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

\[ T(\nu, x_0) = \frac{x_0}{\nu} \]

2. Theory of Stochastic Distribution

\[ f(t; \nu, x_0) = \frac{x_0}{\sqrt{4\pi Dt^3}} e^{-(x_0-\nu t)^2/(4Dt)} \]

3. Characterization \( D, x_0 \)

4. Analysis of Statistical data
Time-dependent trapping in pre-existing traps

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

Ref. Pierret, Ch. 18

Silicon

K⁺ Na⁺

Polysilicon gate

Mobile ions

Fixed charge

Trapped charge

x=0
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; 
   \textit{High N2 film, high-k})

3. Bulk trap. Gen.(TDDB, PBTI, etc.)
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Recall: Carrier capture by a trap

\[ \frac{1}{2} m^* \nu_{th}^2 = \frac{3}{2} kT \]

\[ p_T = N_T \left( 1 - f_T \right) \]

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

\[ \frac{dn_e}{dt} = -n_e \times \nu_{th} \times \sigma_n \times p_T \]

Ref. ECE606: L13
Fluxes into pre-existing traps and Transmission Coefficients

\[ \frac{dn_o}{dt} = n_e \times \sigma v_{th} \times T_1 \times N_o \left( 1 - f_o \right) \]

\[ \phi(x) \sim E \times x \]

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

\[ f_o \equiv \frac{n}{N_o} \]

WKB approximation

\[ -\frac{2}{\hbar} \int_0^x \sqrt{2m^* (\Phi_B - q\phi(x) - E)} \, dx \]

\[ = e^{-\frac{2}{\hbar} \sqrt{2m_{ox}^* (\Phi_B - qx - E)}} \]

\[ \approx e^{-\frac{2}{\hbar} \sqrt{2m_{ox}^* \Phi_B \times x}} \]

\[ \equiv e^{-\frac{x}{x_0}} \]

\[ x_0 = 2-3 \, \text{A in SiO}_2 \]
Voltage-shift due to pre-existing traps in thin oxides

\[ f_0 \equiv \frac{n}{N_o} \]

\[ \frac{dn_o}{dt} = \frac{d(N_o f_o)}{dt} = N_o \sigma v_{th} \left[ n_e T_1 (1 - f_o) - p_s T_1 f_o - p_g T_2 f_o \right] \]

\[ f_o = \frac{T_1 \left[ 1 - \exp \left( -\sigma v_{th} \left( n_e T_1 + p_s T_1 + p_g T_2 \right) t \right) \right]}{(1 + p_s / n_e) T_1 + p_g T_2 / n_e} \equiv b \left[ 1 - \exp \left( -t / \tau_c \right) \right] \]

\[ \tau_c \propto T_1^{-1} \propto e^{\frac{x}{x_0}} \]

\[ Q(t) = q N_o f_o \]
Detrapping of filled traps

\[ f_o \equiv \frac{n_0}{N_0} \]

\[
\frac{dn_o}{dt} = \frac{d(N_0 f_o)}{dt} = N_0 \sigma_{th} \left[ n_e T_1 (1 - f_o) - p_s T_1 f_o - p_G T_2 f_o \right]
\]

\[
f_o = \left[ \exp(-\sigma_{th} (p_s T_1 + p_G T_2) t) \right] \equiv c e^{-\frac{t}{\tau_e}}
\]

\[
Q(t) = qN_0 \left[ 1 - \exp(-t / \tau_c) \right] \left[ \exp(-t / \tau_e) \right]
\]

\[ \tau_c \propto T_1^{-1} \propto e^{\frac{x}{x_0}} \]

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Material dependence of bulk trapping

Recall defect properties from lectures 5-6 …

Plasma Nitrided Oxides (PNO)

Few defects

Large nos. of defects

Thermal Nitrided Oxides (TNO)

PNO + high-k

Shallenberger JVST 99;
Rauf, JAP 05
Thickenss dependence of bulk trapping

\[ \frac{df_O}{dt} \approx \sigma v_{th} n_e T_1 (1 - f_T) - \sigma v_{th} p_G T_f f_T \]

\[ \frac{df_T}{dt} \approx \sigma v_{th} n_e T_1 (1 - f_T) \]

\[ \Delta V_T = - \frac{q_\gamma N_o(t)}{C_o} = - \frac{q_\gamma N_o(t) x_0}{K_o \varepsilon_0} \]

Effect of trapping reduces with thickness of the oxide …
Trapping in thick oxides

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

\[
\frac{df_o(x)}{dt} = \sigma_0 v_{th} n_e T_1(x) (1 - f_o(x))
\]

\[
\frac{dn(x)}{dt} = \sigma_0 \frac{J_0}{q} ke^{\frac{x}{x_0}} (N_0 - n(x))
\]
Trapping in thick oxides

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

First characteristic time

\[ a(x^*) t^* = 1 \]

Substituting for \( a(x) \), we get

\[ x^* = x_0 \ln \left( k\sigma_0 \frac{J_0}{q} t^* \right) \]
Reflection of trapping ...

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

\[ \Delta V_T = - \int_{x_0}^{x_0 - x^*} \frac{x \rho(x)}{K_0 \varepsilon_0} \sim \frac{\rho_T}{K_0 \varepsilon_0} x_0 x^* \sim \left( \frac{\rho_T x_0^2}{K_0 \varepsilon_0} \right) \ln \left( \frac{t}{t_0} \right) \]

The threshold voltage increases as a power-law in time ..
Numerical validation of the results

\[ Q \sim A \ln(t) + B \]

\[ \Delta V_t \sim C \ln(t) \]

\[ J(t) \sim t^{-\alpha} \]

See HW3

S. Palit, 2013
Trapping in interface defects

\[ \Delta V_T = -\frac{qN_{IT}(t)}{C_0} - \frac{q\gamma N_O(t)}{C_0} \]
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

\[ V_T = V_T^* - \frac{1}{C_0x_0} \int_0^{x_0} x \times \alpha(V_G) \times Q_o(x) \delta(x - x_o) \, dx \]

\[ = V_T^* - \frac{\alpha(V_G)Q_o(x_0)}{C_0} \]

- \( \alpha(V_G) = 0 \)
- \( 0 < \alpha(V_G) < 1 \)
- \( \alpha(V_G) \sim 1 \)
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3. Characterization
\[ D, x_0 \]

4. Analysis of Statistical data
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