

# **Interface Traps in Surface-Potential- Based MOSFET Models**

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# Interface Traps in Surface-Potential-Based MOSFET Models

## Outline

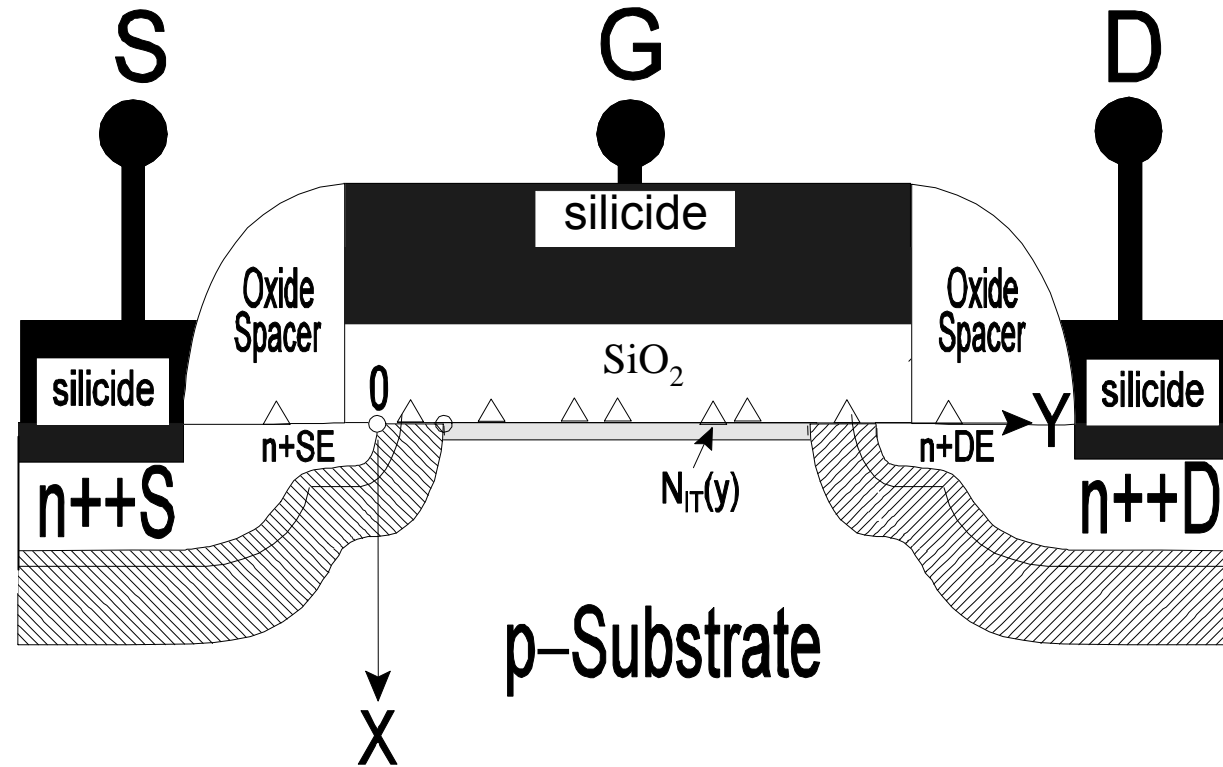
- Motivations.
- Theory of interface traps.
- Theory of unified regional surface potential.
- Theory of unified regional drain current.
- Effects of interface-trap density on surface potential.
- Effects of interface-trap density on drain current.
- Summary

# Motivation

## Reasons for investigating interface traps

- The density and spatial distribution of interface traps at the  $\text{SiO}_2/\text{Si}$  interface increasingly impacts the performance and endurance of metal-oxide-silicon capacitors and transistors in integrated circuits.
- Interface traps are generated in MOS transistors during program-erase cycles, which are the main mechanism that limits the endurance of non-volatile MOS memory transistors such as the floating gate and recent SONOS.

# Interface traps in MOSFETs



# Theory of interface traps

$$(1) Q_{ETi} = -qN_{ETi} \times \frac{c_{ns}n_s + e_{ps}}{c_{ns}n_s + e_{ns} + c_{ps}p_s + e_{ps}}$$

$$(2) Q_{HTi} = qN_{HTi} \times \frac{c_{ps}p_s + e_{ns}}{c_{ns}n_s + e_{ns} + c_{ps}p_s + e_{ps}}$$

$$(3) n_s = n_i \exp[(\phi_s - \phi_{Fn}) / v_{th}]$$

$$(4) p_s = n_i \exp[(\phi_{Fp} - \phi_s) / v_{th}]$$

$$(5) e_{ns} = c_{ns}n_i \exp(+E_{Ti} / kT)$$

$$(6) e_{ps} = c_{ps}n_i \exp(-E_{Ti} / kT)$$

$$(7) R = \frac{D_{ET0}}{D_{HT0}} = \frac{1.09412}{0.5228205} = 2.095526$$

$$(8) N_{ET} = \int_0^{E_{ET}} (D_{ET0} \times E) dE = \frac{D_{ET0}}{2} (E_{ET})^2$$

