,z)}dEdydz$$

$$+\int_{E_v}^{E_c}\int_{0}^{W}\int_{T_{IL}}^{T_{HK}+T_{IL}}4N_{t\,HK}(E,x,y,z)\Delta x f_t(1-f_t)\frac{\tau(E,x,y,z)}{1+\omega^2\tau^2(E,x,y,z)}dEdydz$$

Z. Çelik-Butler, “Different noise mechanisms in high-*k* dielectric gate stacks,” in *Proc. SPIE—Noise and Fluctuations*, pp. 177–184, 2005.

B. Min, S. P. Devireddy, Z. Çelik-Butler, A. Shanware, L. Colombo, K. Green, J. J. Chambers, M. R. Visokay, and A. L. P. Rotondaro, “Impact of interfacial layer on low-frequency noise of HfSiON dielectric MOSFETs,” *IEEE Trans. Electron Devices*, vol. 53, pp. 1459–1466, 2006.

MSUN Noise Model Simplification

- $f_t(1-f_t)$ ensures that only traps within few kT of E_{fn} contribute to fluctuations.
- Integral along the channel (x) approximated.
- The shape of the spectral density is modified from pure 1/f through functional form of N_t.
- Contribution to fluctuations from the high-k dielectric layer is much higher than that from the interfacial layer.

MSUN Noise Model Expressions

After appropriate substitution of various parameters, the power spectral density of the mean square fluctuations can be written as

$$S_{\Delta N_t}(x,f)=\left[\frac{N_{tIL0}\exp[\xi_{IL}(E_{fn}-E_i)]}{\gamma_{IL}\left(\omega\tau_0\right)^{(\beta_{IL}/\gamma_{IL})}}\int_{\omega\tau_0}^{\omega\tau_0\exp(\gamma_{IL}T_{IL})}\frac{u^{(\beta_{IL}/\gamma_{IL})}}{1+u^2}du+\frac{N_{tHK0}\exp[\xi_{HK}(E_{fn}-E_i)]}{\gamma_{HK}\left[\omega\tau_0\exp\{(\gamma_{IL}-\gamma_{HK})T_{IL}\}\right]^{(\beta_{HK}/\gamma_{HK})}}\int_{\omega\tau_0\exp(\gamma_{IL}T_{IL})}^{\omega\tau_0\exp(\gamma_{HK}T_{HK}+\gamma_{IL}T_{IL})}\frac{u^{(\beta_{HK}/\gamma_{HK})}}{1+u^2}du\right]$$

$$X\frac{4kTW\Delta x}{\omega}$$

Conduction Band Offset with Si

Tunneling Coefficients

$$\begin{cases}\gamma_{IL}=\dfrac{4\pi}{h}\sqrt{2m_{IL}{}^{*}\Phi_{IL}}\\ \gamma_{HK}=\dfrac{4\pi}{h}\sqrt{2m_{HK}{}^{*}\Phi_{HK}}\end{cases}$$

$$\beta_{IL}=[(q\lambda_{IL}V_{gIL}/T_{IL})+\eta_{IL}]$$

$$\beta_{HK}=[(q\lambda_{HK}V_{gHK}/T_{HK})+\eta_{HK}]$$

MSUN Model Expressions (con.)

Power spectral density for local current fluctuations

$$S_{\Delta I_d}(x,f) = \left[\frac{I_d}{W\Delta x} \left(\frac{1}{N(x)} \pm \alpha_{sc}\mu_{eff} \right) \right]^2 S_{\Delta N_t}(x,f)$$

Total noise power spectral density

$$S_{I_d}(f) = \frac{1}{L^2} \int_0^L S_{\Delta I_d}(x,f)\Delta x dx$$

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Experimental Verification

- Split C-V and DC Measurements
  - 10µm × 10µm devices
  - 78K & 100K – 350K in steps of 25K (metal gate)
  - 172K – 300K (poly gate)

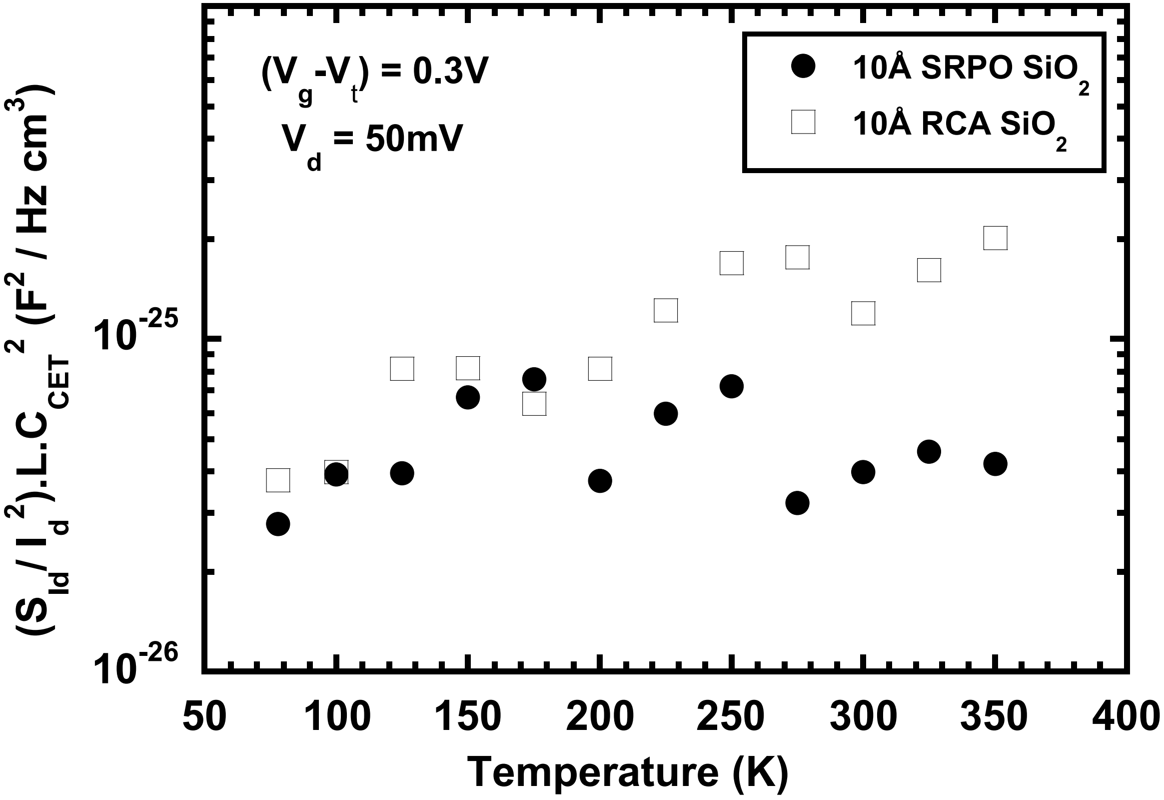
- Noise and DC Measurements
  - Metal gate
    - 0.165µm × 10µm devices
    - 78K & 100K – 350K in steps of 25K
  - Poly gate
    - (0.20-0.25)µm × 10µm devices
    - 172K – 300K

- Noise Modeling and Analysis
  - Unified Flicker Noise Model
  - Multi-Stack Unified Model

Metal Gated HfO_2/SiO_2 MOSFETs

Gate Electrode	High-k	IL Type	IL Thickness
TaSiN	27Å HfO_2 (ALD)	SRPO SiO_2	10Å
TaSiN	27Å HfO_2 (ALD)	RCA SiO_2	10Å

