Noise and Random Telegraph Signals in Nanoelectronic Devices

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Outline

- **Motivation:** **Problems Encountered as the Devices Shrink, Frequencies Increase, and Voltages Reduce**
- **Improved Model for 1/f Noise in MOSFETs**
- **Random Telegraph Signals in MOSFETs**
  - **Complex RTS**
  - **Extraction of trapping parameters using RTS**

UTA - Noise Characterization Facilities

- 6' x 6' x 8' Shielded Room
- 3 Spectrum and Signal Analyzers, *f*=1 μHz - 20 GHz.
- 3 Cryostats, *T*= 2 K to 350 K.

- Various Lock-ins, Preamps, System Controllers, Battery Operated Sources etc.
- Optical Equipment
- Computer Software for Modeling

Problems Encountered as the Devices Shrink, Frequencies Increase, and Voltages Reduce

- Signal-to-noise ratio decreases.

- Noise models based on large number of electrons break down.

- Quantum effects become dominant.

Signal to Noise Ratio Decreases

- For a MOSFET
  - Start from W=100µm, L=10µm, t_{ox}=800Å, N_{SS}=4x10^{10} eV^{-1}cm^{-2}.
  - Assume scaling factor is K.
  - Assume trap and surface state densities remain the same.

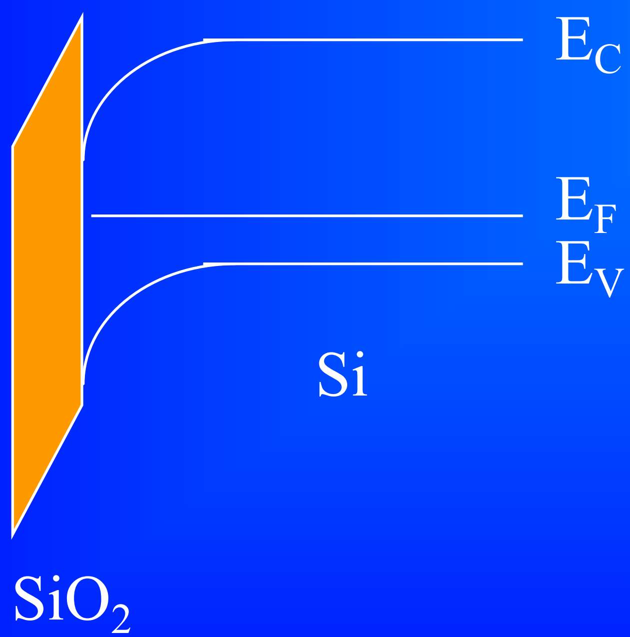
$$W \Rightarrow W/K,\ L \Rightarrow L/K,\ t_{ox} \Rightarrow t_{ox}/\sqrt{K}$$

  - Increase in noise level due to the $K^{1/2}$ law chosen for t_{ox}.
  - Unpredictability of noise level for K>20.
  - N_{SS} is actually a two dimensional Poisson variable.

Large Area Noise Models Break Down

◆Single electron, single trap effects.

N_{SS}=4x10^{10} eV^{-1} cm^{-2}, W=1µm, L=0.1µm.



kT=26 meV

1 trap per channel

Large Area Noise Models Break Down

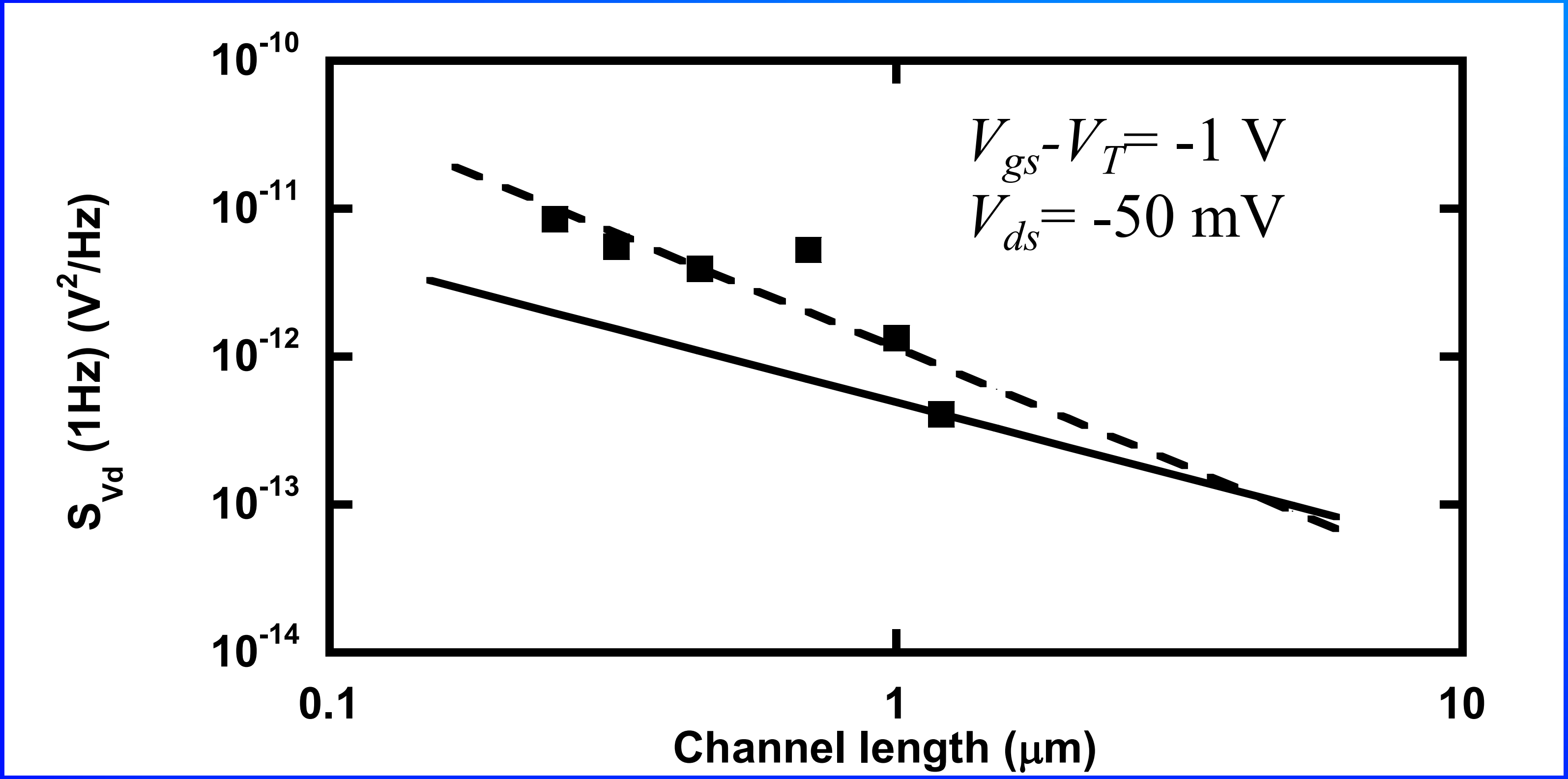
Break-down of large-area models for sub-micron channel length.

$$S_{Id}(f) = \frac{kTq^2 I_d \mu_{eff}}{\gamma f L^2 C_{ox}} \left[A \ln \frac{N_O + N^*}{N_L + N^*} + B(N_O - N_L) + \frac{1}{2} C\left(N_O^2 - N_L^2\right) \right]$$

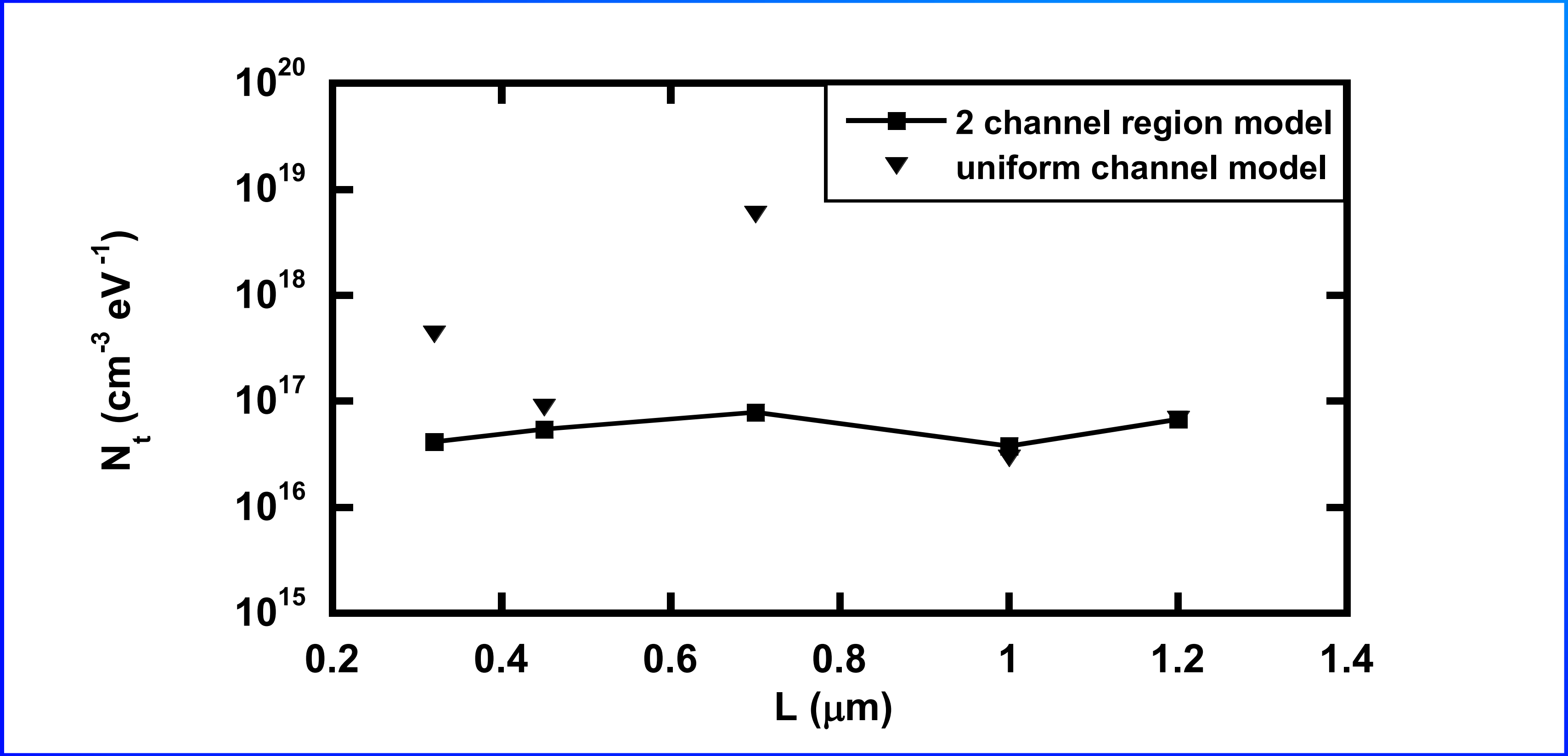
- $A = N_t$ (cm^{-3} eV^{-1})
- $B = \pm\alpha\mu_{eff} N_t$ (cm^{-1} eV^{-1})
- $C = \alpha^2 \mu_{eff}^2 N_t$ (cm eV^{-1})
- $\boldsymbol{A = B^2/(4C)}$