$$(9) N_{HT} = \int_{E_{HT}}^1 D_{HT0} \times (1 - E_{HT}) dE = \frac{D_{HT0}}{2} (1 - E_{HT})^2$$

$$(10) Q_{IT} = \int_{E_v}^{E_c} (Q_{ETi} + Q_{HTi}) dE$$

# Theory of unified regional surface potential

$$(1) \quad V_{gb} = \phi_s + \Phi_{MS} - \frac{Q_{IT}}{C_{ox}} + \text{sgn}(\phi_s) \gamma \sqrt{f_\phi}$$

$$(1a) \quad f_\phi = v_{th} \left[ \left( e^{\frac{-\phi_s}{v_{th}}} + \frac{\phi_s}{v_{th}} - 1 \right) + \left( e^{\frac{\phi_s}{v_{th}}} - \frac{\phi_s}{v_{th}} - 1 \right) e^{\frac{-(2\phi_{Fp} + V_{cb})}{v_{th}}} \right]$$

$$(2a) \quad V_{gb} = \phi_s + \Phi_{MS} + v_{th} \gamma \sqrt{\exp(-\phi_s / v_{th})}, \quad (V_{gb} \ll \Phi_{MS})$$

$$(2b) \quad V_{gb} = -\phi_s + \Phi_{MS} + \gamma \sqrt{-\phi_s}, \quad (V_{gb} < \Phi_{MS})$$

$$(3c) \quad V_{gb} = \phi_s + \Phi_{MS} + \gamma \sqrt{\phi_s}, \quad (\Phi_{MS} < V_{gb} < V_t)$$

$$(2d) \quad V_{gb} = \phi_s + \Phi_{MS} + v_{th} \gamma \sqrt{\exp[(-\phi_s - 2\phi_{Fp} - V_{cb}) / v_{th}]}, \quad (V_{gb} \gg V_t)$$

# Theory of unified regional drain current

$$(1) I_{ds} = \beta \left( \bar{q}_i + v_{th} \bar{A}_b \right) V_{ds,eff}$$

$$(2) \bar{q}_i = V_{gb} - V_{fb} - \bar{\phi}_s - \gamma \sqrt{\bar{\phi}_s}$$

$$(3) \bar{A}_b = 1 + \frac{\gamma}{2 \sqrt{\bar{\phi}_s}}$$

$$(4) \bar{\phi}_s = \frac{\phi_s(V_{s,eff}) + \phi_s(V_{d,eff})}{2}$$

$$(5) \beta = WuC_{ox} / L_{eff}$$

$$(6) V_{fb} = \Phi_{MS} - Q_{IT} / C_{OX}$$

$$(7) V_{db,sat} = \frac{V_{gt,d} L_{eff} E_{sat,d}}{V_{gt,d} + 4A_{b,d} v_{th} + A_{b,d} L_{eff} E_{sat,d}}$$

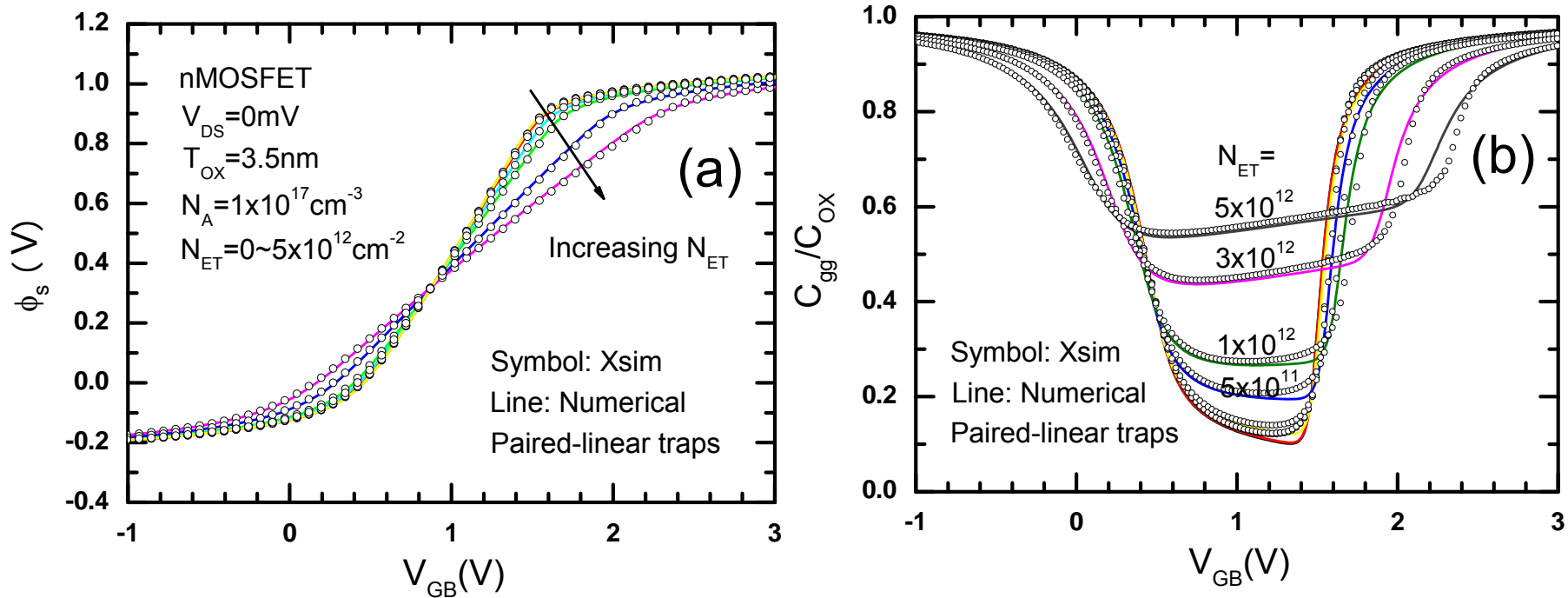
$$(8) V_{sb,sat} = \frac{V_{gt,s} L_{eff} E_{sat,s}}{V_{gt,s} + 4A_{b,s} v_{th} + A_{b,s} L_{eff} E_{sat,s}}$$