Normalized Noise vs. Temperature

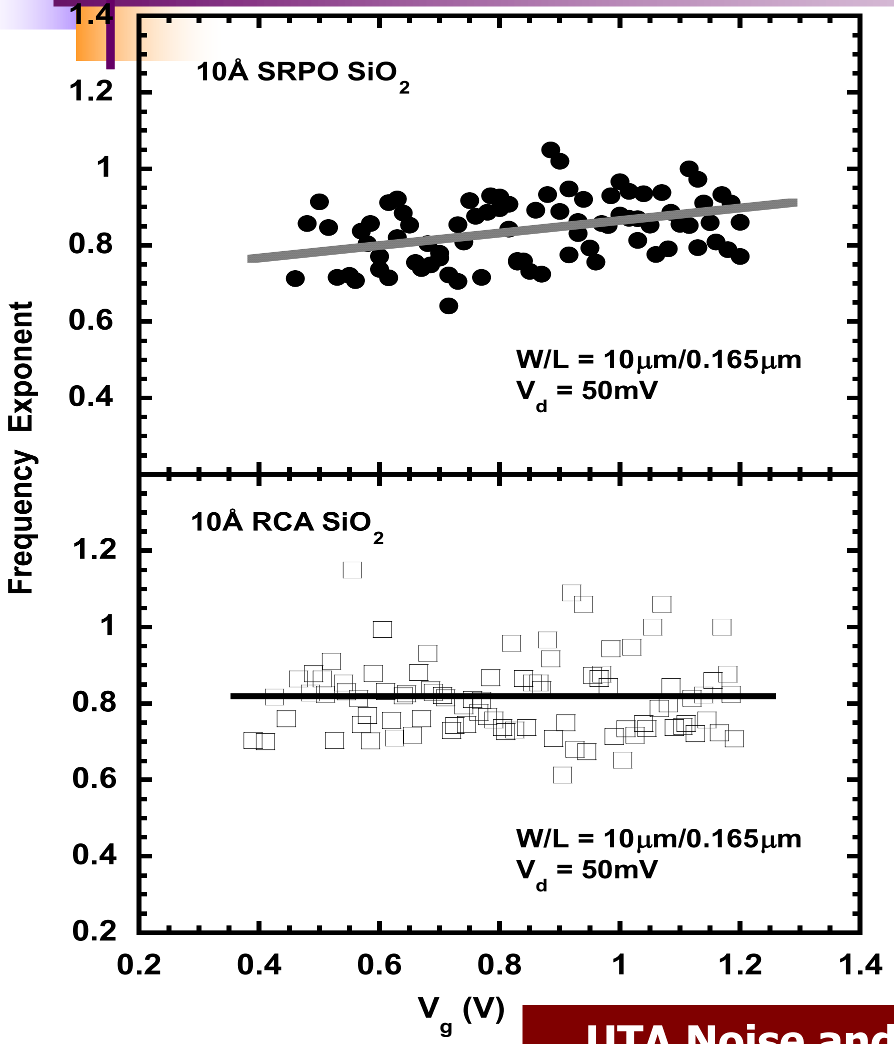


Normalized noise for the two process splits shows no clear dependence on temperature at all bias points.

Generally, the magnitude of 10Å SRPO device is lower.

Metal-Gated HfO_2/SiO_2

Parameter Extraction



The dependence of noise power spectral density on frequency mainly comes from the term,

$(\omega)^{-(1+\beta_{HK}/\gamma_{HK})}$ where,

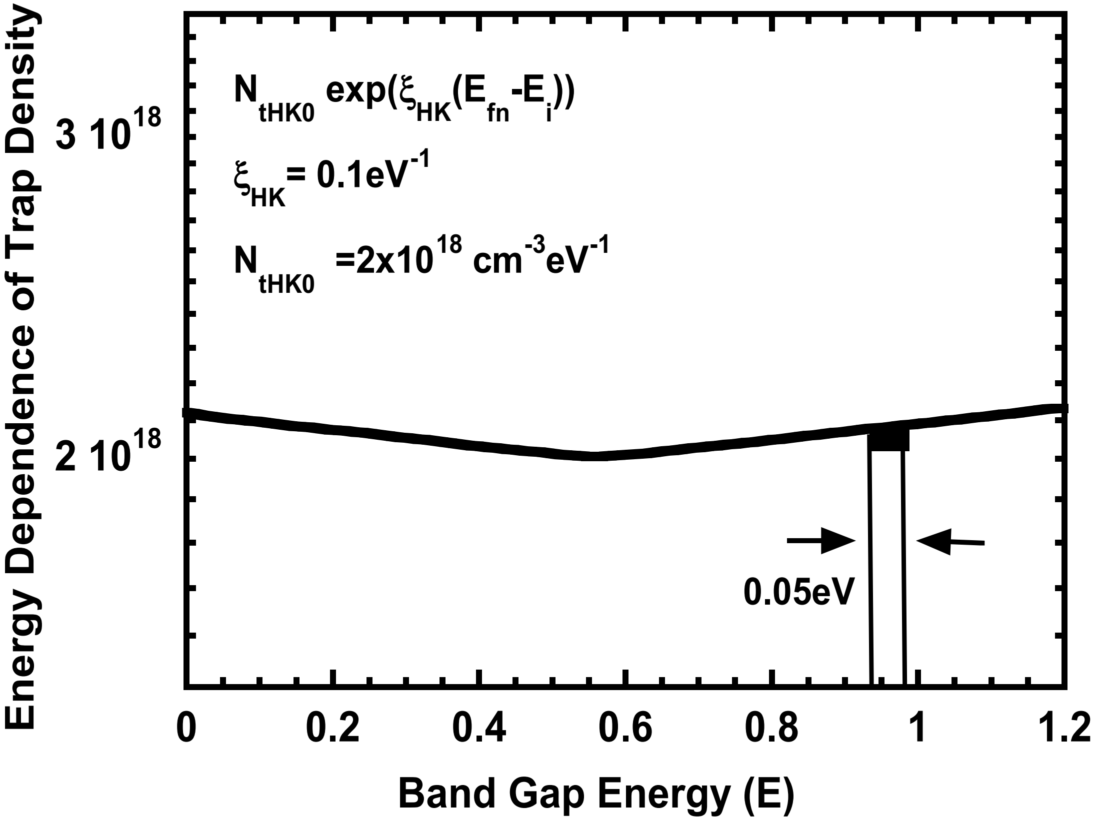
$$\beta_{HK} = [(q\lambda_{HK}V_{gHK}/T_{HK}) + \eta_{HK}]$$

The frequency exponent α for the 1-100Hz region is plotted against the applied gate bias.

A straight line fit is made to the data from which η_{HK} ,λ_{HK} are extracted

Metal-Gated HfO$_2$/SiO$_2$

Energy Dependence of Trap Density



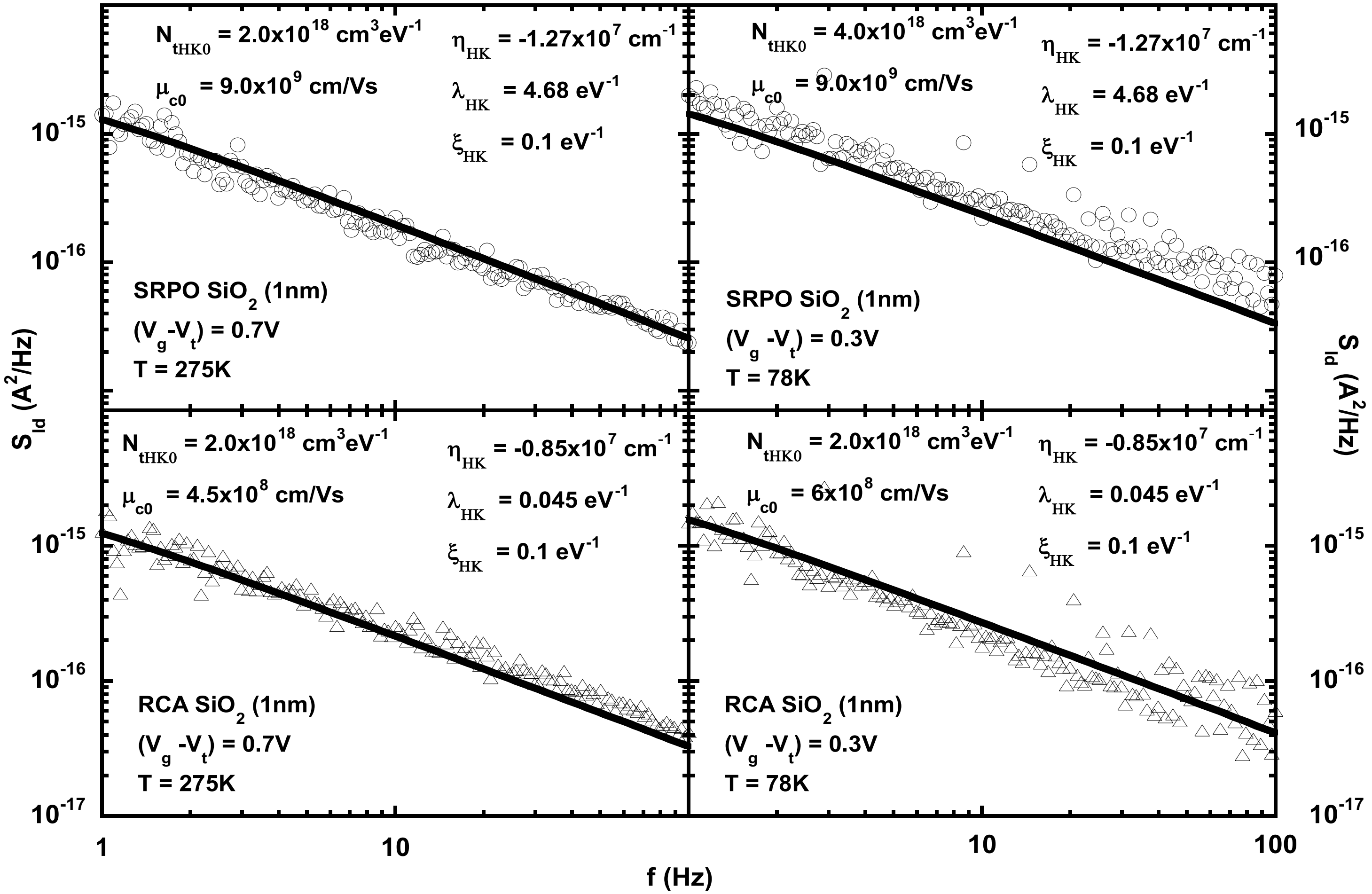
The trap density variation with respect to energy is represented as an exponentially varying function.