Independent parameters: α and N_t

Large Area Noise Models Break Down



Large Area Noise Models Break Down



Large Area Noise Models Break Down

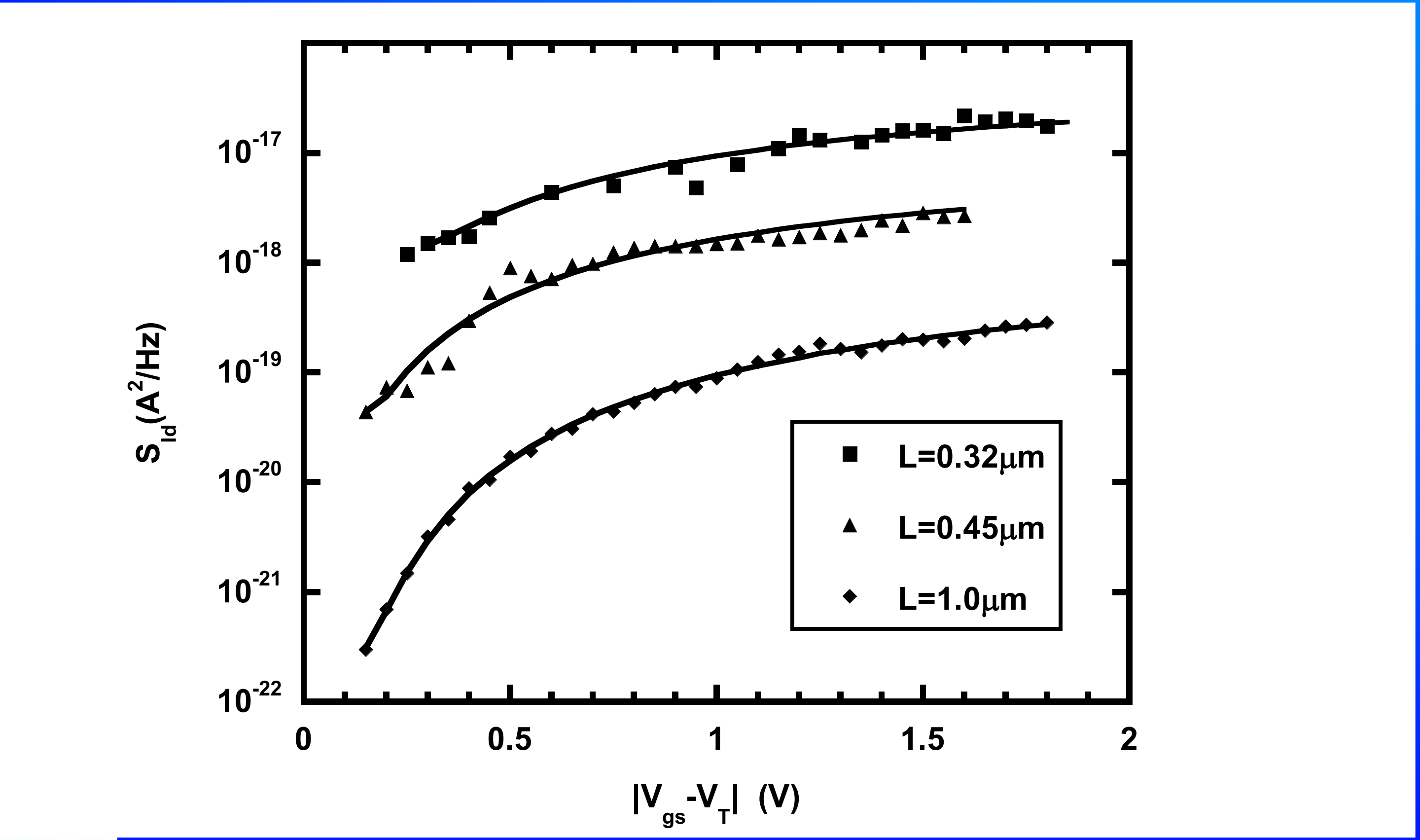
Modified 1/f noise model that takes into account threshold variation along the channel.

- For simplicity assume two regions:
  - ΔV, ΔL, V_{T2},, A_2, B_2, C_2
  - V_{ds}-ΔV, L-ΔL, V_{T1}, A_1, B_1, C_1
  - $\Delta L << L$, $V_T \approx V_{T1}$
  - $A_1 = A_2$, since $N_{t1} = N_{t2}$
  - $B_1^2/C_1 = B_2^2/C_2 = 4A$
  - $I_1 = I_2 = I_d$
  - $\mu_{eff1} = \mu_{eff2}$,

Independent parameters: N_t, α_1, α_2, V_{T2}, *and* ΔV

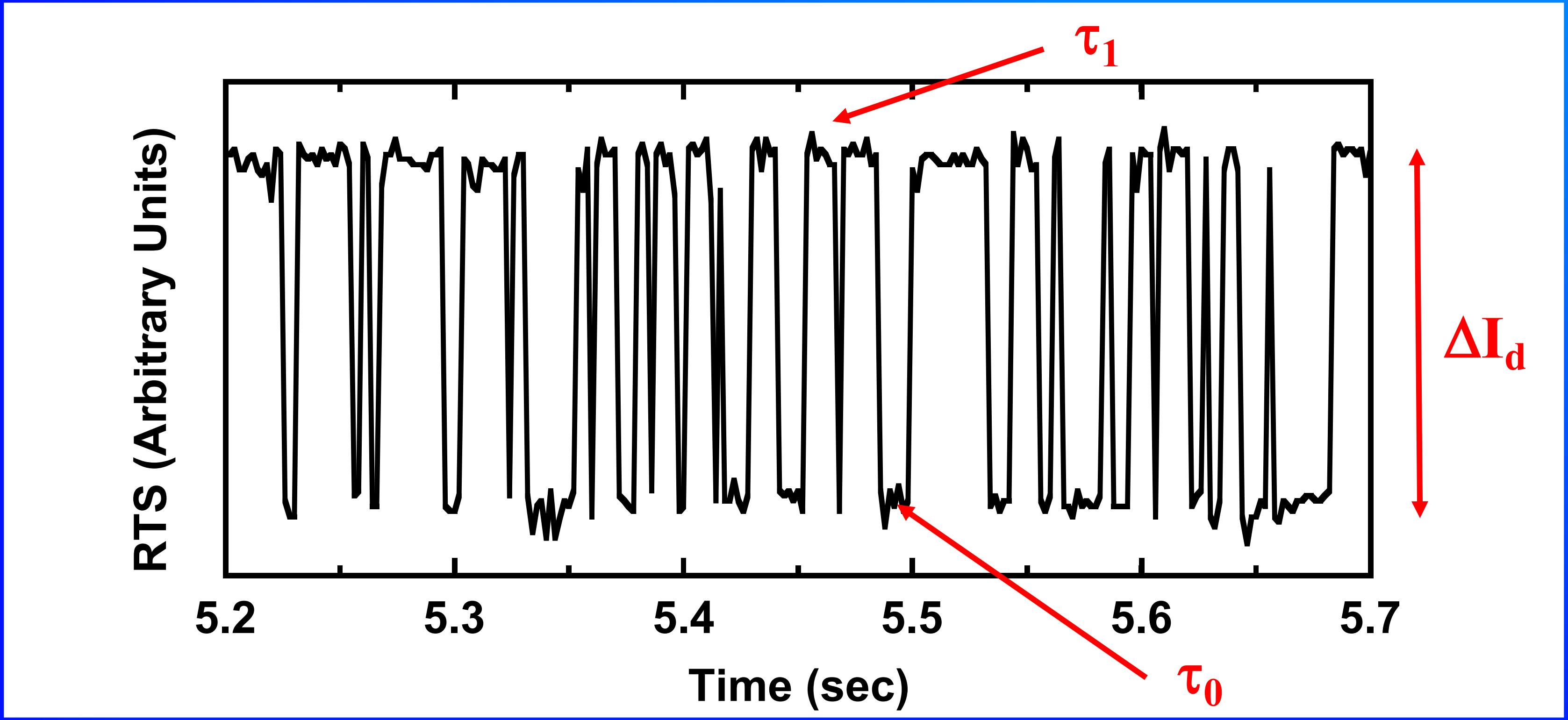
Large Area Noise Models Break Down

Modified 1/f noise model that takes into account threshold variation along the channel.



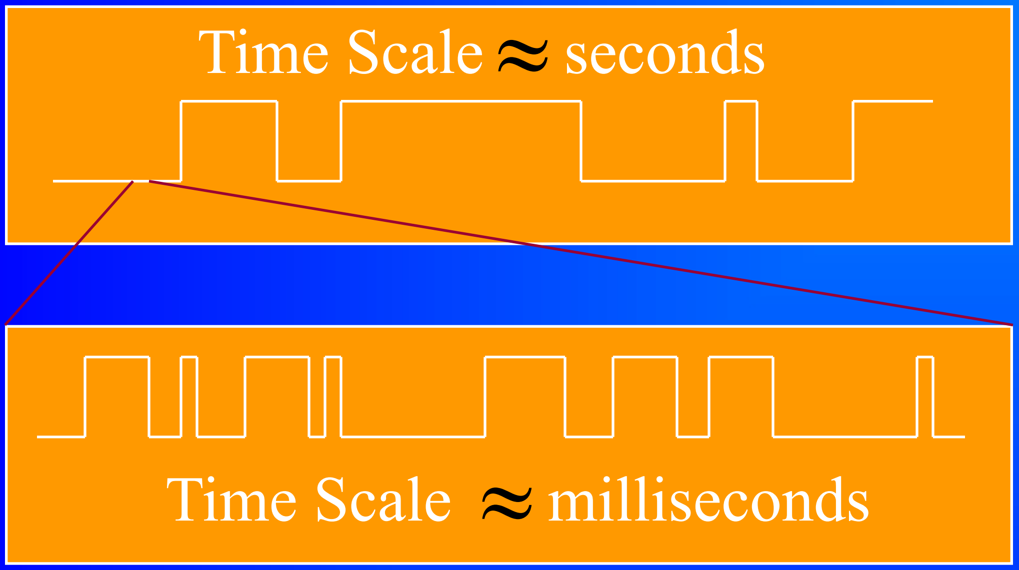
RTS in MOSFETs

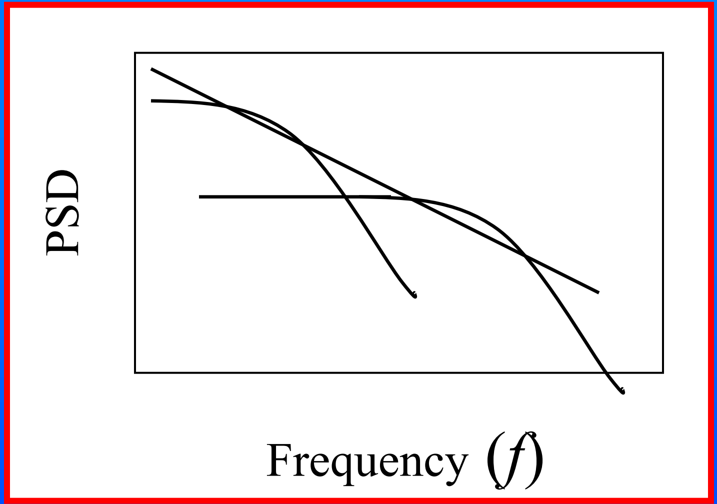
Random Telegraph Signals: single electron switching.



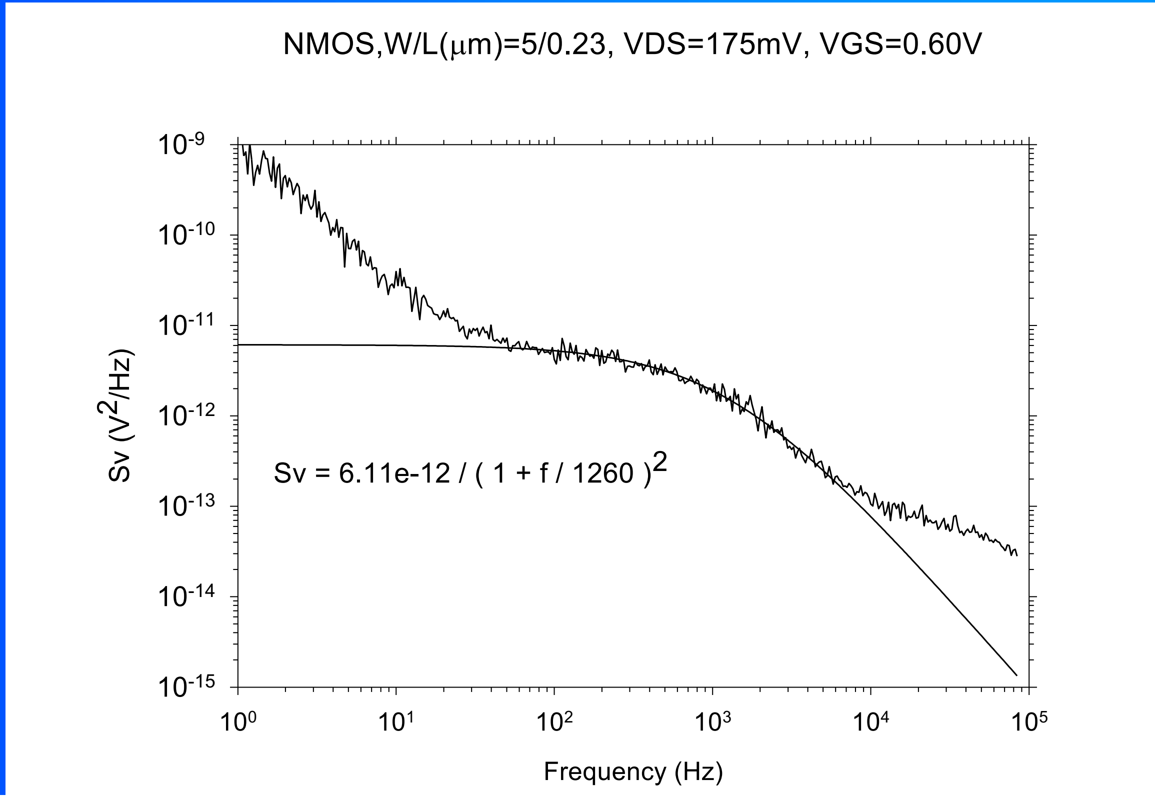
RTS in MOSFETs

Random Telegraph Signals (RTS) with a Lorentzian on *1/f* spectum.