$$(9) V_{gt,d} = \gamma \sqrt{\phi_{s,d} + v_{th} e^{[\phi_{s,d} - 2\phi_F - V_{db}]/v_{th}}} - \gamma \sqrt{\phi_{s,d}}$$

$$(10) V_{gt,s} = \gamma \sqrt{\phi_{s,s} + v_{th} e^{[\phi_{s,s} - 2\phi_F - V_{sb}]/v_{th}}} - \gamma \sqrt{\phi_{s,s}}$$

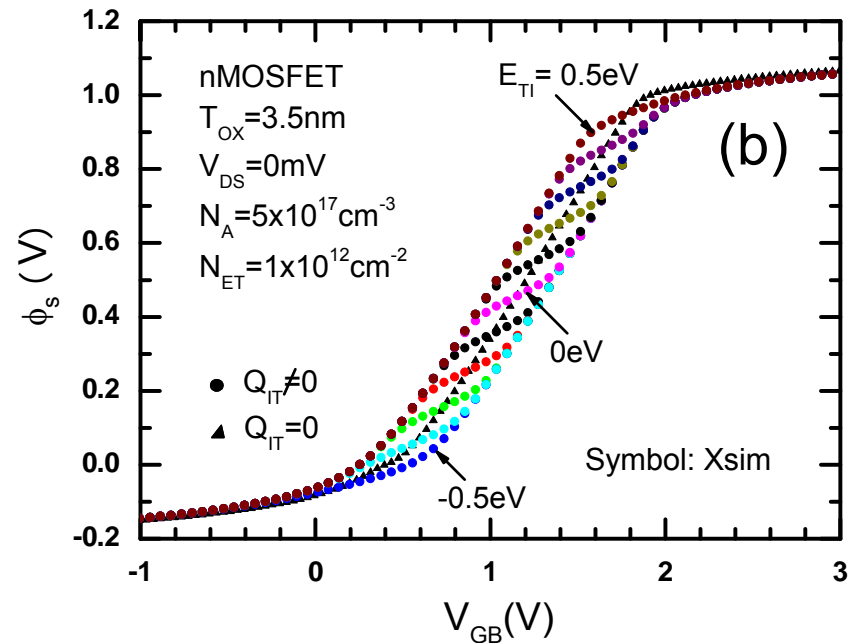
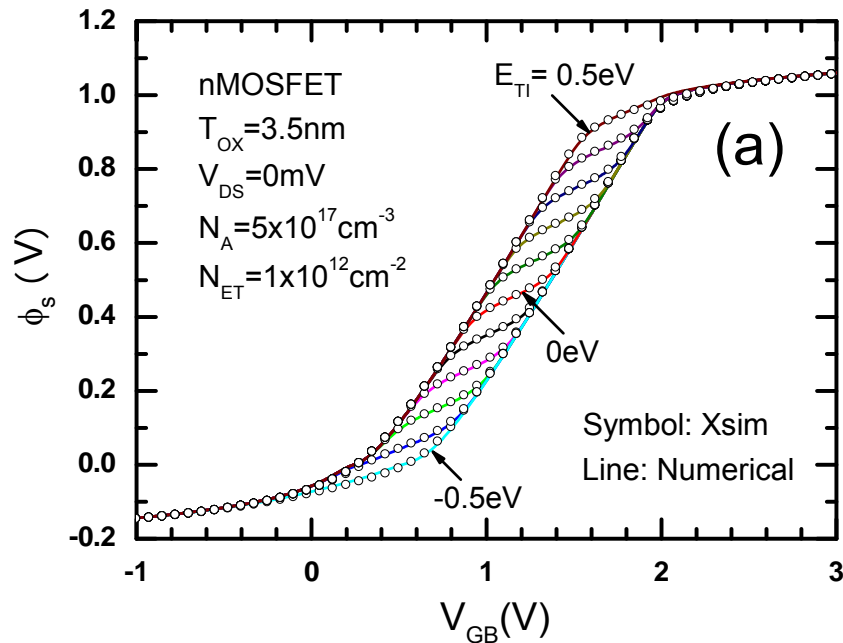
$$(11) V_{ds,eff} = V_{db,eff} - V_{sb,eff}$$