The energy interval swept by the quasi Fermi level for the temperature and the bias range considered in this work is 0.05eV.

Metal-Gated HfO_2/SiO_2

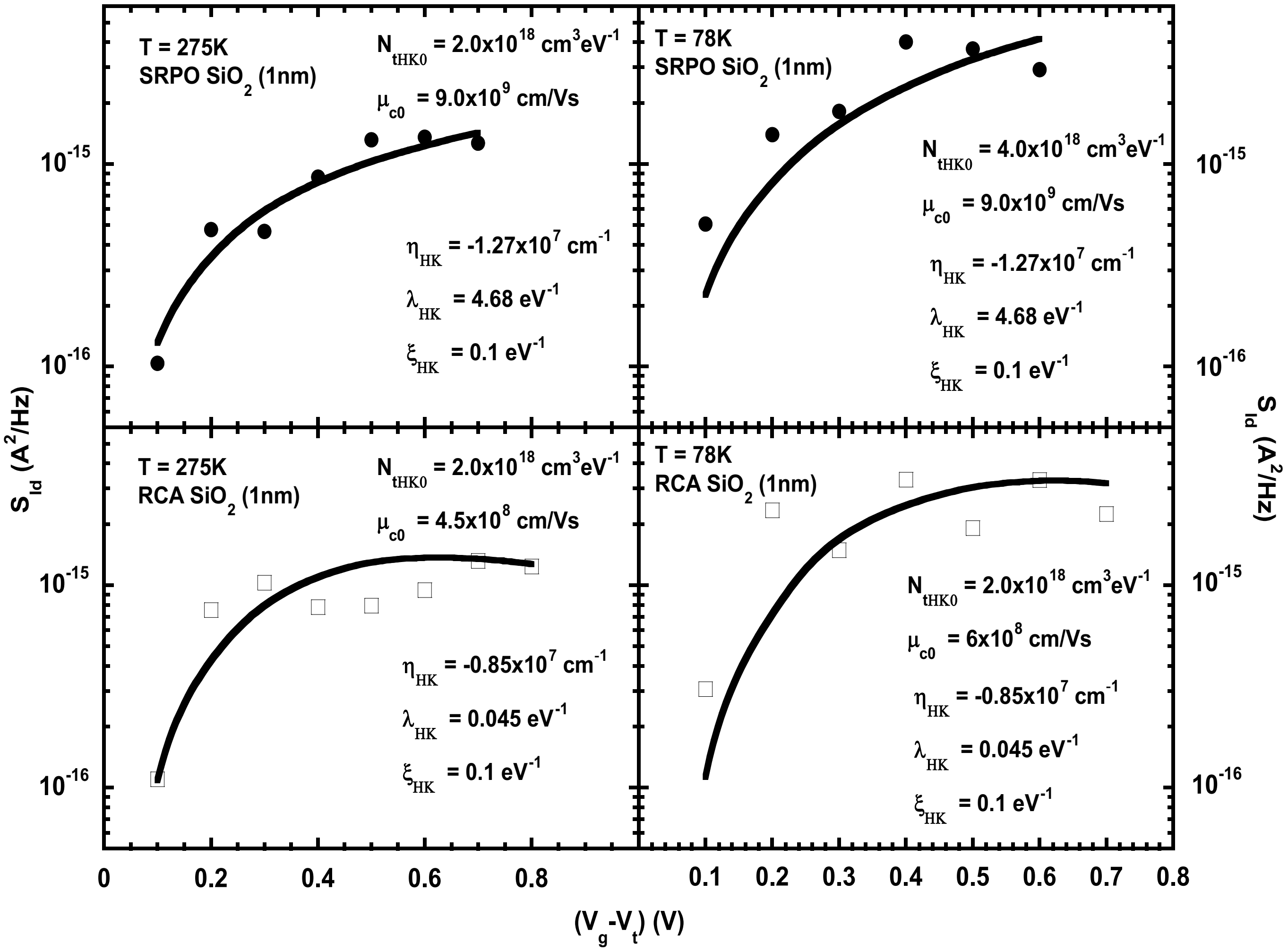
MSUN Model

Metal-Gated HfO_2/SiO_2



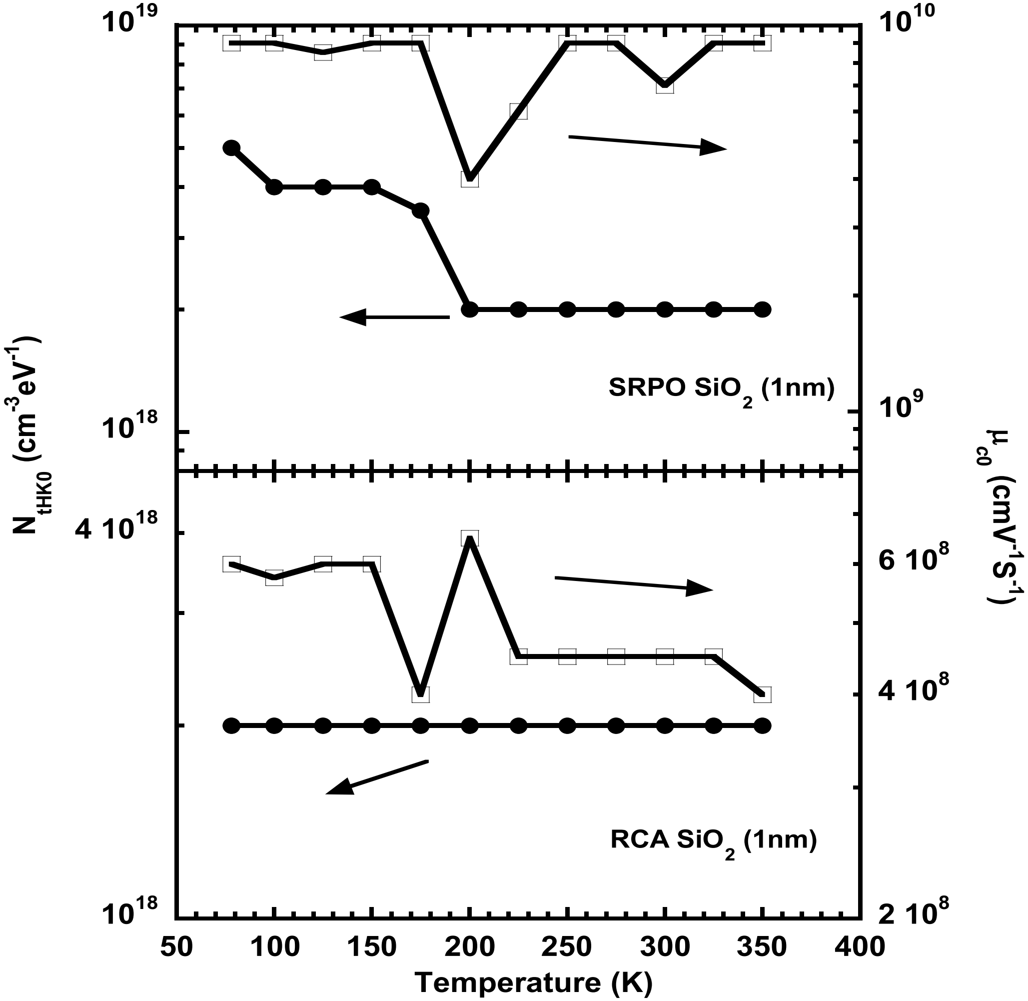
MSUN Model

Metal-Gated HfO_2/SiO_2



Effective Oxide Trap Density vs. Temperature

N_{t0HK} is constant for all temperatures and the non-uniformity in trap density is modeled by η_{HK} ,λ_{HK}



