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# ECE695: Reliability Physics of Nano-Transistors
## Lecture 7: Trapping in Pre-existing Traps

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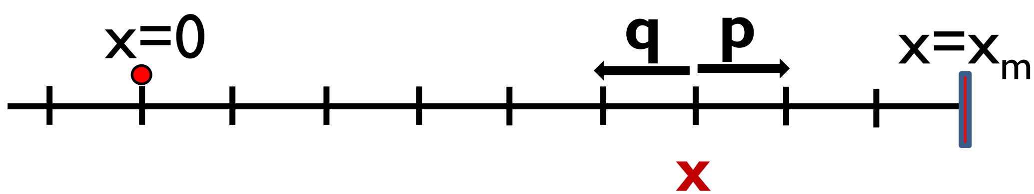
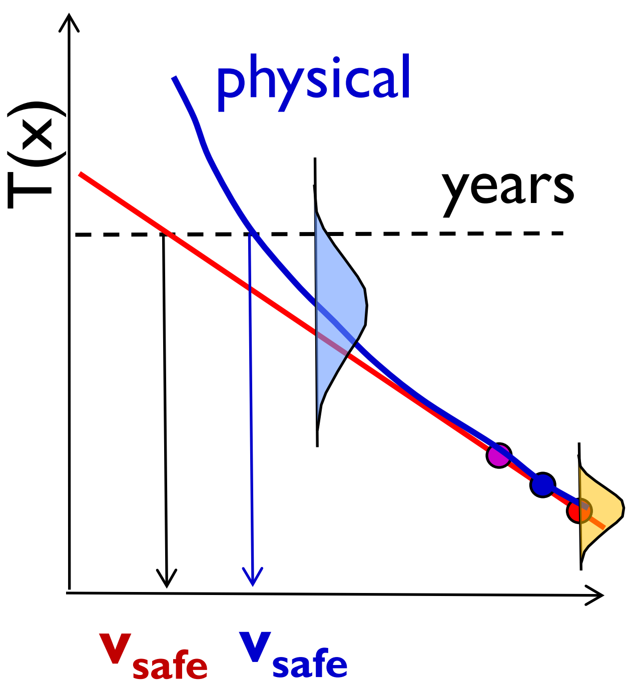
# Outline

1. Pre-existing vs. stress-induced traps
2. Voltage-shift in pre-existing bulk/interface traps
3. Random Telegraph Noise, 1/f noise
4. Conclusion

# Four Elements of Physical Reliability




1. Theory of Stress Acceleration

$$T(\upsilon, x_0) = \frac{x_0}{\upsilon}$$

2. Theory of Stochastic Distribution

$$f(t; \upsilon, x_0) = \frac{x_0}{\sqrt{4\pi D t^3}} e^{-(x_0 - \upsilon t)^2 / 4Dt}$$

3. Characterization $D, x_0$

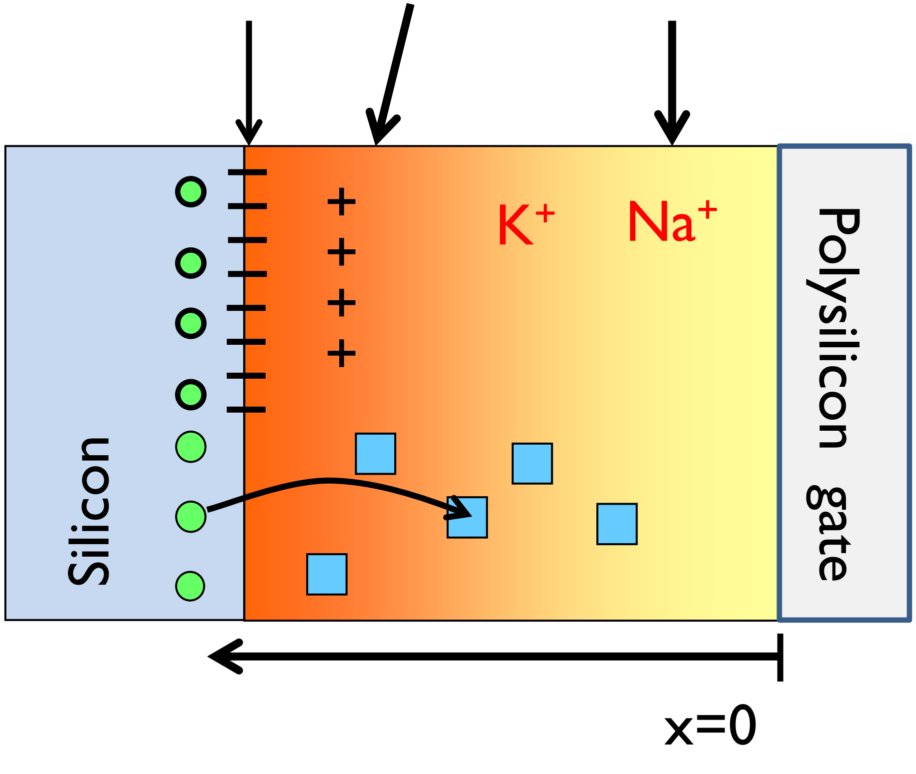
4. Analysis of Statistical data

# Time-dependent trapping in pre-existing traps

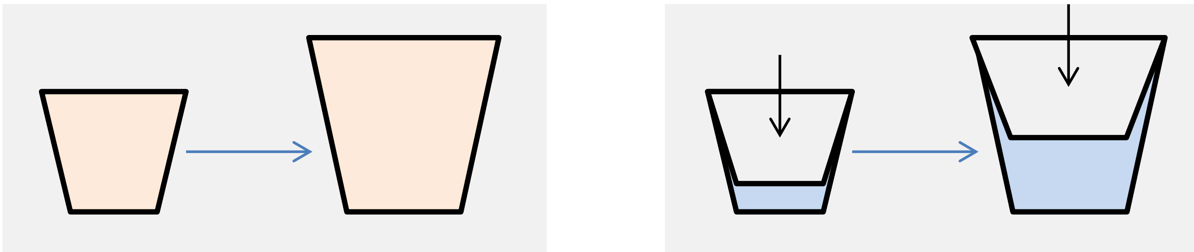
Fixed charge   Mobile ions   Trapped charge

$$V_T = V_T^{(ideal)} + \phi_{MS} - \frac{Q_{IT}(\phi_s)}{C_O} - \frac{Q_F}{C_O} - \frac{\gamma_M Q_M}{C_O} - \frac{\gamma_T Q_O(t)}{C_O}$$