# Effect of interface-trap density on surface potential (1)



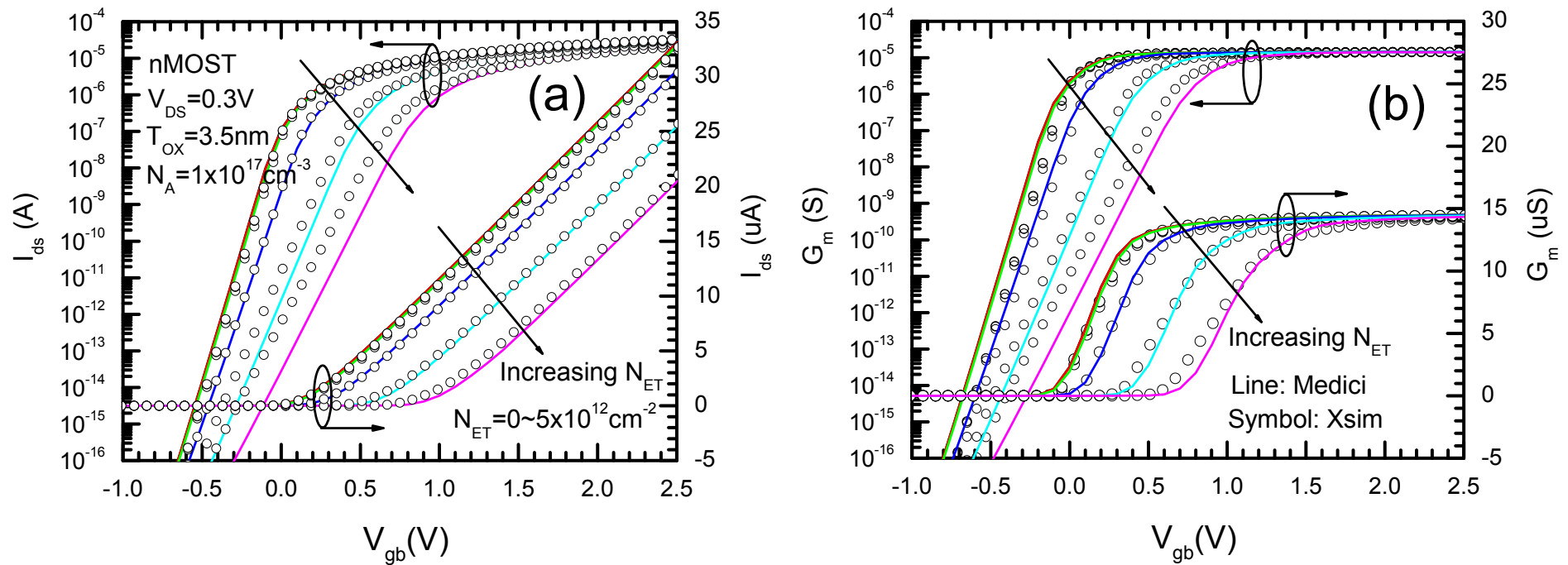
(a) Effect of interface-trap density on surface-potential lineshape, (b) effect of interface-trap density on normalized C-V curves.  $N_{ET} = 0, 1.0 \times 10^{10}, 1.0 \times 10^{11}, 5.0 \times 10^{11}, 1.0 \times 10^{12}, 3.0 \times 10^{12},$  and  $5.0 \times 10^{12}\text{ cm}^{-2}$ .