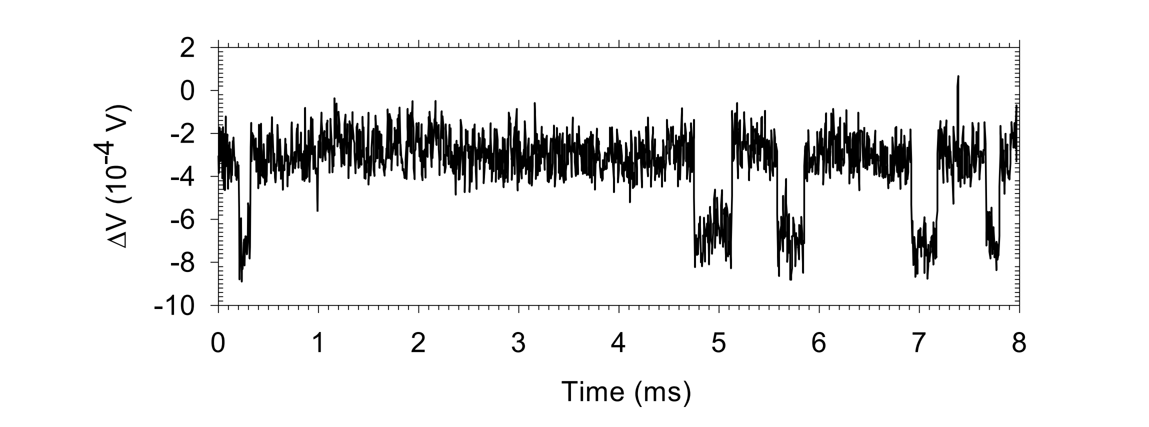




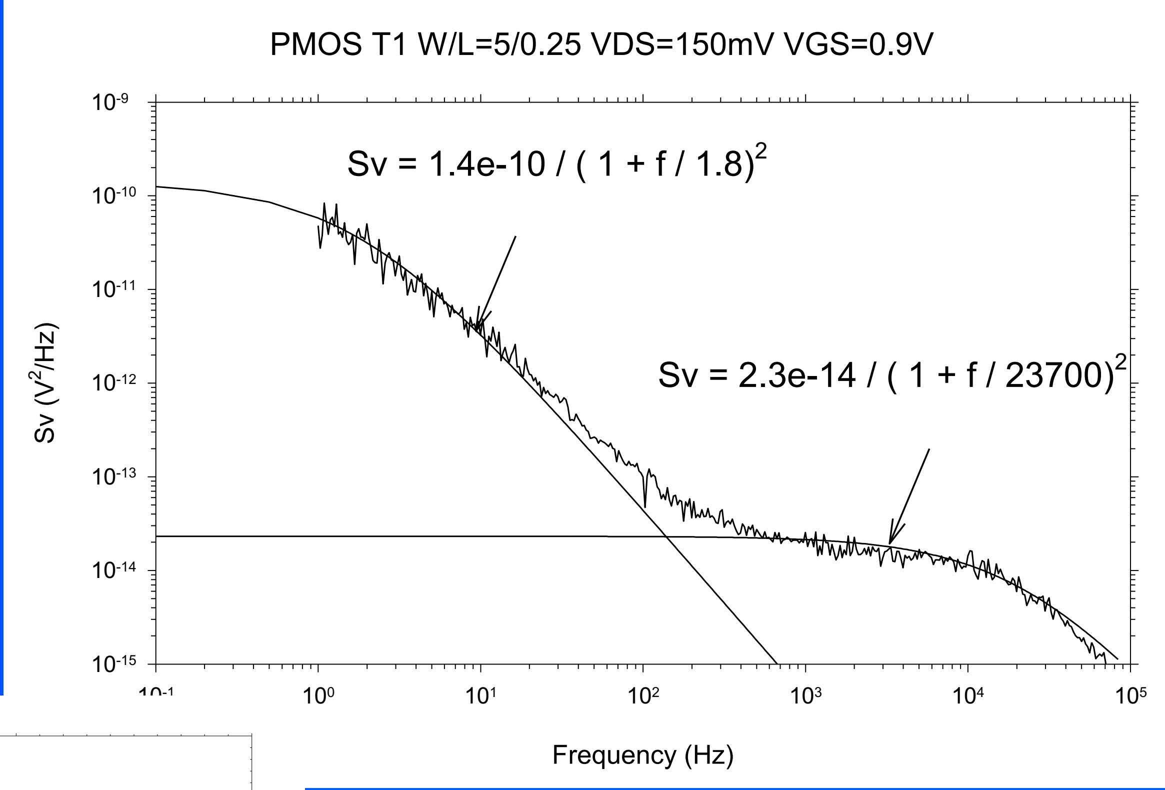
$$S(f) = \frac{4(\Delta I)^2}{(\bar{\tau}_0 + \bar{\tau}_1)\left[(1/\bar{\tau}_0 + 1/\bar{\tau}_1)^2 + (2\pi f)^2\right]}$$