MSUN Model

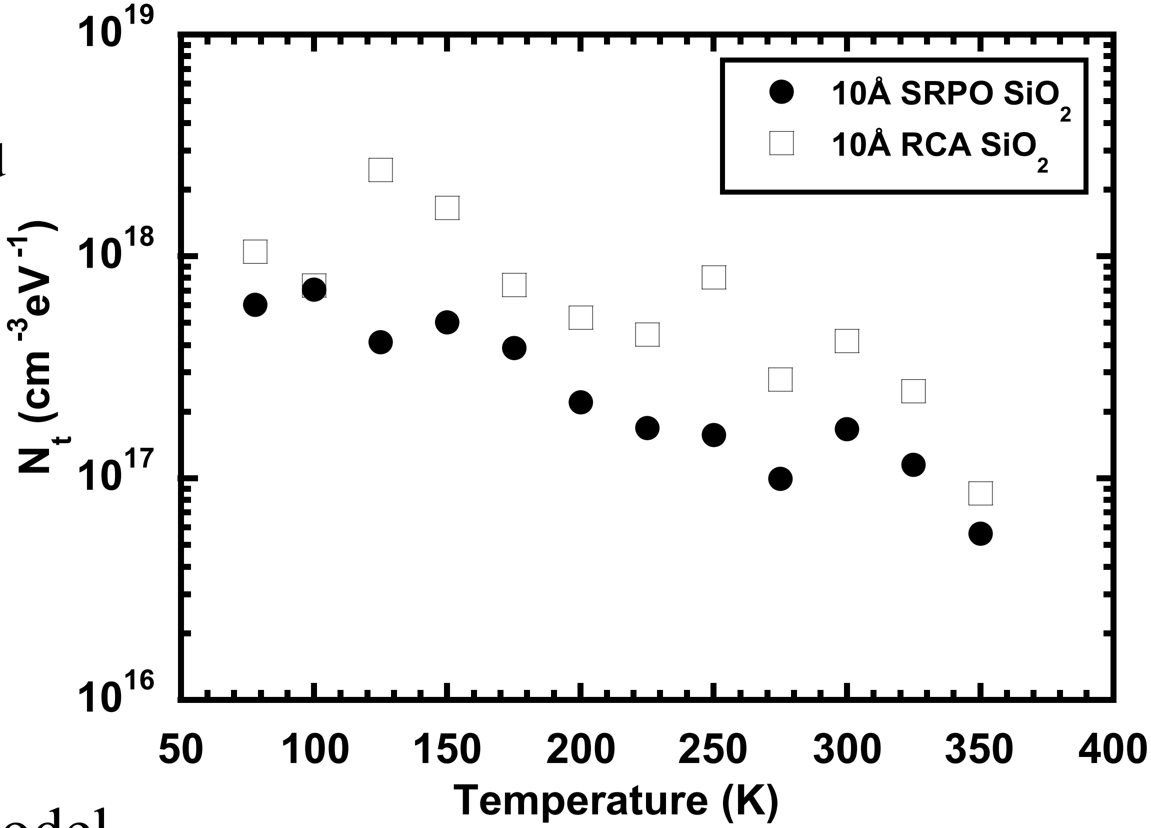
Metal-Gated HfO_2/SiO_2

Effective Oxide Trap Density vs. Temperature

The overall effective trap density (N_t) is extracted using the Unified Flicker Noise Model.

In general, the values tend to increase with a decrease in temperature.

This is not consistent with the uniform trap density assumption at the core of the model.



Original Unified Noise Model

Metal-Gated HfO_2/SiO_2

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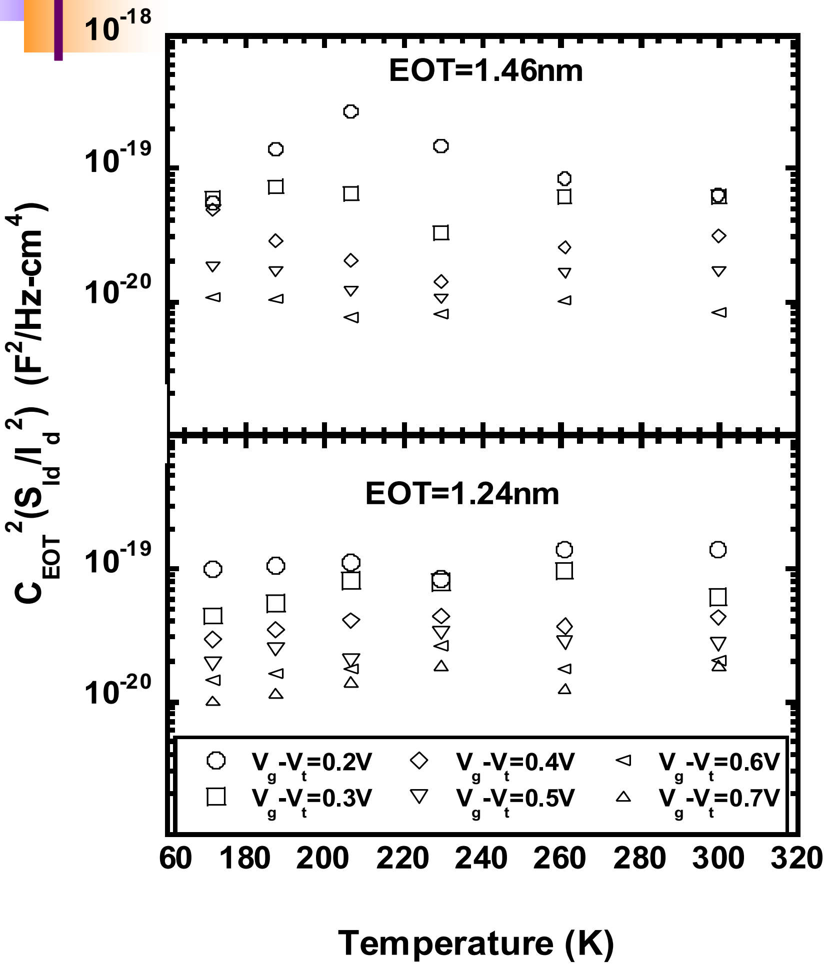
Poly Gated HfSiON/SiON MOSFETs

- NMOS HfSiON with same high-k thickness (3.0 nm) and different interfacial layers (IL)

Dielectrics	EOT (nm)	IL (nm)	Length (μm)	Width (μm)	
HfSiON	1.24	0.8	0.20	10	Variable temperature 1/f noise measurement has been done.
HfSiON	1.33	1.0	0.20,0.25	10	
HfSiON	1.46	1.5	0.20,0.25	10	
HfSiON	1.66	1.8	0.14 ~ 0.25	10	

Temperature Dependence of Low Frequency Noise Spectral Density



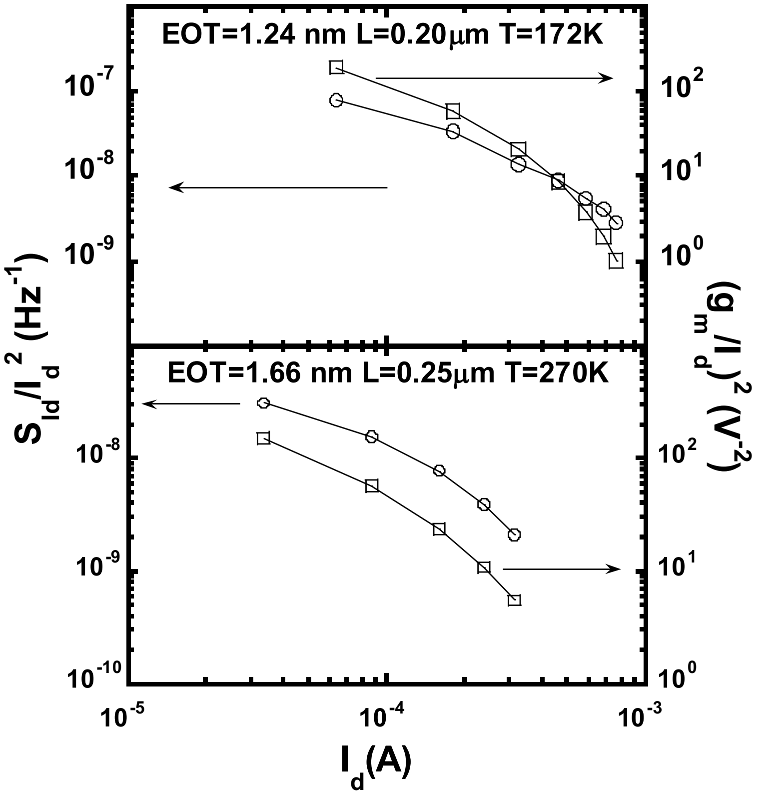
- Normalized current noise spectral density did not show any noticeable dependence on temperature.