# Effect of interface-trap density on surface potential (2)



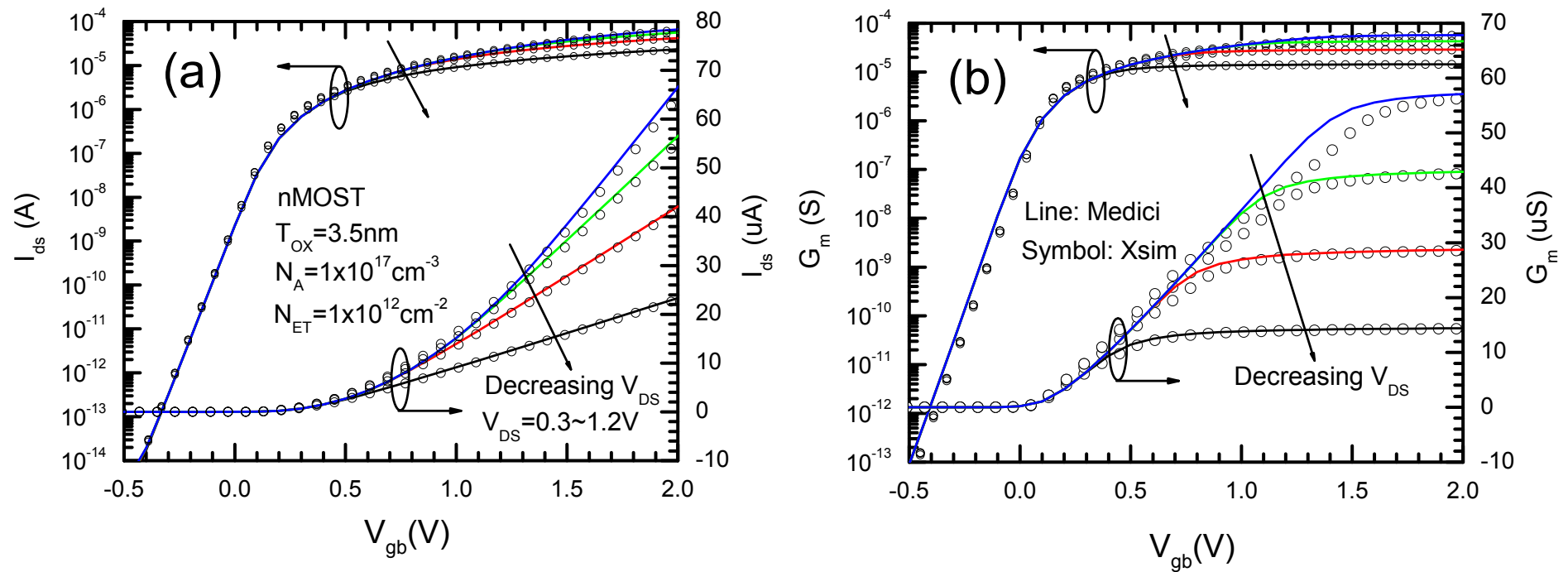
Effect of discrete energy-level position of interface traps on the surface-potential lineshape with  $E_{TI} = -0.5$  to  $+0.5$  eV in  $0.1\text{-eV}$  steps: (a) comparison between the URSP approach and the exact iterative solution, and (b) comparison between devices with and without interface traps.

# Effect of interface-trap density on drain current (1)



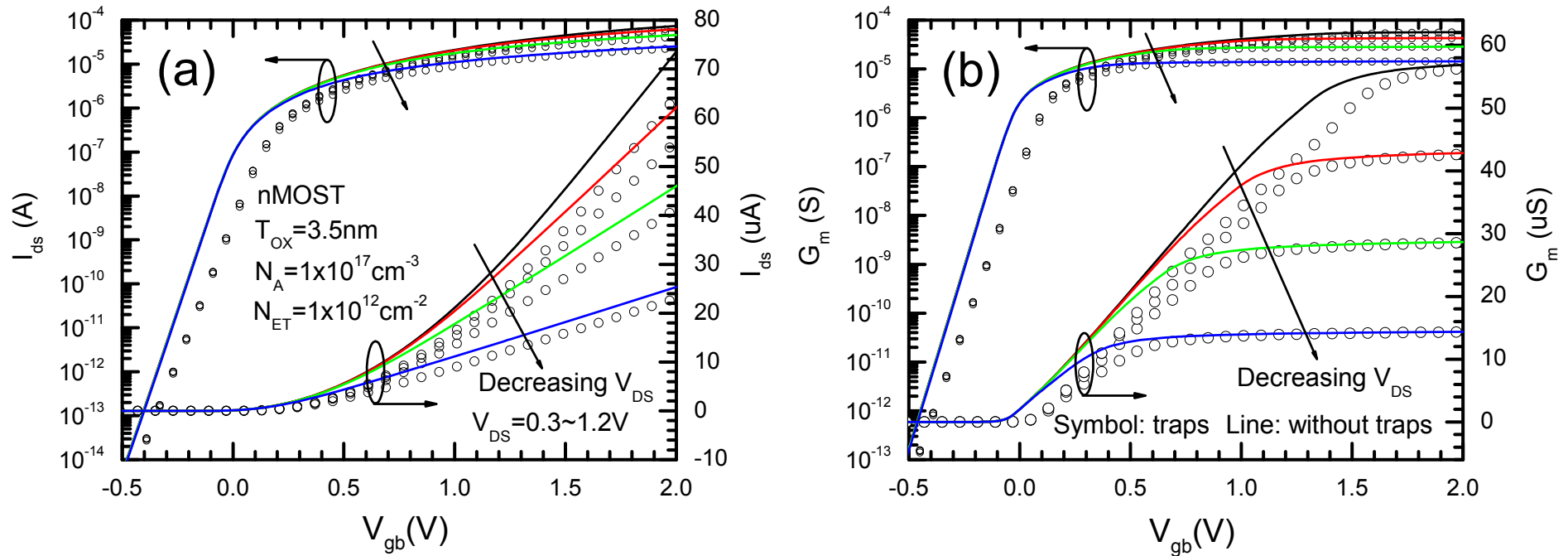
Interface-trap effect on drain-source current curves and transverse conductance  $G_m$  as a function of neutral electron interface-trap density  $N_{ET} = 0, 1.0 \times 10^{10}, 1.0 \times 10^{11}, 1.0 \times 10^{12}, 3.0 \times 10^{12},$  and  $5.0 \times 10^{12} cm^{-2}$ .