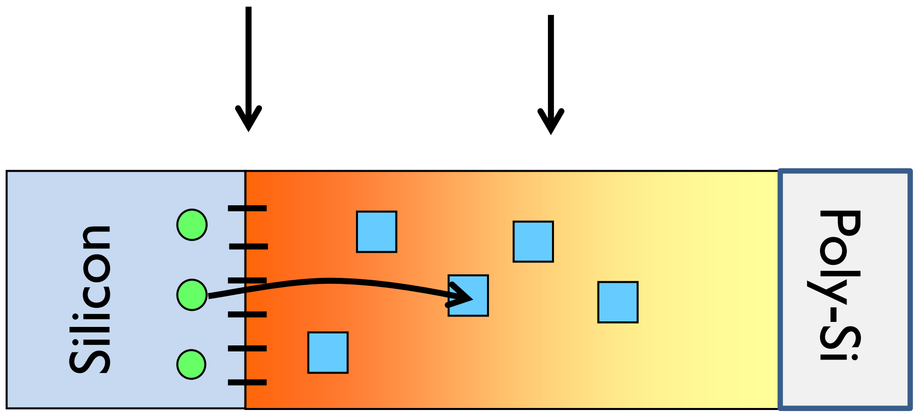
*Ref. Pierret, Ch. 18*



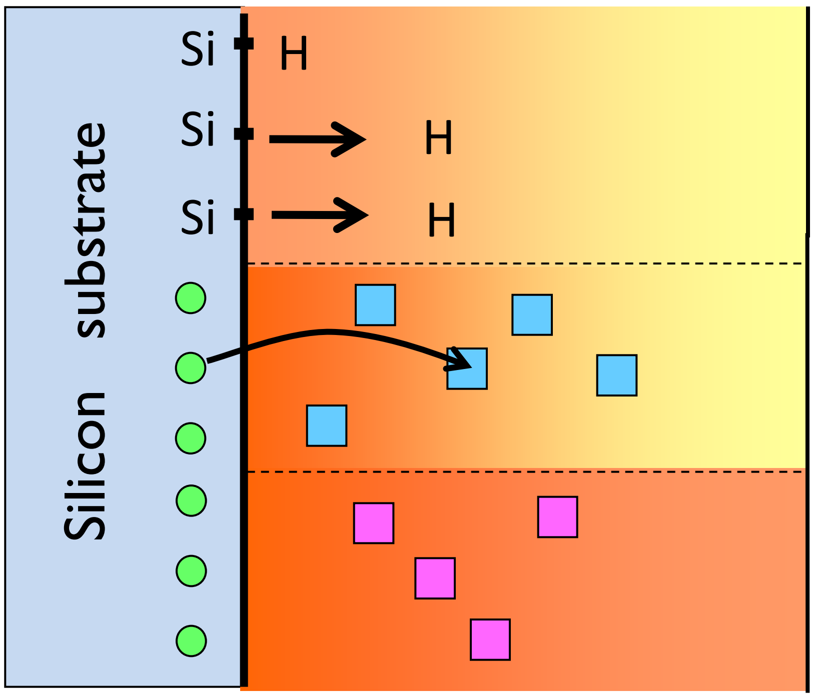
# Trapping in pre-existing vs. newly created defects



$$\Delta V_T = -\frac{qN_{IT}(t)}{C_O} - \frac{q\gamma N_O(t)}{C_O}$$



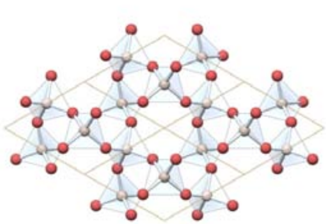
# Trapping and defect generation ….

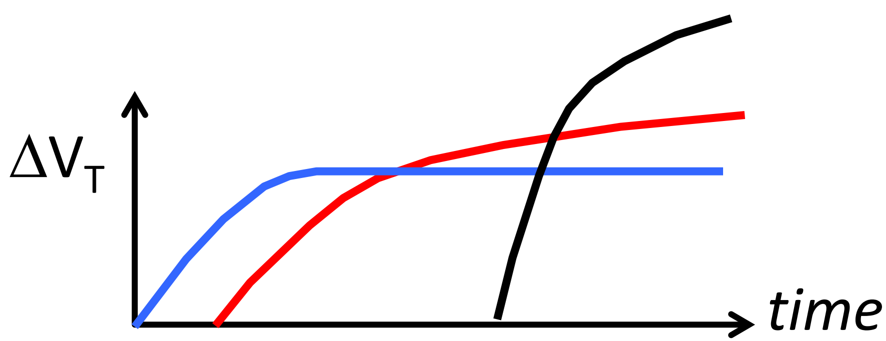



1 $N_{IT}$ generation (NBTI)

2 Hole trapping (PBTI;
*High N2 film, high-k*)

3 Bulk trap. Gen.(TDDB, PBTI, etc.)





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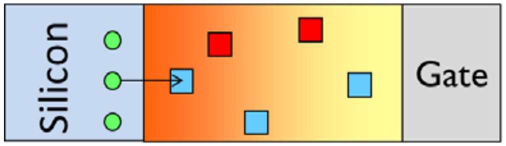
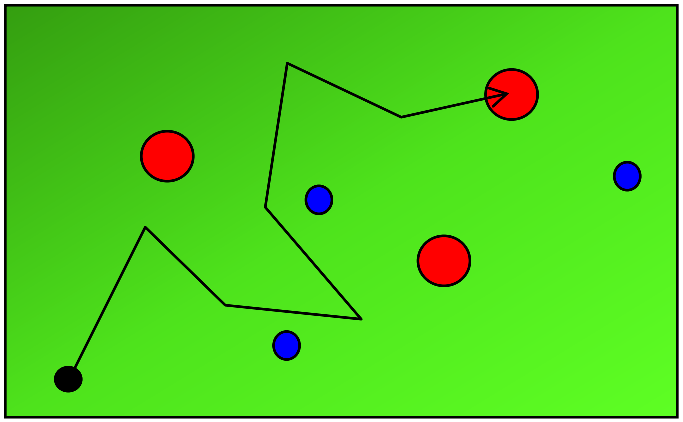
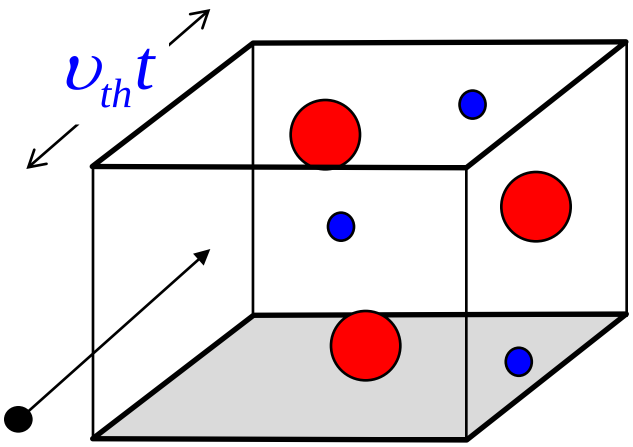
# Recall: Carrier capture by a trap






$$\frac{1}{2} m^* \upsilon_{th}^2 = \frac{3}{2} kT$$

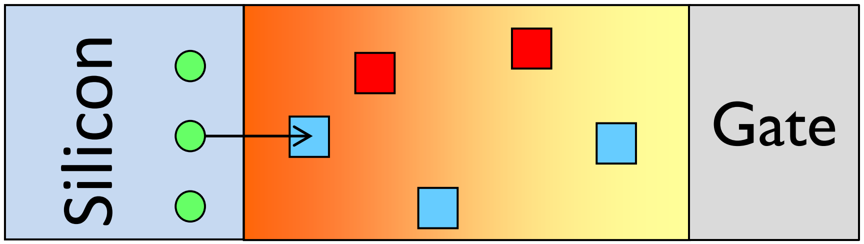
$$p_T = N_T \left(1 - f_T\right)$$

$$\frac{dn_e}{dt} = -n_e \times \left[ \frac{A \times \upsilon_{th} t \times p_T \times \sigma_n}{A \times t} \right]$$

