NEW VERSION OF LETI-UTSOI2 FEATURING FURTHER IMPROVED PREDICTABILITY, AND A NEW STRESS MODEL FOR FDSOI TECHNOLOGY

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Leti-UTSOI2.1: new version of Leti compact model for FDSOI technologies

- Status of Leti-UTSOI2
- Improvements implemented on the new version
  - Predictability of 2D-electrostatic model
  - Weak/moderate inversion regime description
  - Gate current model
  - Narrow channel effects
- Summary
Leti-UTSOI2 is the first compact model able to describe FDSOI transistor behavior in all bias configurations, including strong forward back bias.

- Presented in T. Poiroux et al, IEDM 2013 and T. Poiroux et al, MOS-AK dec 2013
- Leti-UTSOI2 is currently used in industrial PDKs from ST Microelectronics
- End of 2014, a new version of the model, Leti-UTSOI2.1, has been implemented in all major SPICE simulation tools
Model structure

Leti-UTSOI2 is a surface potential model featuring local / global scale levels, as PSP and Leti-UTSOI1
Predictability of 2D electrostatics

- 2D electrostatics in Leti-UTSOI2 is based on equivalent 1D model accounting for 2D couplings
  - Effective geometry and biases allowing 2D interface potentials calculation with 1D model
Predictability of 2D electrostatics

- Link with process parameters at front gate (Leti-UTSOI2.1)

\[ V'_{GS} - \Delta \phi_m - \frac{E_G}{2q} = \frac{V_{GS} - \Delta \phi_m - E_G/(2q) + (C_{D,FC}/C_{ox})V_{DS}}{1 + (C_{S,FC} + C_{D,FC})/C_{ox}} \]

\[ C'_{ox} = C_{ox} \left(1 + \frac{C_{S,FC} + C_{D,FC}}{C_{ox}}\right) \]

Subthreshold swing degradation factor: local parameter \textbf{PSCE}

\[ \text{PSCE} = 2 \times \text{PSCEL} \left(\sqrt{\frac{\varepsilon_{ch} t_{Si}/2 t_{ox} + t_{ds}}{L_{eff}/2 \varepsilon_{ox} L_{eff}}}\right)^{\text{PSCEEXP}} \]

\[ \text{PSCE} = 2 \times \text{PSCEL} \left(\frac{\lambda_{2D}/L_{eff}}{}\right)^{\text{PSCEEXP}} \]

with \[ \lambda_{2D} = \sqrt{\frac{\varepsilon_{ch}}{\varepsilon_{ox}}} t_{Si}(t_{ox} + t_{ds}) \] (same as K.K. Young, IEEE TED, 1989)
Predictability of 2D electrostatics

- Link with process parameters at front gate (Leti-UTSOI2.1)

\[
V'_{GS} - \Delta \phi_m - \frac{E_G}{2q} = \frac{V_{GS} - \Delta \phi_m - E_G/(2q) + \frac{C_{D,FC}/C_{ox}}{1 + (C_{S,FC} + C_{D,FC})/C_{ox}}}{V_{DS}}
\]

\[
C'_{ox} = C_{ox} \left(1 + \frac{C_{S,FC} + C_{D,FC}}{C_{ox}}\right)
\]

DIBL factor: local parameter $\text{CF}$

\[
\text{CF} = \text{CFL} \left(\frac{\lambda_{2D}}{L_{eff}}\right)^\text{CFLEXP}
\]
Predictability of 2D electrostatics

- Link with process parameters at back gate (Leti-UTSOI2.1)

\[ V'_{BS} - \Delta \phi_{mb} - \frac{E_g}{2q} = \frac{V_{BS} - \Delta \phi_{mb} - \frac{E_g}{2q} + \left( \frac{C_{D,BC}}{C_{box}} \right) V_{DS}}{1 + \frac{C_{S,BC} + C_{D,BC}}{C_{box}}} \]

\[ C'_{box} = C_{box} \left( 1 + \frac{C_{S,BC} + C_{D,BC}}{C_{box}} \right) \]

Sub. swing degradation factor: asymmetry local parameter \textbf{PSCEB}

\[ PSCE_{back} = \text{PSCE} \times \text{PSCEB} \times \frac{t_{box}}{t_{ox}} \quad \text{with} \quad \text{PSCEB} = \frac{C_{S,BC} + C_{D,BC}}{C_{S,FC} + C_{D,FC}} \]