# Effect of interface-trap density on drain current (2)



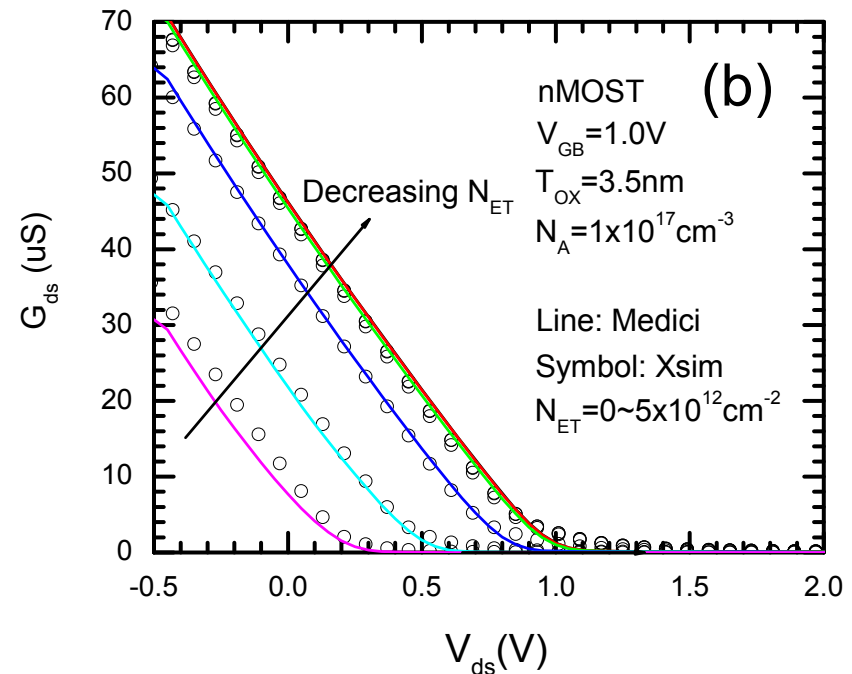
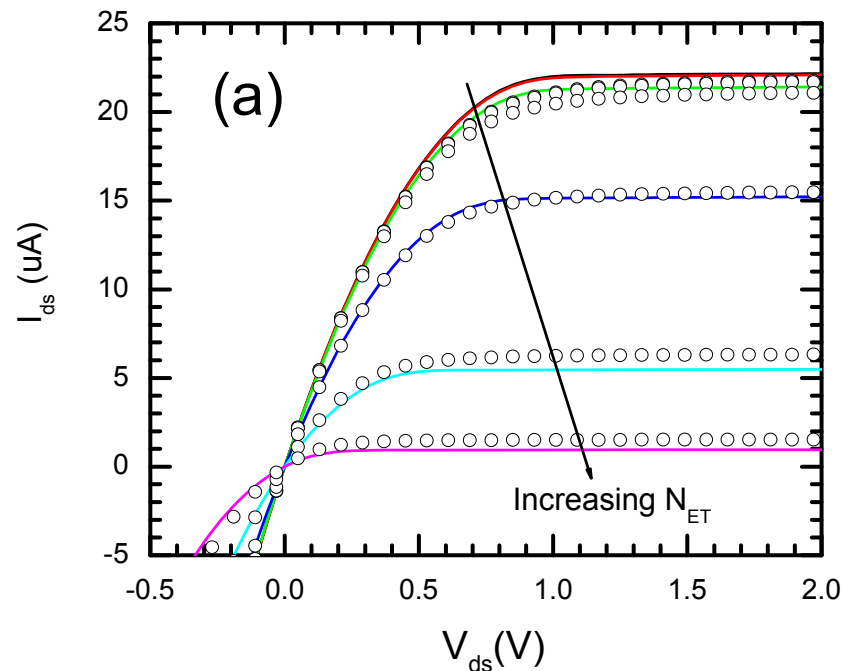
Interface-trap effect on drain-source current curves and transverse conductance  $G_m$  as a function of drain-source voltage  $V_{ds} = 0.3, 0.6, 0.9$  and  $1.2$  V.