$$\frac{dn_e}{dt} = -n_e \times \upsilon_{th} \times \sigma_n \times p_T$$

*Ref. ECE606: L13*

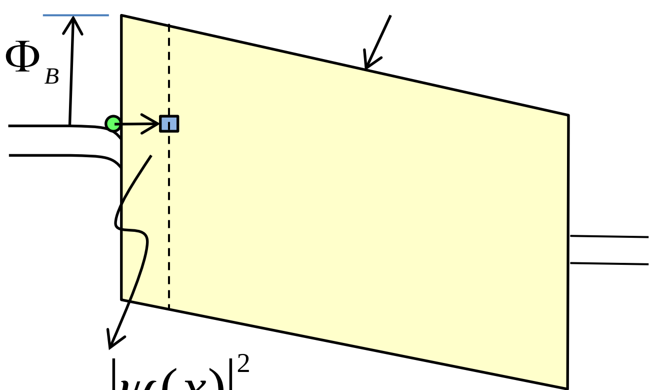
# Fluxes into pre-existing traps and Transmission Coefficients




$$f_O \equiv \frac{n}{N_O}$$

$$\frac{dn_O}{dt} = n_e \times \sigma \upsilon_{th} \times T_1 \times N_O (1 - f_O)$$

WKB approximation




$$T_1(x) = \frac{|\psi(x)|^2}{|\psi(0)|^2}$$

$$T_1(x) \propto e^{-\frac{2}{\hbar}\int_0^x \sqrt{2m^*(\Phi_B - q\phi(x) - E)}\,dx}$$

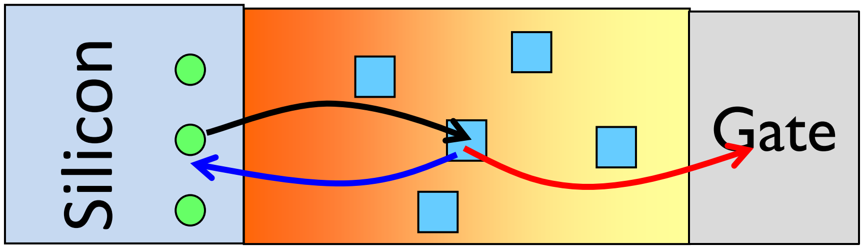
$$= e^{-\frac{2}{\hbar}\int_0^x \sqrt{2m^*_{ox}(\Phi_B - q\mathcal{E}x - E)}\,dx}$$

$$\approx e^{-\frac{2}{\hbar}\sqrt{2m^*_{ox}\Phi_B} \times x}$$

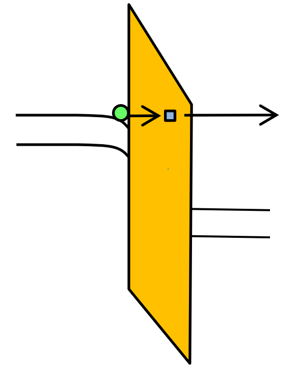
$$\equiv e^{-\frac{x}{x_0}}$$

$x_0$=2-3 A in SiO2

# Voltage-shift due to pre-existing traps in thin oxides



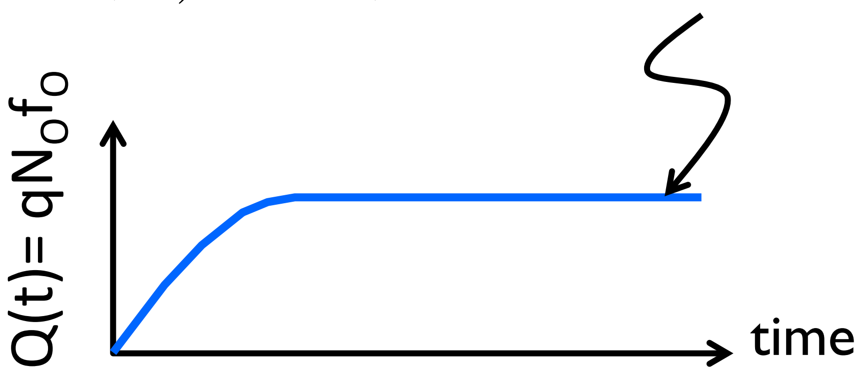

$$f_O \equiv \frac{n}{N_O}$$



$$T_1 = k \times e^{-\frac{x}{x_0}}$$

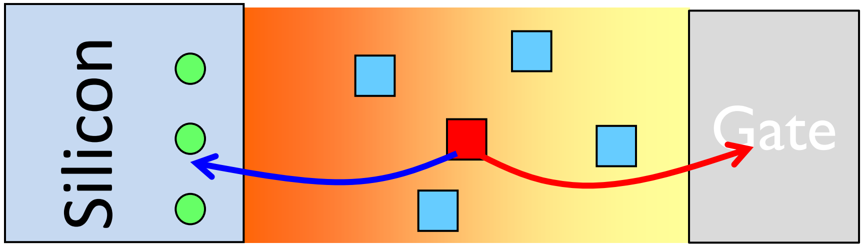
$$\frac{dn_O}{dt} = \frac{d(N_O f_O)}{dt} = N_O \sigma \upsilon_{th}\left[n_e T_1 (1 - f_O) - p_S T_1 f_O - p_G T_2 f_O\right]$$

$$f_O = \frac{T_1\left[1-\exp\left(-\sigma\upsilon_{th}\left(n_e T_1 + p_s T_1 + p_G T_2\right)t\right)\right]}{(1+p_S/n_e)T_1 + p_G T_2/n_e} \equiv b\left[1-\exp\left(-t/\tau_c\right)\right]$$




$$\tau_c \propto T_1^{-1} \propto e^{+\frac{x}{x_0}}$$

# Detrapping of filled traps



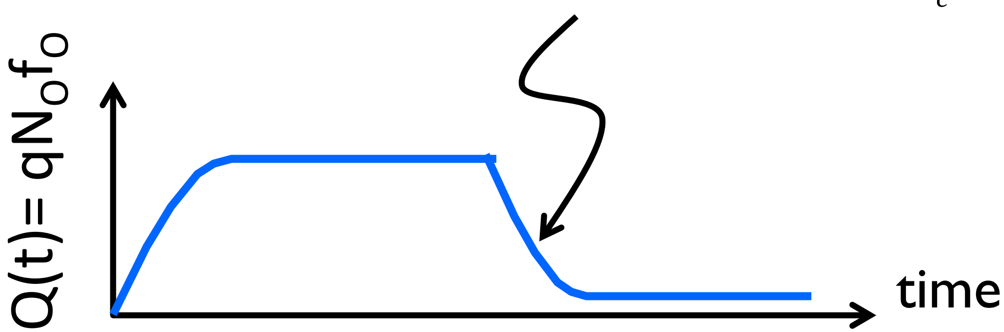

$$f_O \equiv \frac{n_0}{N_O}$$

$$\frac{dn_O}{dt} = \frac{d(N_O f_O)}{dt} = N_O \sigma \upsilon_{th} \left[ \cancel{n_e T_1 (1 - f_O)} - p_S T_1 f_O - p_G T_2 f_O \right]$$

$$f_O = \left[ \exp\left(-\sigma \upsilon_{th} \left( p_s T_1 + p_G T_2 \right) t \right) \right] \equiv c\, e^{-\frac{t}{\tau_e}}$$