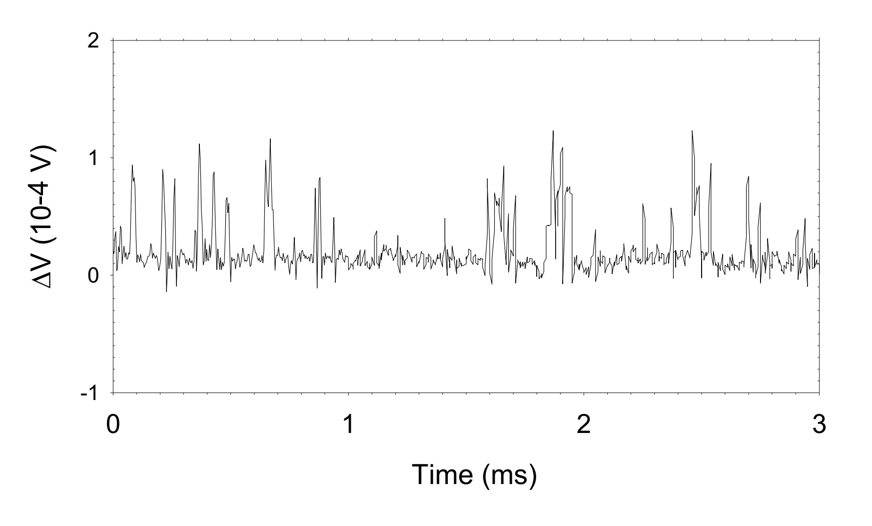
1 RTS process



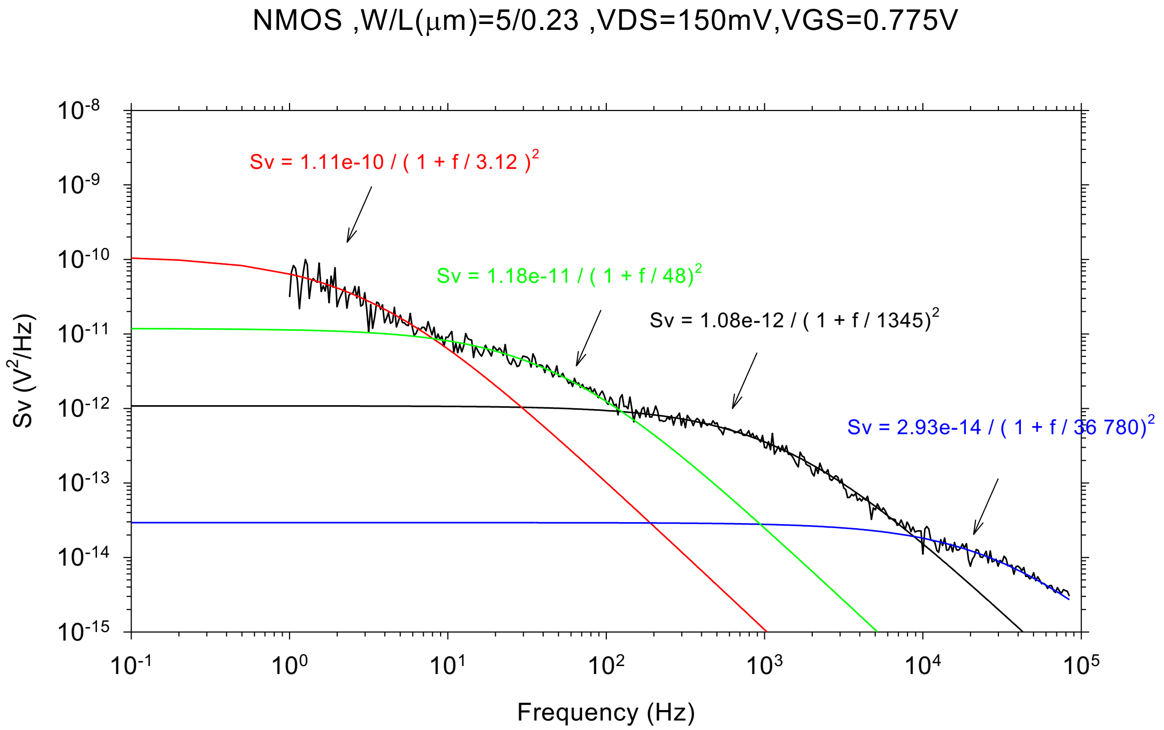
2 RTS levels



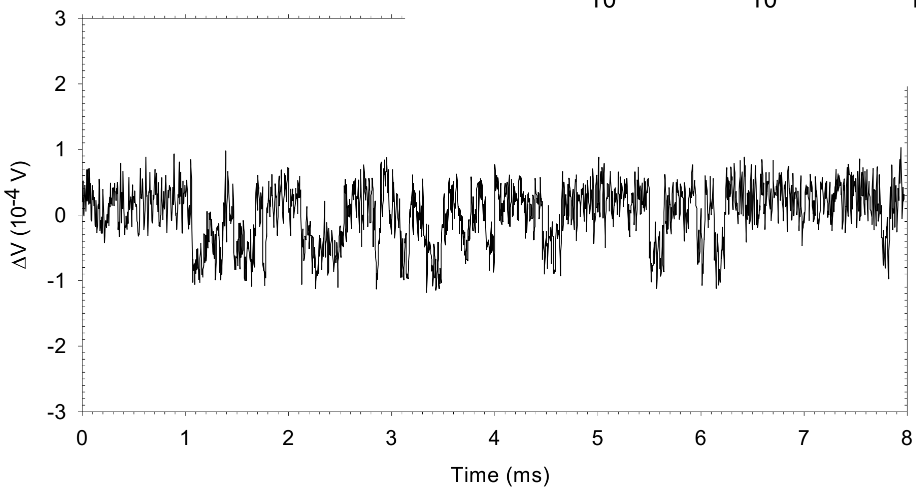
2 RTS processes



3 RTS levels

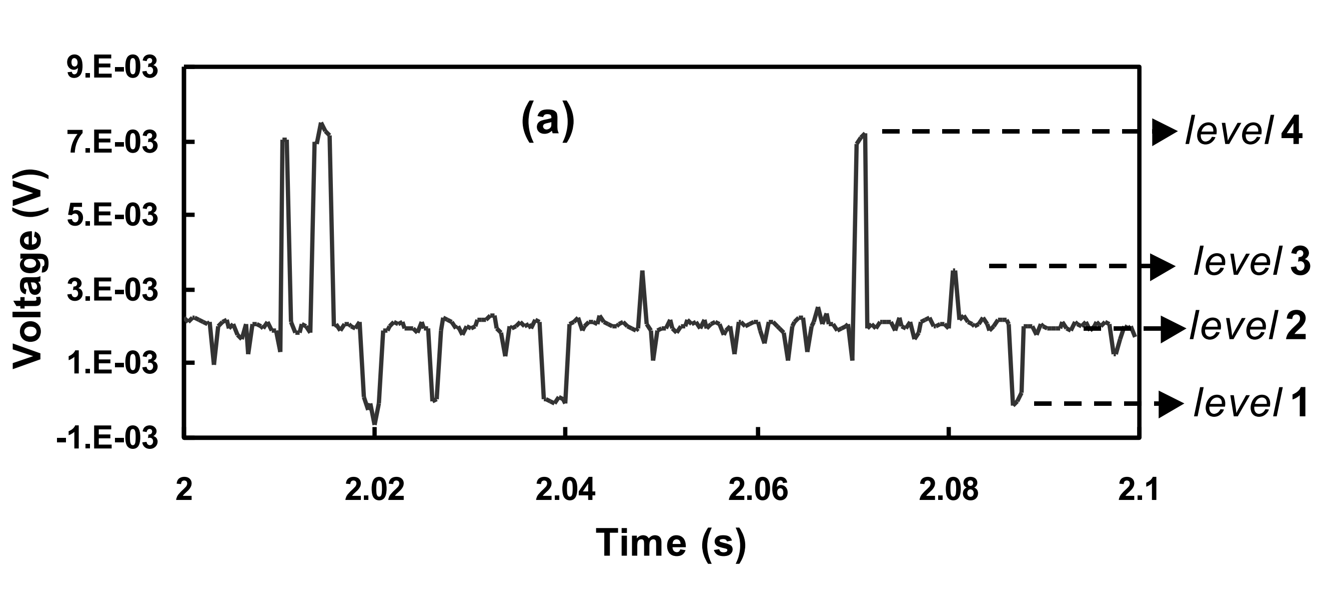


4 RTS processes



5 RTS levels

COMPLEX RTS

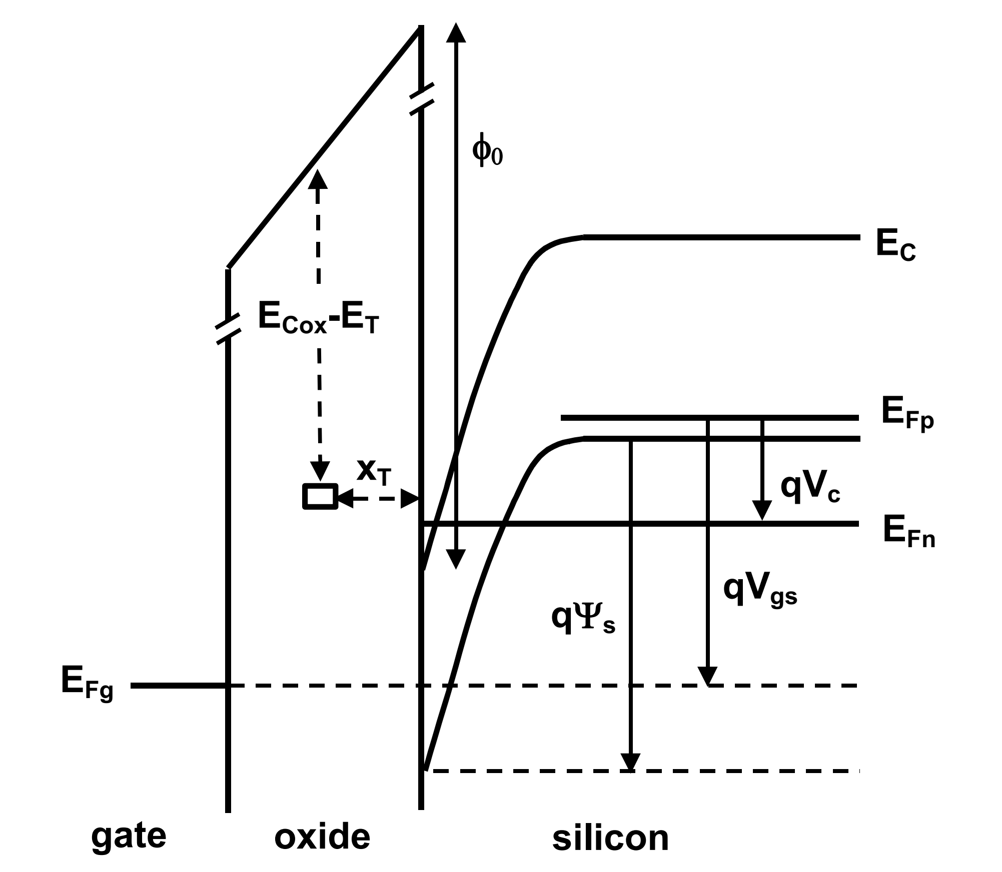


Complex random telegraph signals due to multiple traps

$$\frac{S_I(f)}{I^2} \propto \sum_{k=1}^{N_{traps}} \frac{(\Delta I/I)_k^2}{(\bar{\tau}_0 + \bar{\tau}_1)_k \left[(1/\bar{\tau}_0 + 1/\bar{\tau}_1)_k^2 + (2\pi f)^2\right]}$$

RTS in MOSFETs

RTS can be used to characterize trapping sites.



RTS modeling.

$$S(f) = \frac{4(\Delta I)^2}{(\bar{\tau}_0 + \bar{\tau}_1)\left[(1/\bar{\tau}_0 + 1/\bar{\tau}_1)^2 + (2\pi f)^2\right]}$$

$$S(f) = \frac{AF \cdot I_d^2}{\left[(2\pi f)^2 + KF^2\right]}$$

RTS in MOSFETs

RTS can be used to characterize trapping sites.

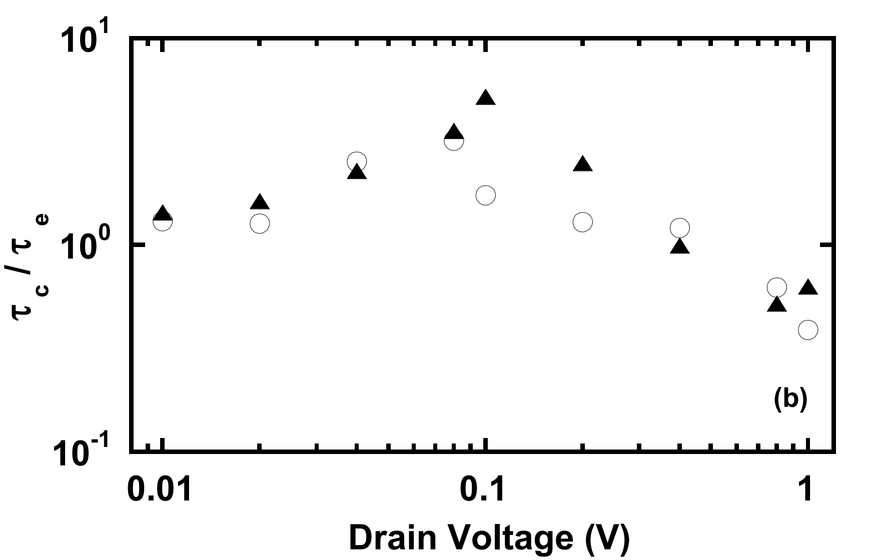
$$V_c \approx y V_{ds} / L$$

- Position of the trap along the channel, y_T
- Position of the trap in the oxide, x_T
- Trap energy, $E_{Cox} - E_T$
- Screened scattering coefficient, α

$$\frac{\Delta I_d}{I_d} = \frac{\Delta N}{N} \pm \frac{\Delta \mu}{\mu} = -\frac{1}{W_{eff} L_{eff}} \left[\frac{1}{N} \pm \alpha \mu \right]$$

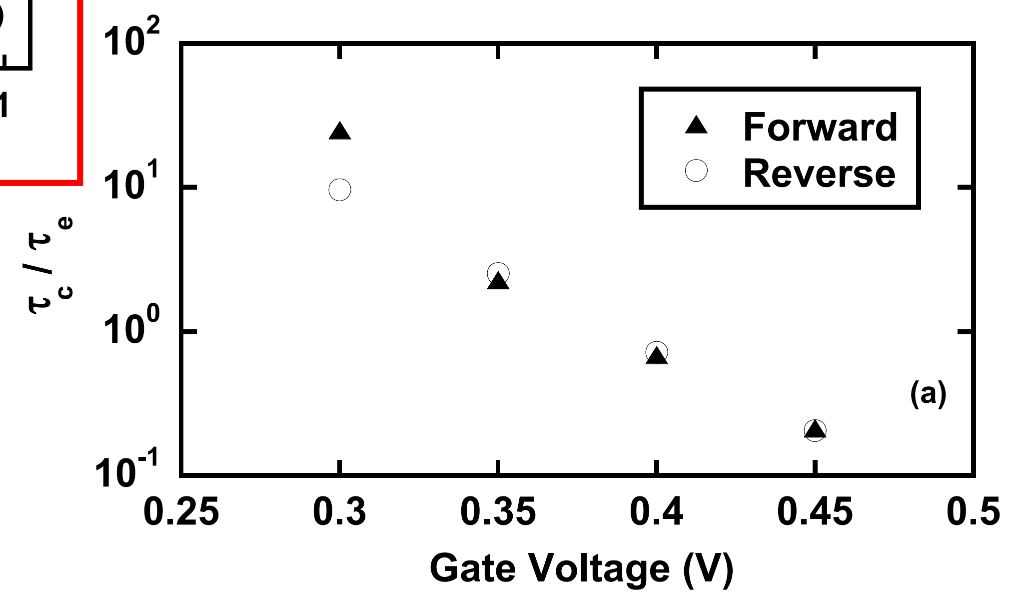
$$\ln \frac{\bar{\tau}_c}{\bar{\tau}_e} = -\frac{1}{kT} \left[\left(E_{Cox} - E_T \right) - \left(E_C - E_{F_p} + qV_c \right) - \phi_0 + q\psi_s + q\frac{x_T}{T_{ox}} \left(V_{gs} - V_{FB} - \psi_s \right) \right]$$