# Effect of interface-trap density on drain current (3)



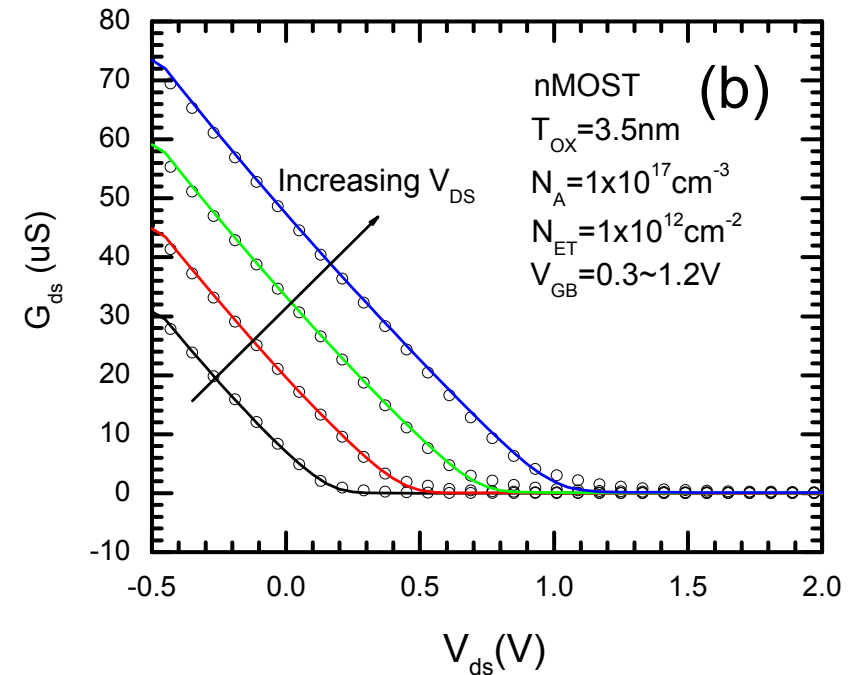
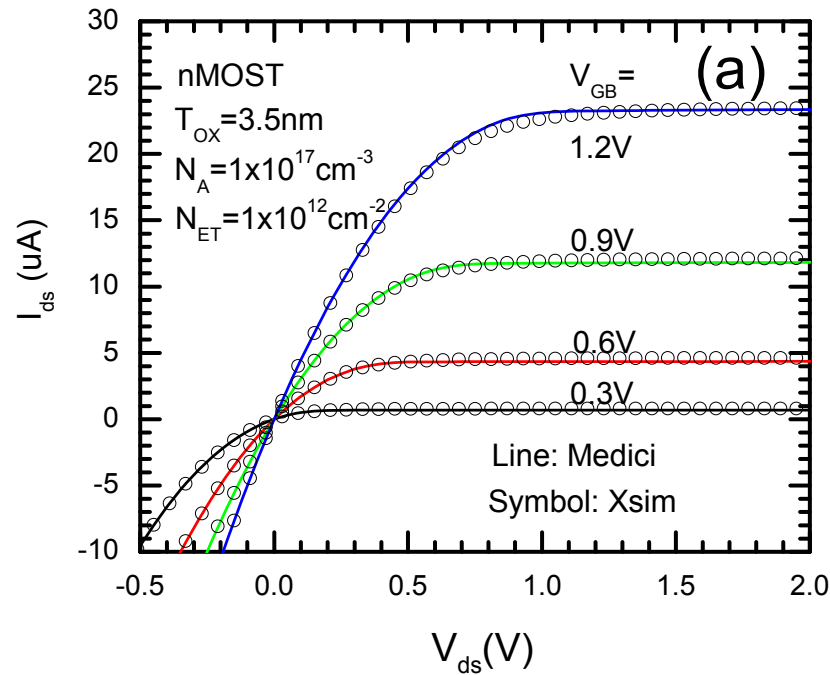
Interface-trap effect on drain-source current curves and transverse conductance  $G_m$  as a function of drain-source voltage  $V_{ds} = 0.3, 0.6, 0.9$  and  $1.2\text{V}$  (comparisons between devices with and without interface traps, the curves are generated using Xsim.).