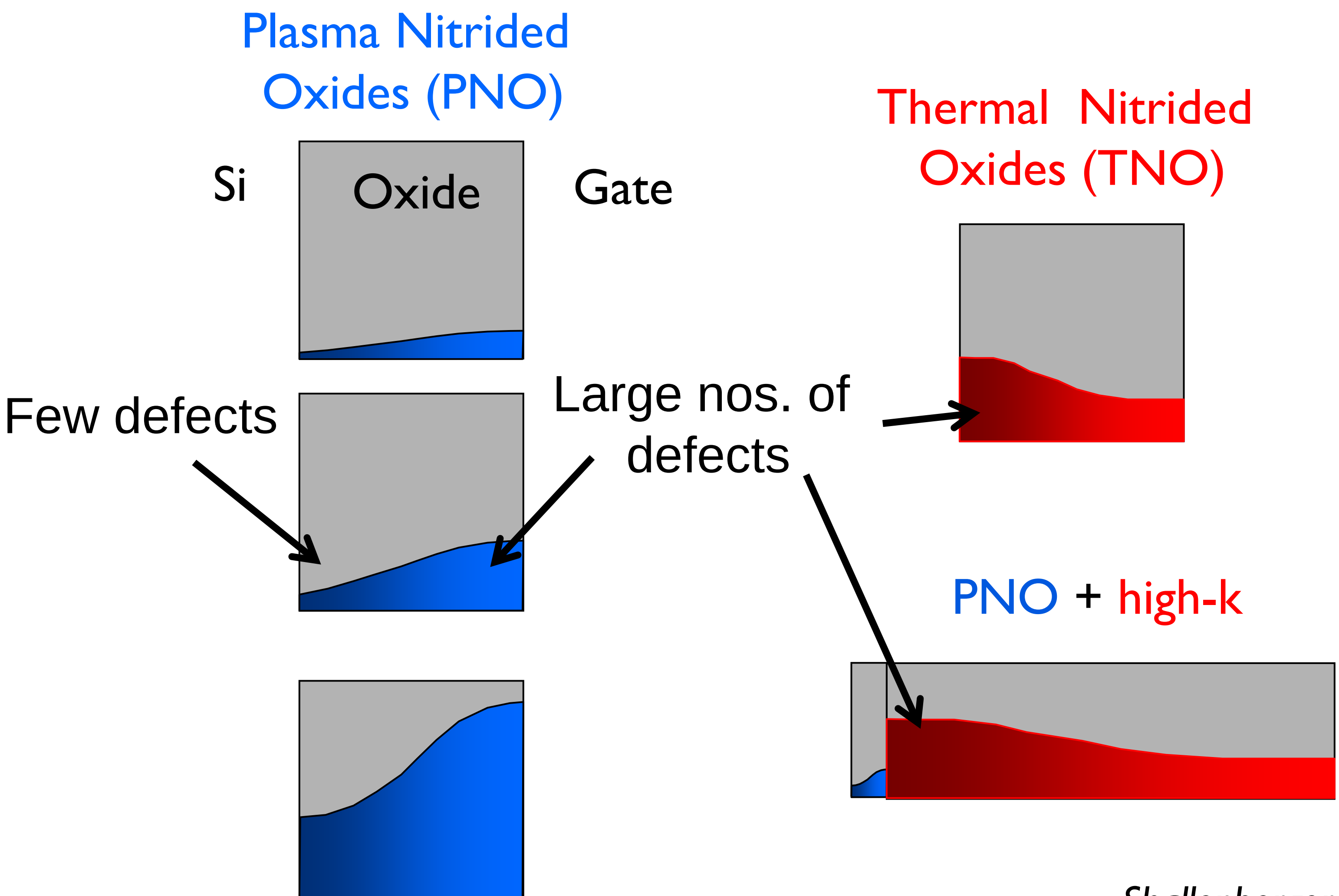
$$Q(t) = qN_O \left[ 1 - \exp\left(-t_H / \tau_c\right) \right] \left[ \exp\left(-t/\tau_e\right) \right]$$

$$\tau_c \propto T_1^{-1} \propto e^{+\frac{x}{x_0}}$$



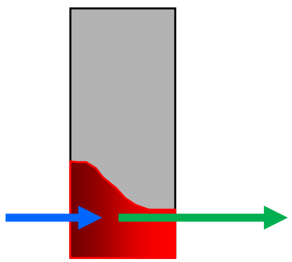
# Material dependence of bulk trapping

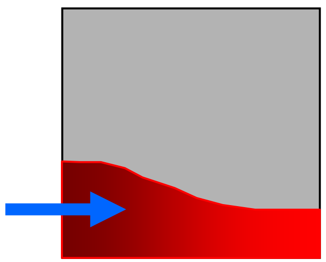
Recall defect properties from lectures 5-6 …




*Shallenberger JVST 99;*
*Rauf, JAP 05*

# Thickness dependence of bulk trapping





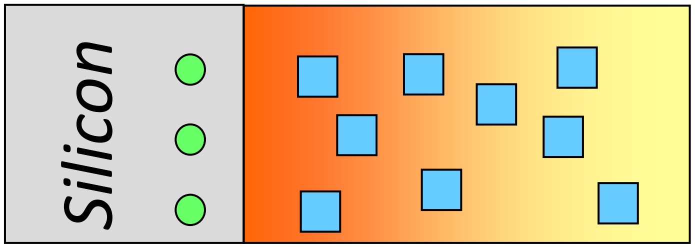
$$\frac{df_O}{dt} \approx \sigma\upsilon_{th} n_e T_1 \left(1 - f_T\right) - \sigma\upsilon_{th} p_G T_2 f_T$$

$$\frac{df_T}{dt} \approx \sigma\upsilon_{th} n_e T_1 \left(1 - f_T\right)$$

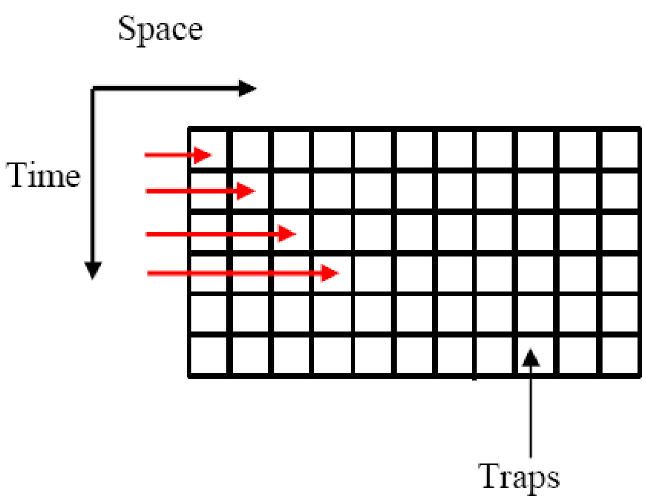
$$\Delta V_T = -\frac{q\gamma N_O(t)}{C_O} = -\frac{q\gamma N_O(t) x_0}{K_O \varepsilon_0}$$