Trapping Parameters Through RTS in MOSFETs



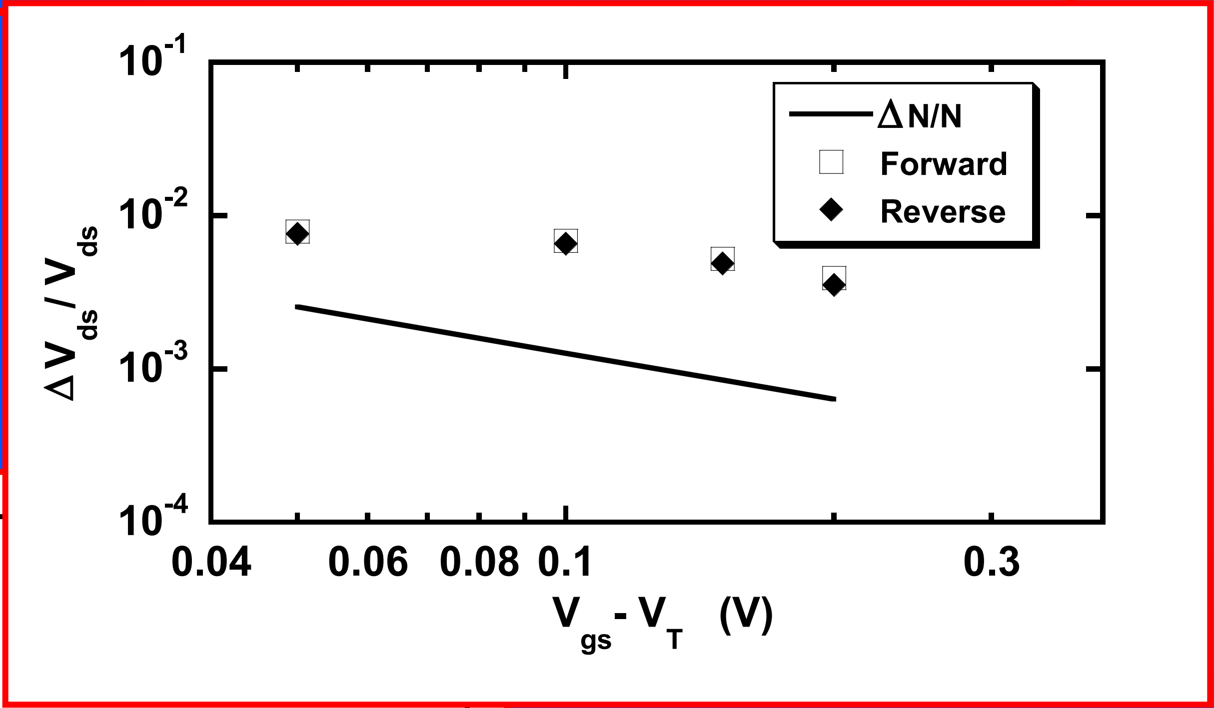
$y_T/L=0.6$

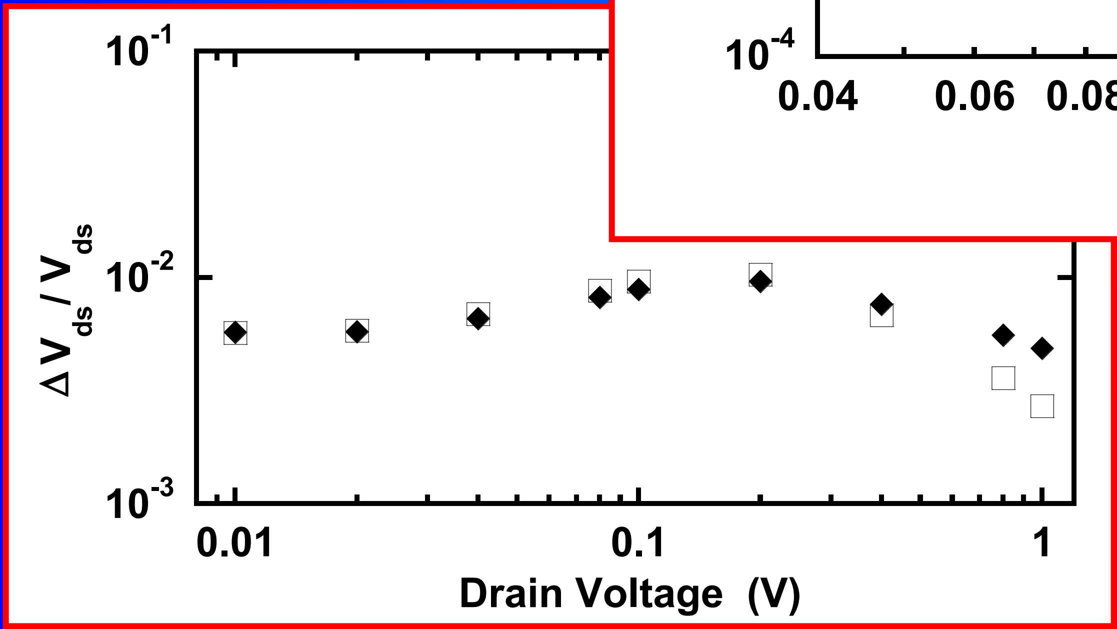
$E_{Cox}-E_T=3.04$ eV



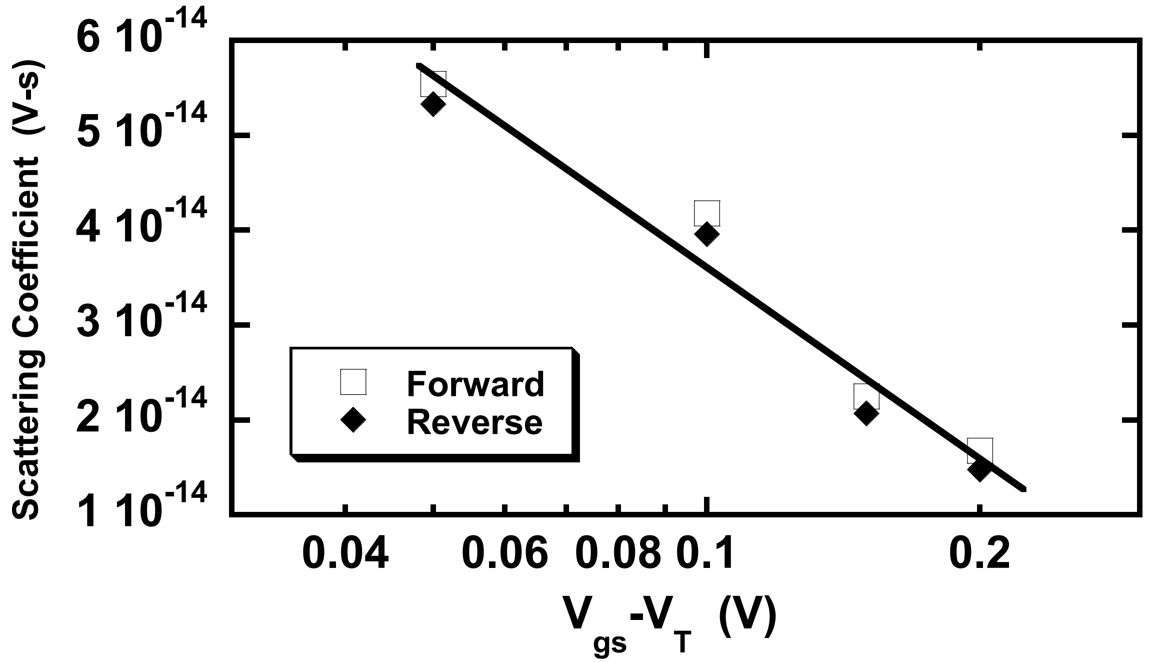
$x_T=2.7$ nm

Trapping Parameters Through RTS in MOSFETs



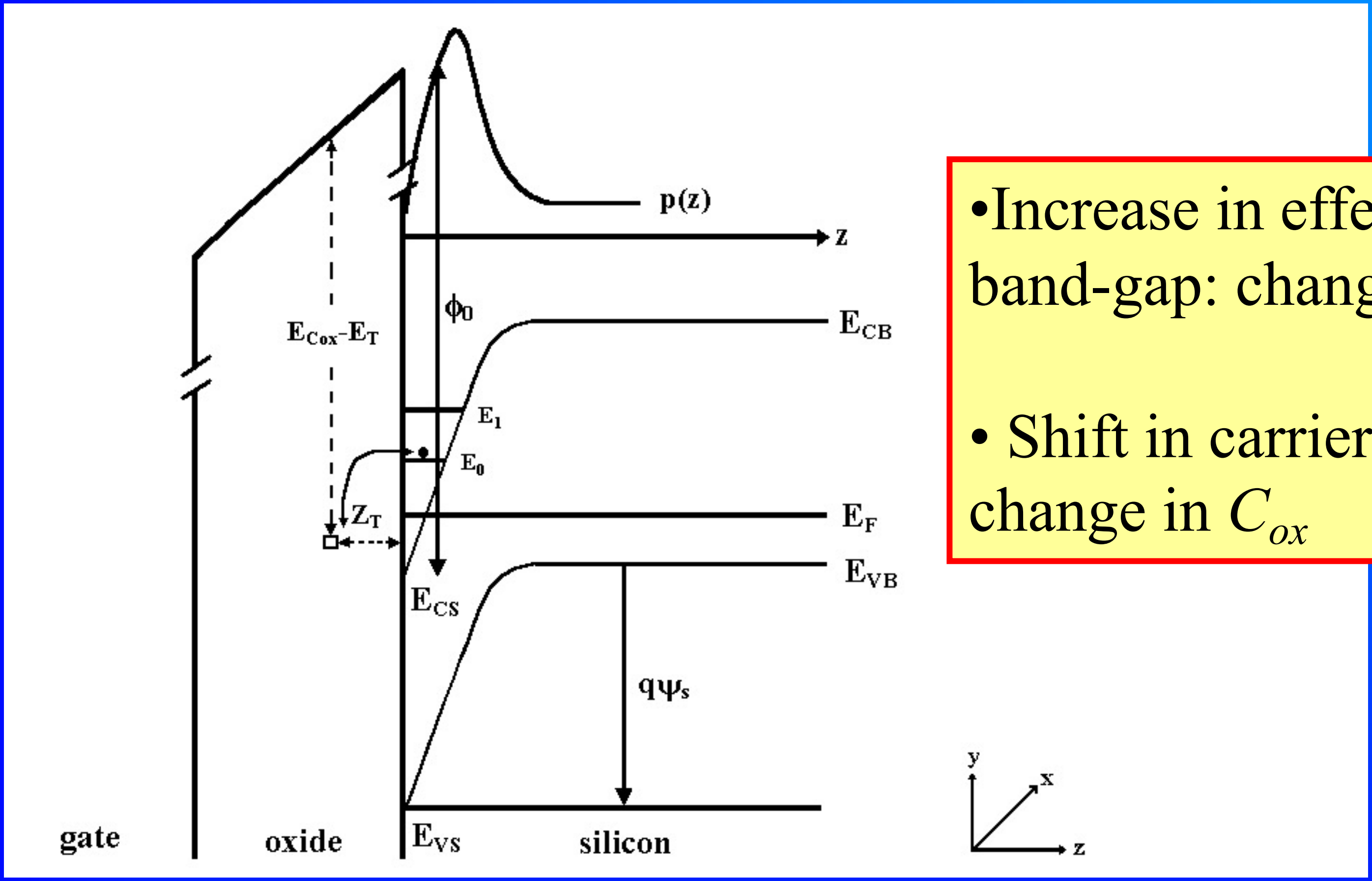


Trapping Parameters Through RTS in MOSFETs



$$\alpha = K_1 + K_2 \ln N$$

Effects of Quantization



- Increase in effective energy band-gap: change in τ_e and τ_c
- Shift in carrier distribution: change in C_{ox}

3-D Treatment of RTS

$$\tau_c = \frac{1}{\bar{c}_n \cdot n_{3D}} = \frac{1}{\sigma_n(3D) \cdot V_{th} \cdot n_{3D}}$$

$$\tau_e = \frac{\exp\left[(E_F - E_T)/k_B T\right]}{\sigma_n(3D) \cdot V_{th} \cdot n_{3D}}$$

$$\bar{c}_n = \sigma_n\left(3D\right) \cdot V_{th}$$

2-D Treatment of RTS - τ_c and τ_e

$$\tau_c = \frac{1}{\overline{c_n} \cdot n_{2D} \cdot \int_0^{\bar{z}} \frac{p(z)}{\bar{z}} dz} = \frac{1}{\sigma_n(2D) \cdot V_{th} \cdot n_{2D} \cdot \int_0^{\bar{z}} \frac{p(z)}{\bar{z}} dz}$$

$$\tau_e = \frac{1}{\bar{e}_n} = \frac{\exp\left[(E_F - E_T)/k_B T\right]}{\sigma_n(2D) \cdot V_{th} \cdot n_{2D} \cdot \int_0^{\bar{z}} \frac{p(z)}{\bar{z}} dz}$$

$$\bar{c}_n = \sigma_n\left(2D\right) \cdot V_{th}$$

2-D Treatment of RTS

- From Stern - Howard wave-function:

$$p(z) = \frac{b^3}{2} z^2 \exp(-bz)$$

$$b = \left[\frac{12 q m_l}{\hbar^2 \varepsilon_{Si} \varepsilon_0} \cdot \left(Q_B + \frac{11}{32} \cdot Q_{inv} \right) \right]^{1/3}$$

$$\bar{z} = 3/b$$

2-D Treatment of RTS

- Calculate the inversion carrier concentration assuming they are located primarily at E_0:

$$\frac{1}{N} = \frac{1}{\int n_{2D} \cdot p(z)dz}$$

$$= \left\{ \frac{2k_B T m_t}{\pi\hbar^2} \exp\left[-\left(E_{CS} + \Delta E_0 - E_F\right)/k_B T\right] \cdot \int_0^{\bar{z}} p(z)dz \right\}^{-1}$$

$$\Delta E_0 \approx \left(\frac{\hbar^2}{2m_l}\right)^{1/3} \left[\frac{9\pi q}{8\varepsilon_{Si}\varepsilon_0}\right]^{2/3} \left[2\varepsilon_{Si}\varepsilon_0 q N_B (V_{SB} + 2\phi_F)\right]^{1/3}$$