\textbf{PSCEB} = \textbf{PSCEO} not scalable
Predictability of 2D electrostatics

- Link with process parameters at back gate (Leti-UTSOI2.1)

\[ V'_{BS} - \Delta \phi_{mb} - \frac{E_G}{2q} = \frac{V_{BS} - \Delta \phi_{mb} - E_G/(2q) + \left(\frac{C_{D,BC}}{C_{box}}\right)V_{DS}}{1 + \left(\frac{C_{S,BC} + C_{D,BC}}{C_{box}}\right)} \]

\[ C'_{box} = C_{box} \left(1 + \frac{C_{S,BC} + C_{D,BC}}{C_{box}}\right) \]

DIBL factor: asymmetry local parameter \( \text{CFB} \)

\[ CF_{back} = CF \times \text{CFB} \times \frac{t_{box}}{t_{ox}} \quad \text{with} \quad \text{CFB} = \frac{C_{D,BC}}{C_{D,FC}} \]

\( \text{CFB} = \text{CFBO} \) not scalable
Predictability of 2D electrostatics: sub. swing

- Comparison to TCAD simulations (lines: model, dots: TCAD)

Parameters PSCEL, PSCELEXP, PSCEBO set on "Vb effect" curve
Predictability of 2D electrostatics: DIBL

• Comparison to TCAD simulations (lines: model, dots: TCAD)

Parameters CFL, CFLEXP, CFBO set on « Vb effect » curve

* For large \( t_{\text{box}} \) variations, slight dependence of CFBO with \( t_{\text{box}} \) is required to capture properly fringing fields effect
Predictability of 2D electrostatics: linear $V_{th}$

- Comparison to TCAD simulations (lines: model, dots: TCAD)

No additional parameters
Predictability of 2D electrostatics: sat. $V_{th}$

- Comparison to TCAD simulations (lines: model, dots: TCAD)

No additional parameters

* including slight dependence of CFBO with $t_{\text{box}}$
Accuracy in weak/moderate inversion regime

- Depletion of source/drain LDD tails depends on front/back bias
  - Electrical channel length is not constant in subthreshold regime
  - Subthreshold slope is non uniform => Gm/Id is varying vs Vg and Vb

Results from TCAD simulations
Leti-UTSOI2 improvements

Accuracy in weak/moderate inversion regime

- Leti-UTSOI2 has been improved to capture this effect
- Comparison to hardware data

Without $L_{\text{eff}}$ dependence (Leti-UTSOI2.0)  
With $L_{\text{eff}}$ dependence (Leti-UTSOI2.1)
Accuracy of gate current model

- Model completed to account for a TAT-like component of gate to channel current with a single new parameter NIGINV

- Improved description in the subthreshold regime
Refined description of narrow channel effect

- Leti-UTSOI2.1 accounts for possible evolution of body factor with channel width through PNCE parameter
- Slight effect accurately captured
Other model improvements

- Device thermal node is now accessible (optional 5\textsuperscript{th} node)
  - Possibility to connect external thermal RC network at circuit level

- Mobility scaling law has been modified for more accuracy
  - PSP-like scaling law adopted

- Modified VFB scaling law
  - Easier extraction of narrow channel effects
Summary

• Improved version of Leti-UTSOI2 is available
• Main improvements concerns:
  ▪ Predictability of 2D electrostatic model over process parameters
  ▪ Accuracy of weak/moderate inversion regime description
  ▪ Accuracy of gate current modeling
  ▪ Refined description of narrow channel effects
• In addition, device thermal node is now available as an optional 5\textsuperscript{th} node

References about Leti-UTSOI2

T. Poiroux et al., “UTSOI2: A Complete Physical Compact Model for UTBB and Independent Double Gate MOSFETs”, IEDM 2013
New stress model for FDSOI technologies

- Motivations
- Analytical model presentation
- Validation with respect to silicon data
- Summary
Motivations

- Performance of next generation technologies increasingly rely on strain engineering
- Efficient usage of strained materials demonstrated in UTBB FDSOI 14nm [1]
- Supported by 3D mechanical simulations, quantum simulations and analytical model [2]
- For CAD offer, interest in using and adapting well-known SA/SB approach developed for STI stress [3] to capture geometry dependence of new stress effects

Case study: strain induced by SiGe channel

- Ge induces compressive strain in SOI film
- Strain tends to relax at the edges of the film

Courtesy from [1]

Model assumptions

- Electrical parameters impacted by strain present an evolution along active area similar to that of longitudinal stress, captured by a relaxation factor $g(x, L_{\text{act}})$.