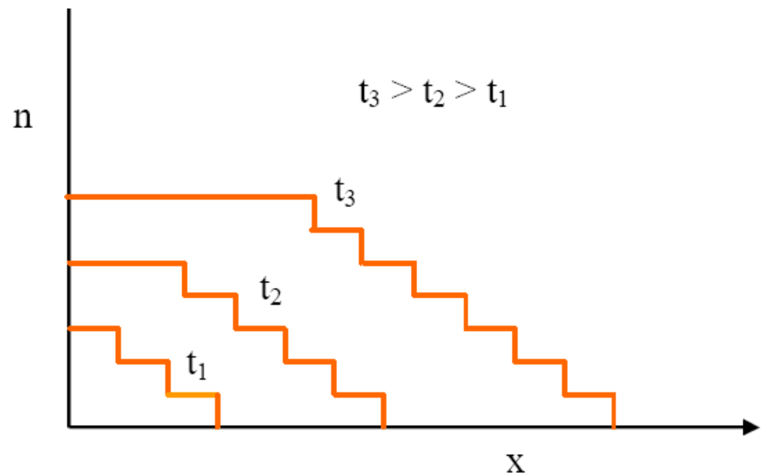
Effect of trapping reduces with thickness of the oxide …

# Trapping in thick oxides




*Wang, Logarithmic time dependence of p-MOSFET degradation, EDL, 1991*

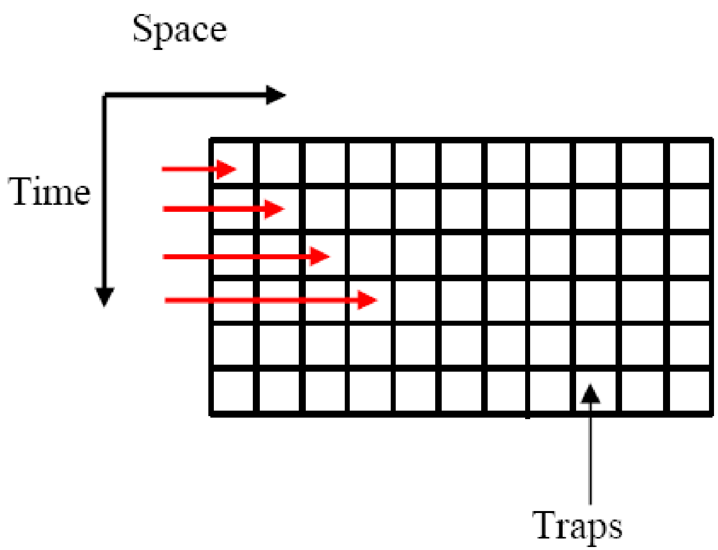



$$\frac{df_O(x)}{dt} = \sigma_0 \upsilon_{th} n_e T_1(x)\left(1 - f_O(x)\right)$$

$$\frac{dn(x)}{dt} = \sigma_0 \frac{J_0}{q} k e^{-\frac{x}{x_0}} \left(N_0 - n(x)\right)$$

# Trapping in thick oxides

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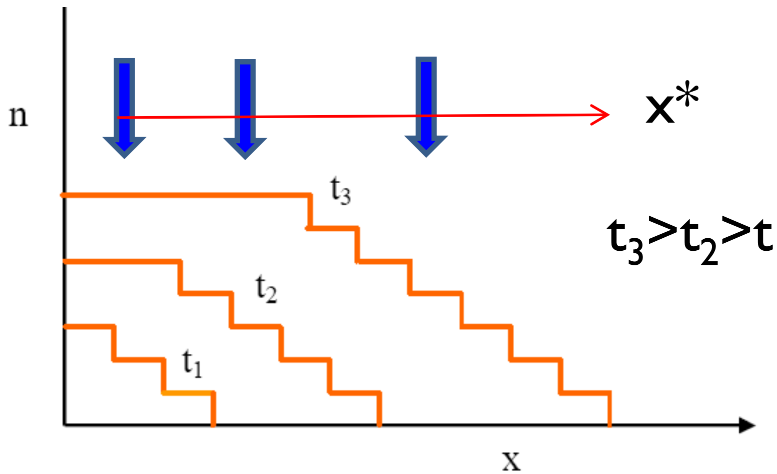



$$\frac{dn}{dt} = \sigma_0 \frac{J_0}{q} k e^{-\frac{x}{x_0}} \left(N_0 - n\right)$$