2-D Treatment of RTS - τ_c and τ_e

$$\tau_e = \frac{\exp\left[(E_{CS} - E_T + \Delta E_0)/k_B T\right]}{\sigma_n(2D)\cdot V_{th}\cdot(2k_B T m_t b/5\hbar^2\pi)}$$

$$\tau_c = \frac{\exp\left[(E_{CS} - E_F + \Delta E_0)/k_B T\right]}{\sigma_n(2D)\cdot V_{th}\cdot(2k_B T m_t b/5\hbar^2\pi)}$$

$$\ln\left(\frac{\tau_c}{\tau_e}\right) = -\frac{1}{k_B T}\left[\left(E_{Cox} - E_T\right) - \left(E_{CB} - E_F\right) - \phi_0 + q\psi_s + q\frac{z_T}{T_{ox}}\left(V_{gs} - V_{FB} - \psi_s\right)\right]$$

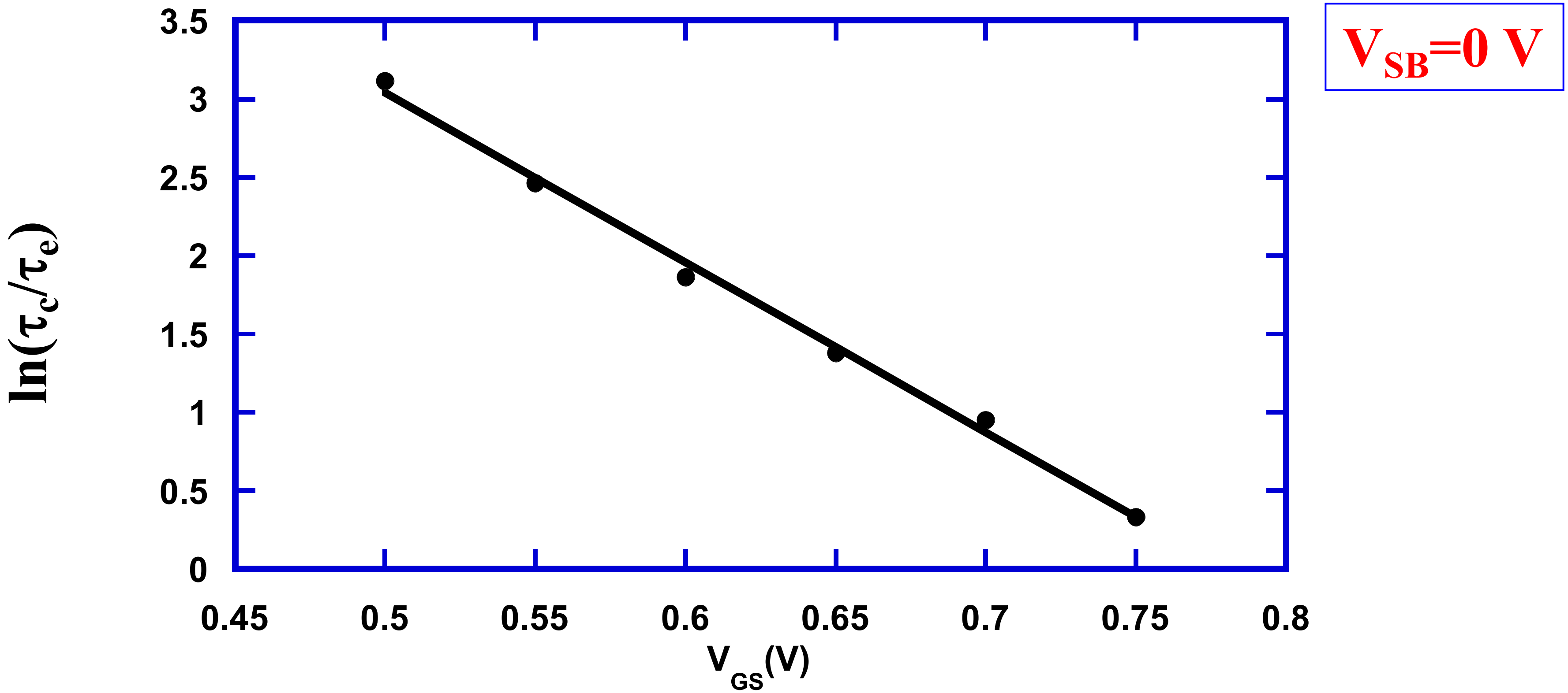
- To first order, the ratio is not affected by quantization.

RTS Measurements

- MDD n-MOSFETs
- $W_{eff} \times L_{eff} = 1.37 \times 0.17\ \mu m^2$
- $T_{ox} = 4$ nm
- $V_T = 0.375$ V for $V_{SB} = 0$ V
- strong inversion, linear region $V_{DS} = 100$ mV
- $V_{SB} = 0 - 0.4$ V, $V_{GS} = 0.5 - 0.75$ V

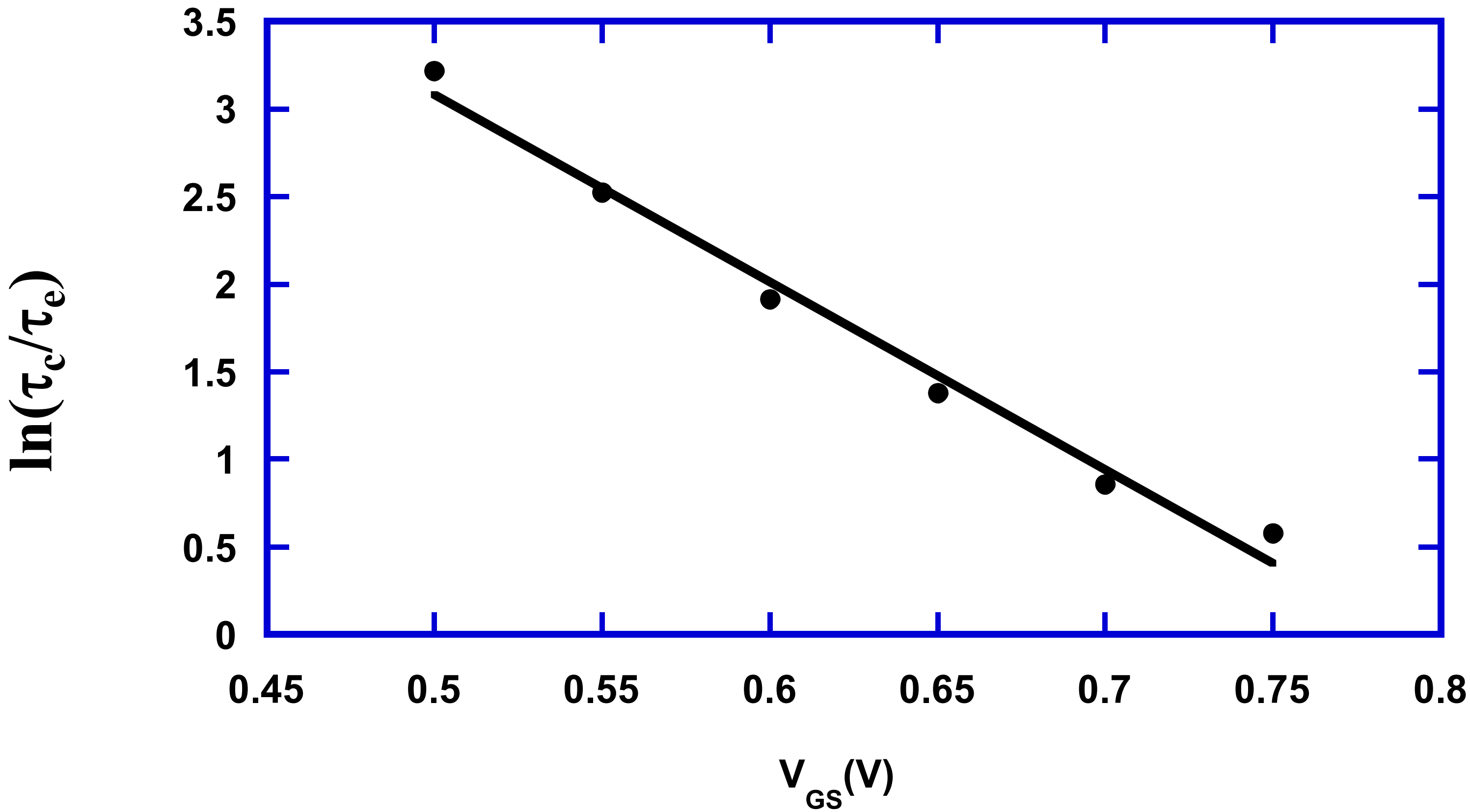
E_{Cox}-E_T and z_T from τ_c and τ_e

$$\ln\left(\frac{\tau_c}{\tau_e}\right) = -\frac{1}{k_B T}\left[\left(E_{Cox} - E_T\right) - \left(E_{CB} - E_F\right) - \phi_0 + q\psi_s + q\frac{z_T}{T_{ox}}\left(V_{gs} - V_{FB} - \psi_s\right)\right]$$



E_{Cox}-E_T and z_T from τ_c and τ_e

$$\ln\left(\frac{\tau_c}{\tau_e}\right) = -\frac{1}{k_B T}\left[\left(E_{Cox} - E_T\right) - \left(E_{CB} - E_F\right) - \phi_0 + q\psi_s + q\frac{z_T}{T_{ox}}\left(V_{gs} - V_{FB} - \psi_s\right)\right]$$