- The observed noise behavior is not affected by any temperature sensitive process.

- Remote optical phonon scattering may not have a significant impact on low frequency noise characteristics although it has a profound effect on mobility behavior (presented last year).

Poly-Gated HfSiON / SiON

Low Frequency Noise Mechanism



Correlated Number and Mobility Fluctuation Model[1]:

$$\frac{S_{Id}}{I_d^2} = (1+\alpha\mu_{eff}C_{ox}I_d / g_m)^2 (\frac{g_m}{I_d})^2 S_{Vfb}$$

Hooge's Bulk Mobility Fluctuation Model[9]:

$$\frac{S_{Id}}{I_d^2} = \frac{q^2\alpha_h < \mu_{eff} > V_d}{fL^2 I_d}$$

Correlated number and surface mobility fluctuation mechanism was observed to dominate for devices with different interfacial layer thicknesses in the experimental temperature range

Poly-Gated HfSiON / SiON

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[9] F.N. Hooge. IEEE Trans. Electron Devices **41.** 1926 (1994).

The *MSUN* Model

According to original Unified Model, current noise spectral density can be shown as

$$S_{\Delta I_d}(x,f) = \left[\frac{I_d}{\Delta N}(1+\alpha\mu N)\right]^2 S_{\Delta N_t}(x,f) \qquad (1)$$

Considering tunneling through a double step barrier, we can show

$$\begin{aligned} S_{\Delta N_t} &= 4kTW\Delta x\int_0^{T_{IL}} N_{tIL0}\exp[\xi_{IL}(E_{fn}-E_i)+q\lambda_{IL}\frac{V_{IL}}{T_{IL}}z+\eta_{IL}z]\frac{\tau_{IL}}{1+\omega^2\tau_{IL}{}^2}\,dz \\ &+ 4kTW\Delta x\int_{T_{IL}}^{T_{IL}+T_{HK}} N_{tHK0}\exp[\xi_{HK}(E_{fn}-E_i)+q\lambda_{HK}\frac{V_{HK}}{T_{HK}}z+\eta_{HK}z]\frac{\tau_{HK}}{1+\omega^2\tau_{HK}{}^2}\,dz \end{aligned} \qquad (2)$$

The final expression of S$_{id}$(A^2/Hz) using the new model for high-k gate devices becomes

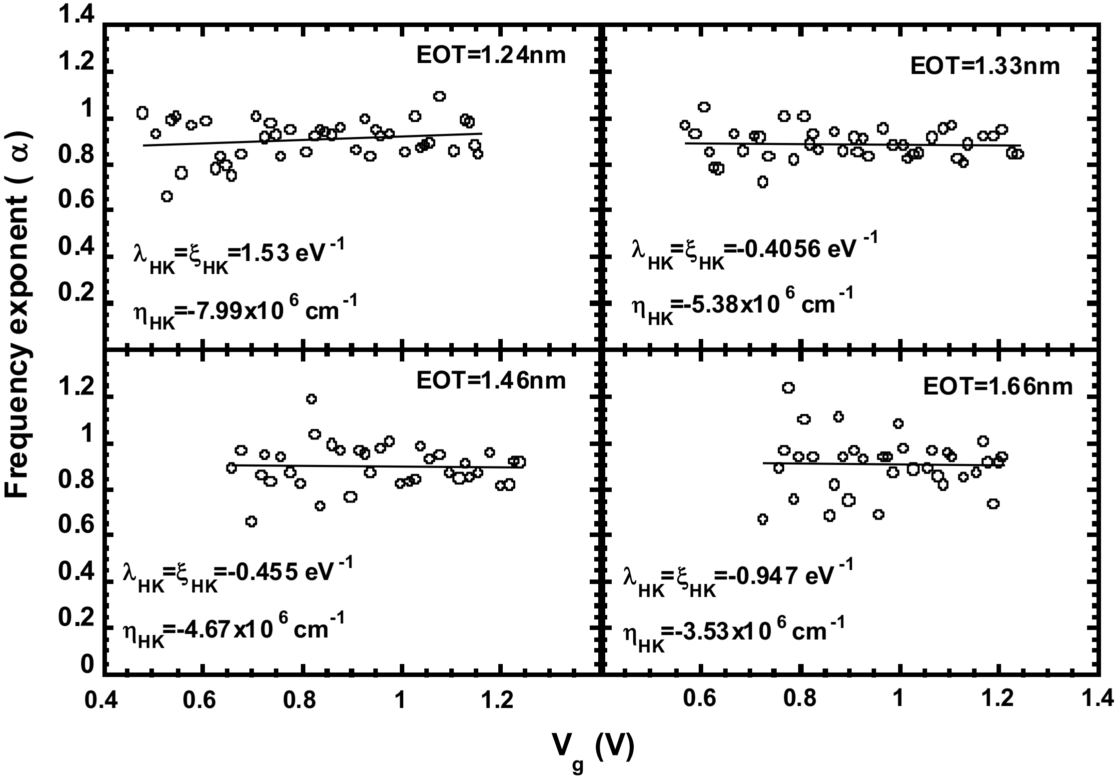
$$S_{I_d}(f) = \frac{4kTI_d{}^2}{WL^2}\int_0^L\left(\alpha\mu_{eff}+\frac{1}{N(x)}\right)^2\left[\begin{aligned} &\frac{N_{tIL0}\exp[\xi_{IL}(E_{fn}-E_i)]}{\gamma_{IL}\tau_{IL0}{}^{(q\lambda_{IL}V_{IL}/T_{IL}+\eta_{IL})/\gamma_{IL}}(2\pi f)^{1+(q\lambda_{IL}V_{IL}/T_{IL}+\eta_{IL})/\gamma_{IL}}}\int_{2\pi f\tau_{IL0}}^{2\pi f\tau_{IL0}\exp(\gamma_{IL}T_{IL})}\frac{u_{IL}{}^{(q\lambda_{IL}V_{IL}/T_{IL}+\eta_{IL})/\gamma_{IL}}}{1+u_{IL}{}^2}\,du_{IL} \\ &+\frac{N_{tHK0}\exp[\xi_{HK}(E_{fn}-E_i)]}{\gamma_{HK}\tau_{HK0}{}^{(q\lambda_{HK}V_{HK}/T_{HK}+\eta_{HK})/\gamma_{HK}}(2\pi f)^{1+(q\lambda_{HK}V_{HK}/T_{HK}+\eta_{HK})/\gamma_{HK}}}\int_{2\pi f\tau_{HK0}}^{2\pi f\tau_{HK0}\exp(\gamma_{HK}T_{HK})}\frac{u_{HK}{}^{(q\lambda_{HK}V_{HK}/T_{HK}+\eta_{HK})/\gamma_{HK}}}{1+u_{HK}{}^2}\,du_{HK}\end{aligned}\right]dx \qquad (3)$$

MSUN Model Parameter List

High-k dielectric layer parameters		Interfacial layer parameters	
N_{tHK0}	Mid-gap trap density at the IL/high-k interface	N_{tIL0}	Mid-gap trap density at the substrate/IL interface
μ_{c0}	Mobility fluctuation coefficient	μ_{c0}	Mobility fluctuation coefficient
λ_{HK}	Band bending parameter corresponding to the high-k layer	λ_{IL}	Band bending parameter corresponding to the IL
η_{HK}	Spatial trap distribution parameter for the high-k layer	η_{IL}	Spatial trap distribution parameter for the interfacial layer
ξ_{HK}	Parameter for the energy distribution of traps in the high-k dielectric layer	ξ_{IL}	Parameter for the energy distribution of traps in the interfacial layer

- If the published trap density values are chosen for N_{tIL0} and N_{tHK0} the noise contribution of the interfacial layer is insignificant when compared to the total device noise. The interfacial layer parameters do not play any effective role in the data fitting
- For the high-k layer, as discussed earlier, $\lambda_{HK}= \xi_{HK}$, so the number of effective fitting parameters reduce to 4.