$$\frac{dn}{dt} \equiv a(x)\left(N_0 - n\right)$$

$$n(x,t) = N_0\left(1 - e^{-a \times t}\right)$$

First characteristic time

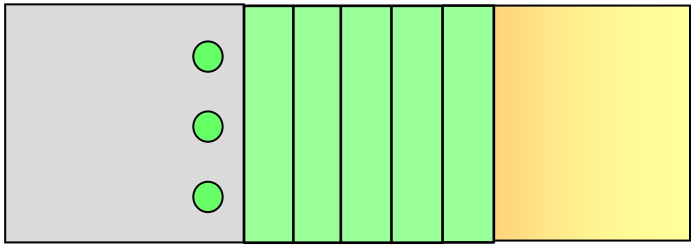
$$a\left(x^*\right)t^* = 1$$

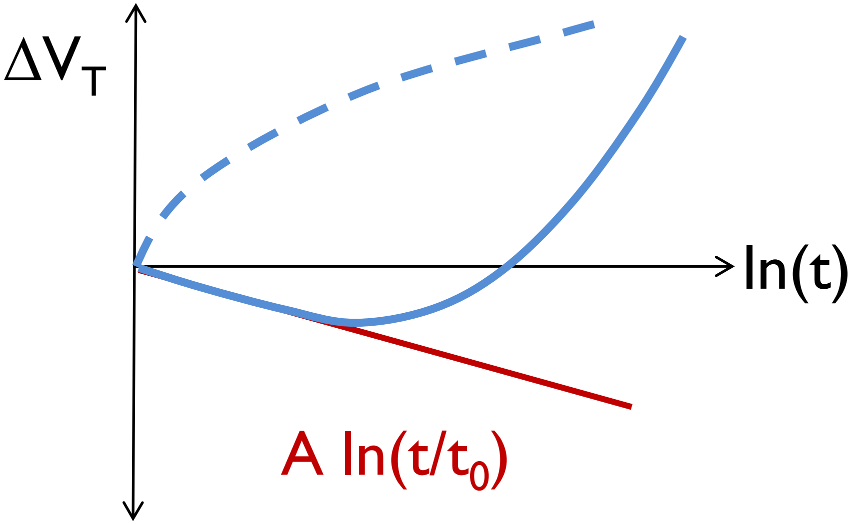
Substituting for a(x), we get

$$x^* = x_0 \ln\left(k\sigma_0 \frac{J_0}{q} t^*\right)$$

# Reflection of trapping …

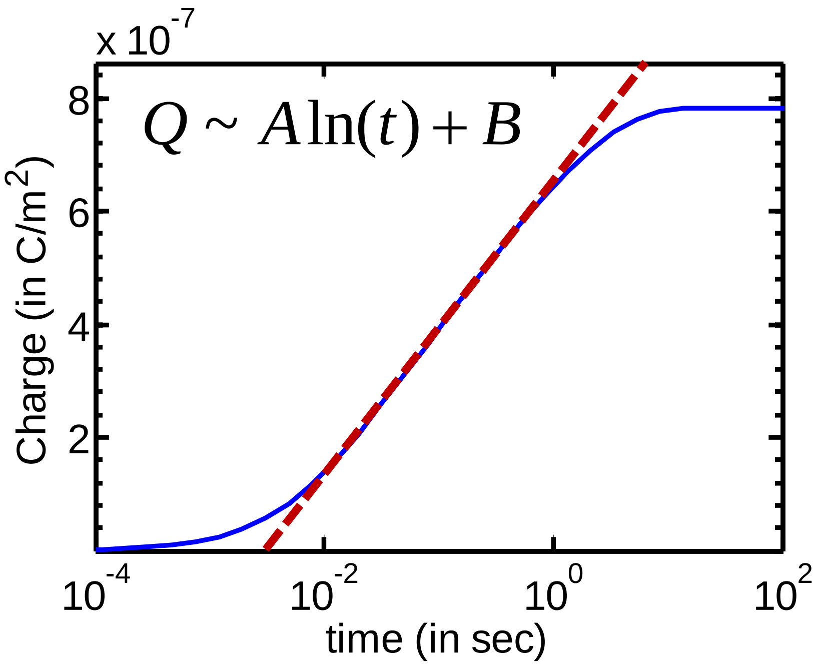
$$x^* = x_0 \ln\left( k\sigma_0 \frac{J_0}{q} t^* \right) \qquad \Delta V_T = -\int_{x_0}^{x_0 - x^*} \frac{x\rho(x)}{K_O\varepsilon_0} \sim \frac{\rho_T}{K_O\varepsilon_0} x_0 x^* \sim \left( \frac{\rho_T x_0^2}{K_O\varepsilon_0} \right) \ln\left( \frac{t}{t_0} \right)$$

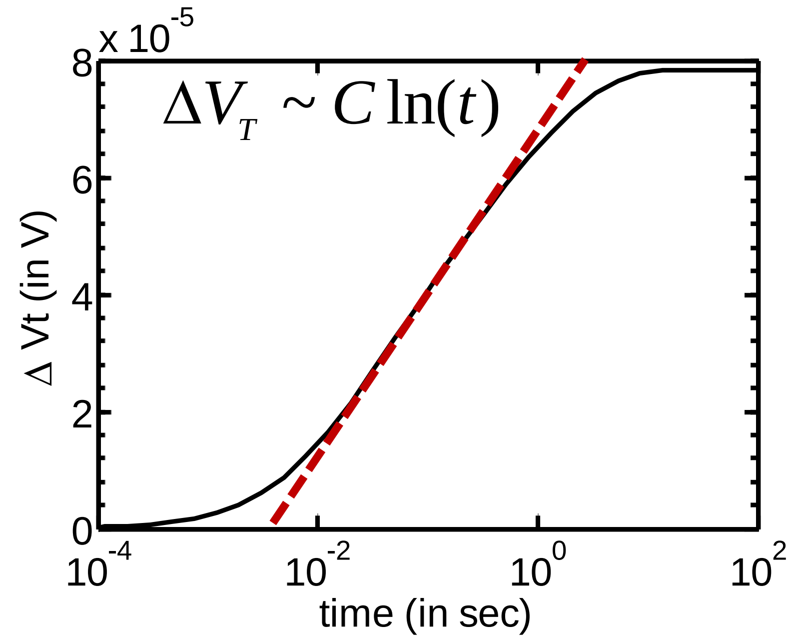


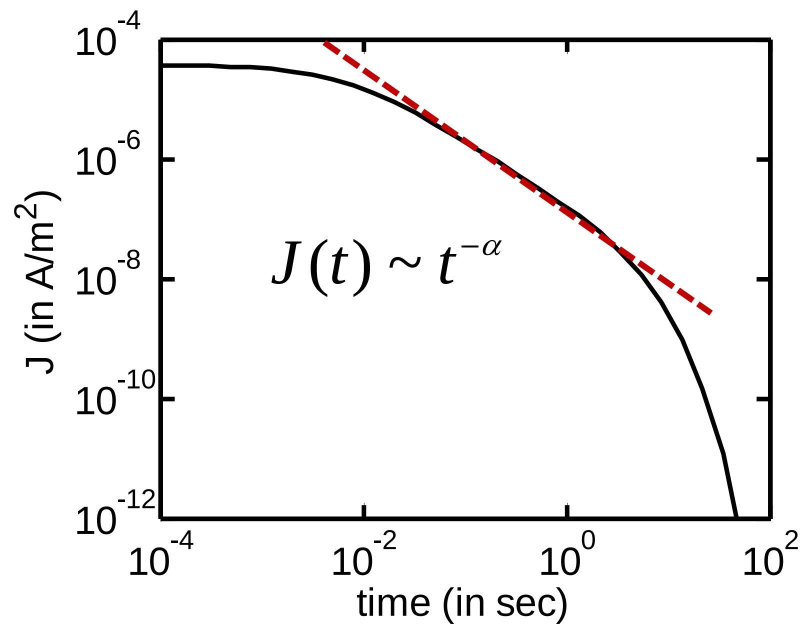



The threshold voltage increases as a power-law in time ..