V_{SB}=0.4 V

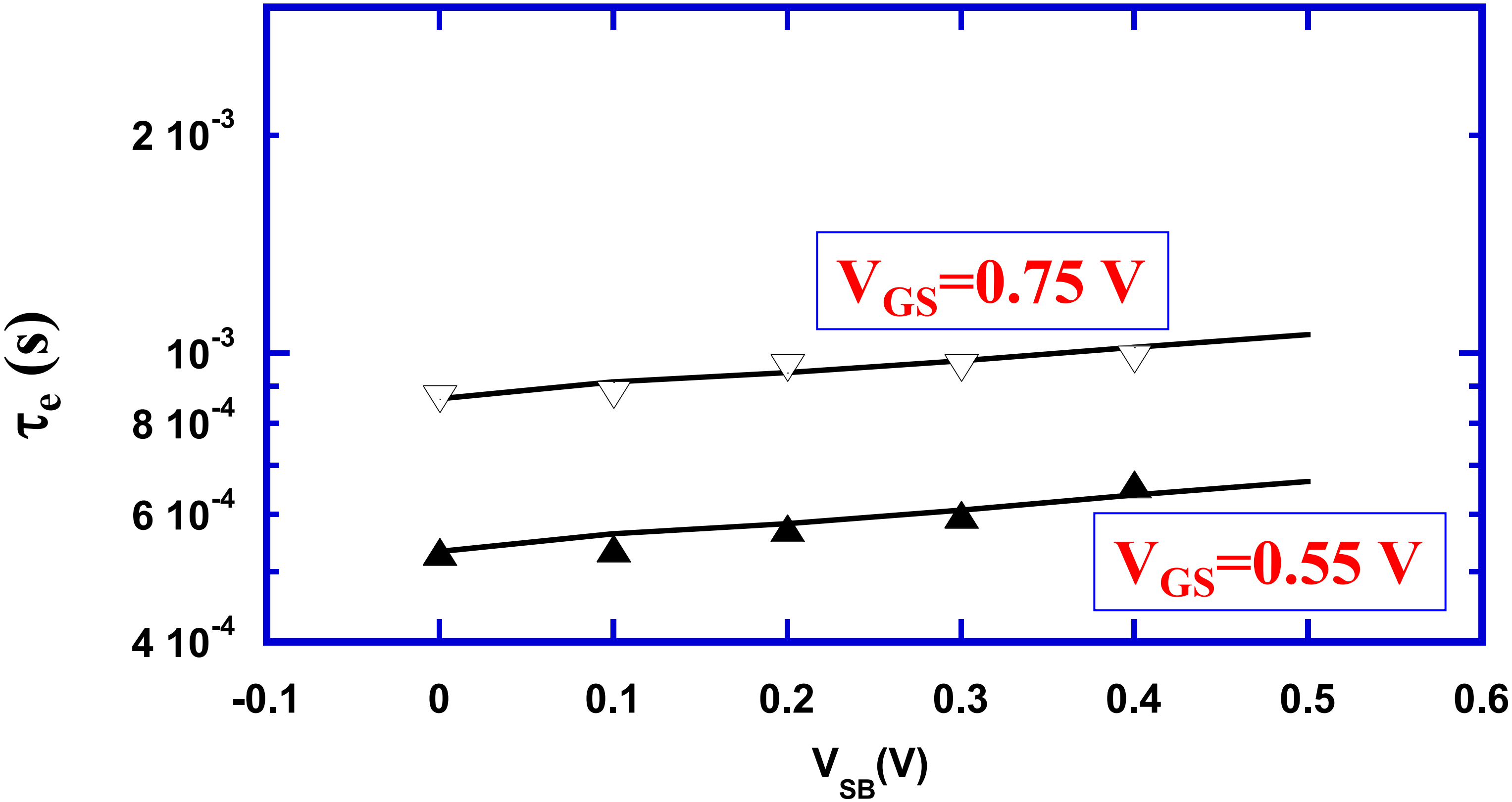
E_{Cox}-E_T and z_T from τ_c and τ_e

T_{ox} =4 nm

V_{SB} (V)	V_T (V)	z_T (Å)	E_{Cox}-E_T (eV)
0	0.375	11.22	3.09
0.1	0.382	11.53	3.08
0.2	0.393	11.37	3.08
0.3	0.401	11.64	3.07
0.4	0.408	11.08	3.08

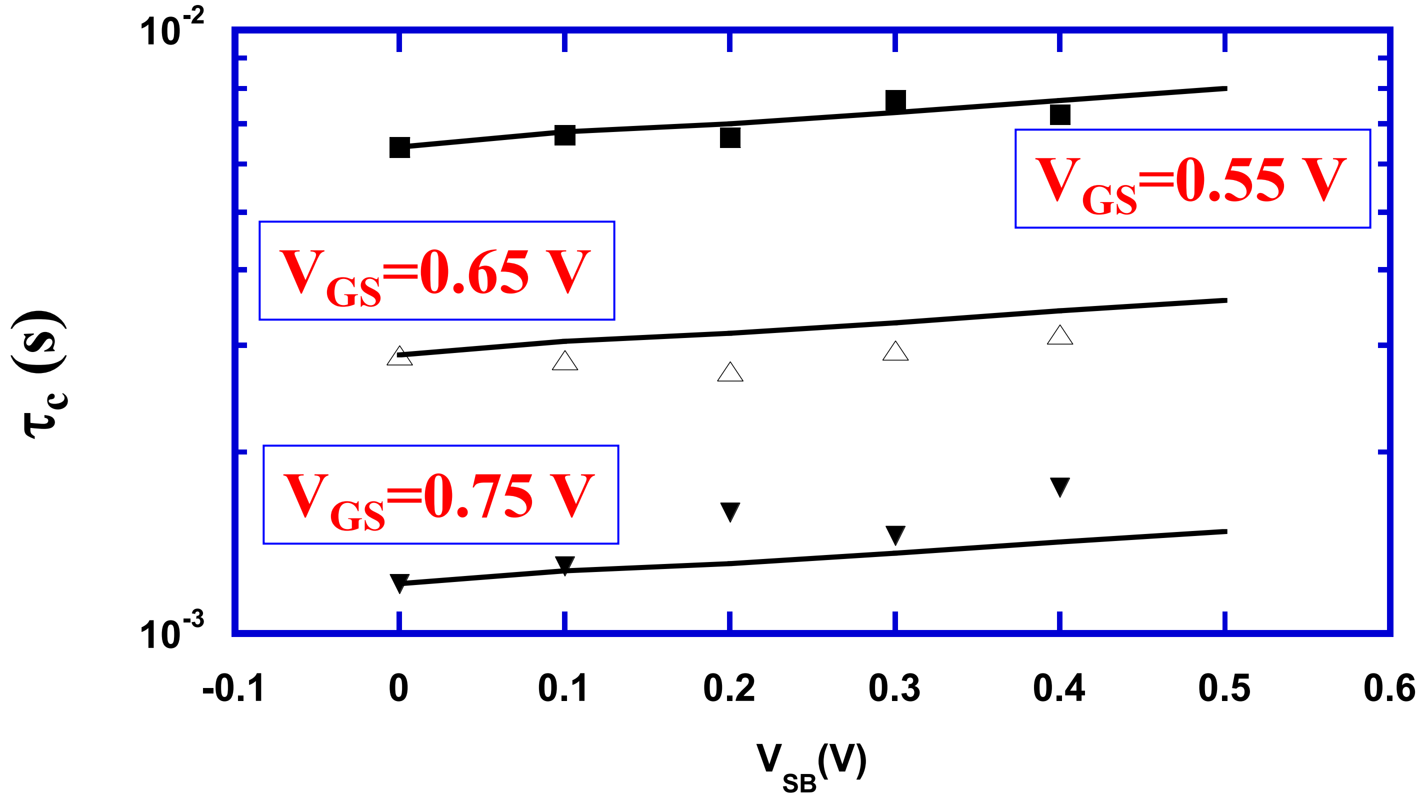
Dependence of τ_e on V_{SB}

$$\tau_e = \frac{\exp\left[(E_{CS} - E_T + \Delta E_0)/k_B T\right]}{\sigma_n(2D)\cdot V_{th}\cdot(2k_B T m_t\, b/5\hbar^2\pi)}$$



Dependence of τ_c on V_{SB}

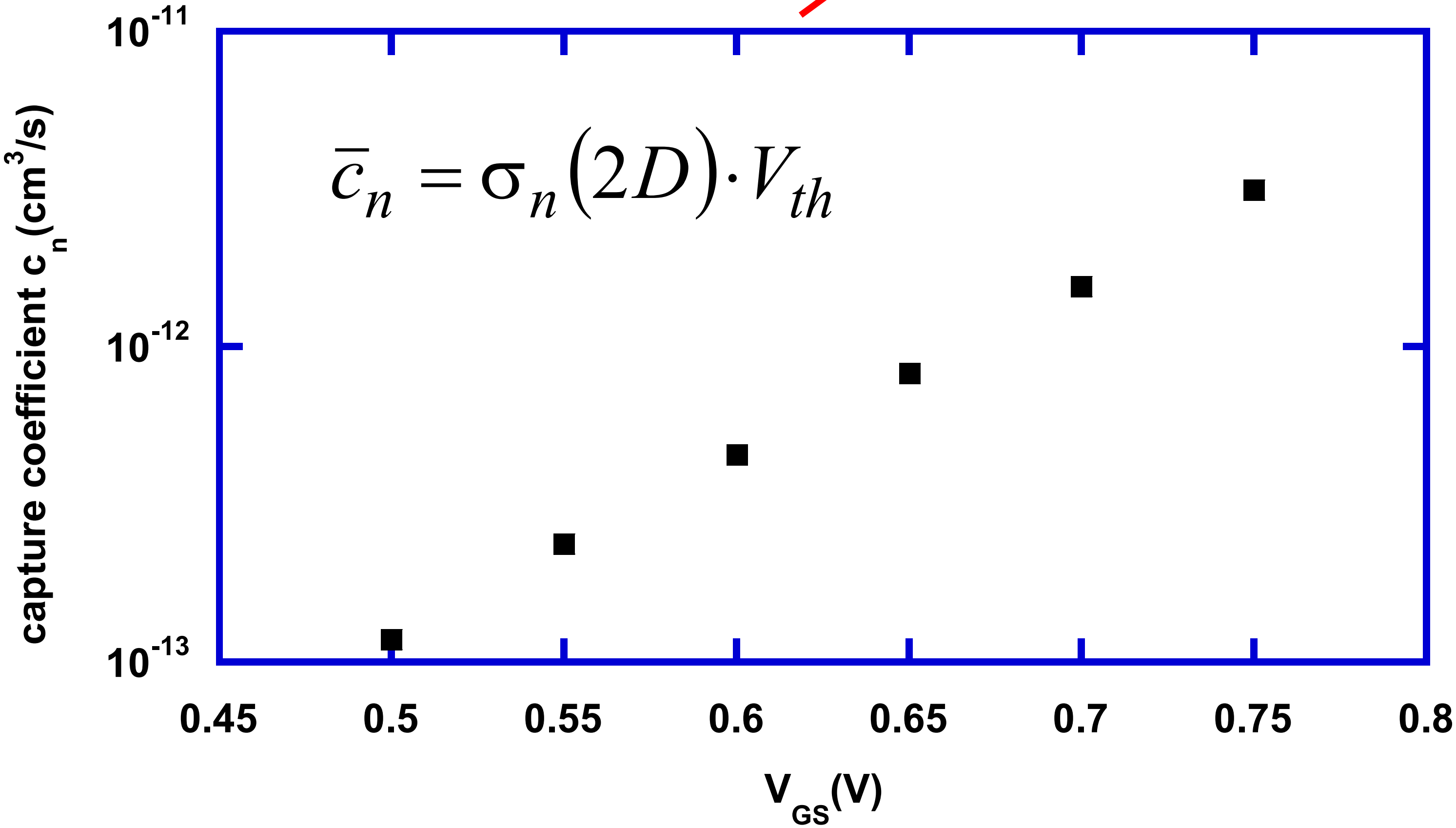
$$\tau_c = \frac{\exp\left[(E_{CS} - E_F + \Delta E_0)/k_B T\right]}{\sigma_n(2D)\cdot V_{th}\cdot(2k_B T m_t b/5\hbar^2\pi)}$$



c_n Extracted from τ_c and τ_e

$$V_{th} = \left(8k_BT / \pi m_n^*\right)^{1/2}$$

$$\sigma_n = \sigma_0 \exp\left(-\Delta E_B / k_BT\right)$$



2-D Treatment of RTS - Amplitude

$$\frac{\Delta I_D}{I_D} = -\left[\frac{1}{\Delta N}\frac{\delta \Delta N}{\delta \Delta N_t} \pm \frac{1}{\mu}\frac{\delta \mu}{\delta \Delta N_t} = \right]\delta \Delta N_t = -\frac{1}{W_{eff} \times L_{eff}}\left(\frac{1}{N} \pm \alpha\mu\right)$$

$$\mu^{-1} = \mu_n^{-1} + \mu_t^{-1} = \mu_n^{-1} + \alpha N_t$$

- Question: How does quantization affect number and mobility fluctuations?
  - Number fluctuation through N
  - Mobility fluctuations through oxide charge scattering, μ_t.