Extracted ξ, λ, η



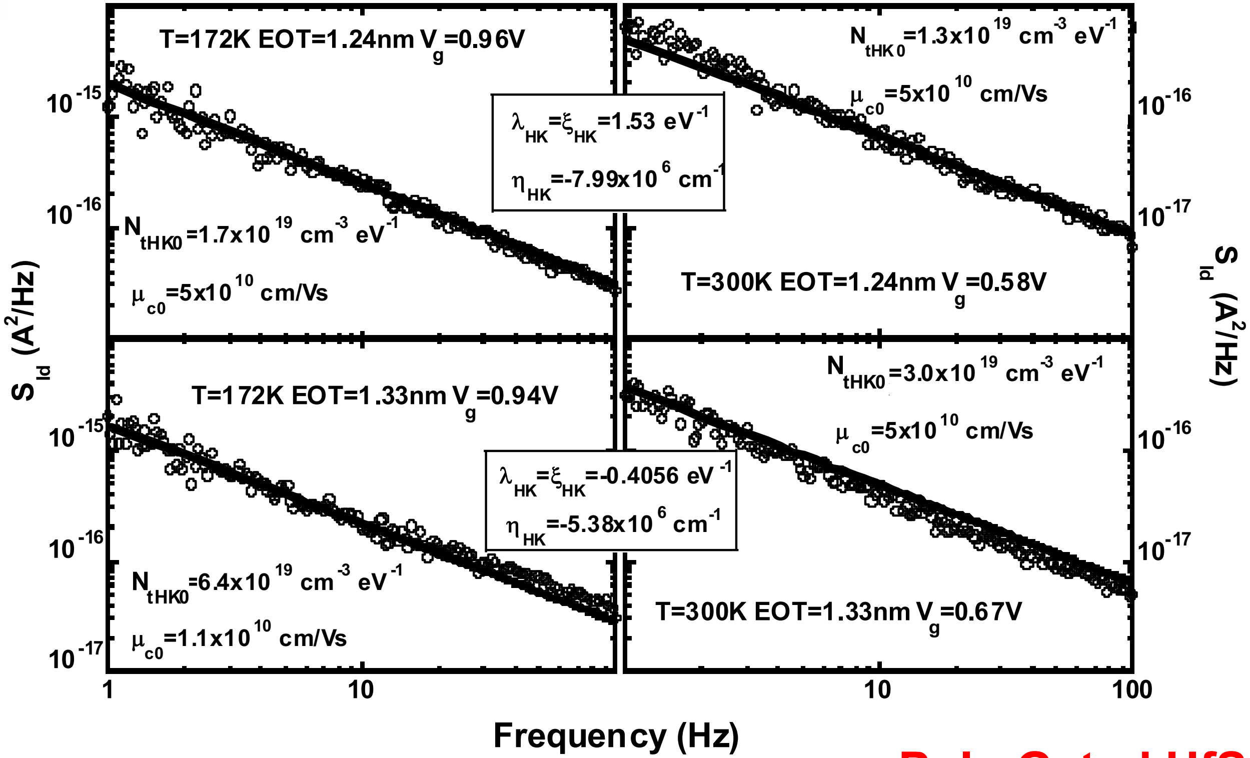
From Eq (3) we can show

$$\alpha = 1+(q\lambda_{HK}V_{HK}/T_{HK}+\eta_{HK})/\gamma_{HK}$$

From a linear fit of *α* as a function of *V_g* for individual devices at all temperatures, the energy dependence parameters ξ, λ and the spatial distribution parameter η were extracted. The extracted values are shown on the plots.

Poly-Gated HfSiON / SiON

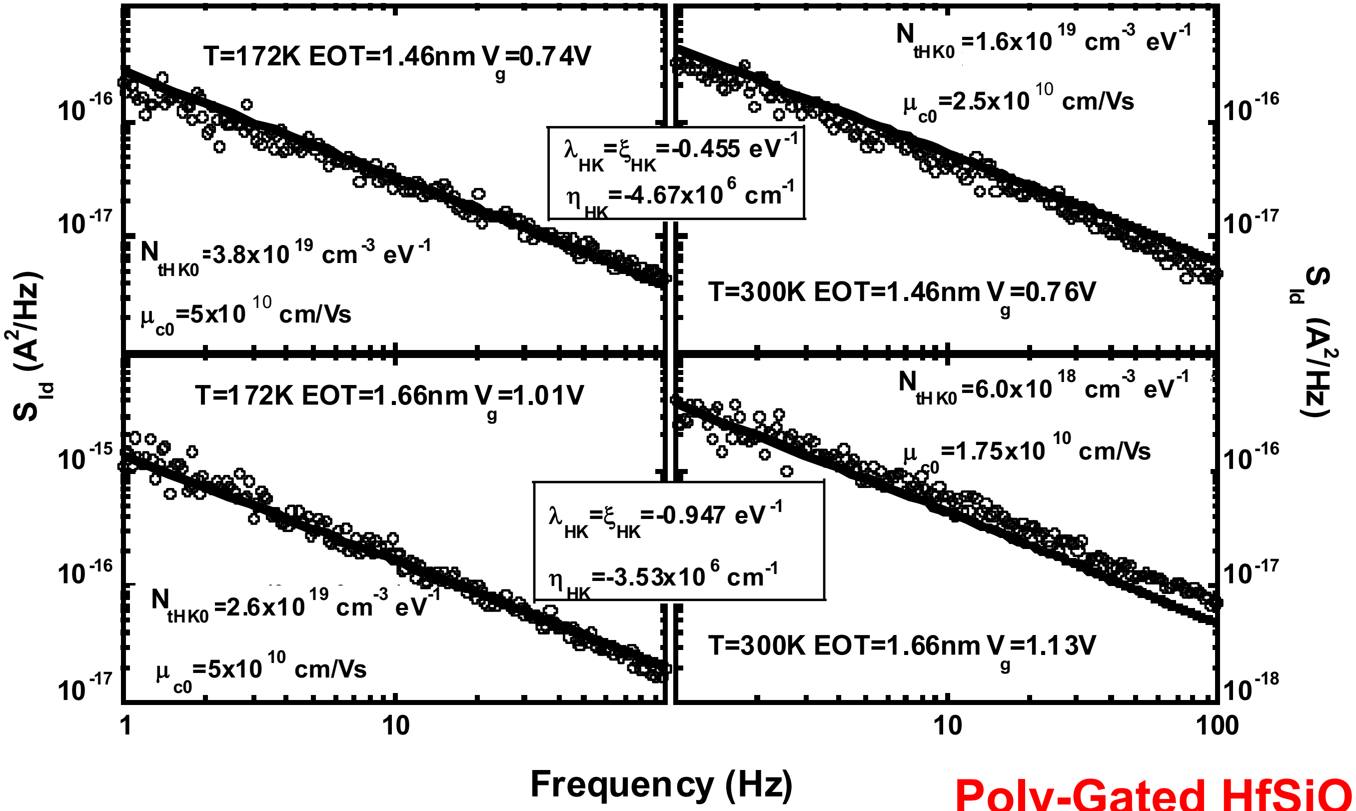
Data Vs *MSUN* Model Predictions for LF Noise Spectra



Poly-Gated HfSiON / SiON

The calculated current noise spectral density S_{Id} is compared to the data for devices with four different IL thicknesses and in the experimental temperature range of 172K-300K.

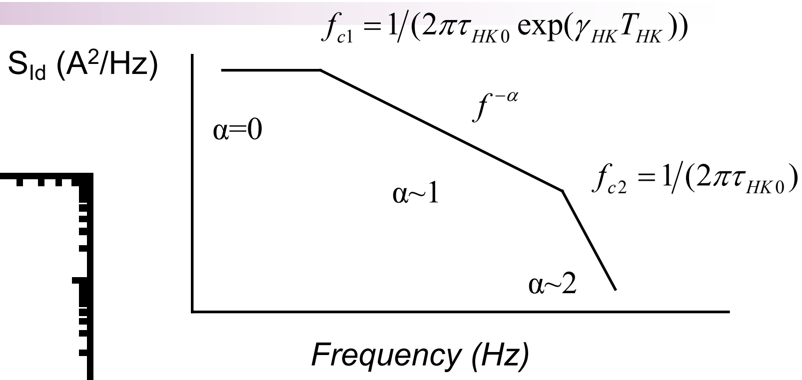
Data Vs *MSUN* Model Predictions for LF Noise Spectra