# Numerical validation of the results



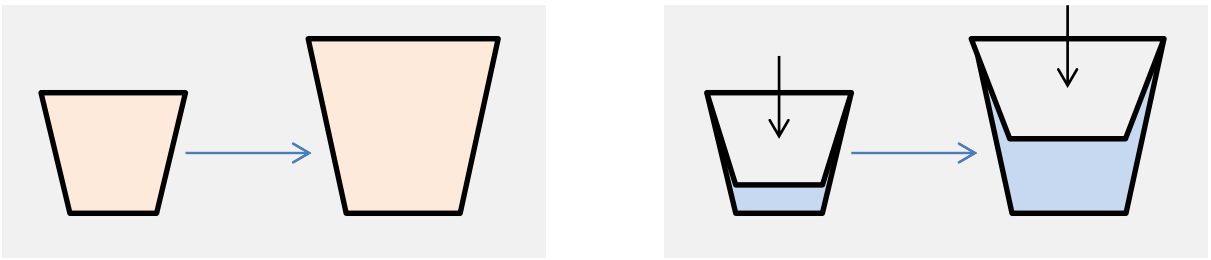



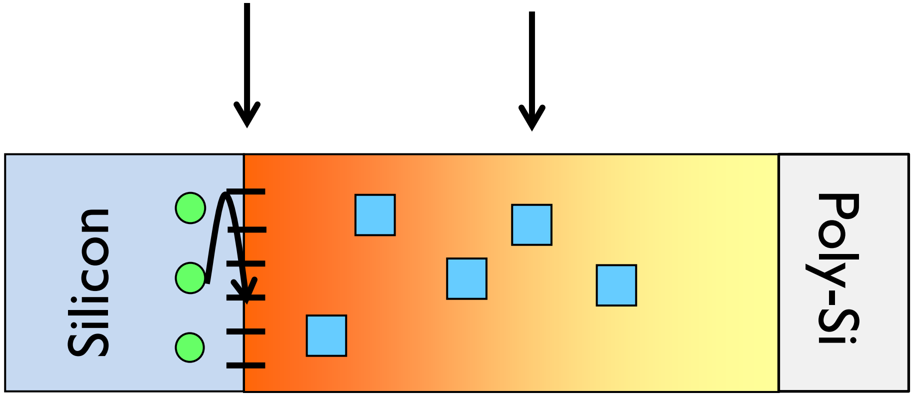

See HW3

*S. Palit, 2013*

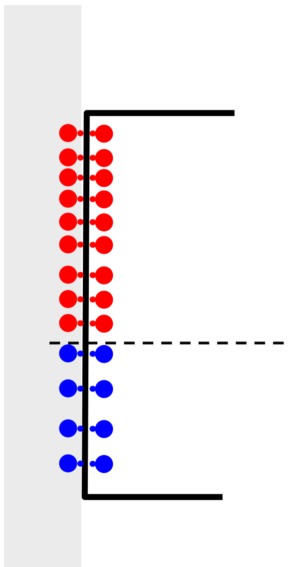
# Trapping in interface defects



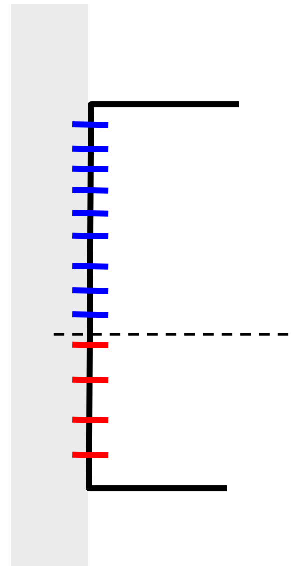
$$\Delta V_T = -\frac{qN_{IT}(t)}{C_O} - \frac{q\gamma N_O(t)}{C_O}$$



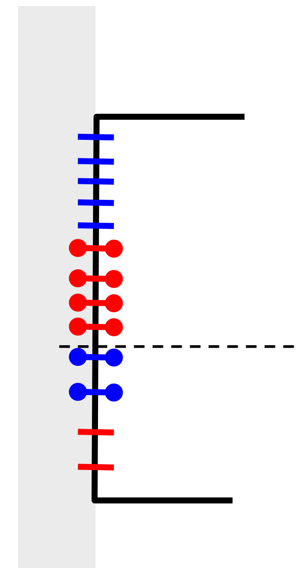
# Nature of donor and acceptor traps



Donor level
Positive when empty
Neutral when full



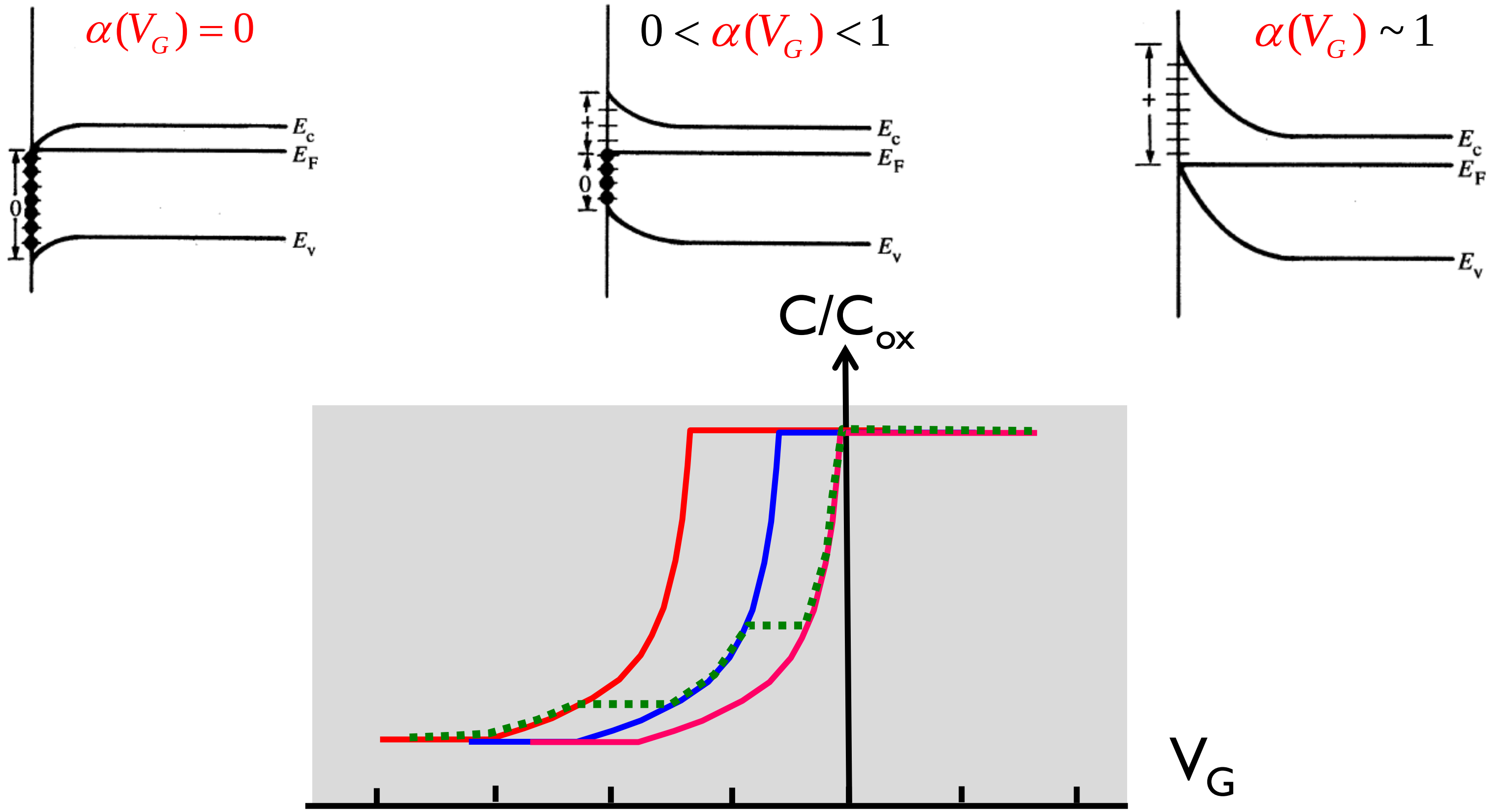
Acceptor level
Neutral when empty
Negative when full