# Effect of interface-trap density on drain current (4)



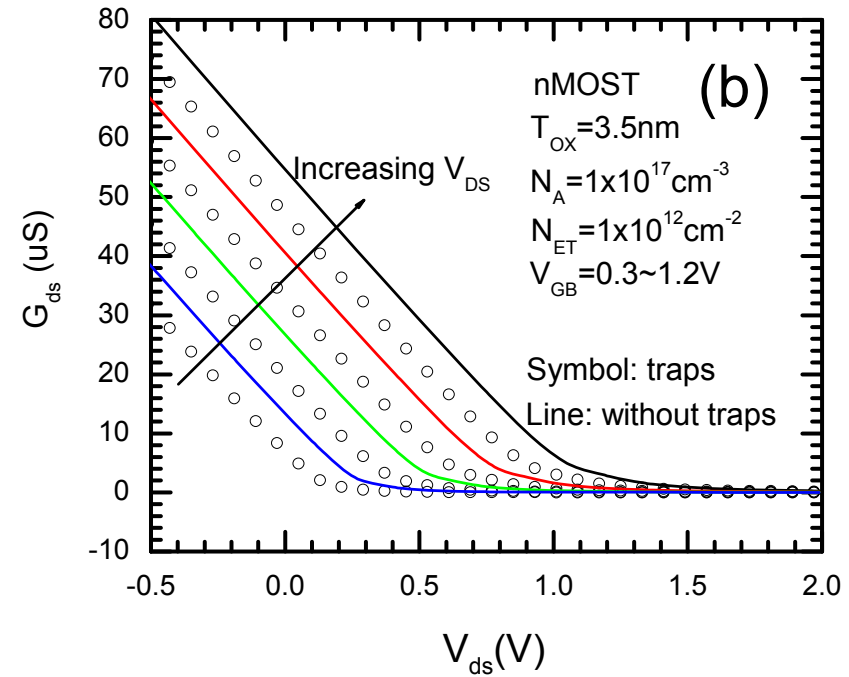
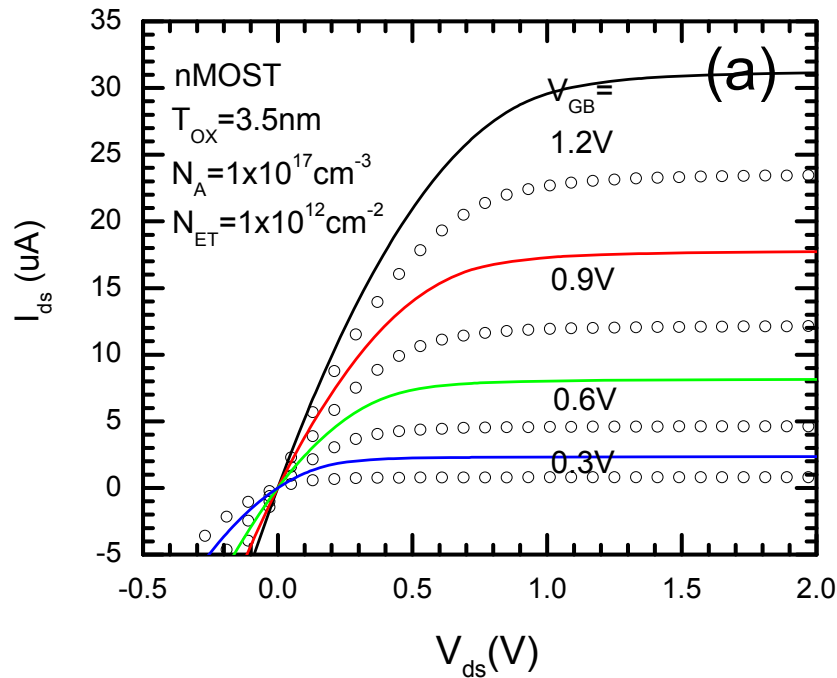
Interface-trap effect on drain-source current curves and output conductance  $G_{ds}$  as a function of neutral electron interface-trap density  $N_{ET} = 0, 1.0 \times 10^{10}, 1.0 \times 10^{11}, 1.0 \times 10^{12}, 3.0 \times 10^{12},$  and  $5.0 \times 10^{12} cm^{-2}$ .

# Effect of interface-trap density on drain current (5)



Interface-trap effect on drain-source current curves and output conductance  $G_{ds}$  as a function of gate voltage  $V_{gb} = 0.3, 0.6, 0.9$  and  $1.2\text{V}$ .

# Effect of interface-trap density on drain current (6)



Interface-trap effect on drain-source current curves and output conductance  $G_{ds}$  as a function of gate voltage  $V_{gb} = 0.3, 0.6, 0.9$  and  $1.2\text{V}$  (comparisons between devices with and without interface traps, the curves are generated using Xsim).

# Summary

- The device performance is significantly impacted by the presence of interface-trap charges.
- Drain-current characteristics are closer to the linear energy distribution of neutral electron interface traps in silicon energy gap.
- Extraction of device parameters from experimental measurements should consider interface-trap effect, especially for midlife transistors with high interface-trap concentration.
- The explicit analytic unified regional approach offers a simple way with computational efficiency and device physics to track the generation of interface traps and their properties along the surface channel region.

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- (6) **Z. Chen**, B. B. Jie, and C.-T. Sah, “Effects of Energy Distribution of Interface Traps on Recombination DC Current-Voltage Lineshape,” *J. Appl. Phys.* vol.100, 114511(2006).

Plus many references cited in these articles

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