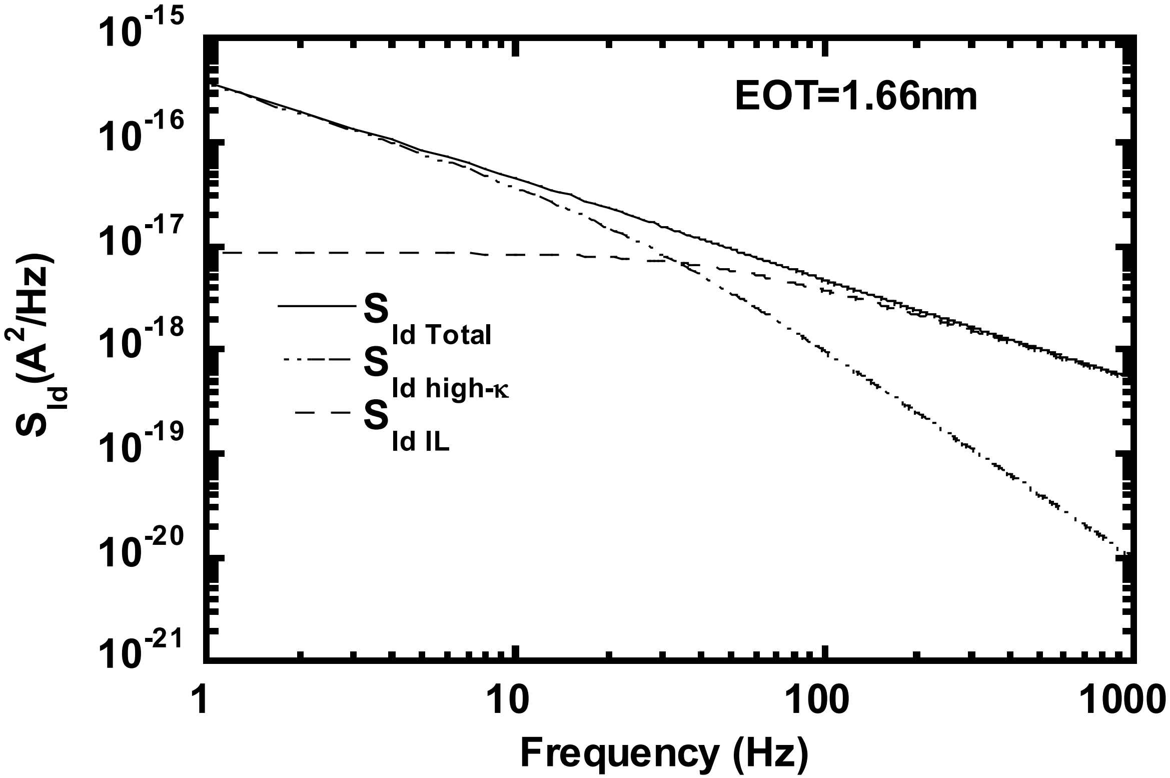


Poly-Gated HfSiON / SiON

Excellent agreement between data and model predictions was observed irrespective of IL thickness at all temperatures.

Data Vs *MSUN* Model Predictions for LF Noise Spectra



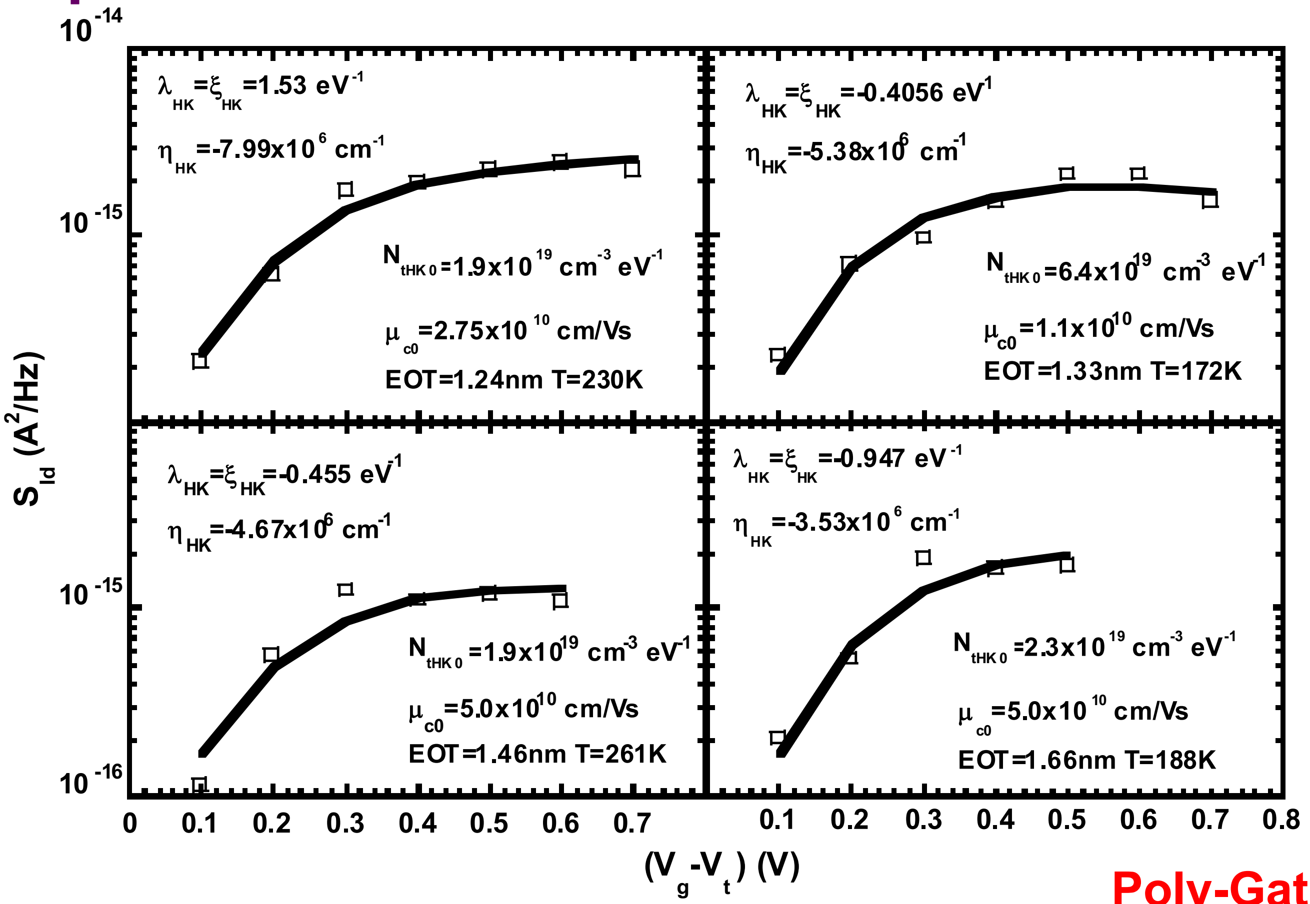


A special phenomena was observed for the devices with the thickest gate oxide.

The higher frequency components in the device noise are contributed by traps closer to the interface, where as the traps further away contribute to the lower frequency components.

For the devices with T_{IL}=1.8nm, the characteristic corner frequency was calculated to be f_{c2}~ 33Hz. Below 33 Hz the noise was contributed by the high-k layer. Above this limit noise contribution was primarily from the IL layer.

Data Vs *MSUN* Model Predictions for Bias Dependence



- The fit was good in the bias range of moderate inversion to strong inversion, for devices with all different IL thicknesses in the experimental temperature range.

Poly-Gated HfSiON / SiON

Extracted *MSUN* Model Parameters

EOT=1.28nm, $\lambda_{HK}=\xi_{HK}$ =1.538eV^{-1}, η_{HK} =-7.99x10^{6} cm^{-1}			EOT=1.33nm, $\lambda_{HK}=\xi_{HK}$ =-0.4056eV^{-1}, η_{HK}=-5.38x10^{6} cm^{-1}		
T(K)	N_{tHK0}(cm^{-3} eV^{-1})	μ_{c0}(cm/Vs)	T(K)	N_{tHK0}(cm^{-3} eV^{-1})	μ_{c0}(cm/Vs)
172	1.7x10^{19}	5.0x10^{10}	172	6.4x10^{19}	1.1x10^{10}
188	1.8x10^{19}	5.0x10^{10}	188	6.1x10^{19}	3.0x10^{10}
207	1.7x10^{19}	3.0x10^{10}	207	5.6x10^{19}	4.5x10^{10}
230	1.9x10^{19}	2.75x10^{10}	230	5.9x10^{19}	3.5x10^{10}
261	1.4x10^{19}	5.0x10^{10}	261	3.6x10^{19}	1.7x10^{10}
300	1.3x10^{19}	5.0x10^{10}	300	3.0x10^{19}	5.0x10^{10}
EOT=1.46nm, $\lambda_{HK}=\xi_{HK}$ = -0.455eV^{-1}, η_{HK}=-4.67x10^{6} cm^{-1}			EOT=1.66nm, $\lambda_{HK}=\xi_{HK}$ = -0.947eV^{-1}, η_{HK}=-3.53x10^{6} cm^{-1}		
T(K)	N_{tHK0}(cm^{-3} eV^{-1})	μ_{c0}(cm/Vs)	T(K)	N_{tHK0}(cm^{-3} eV^{-1})	μ_{c0}(cm/Vs)
172	3.8x10^{19}	5.0x10^{10}	172	2.6x10^{19}	5.0x10^{10}
188	3.1x10^{19}	5.0x10^{10}	188	2.3x10^{19}	5.0x10^{10}
207	2.4x10^{19}	5.0x10^{10}	207	1.4x10^{19}	7.5x10^{10}
230	1.5x10^{19}	2.25x10^{10}	230	1.6x10^{19}	5.0x10^{10}
261	1.9x10^{19}	5.0x10^{10}	250	1.6x10^{19}	5.0x10^{10}
300	1.6x10^{19}	2.5x10^{10}	270	9.0x10^{18}	3.0x10^{10}
			300	6.0x10^{18}	1.75x10^{10}