Combination when both are present

# Donor like interface states

$$V_T = V_T^* - \frac{1}{C_o x_0}\int_0^{x_0} x \times \alpha(V_G) \times Q_o(x)\delta(x - x_o)dx \quad = V_T^* - \frac{\alpha(V_G) Q_o(x_0)}{C_o}$$



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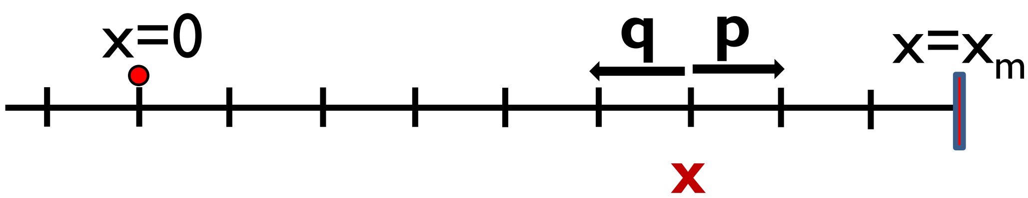


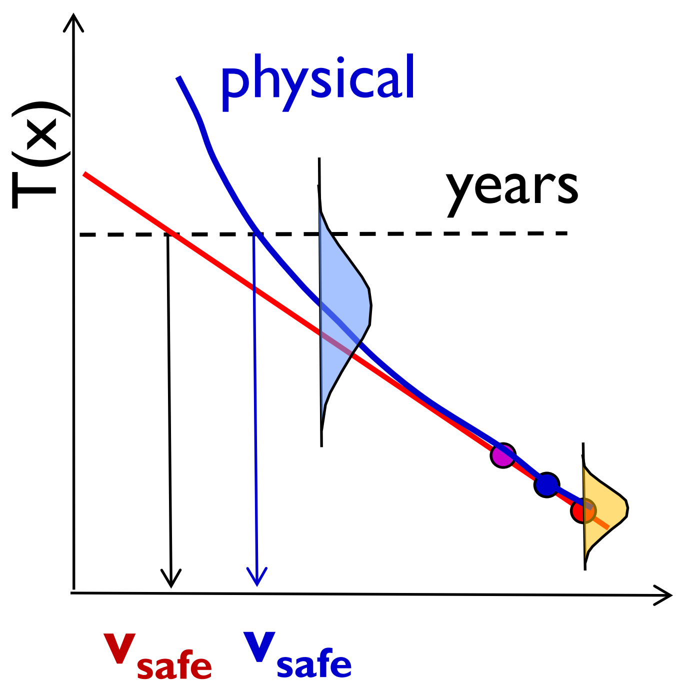


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3. Characterization $D, x_0$

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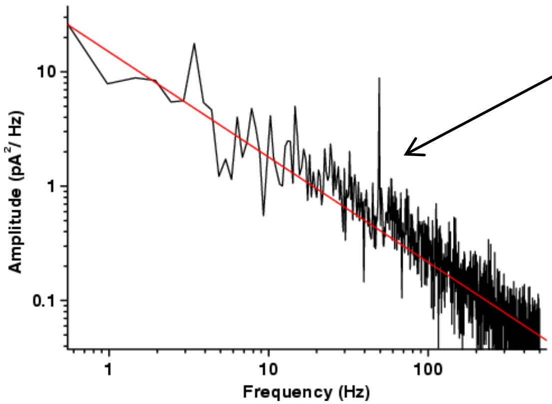
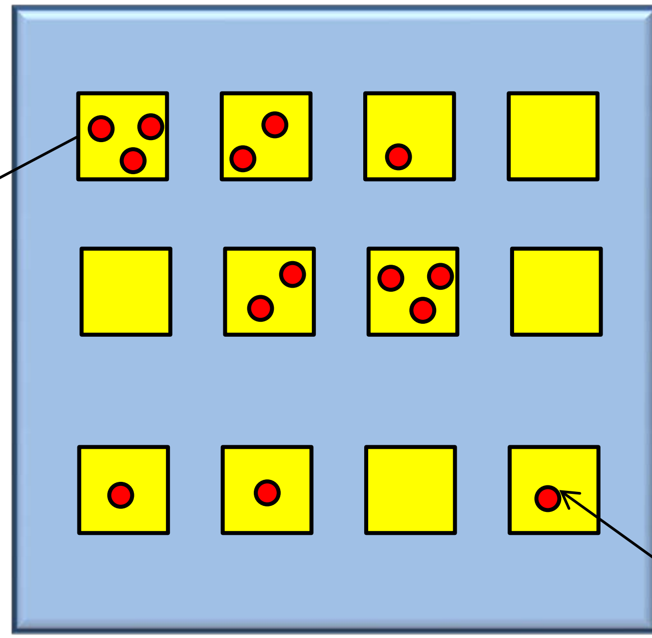
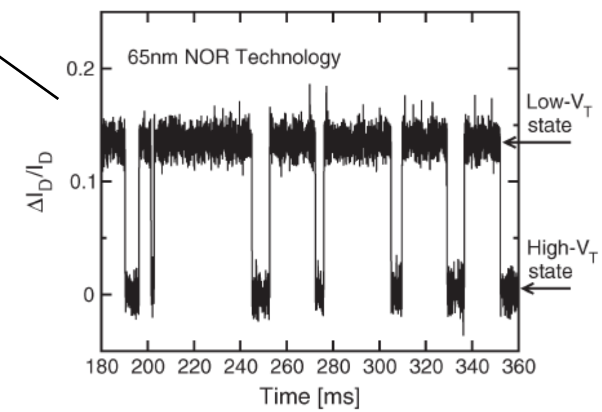
# Statistics of trapping

$$10^{17}\,\text{cm}^{-3} \times 2\text{nm} \times 100\text{nm} \times 100\text{nm} = 2 \text{ traps/device}$$



$$P_n = \frac{N^n e^{-N}}{n!}$$



# Conclusion

- Pre-existing defects are integral part of all materials – the numbers of course depend on composition, process conditions, etc.
- Time-dependent trapping in pre-existing defects causes shift in threshold voltage and corresponding changes in operating conditions.
- Effect of trapping is more significant for thick oxide than thin oxides. Passivation of interface defects is the key to essential MOSFET operation.
- Fluctuation due to Random telegraph noise is a significant reliability issue, especially for memories

# References


- *S. Zafar, "Charge trapping in high-k gate dielectric stacks," IEDM Digest 2002.*
- *Various approximations to direct tunneling current exists, for example, see Y.-C. Yeo, EDL, 2000. p. 540. W.-C. Lee, TED, 48(7), 2001, p. 1366. The subtly of tunneling in thick oxides is discussed by P..C. Arnett and D. J. DiMaria, "Contact currents in silicon nitrides," JAP, 47(5), 1976.*
- *E. Milotti, A pedagogical View of 1/f noise, arxib, 2002.*
- *Thomas Lee, "Design of CMOS Radio Frequency Circuits", Cambridge, 1998.*
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- *K. Hung et al., Random Telegraph Noise in Deep-Submicrometer MOSFETs, 11(2), p. 90, 1990.*
- B. Gross and Charles G. Sodini. 1/f noise in MOSFETs with ultrathin gate dielectrics.

  In IEDM Technical Digest, pages 881{884, 1992.