Extraction of Scattering Coefficient

- Mobility Fluctuations:
  - Using Surya's 2D surface mobility fluctuations model,

$$\mu_t^{-1} = \frac{m_n^{*} q^3}{8\hbar\pi\varepsilon_{av}^2 E_p} \int dz \int dE \int_0^{\pi/2} \frac{\exp(-4kz\sin\phi)\sin^2\phi}{(\sin\phi + \frac{c}{2k})^2} d\phi N_t(E,z)$$

$$k = 0.8(2\pi/a_{Si})$$

$$c = \frac{2q^2 d_v m_n^{*}}{4\hbar^2\pi\varepsilon_{si}}\left\{1 - \exp\left[-\left(\frac{\hbar^2\pi N}{k_B T d_v m_n^{*}}\right)\right]\right\}$$

Calculation of Scattering Coefficient

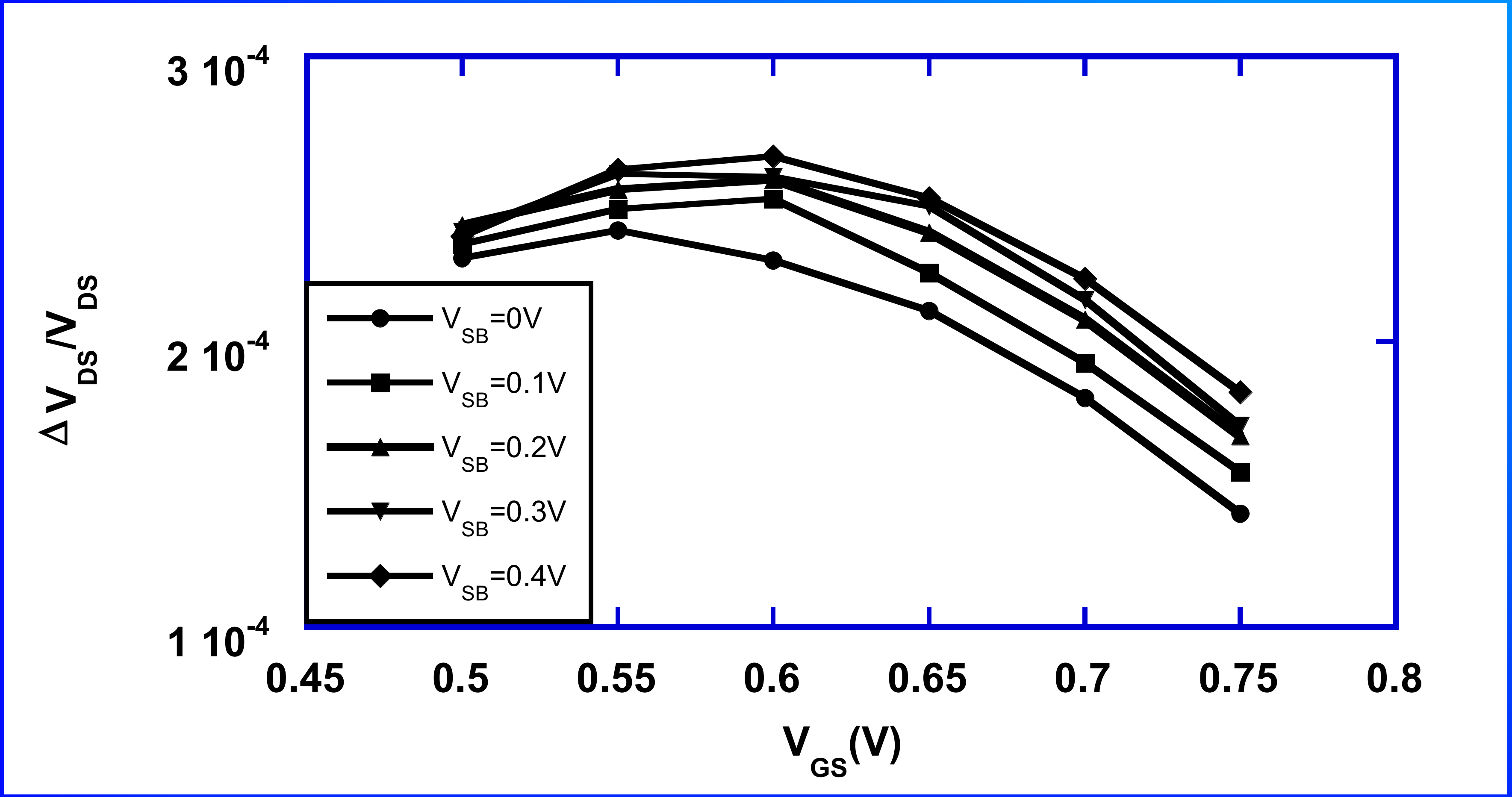
- Considering a single trap:

$$N_t(E,z) = N_t\delta(E-E_T) \times \delta(z-z_T)$$

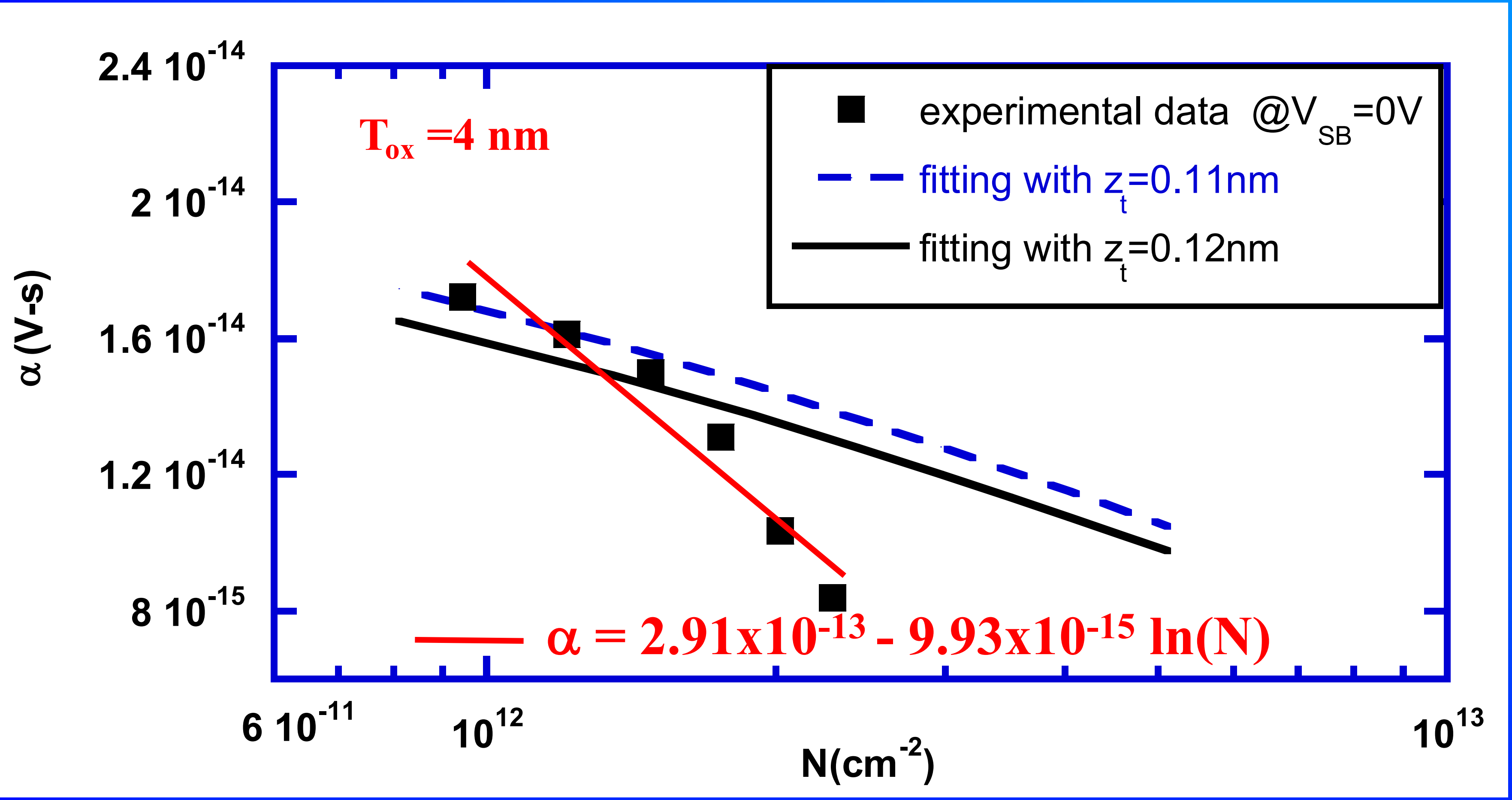
$$\mu_t^{-1} = \frac{m_n^{*} q^3}{8\hbar\pi\varepsilon_{av}^2 E_p} \int_0^{\pi/2} \frac{\sin^2\phi}{(\sin\phi + \frac{c}{2k})^2} \exp(-4kz_T \sin\phi) d\phi N_t$$

α

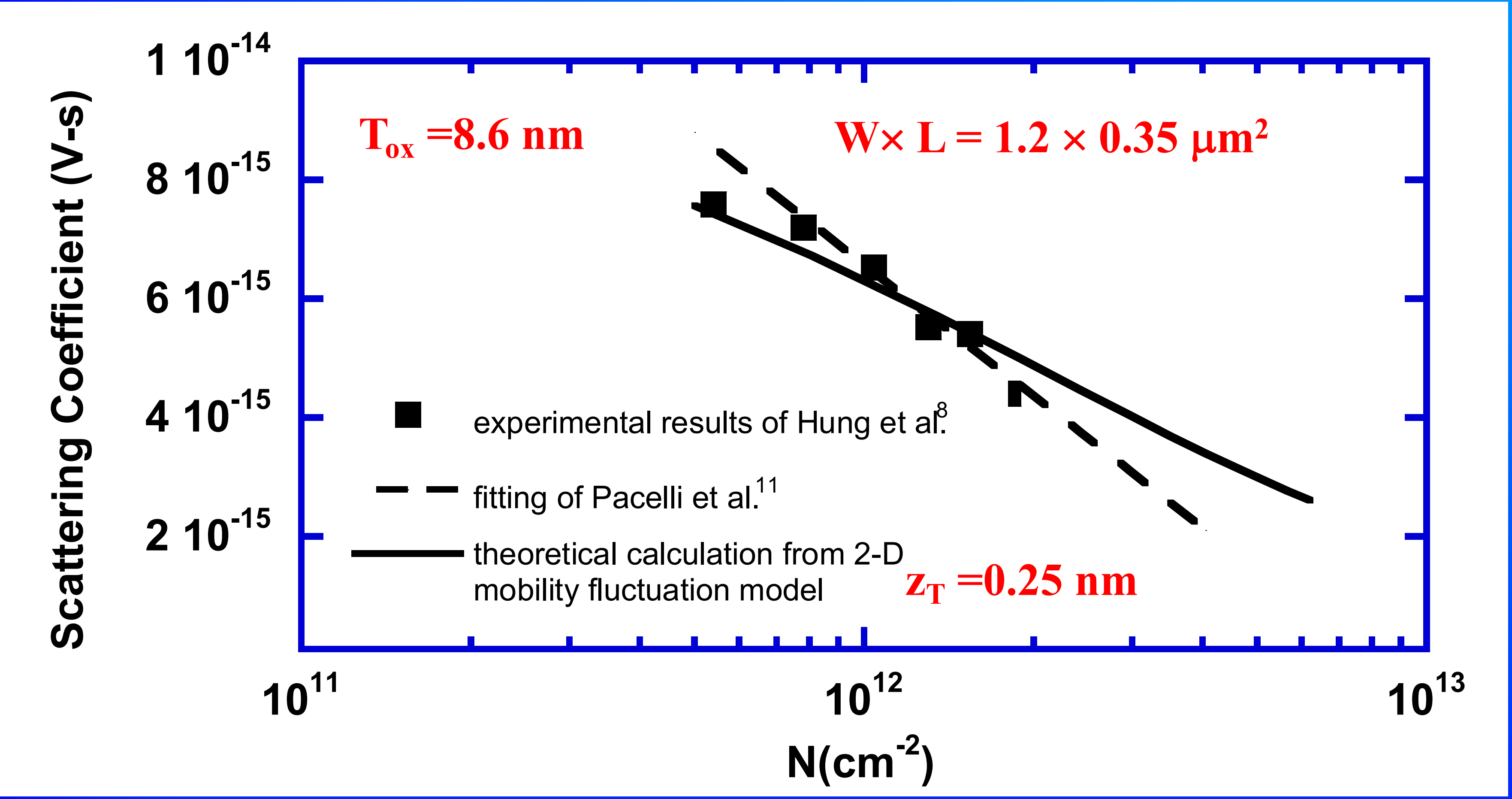
RTS Amplitude



Extraction of Scattering Coefficient



Extraction of Scattering Coefficient



Possible Reasons for Discrepancy

- Threshold non-uniformity along the channel is not taken into account.
- Location of the trap along the channel
- Variation of the channel voltage from source to drain is neglected.
- $\delta \Delta N / \delta \Delta N_t \approx 1$ is not valid, even in strong inversion, for very thin oxides.

ACKNOWLEDGEMENTS

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