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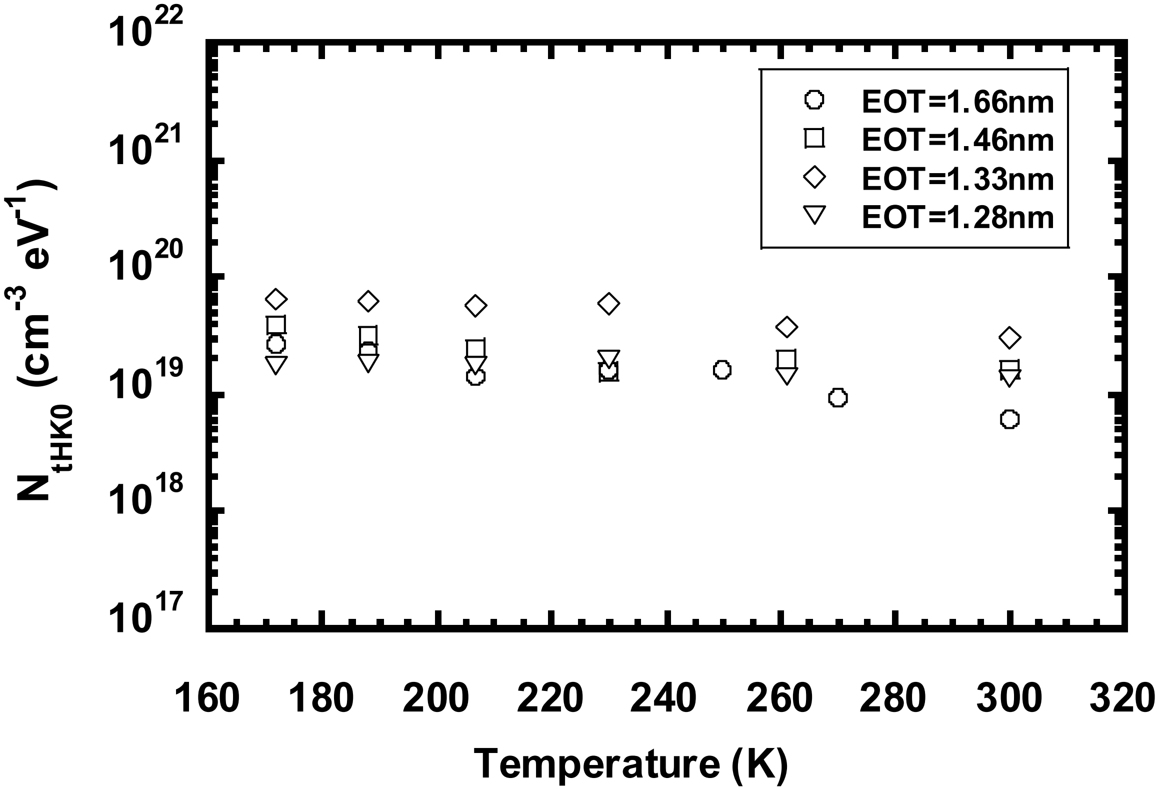
Extracted N_{tHK0}



- N_{tHK0} values extracted using the *MSUN* Model
  - Shows consistency over the whole experimental temperature range
  - Shows consistency with devices having different IL thickness

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Dependence of N_{tHK} on Energy

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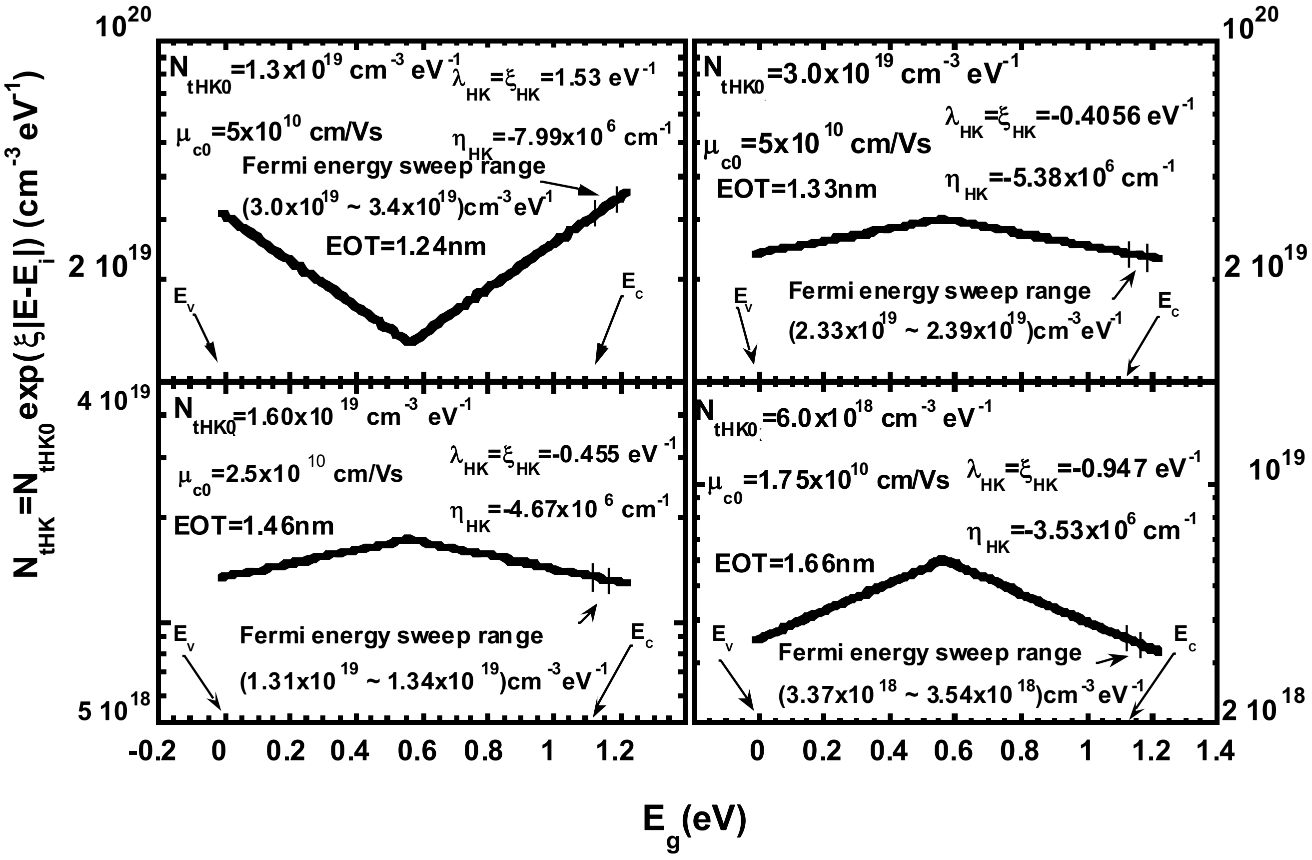

The active trap densities as probed by the quasi-Fermi energy and it's excursion is shown for devices with different IL thicknesses.

As the excursion range is comparatively small, the calculated trap density outside the highlighted region may not correctly represent actual device characteristics.

At 300K, the active trap density was observed to be IL dependent. The thinnest gate oxide devices showed highest active trap density.

Results I

- The temperature dependence of extracted trap density is inconsistent with the core model assumption.
- Multi-Stack Unified Noise (MSUN) model is proposed to predict noise in high-k/interfacial layer MOSFETs.
- It is scalable with respect to HK/IL thicknesses, temperature and applied bias.
- It accounts for the material properties of constituent dielectric materials and the non-uniform dielectric trap density profile with respect to energy and location in dielectric.
- Four model parameters
  - Mid-gap trap density at the IL/high-k interface
  - Parameter for the energy distribution of traps in the high-k dielectric layer
  - Spatial trap distribution parameter for the high-k layer
  - Mobility fluctuation coefficient

Results II

- The model is in excellent agreement with the experimental data down to cryogenic temperatures.
  - Metal-Gated HfO_2/SiO_2 NMOSFETs – different interfacial layer processing
  - Poly-Gated HfSiON/SiON NMOSFETs – variable interfacial layer thickness
  - Metal-Gated HfSiON/SiON MOSFETs – different nitridation techniques

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