- Impacted parameters are:
  - Low field mobility ($\rightarrow I_{\text{odlin}}$, i.e. $I_{\text{lin}}$ at $V_{gs}-V_{th}=0.5V$)
  - «Flat-band» voltage ($\rightarrow V_{\text{tlin}}$)
  - DIBL ($\rightarrow V_{\text{tsat}}$)
  - Saturation velocity ($\rightarrow I_{\text{sat}}, I_{\text{eff}}$)
Model formulation using $x$ and $L_{act}$

- Evolution of electrical parameter $P$

\[
P(x, L_{act}) = P_{full\ strain} + \Delta P \times g(x, L_{act})
\]

\[
\Delta P = P_{edge} - P_{full\ strain} \text{ can be a function of } W, L
\]

\[
g(x, L_{act}) = 1 - \left[ \frac{2}{(1 - e^{-x/\lambda})^{-\alpha} + (1 - e^{(x-L_{act})/\lambda})^{-\alpha}} \right]^{1/\alpha}
\]

$\lambda$ and $\alpha$ are model parameters

$g(x, L_{act})$ for $\lambda = 120\, \text{nm}$ and $\alpha = 3$
Model formulation using SA and SB

- Parameter value is taken at the center of the channel:

\[
g(SA, SB) = 1 - \left[ \frac{2}{(1 - e^{-(SA+L/2)/\lambda})^{-\alpha} + (1 - e^{-(SB+L/2)/\lambda})^{-\alpha}} \right]^{1/\alpha}
\]

- When SA=SB, relaxation factor reduces to:

\[
g(SA, SB = SA) = e^{-(SA+L/2)/\lambda}
\]

- This allows a simple parameter extraction
  - \( \lambda \) (and \( \Delta P \)) extraction on SA scaling with SA=SB
  - \( \alpha \) extraction on SA or SB scaling with SA≠SB
Electrical parameter expressions with respect to $SA_{ref}/SB_{ref}$ reference value

- **Ratio-like expression (e.g. mobility, saturation velocity)**
  \[
P(SA, SB) = P(SA_{ref}, SB_{ref}) \frac{1 + \left(\frac{\Delta P}{P_{full\ strain}}\right)g(SA, SB)}{1 + \left(\frac{\Delta P}{P_{full\ strain}}\right)g(SA_{ref}, SB_{ref})}
\]
  - Amplitude parameter is $\Delta P/P_{full\ strain}$

- **Delta-like expression (e.g. Vth, DIBL)**
  \[
P(SA, SB) = P(SA_{ref}, SB_{ref}) + \Delta P \left( g(SA, SB) - g(SA_{ref}, SB_{ref}) \right)
\]
  - Amplitude parameter is $\Delta P$
New stress model

Model formulation for multi-finger devices (useful for pre-layout simulations)

- In previous model equations, relaxation factor, $g(SA, SB)$ is replaced by $\hat{g}(SA, SB)$

$$\hat{g}(SA, SB) = \frac{1}{NF} \sum_{i=0}^{NF-1} g(SA + i(SD + L), SB + (NF - 1 - i)(SD + L))$$
Experimental validation: Vtlin

![Graph showing Vtlin delta vs SB/SBref](image)
Experimental validation: Vtsat
Experimental validation: $I_{lin} @ V_{gs-Vth}=0.5V$
Summary

• Stress model used in SPICE has to be updated to handle new strain engineering strategies of advanced technologies
• A new semi-empirical model is proposed, which is compatible with SA/SB formalism of initial stress model
• Model accuracy is validated against 14nm UTBB FDSOI silicon data
• This model will be implemented in Leti-UTSOI2 compact model, besides existing STI stress model (stress model selector will be added too)
References

• R.A. Bianchi et al., "Accurate Modeling of Trench Isolation Induced Mechanical Stress Effect on MOSFET Electrical Performance“, IEDM 2002


• B. De Salvo et al., “A mobility enhancement strategy for sub-14nm power-efficient FDSOI technologies”, IEDM 2014
Thank you for your attention